Physical Layer

Lecture Progression

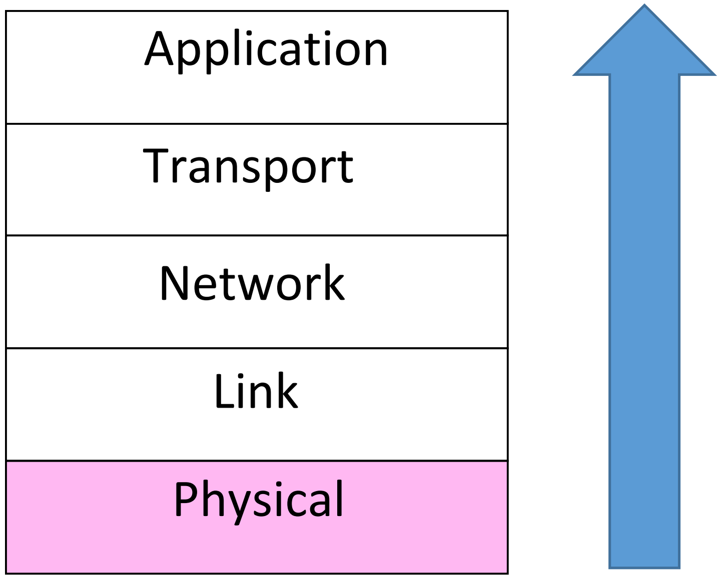
- Bottom-up through the layers:

Application	- HTTP, DNS, CDNs
Transport	- TCP, UDP
Network	- IP, NAT, BGP
Link	- Ethernet, 802.11
Physical	- wires, fiber, wireless

- Followed by more detail on:
  - Quality of service, Security (VPN, SSL)

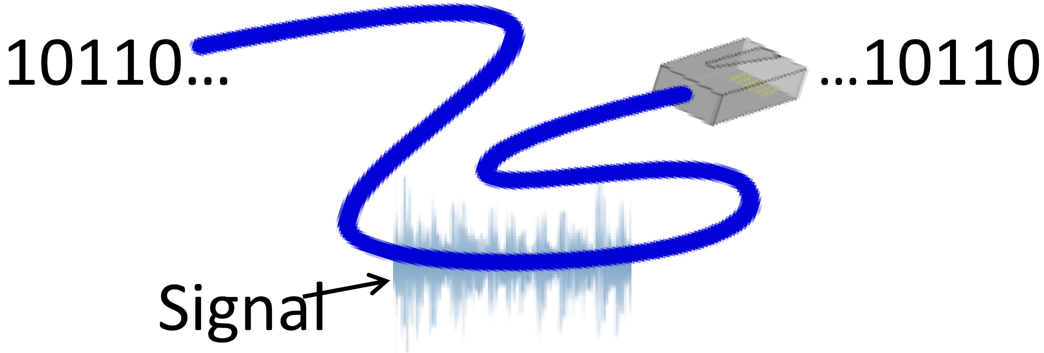
Where we are in the Course

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



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



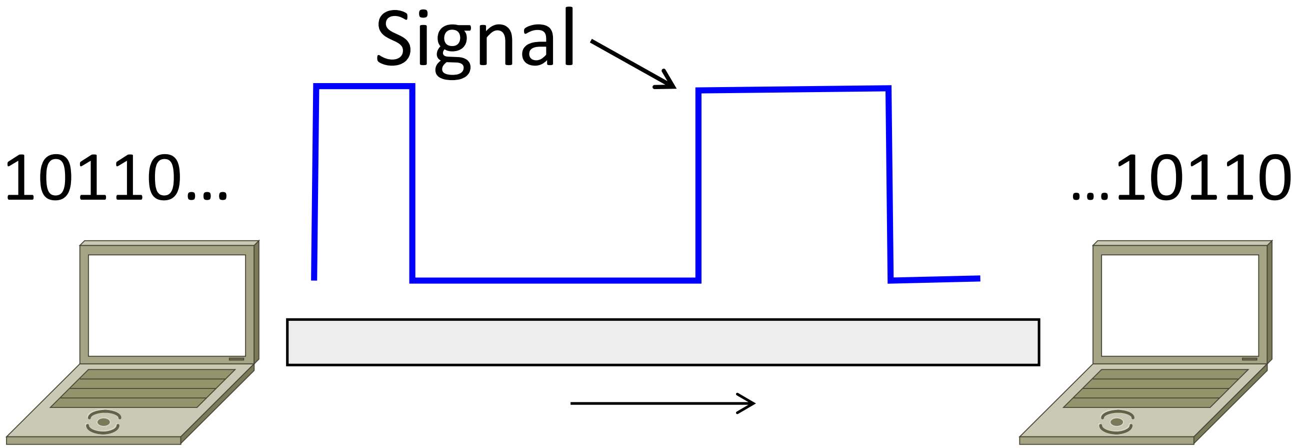
Topics

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

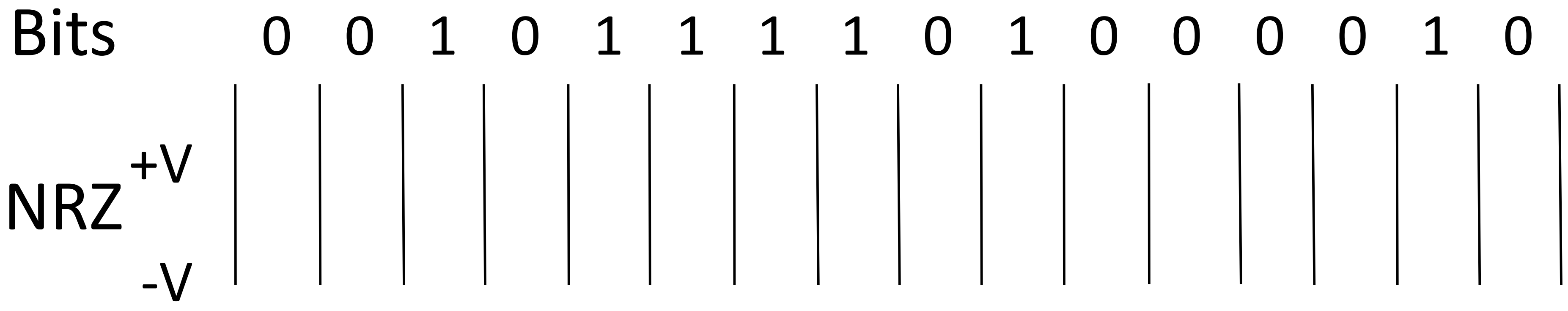
Topic

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



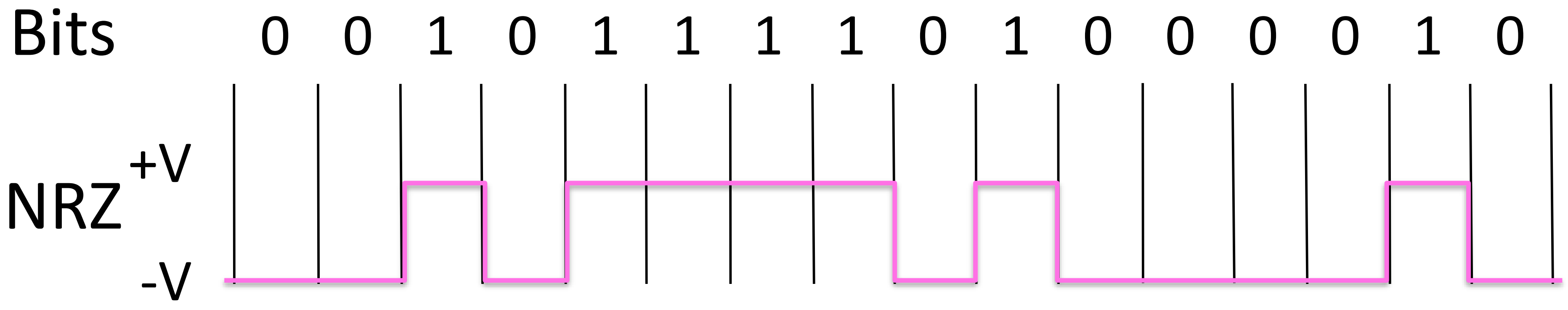
A Simple Coding

- 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)

- 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 (3)

- Problems?

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

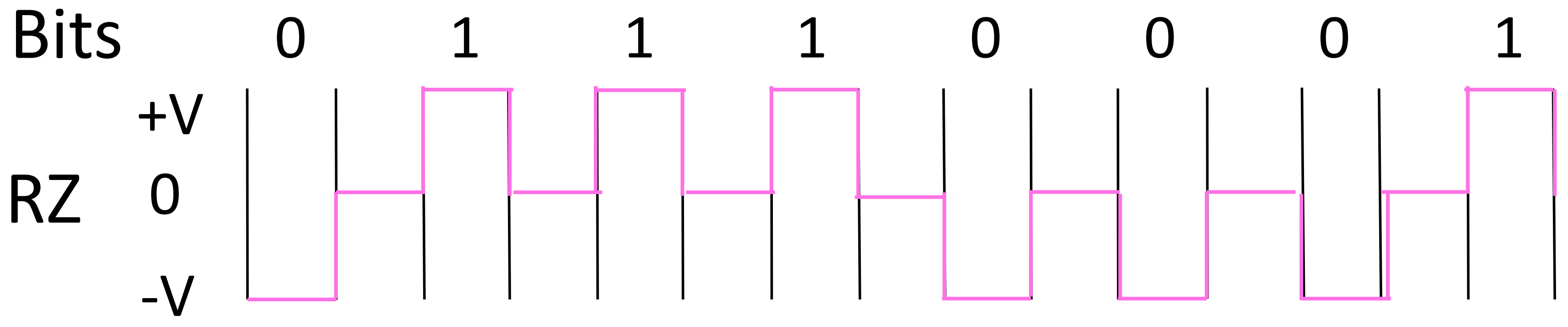
- Um, how many zeros was that?
  - Receiver needs frequent signal transitions to decode bits

- 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:

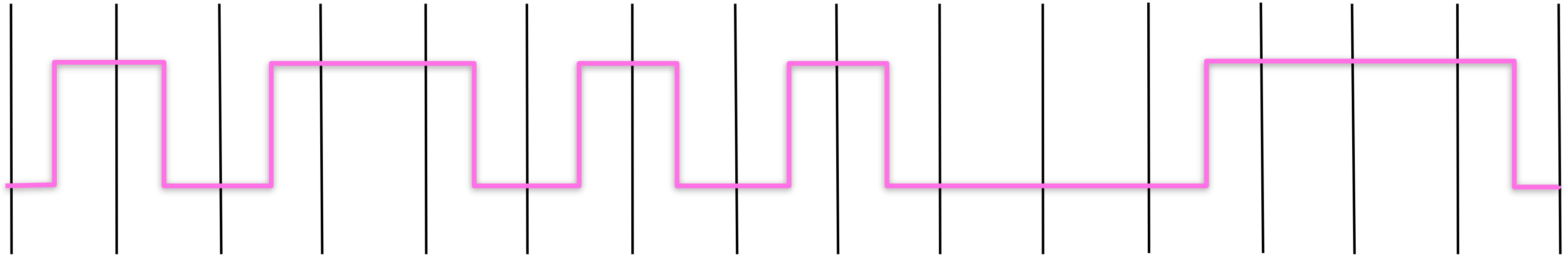
Signal:

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:

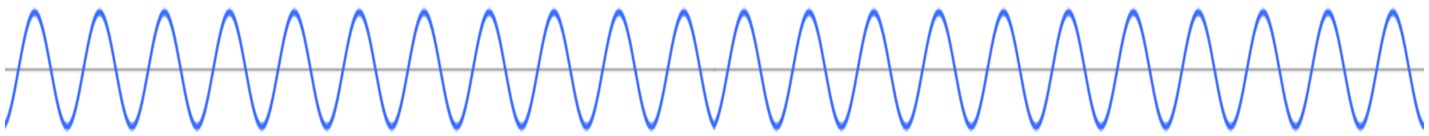


Modulation vs Coding

- What we have seen so far is called <u>coding</u>
  - Signal is sent directly on a wire
- These signals do not propagate well as RF
  - Need to send at higher frequencies
- <u>Modulation</u> 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

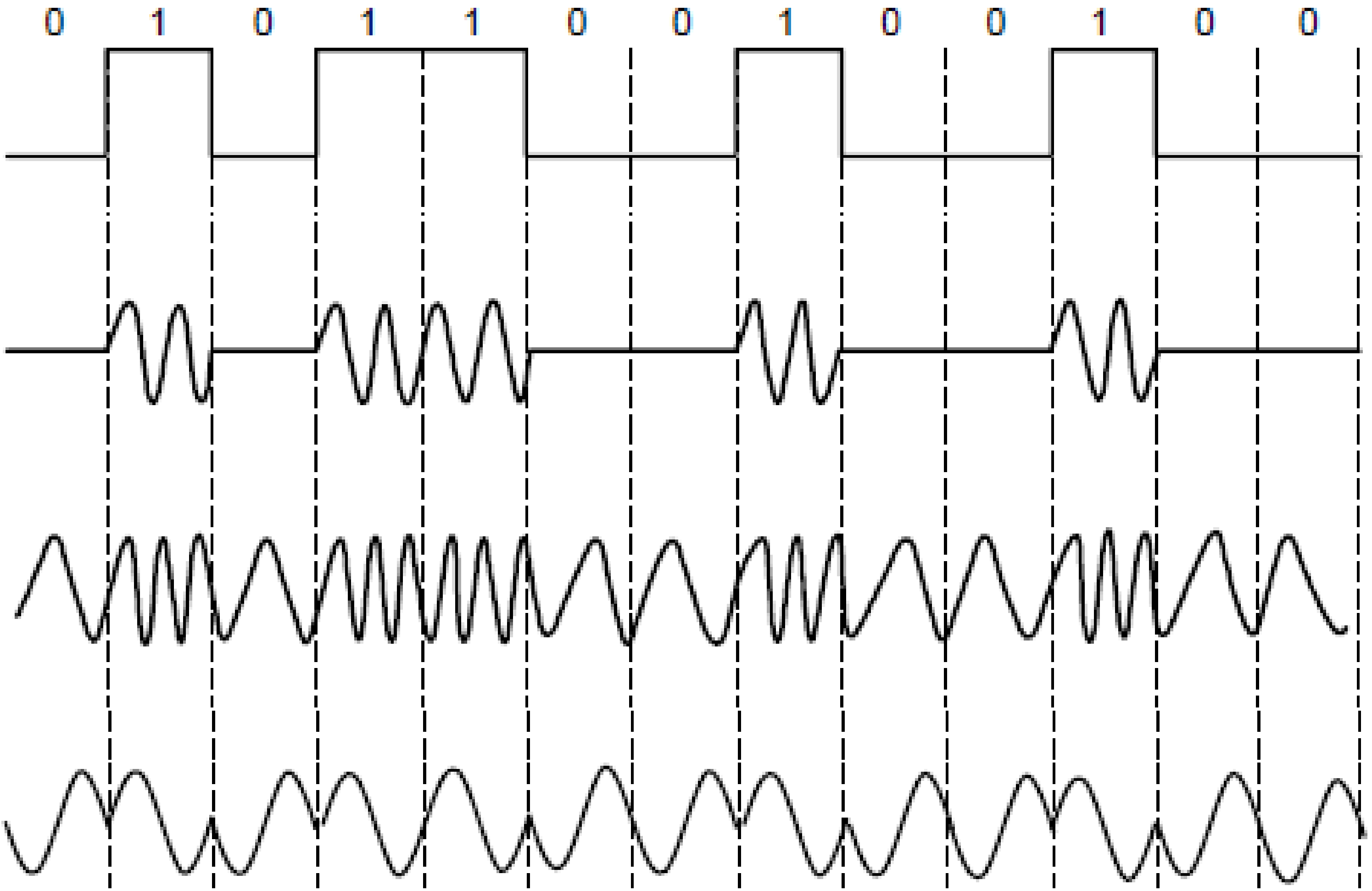
Comparisons

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying

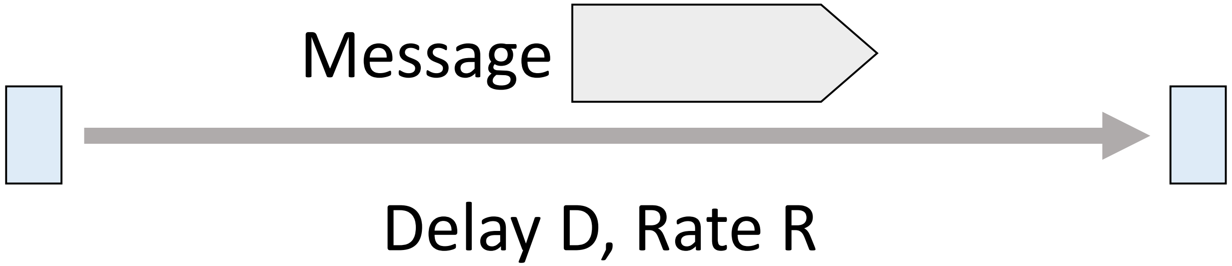


Philosophical Takeaways

- Everything is 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)

Simple Link Model

- We'll end with an 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

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

Message Latency (2)

- 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 = Length / ⅔c = D seconds

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

Latency Examples

Remembering $L = M/R + D$

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

Latency Examples (2)

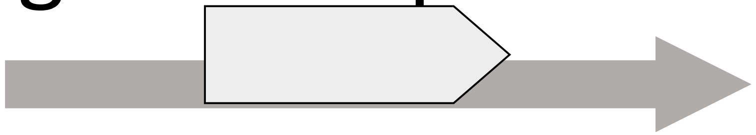
- "Dialup" with a telephone modem:
  - D = 5 ms, R = 56 kbps, M = 1250 bytes
  - L = (1250x8)/(56 x 10^3) sec + 5ms = 184 ms!

- Broadband cross-country link:
  - D = 50 ms, R = 10 Mbps, M = 1250 bytes
  - L = (1250x8) / (10 x 10^6) sec + 50ms = 51 ms

- A long link or a slow rate means high latency: One component dominates

Bandwidth-Delay Product

- Messages take space on the wire!



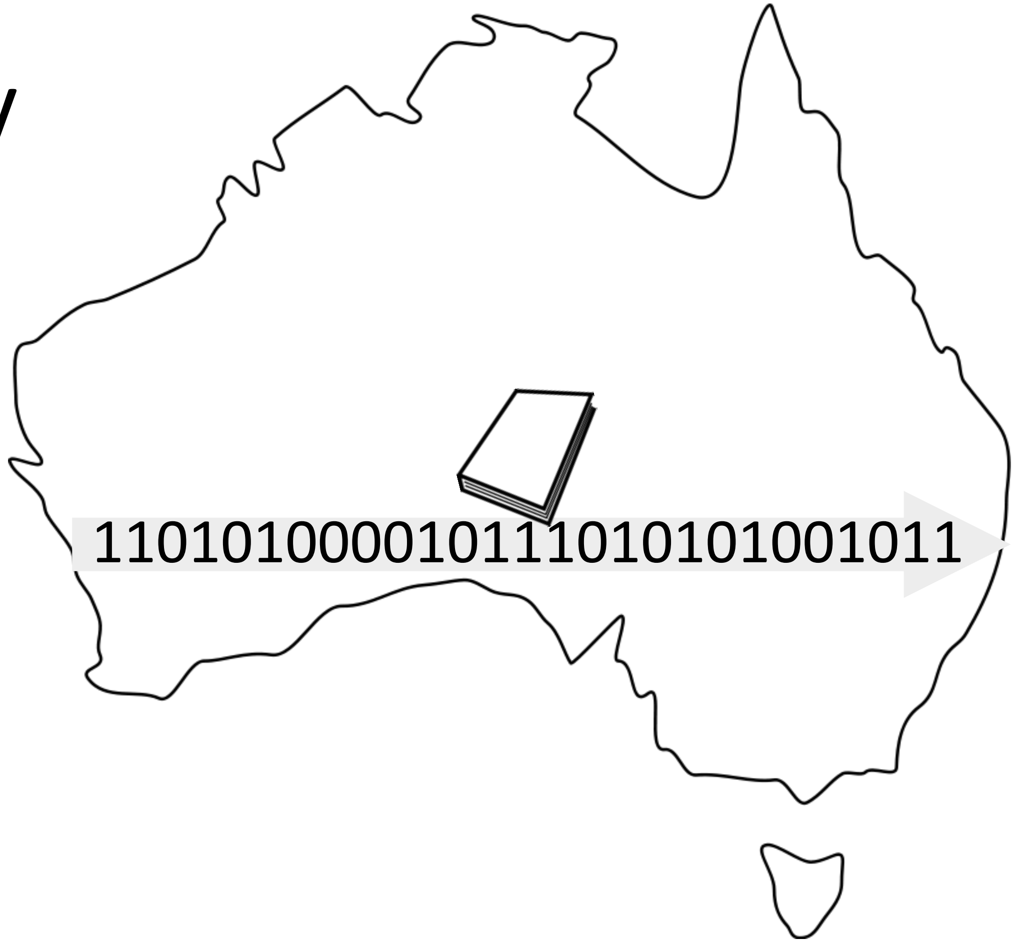
- The amount of data in flight is the bandwidth-delay (BD) product

$$BD = R \times D$$

  - Measure in bits, or in messages
  - Small for LANs, big for "long fat" pipes

Bandwidth-Delay Example

- Fiber at home, cross-country
  R=40 Mbps, D=50 ms



Bandwidth-Delay Example (2)

- Fiber at home, cross-country

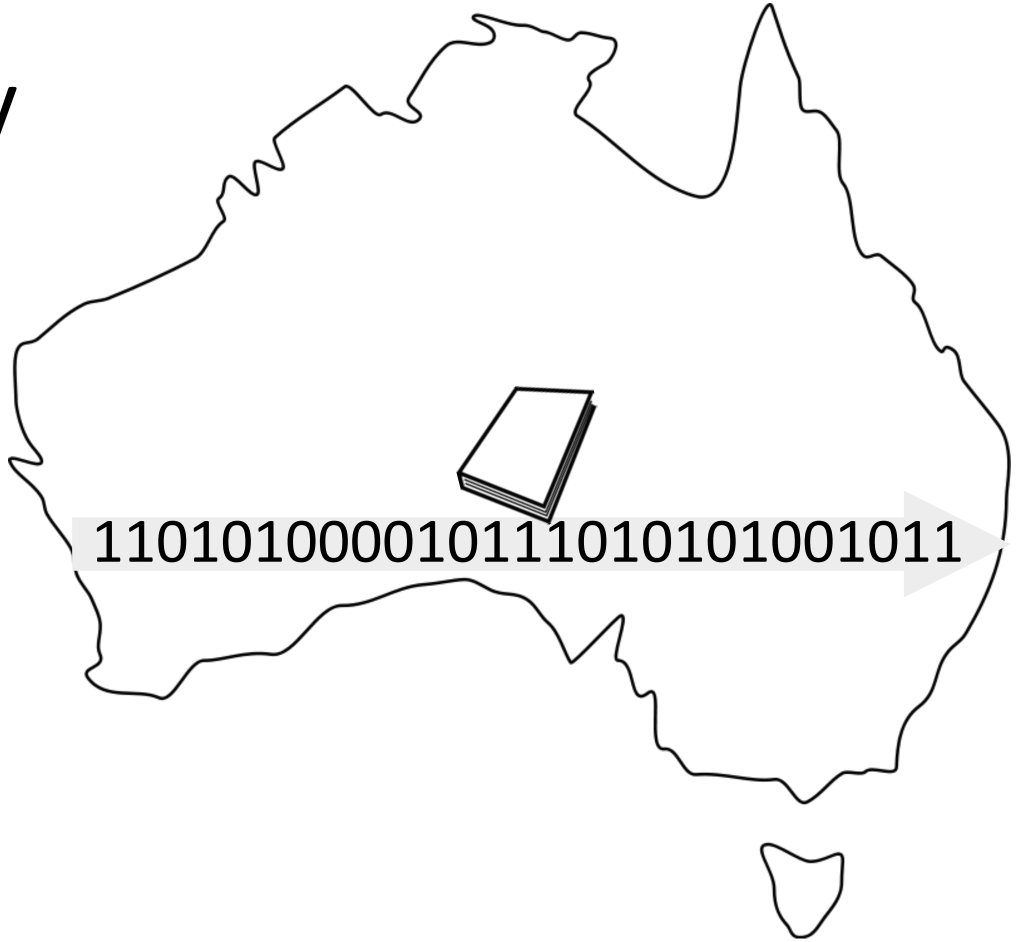
  R=40 Mbps, D=50 ms

  BD = $40 \times 10^6 \times 50 \times 10^{-3}$ bits

  = 2000 Kbit

  = 250 KB

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



Media

[2] media

noun, often attributive

Definition of MEDIA

plural **medias**

1 : a medium of cultivation, conveyance, or expression • Air is a *media* that conveys sound.; *especially* : MEDIUM 2b

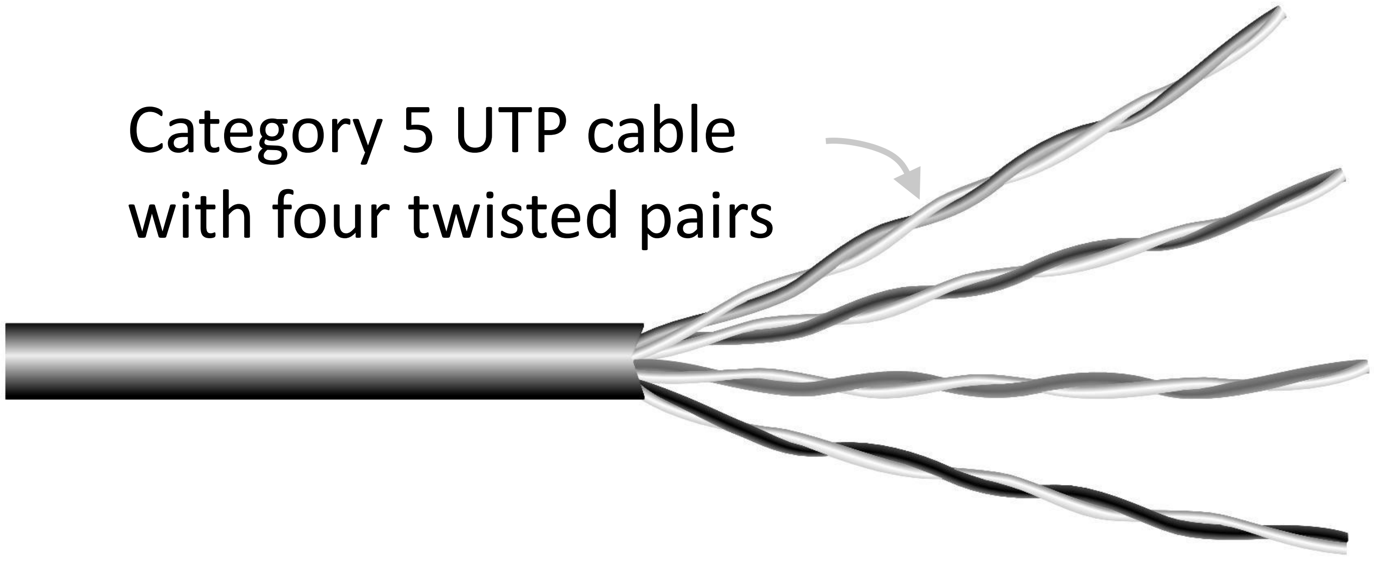
https://www.merriam-webster.com/dictionary/media

Types of Media

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

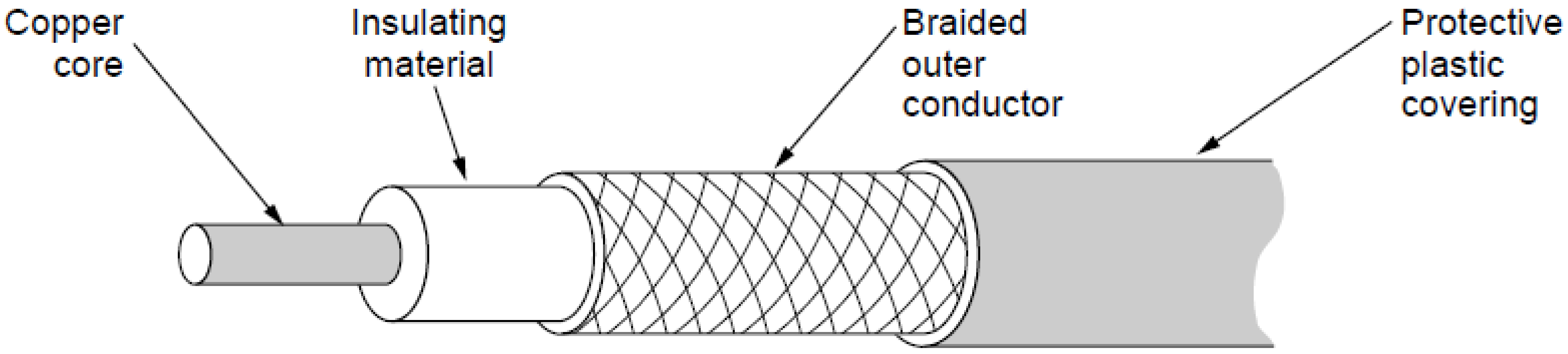
Wires – Twisted Pair

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



Wires – Coaxial Cable

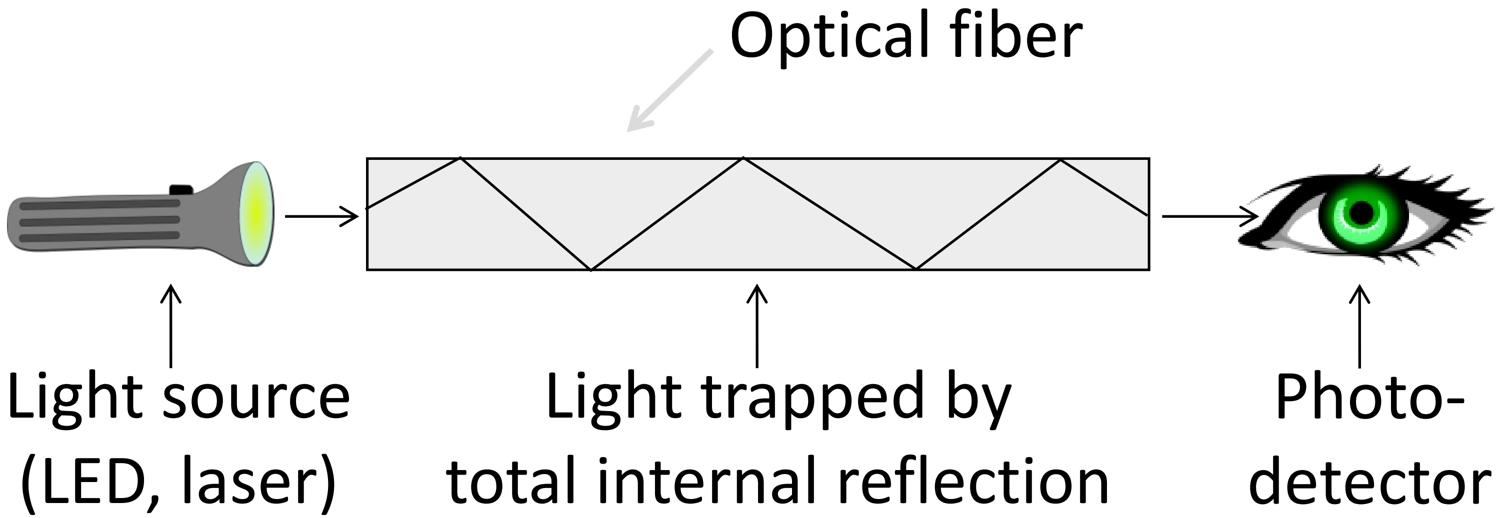
- Also common. Better shielding for better performance



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

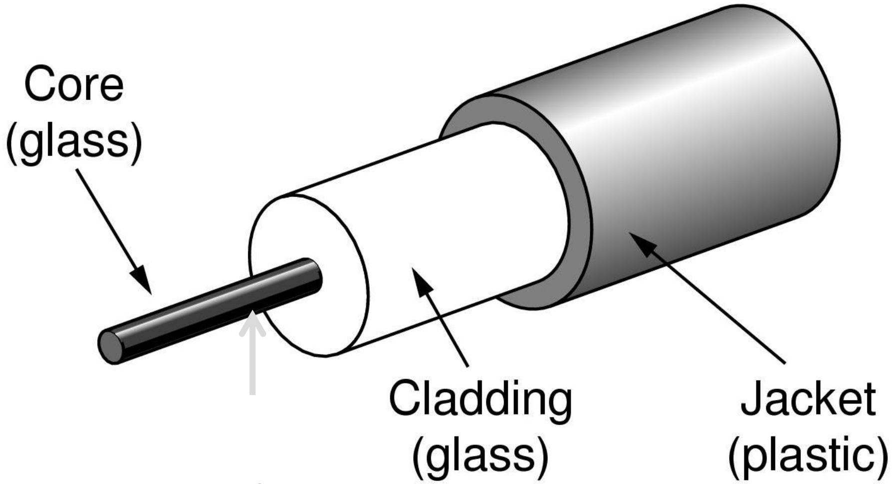
Fiber

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

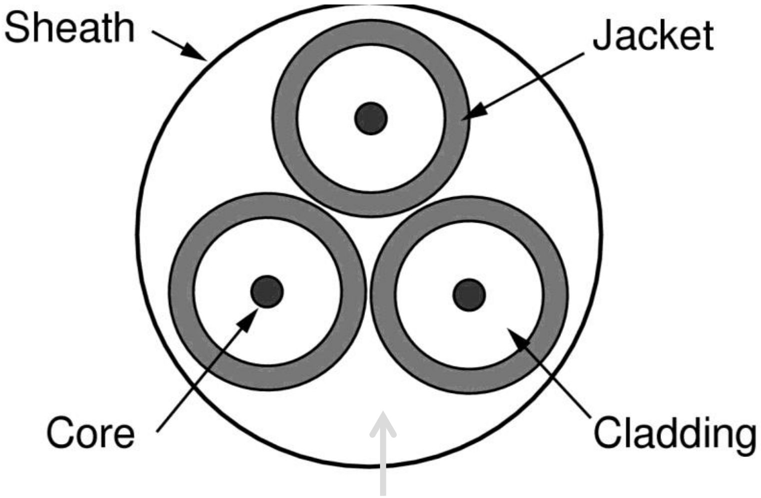


Fiber (2)

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



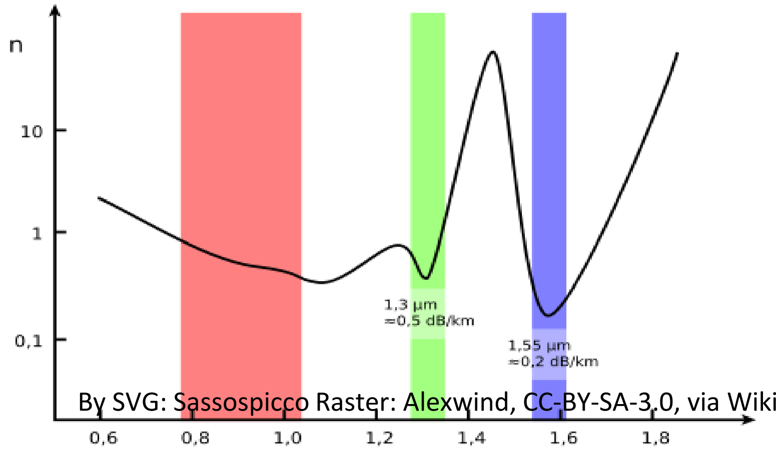
One fiber



Fiber bundle in a cable

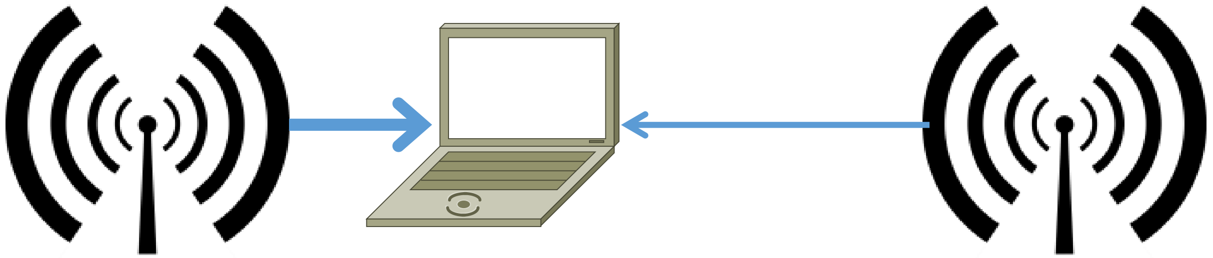
Signals over Fiber

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

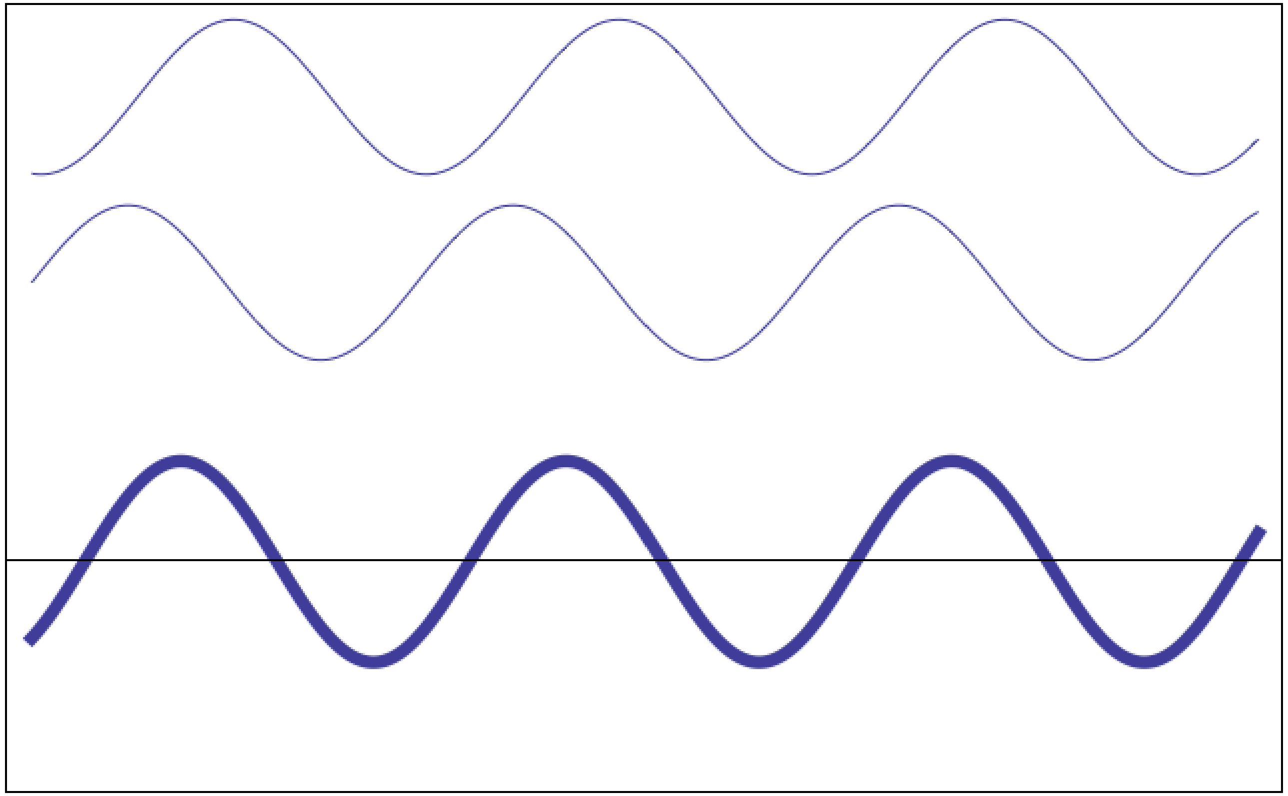


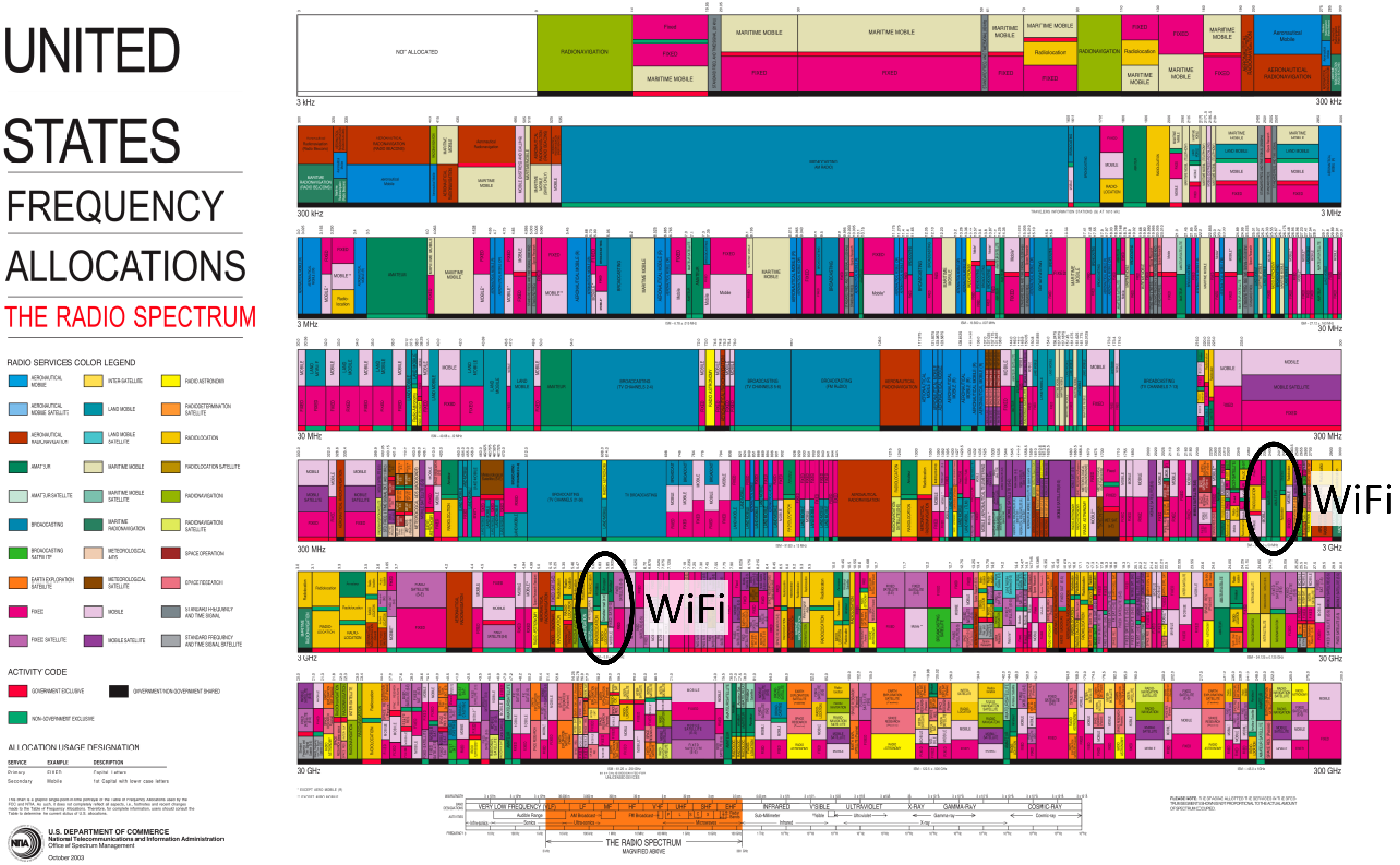
Wireless

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



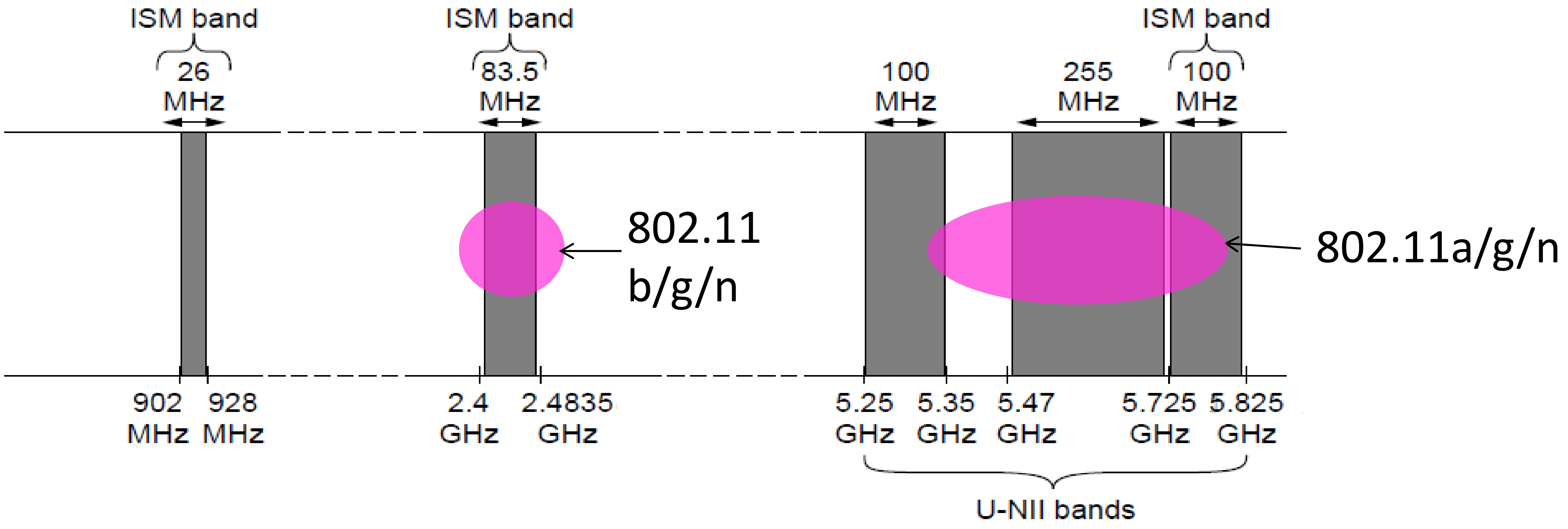
Wireless Interference




UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
WiFi
WiFi
THE RADIO SPECTRUM
U.S. DEPARTMENT OF COMMERCE
October 2003

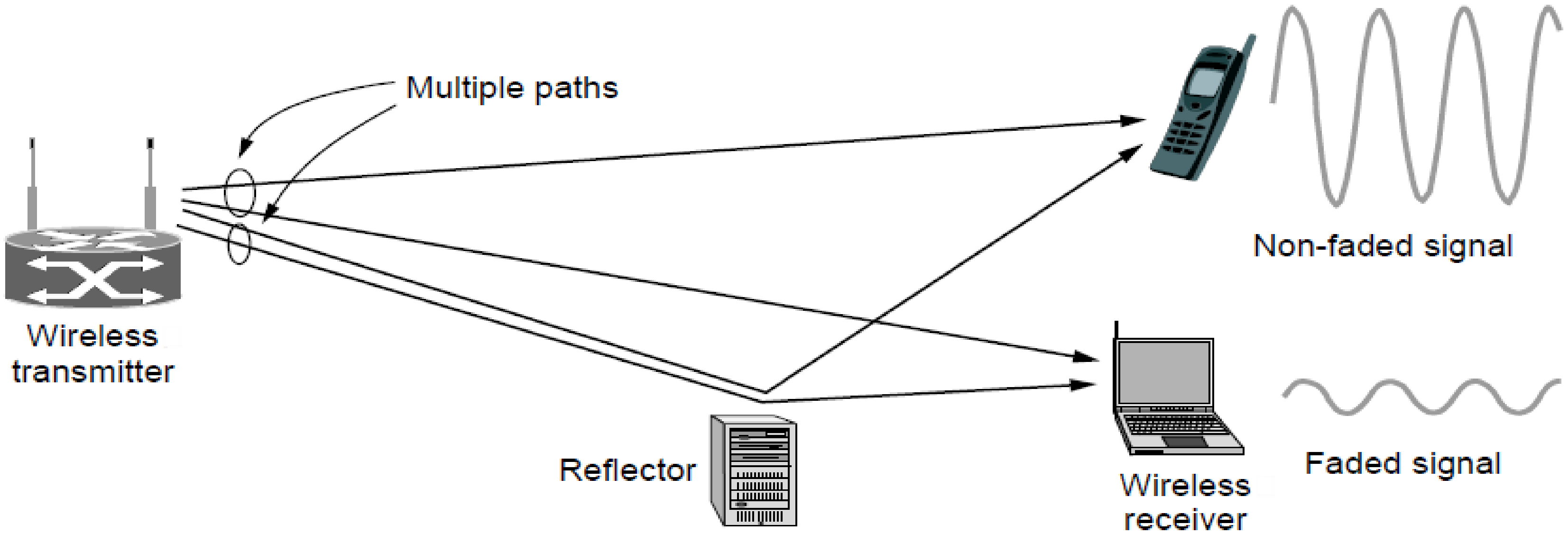
Wireless (2)

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



Multipath (3)

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



Wireless (4)

- Various other effects too!
  - Wireless propagation is complex, depends on environment
- Some key effects are highly frequency dependent,
  - E.g., <u>multipath</u> at microwave frequencies

Limits

Topic

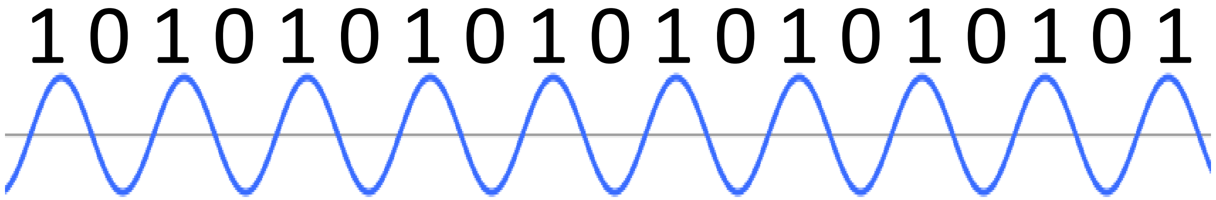
- How rapidly can we send information over a link?
  - Nyquist limit (~1924)
  - Shannon capacity (1948)
- Practical systems are devised to approach these limits

Key Channel Properties

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

Nyquist Limit

- The maximum symbol rate is 2B



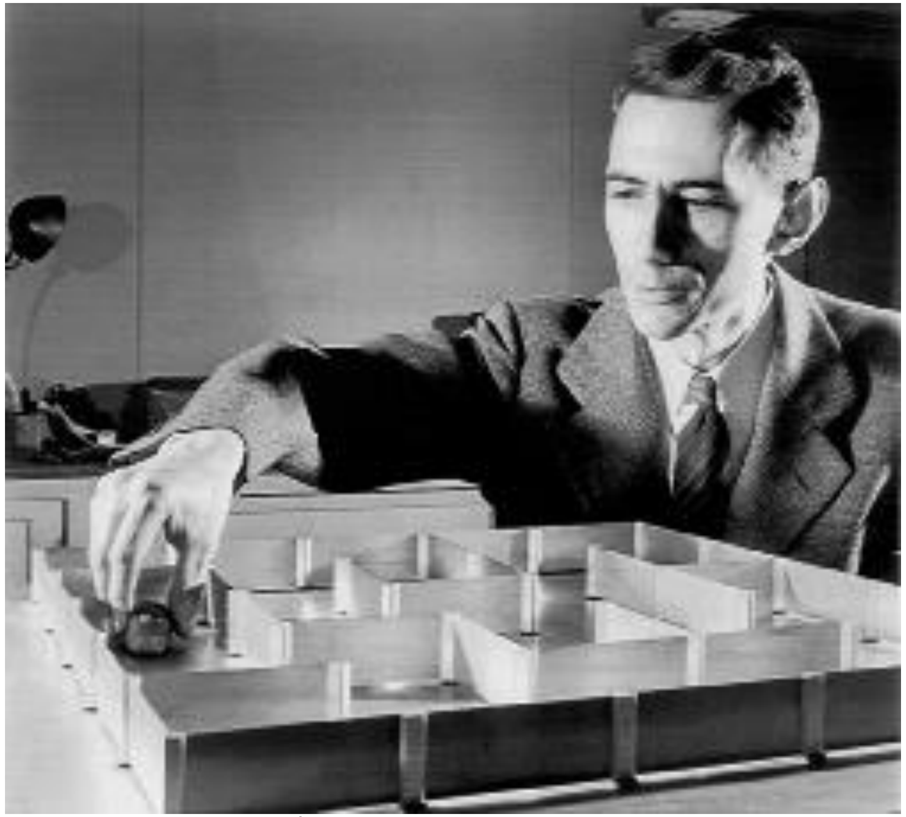
- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

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

Claude Shannon (1916-2001)

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

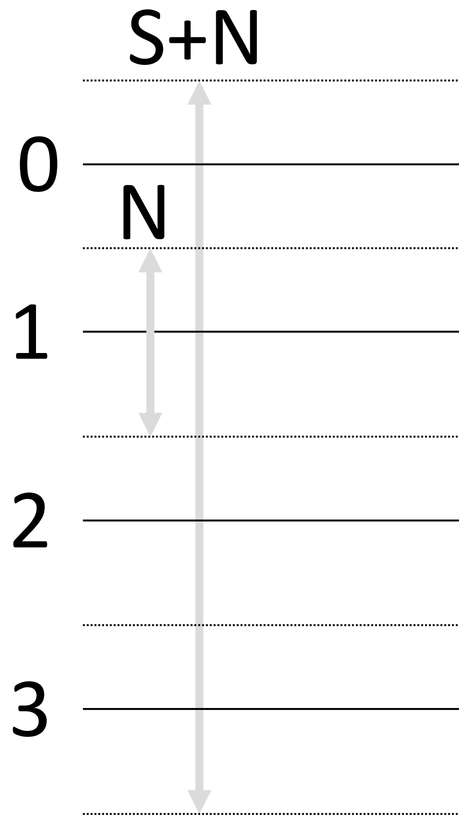
Electromechanical mouse that "solves" mazes!



Credit: Courtesy MIT Museum

Shannon Capacity

- How many levels we can distinguish depends on S/N
  - Or SNR, the 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 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

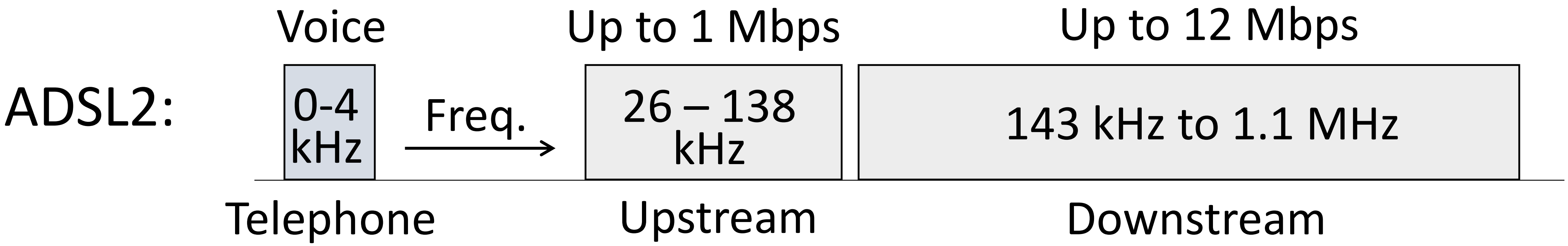
Adapt data rate to SNR

Putting it all together – DSL

- DSL (Digital Subscriber Line, see §2.6.3) is widely used for broadband; many variants offer 10s of Mbps
  - Reuses twisted pair telephone line to the home; it has up to ~2 MHz of bandwidth but uses only the lowest ~4 kHz

DSL (2)

- DSL uses passband modulation (called OFDM)
  - Separate bands for upstream and downstream (larger)
  - Modulation varies both amplitude and phase (QAM)
  - High SNR, up to 15 bits/symbol, low SNR only 1 bit/symbol

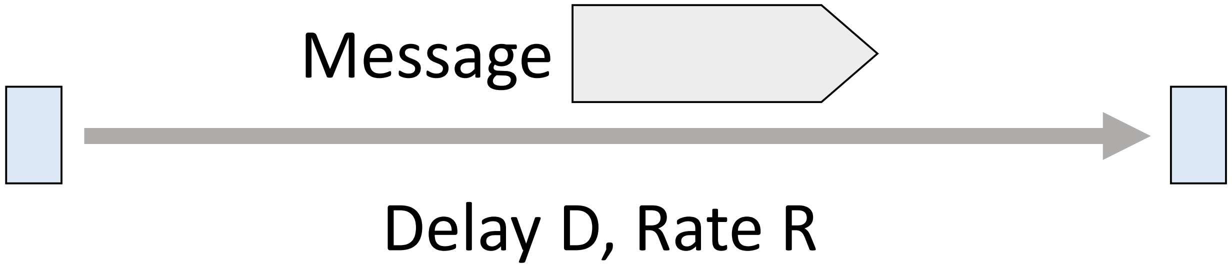


Phy Layer Innovation Still Happening!

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

All distilled to a simple link model

- 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