CSE 461: Computer Networks

Spring 2021

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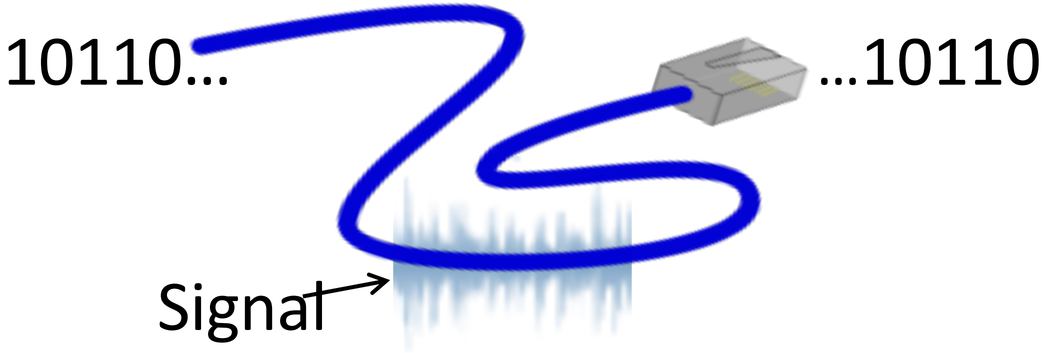
Physical Layer

Physical Layer

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



Topics

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

Media

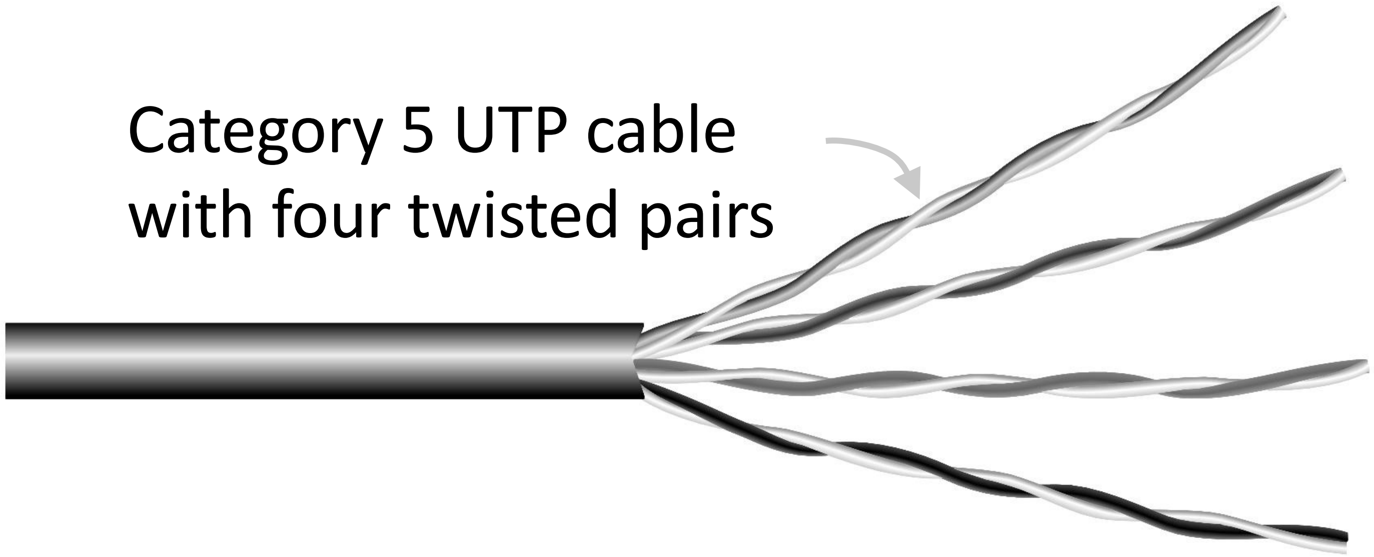
Types of Media

- <u>Media</u> propagate <u>signals</u> that carry <u>bits</u>

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

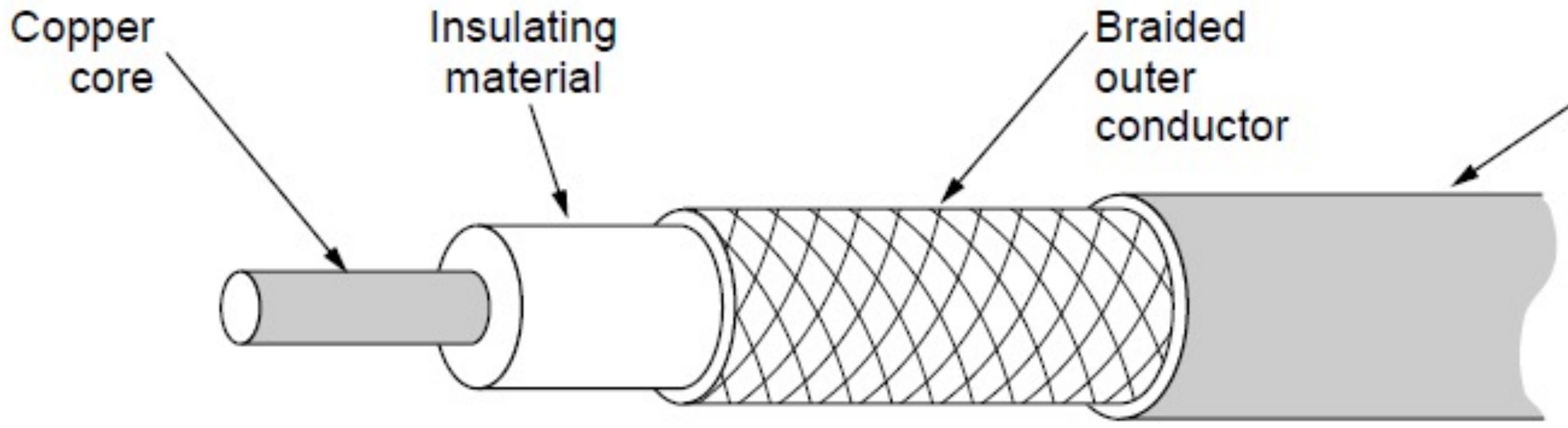
Wires – Twisted Pair

- Very common; used in LANs and telephone lines



Wires – Coaxial Cable

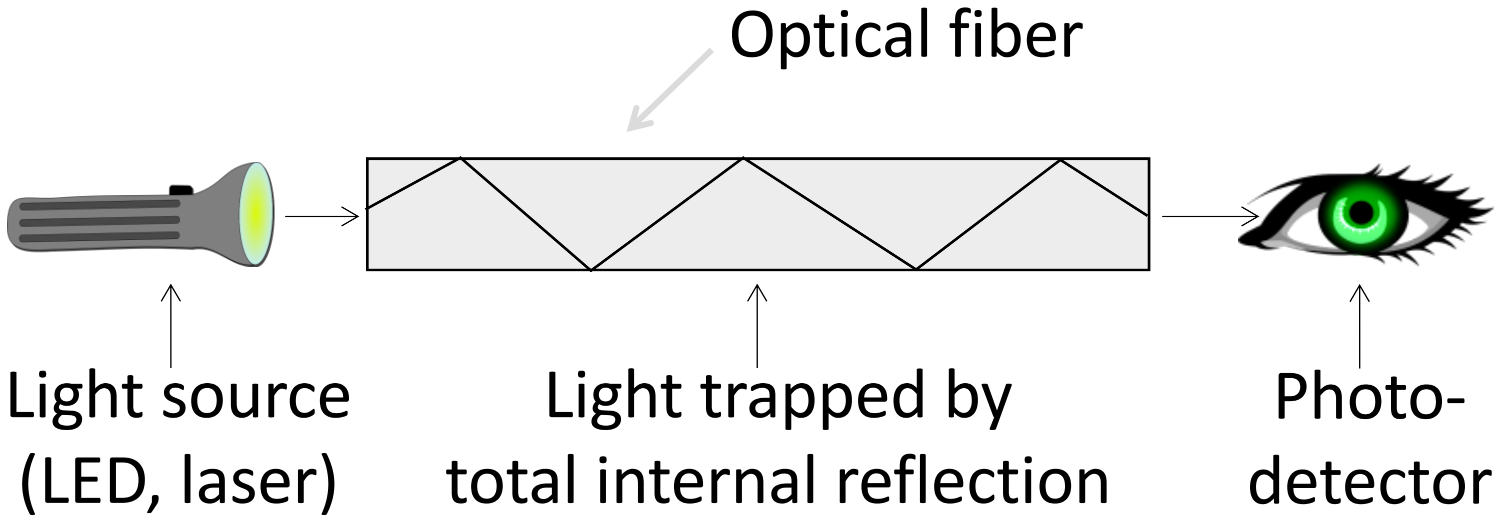
- Also common. Better shielding for better performance



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

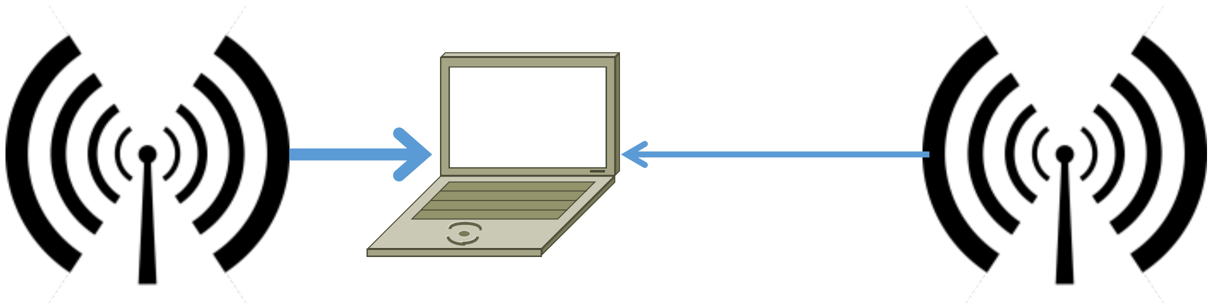
Fiber

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

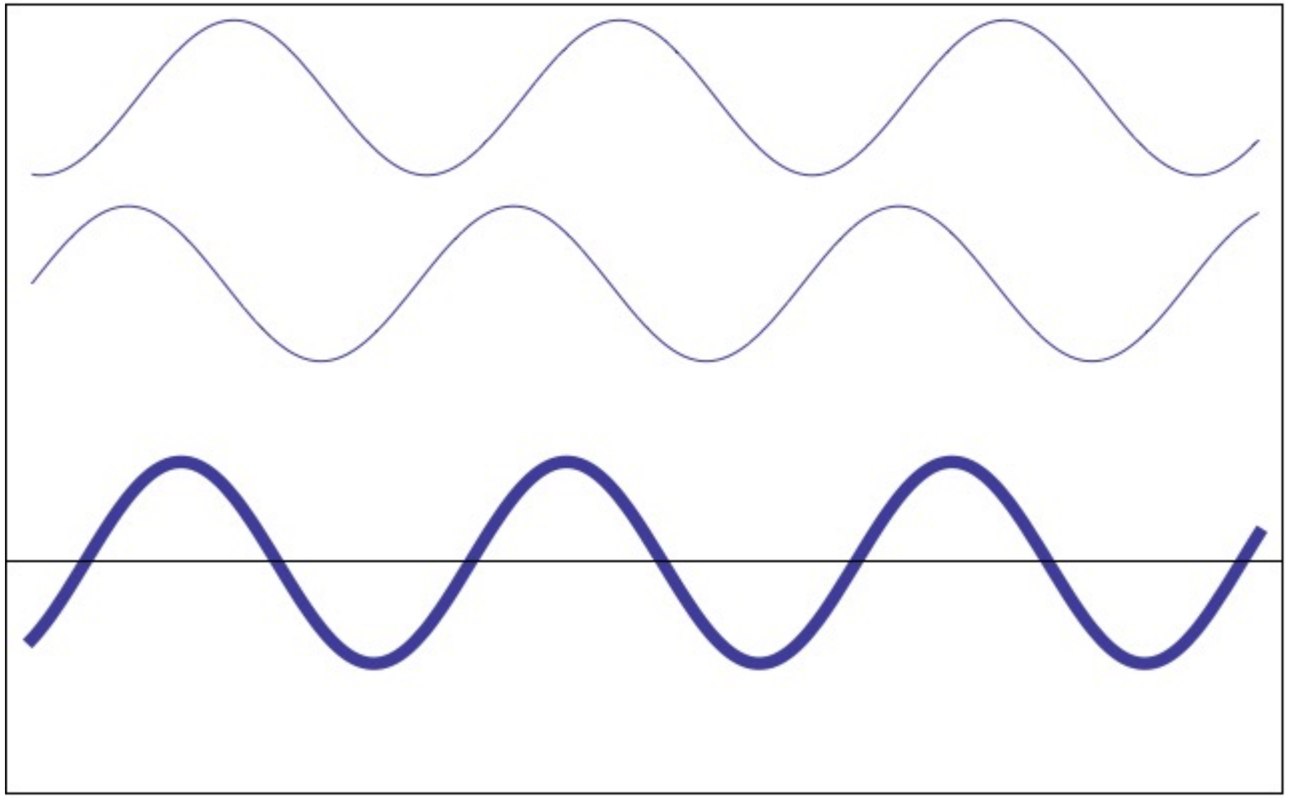


Wireless

- 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

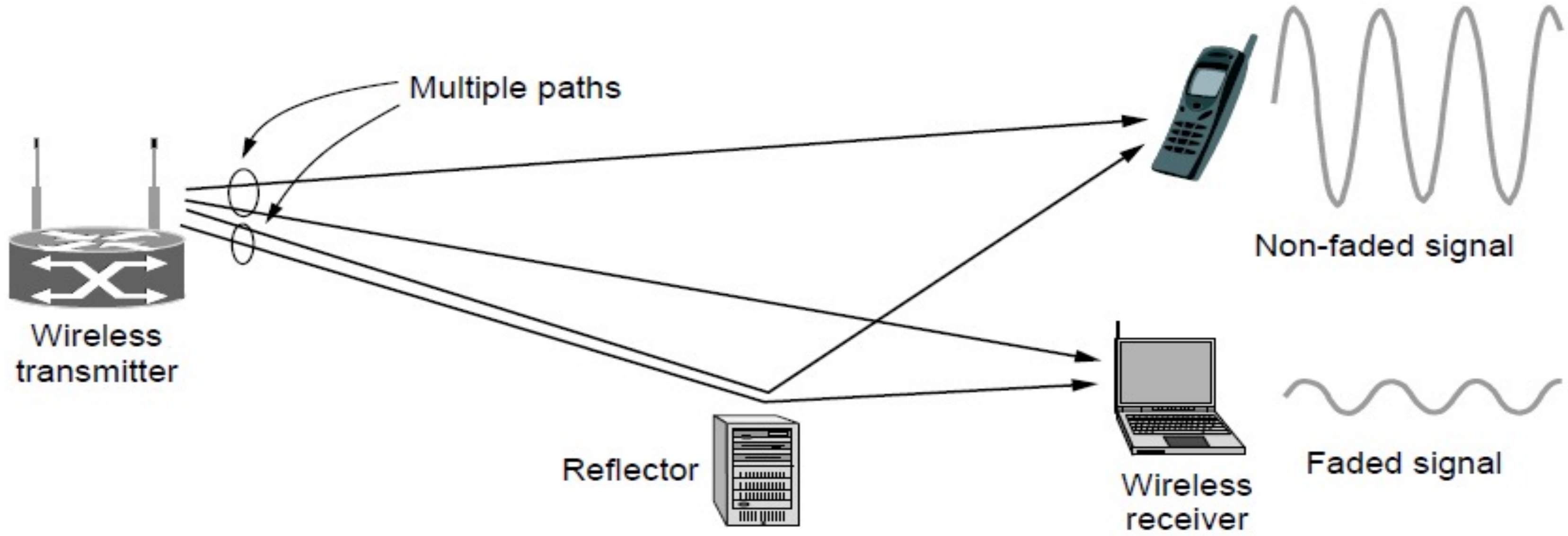


Wireless Interference



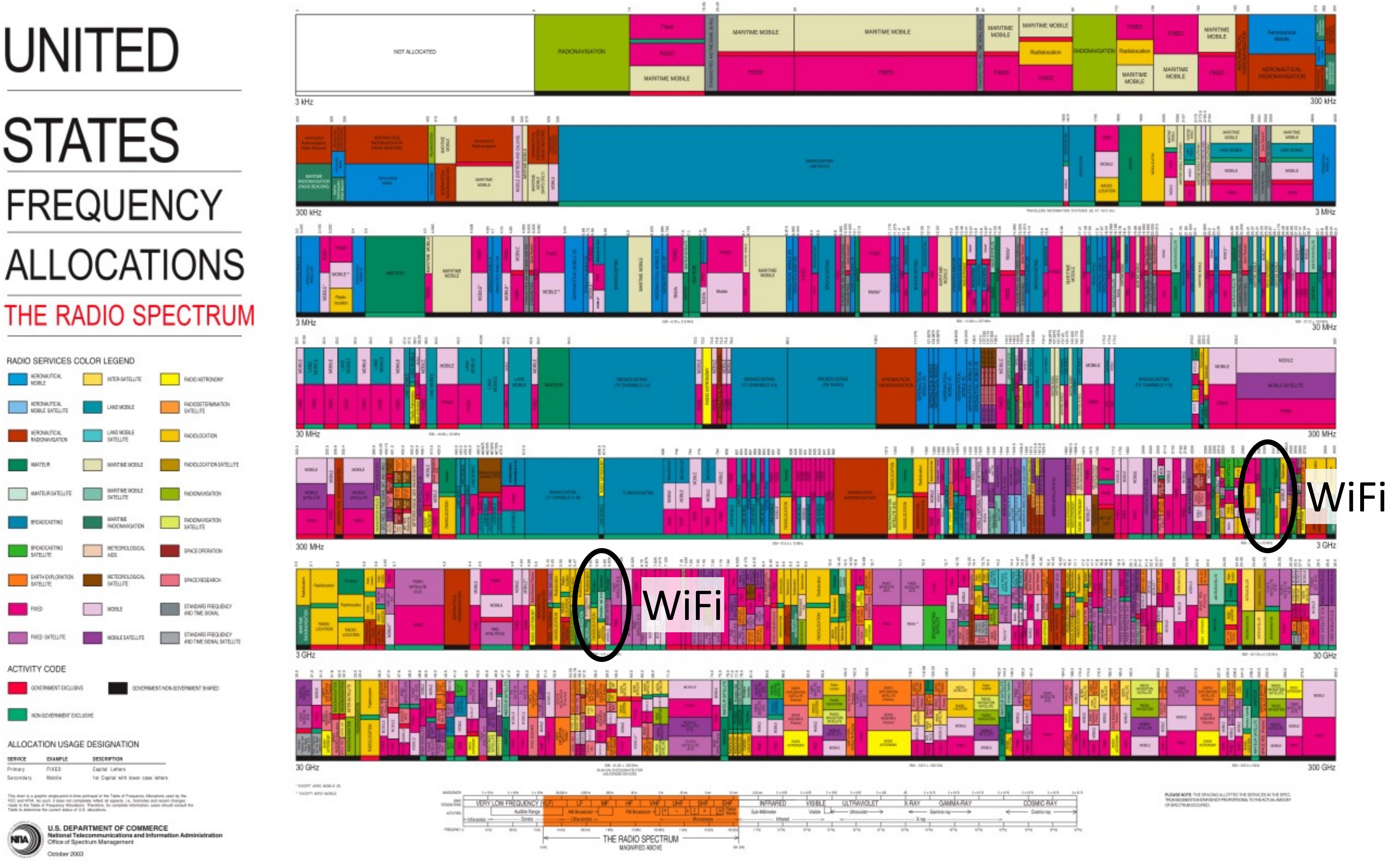
Multipath

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



Many Other Wireless Effects

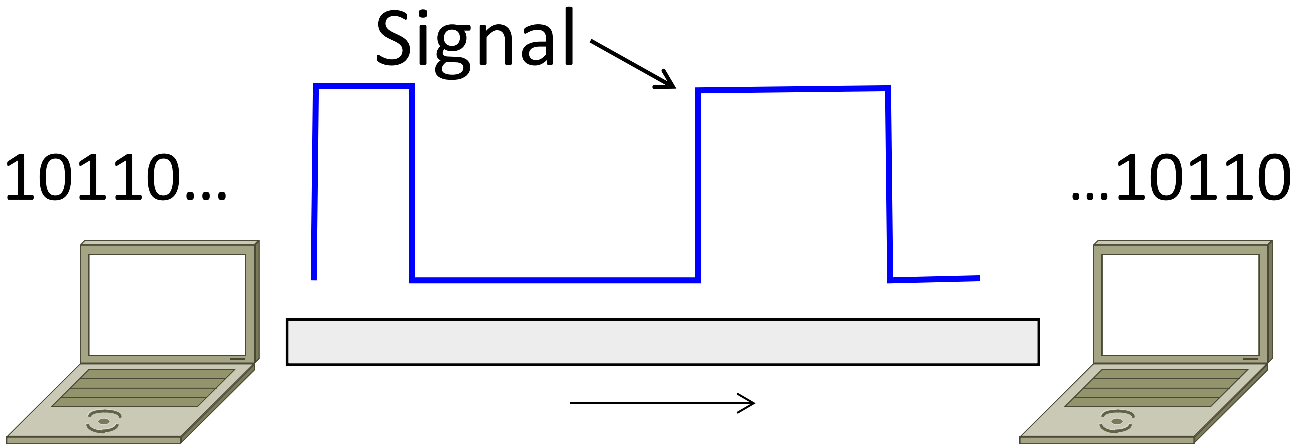
- Wireless propagation is complex, depends on environment
- Some key effects are highly frequency dependent,
  - E.g., <u>multipath</u> at microwave frequencies


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
WiFi
WiFi
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM

Coding and Modulation

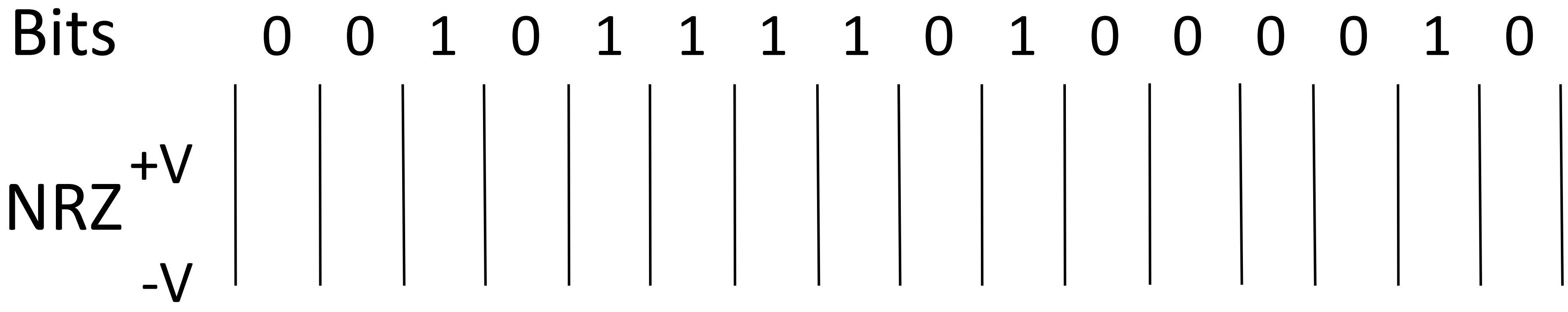
Topic

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



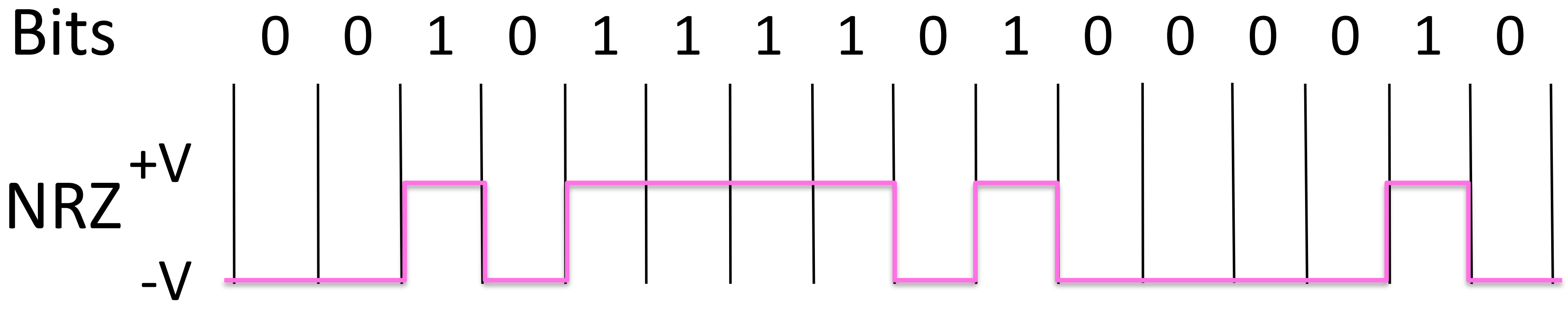
A Simple Coding Scheme

- 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 <u>symbol</u>
- 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

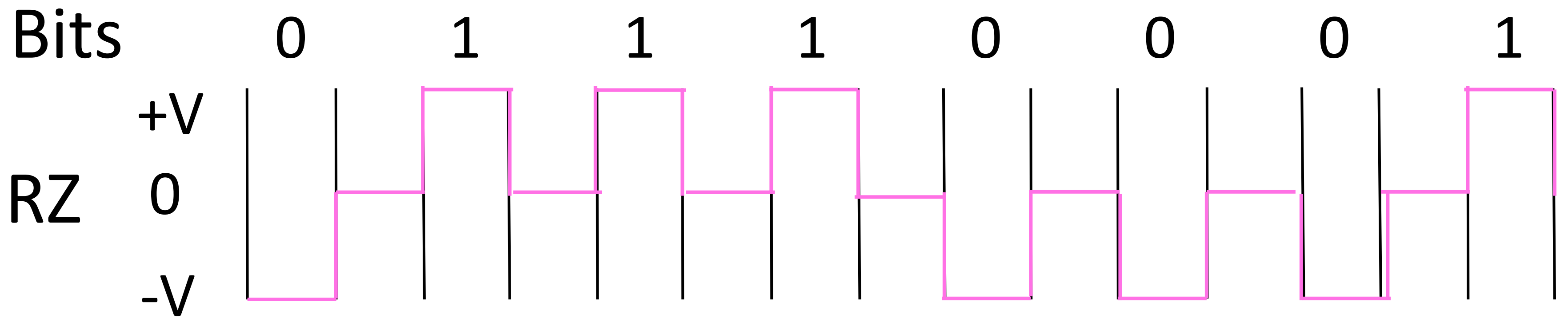
1 0 0 0 0 0 0 0 0 0 … 0

- 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:

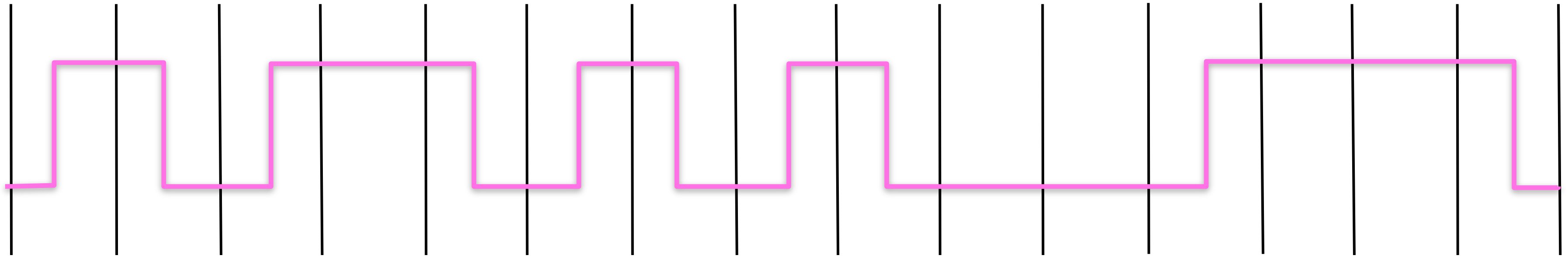
Signal:

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:

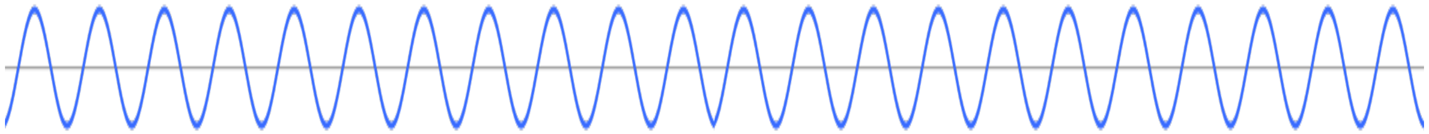


Coding vs. Modulation

- What we have seen so far is <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

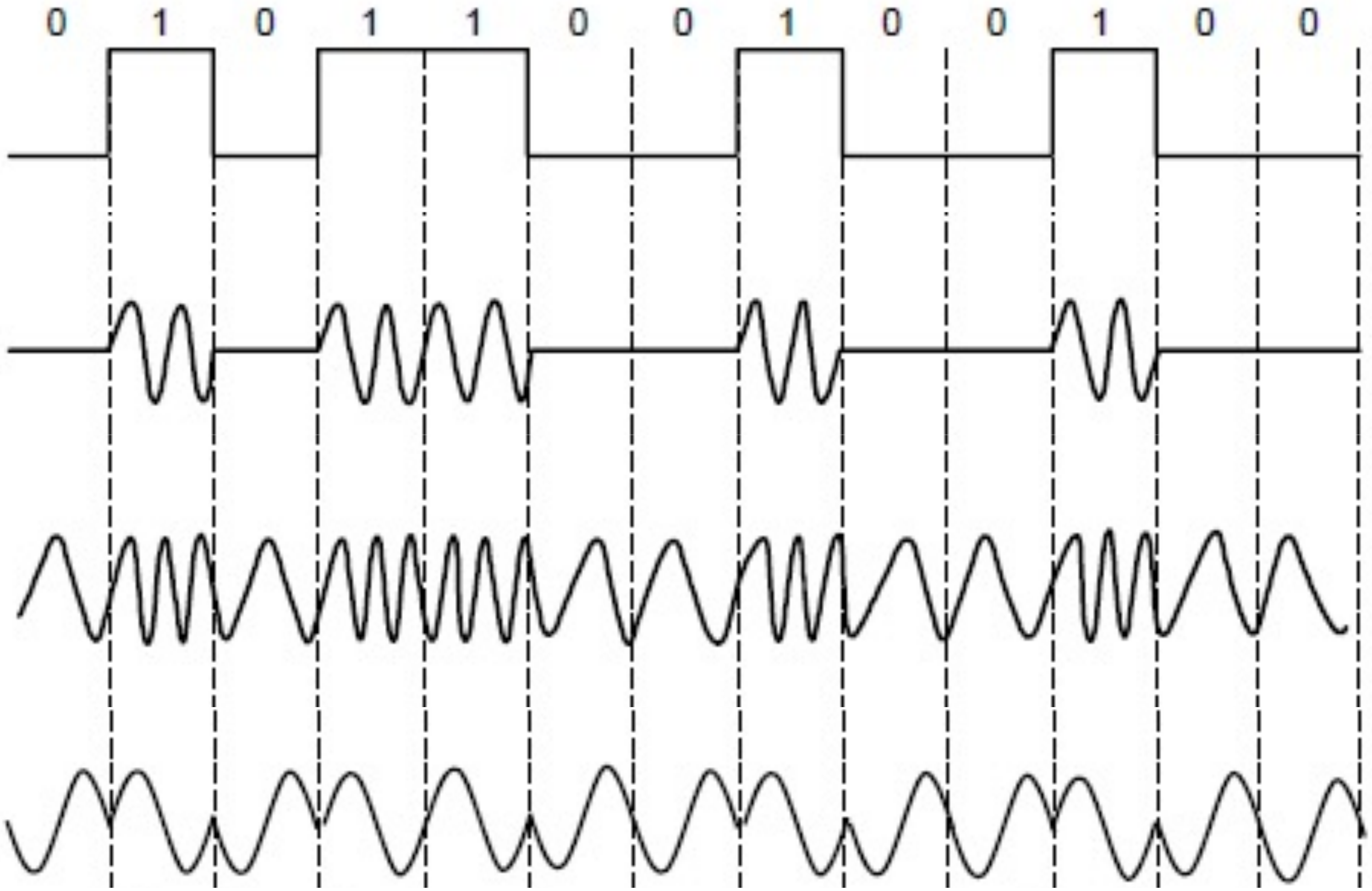
Comparisons

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying



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)

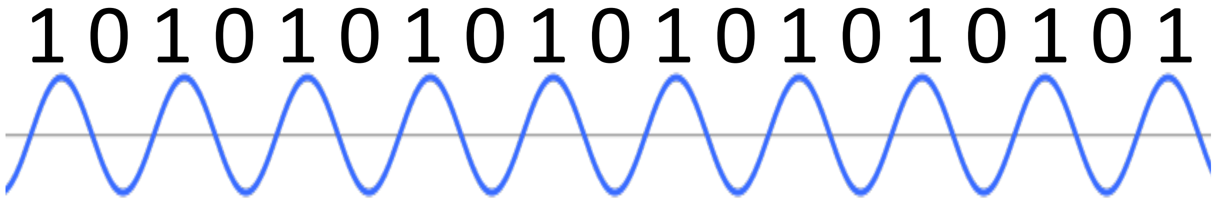
Fundamental Limits

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



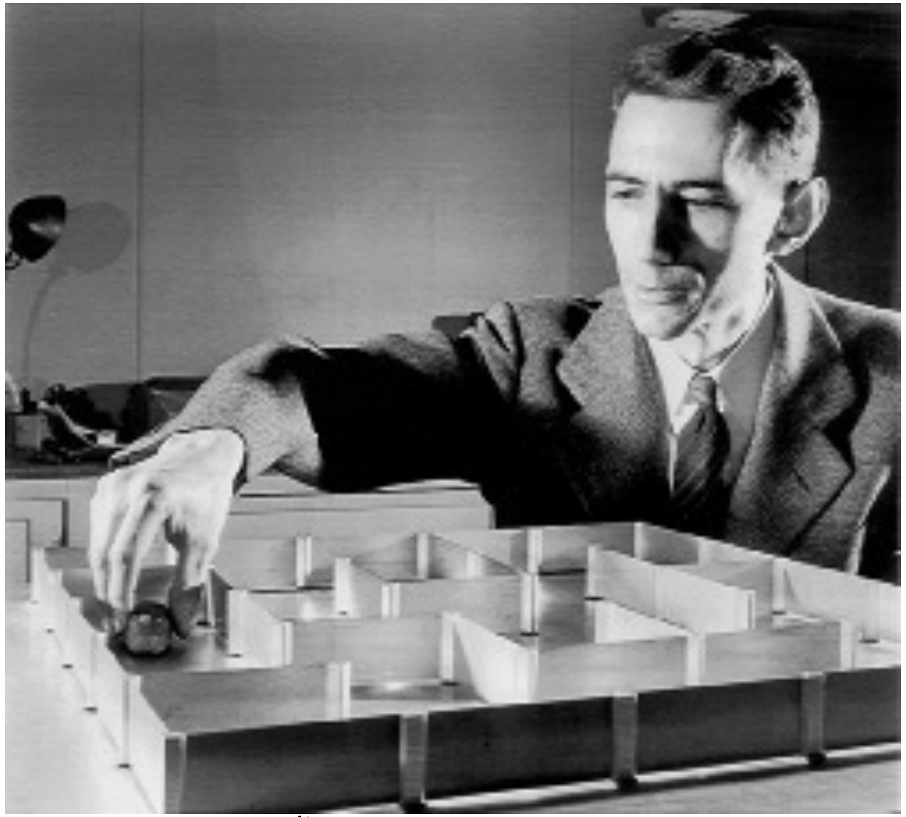
- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

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

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!

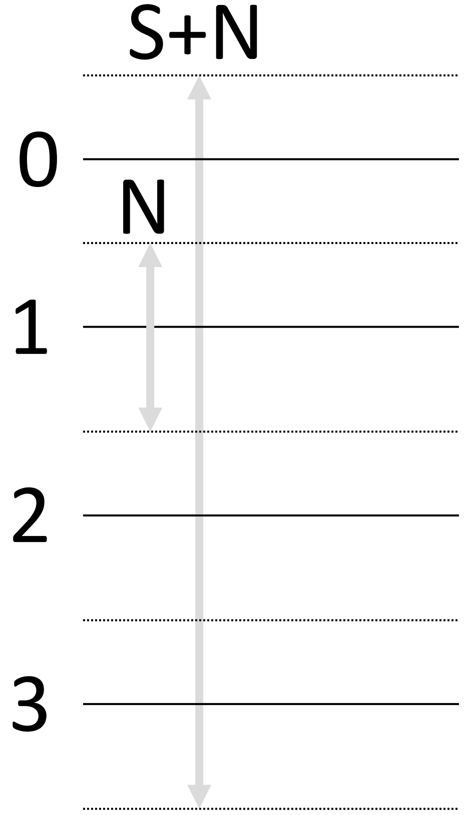


Credit: Courtesy MIT Museum

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

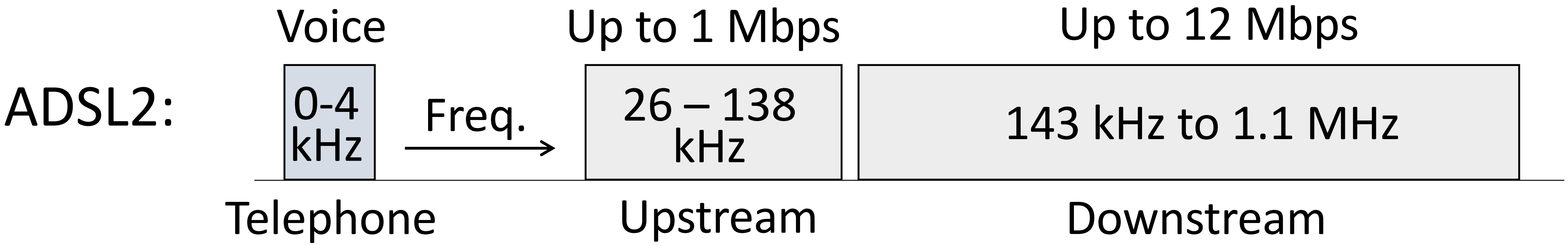
Adapt data rate to SNR

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)



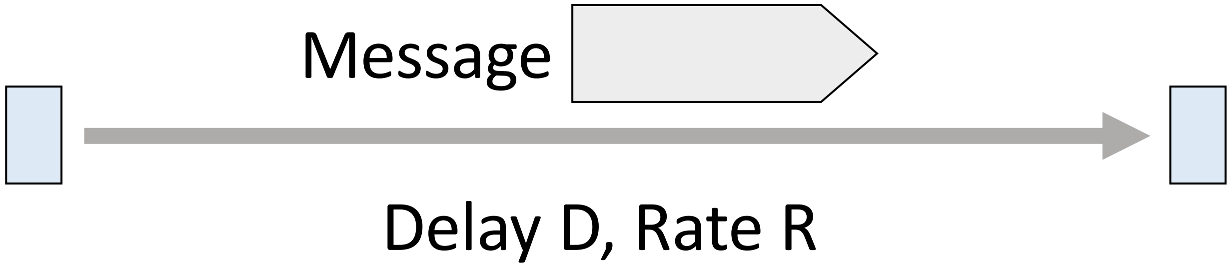
Phy Layer Innovation Still Happening!

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

Backup

All distilled to a simple link model

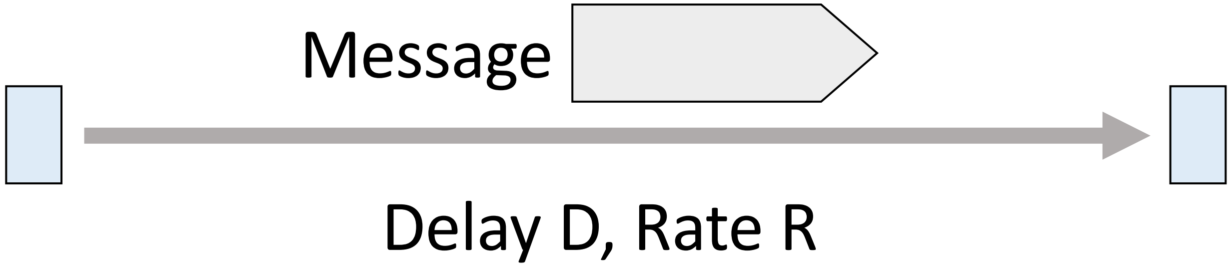
- Rate (or bandwidth, capacity, speed) in bits/second
- Delay in seconds, related to length



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

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

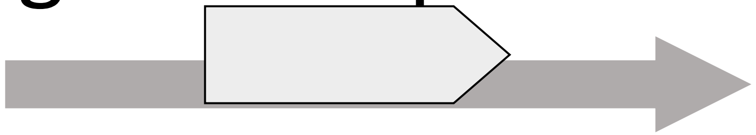
- Broadband cross-country link:
  - $D = 50$ ms, $R = 10$ Mbps, $M = 1250$ bytes

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!



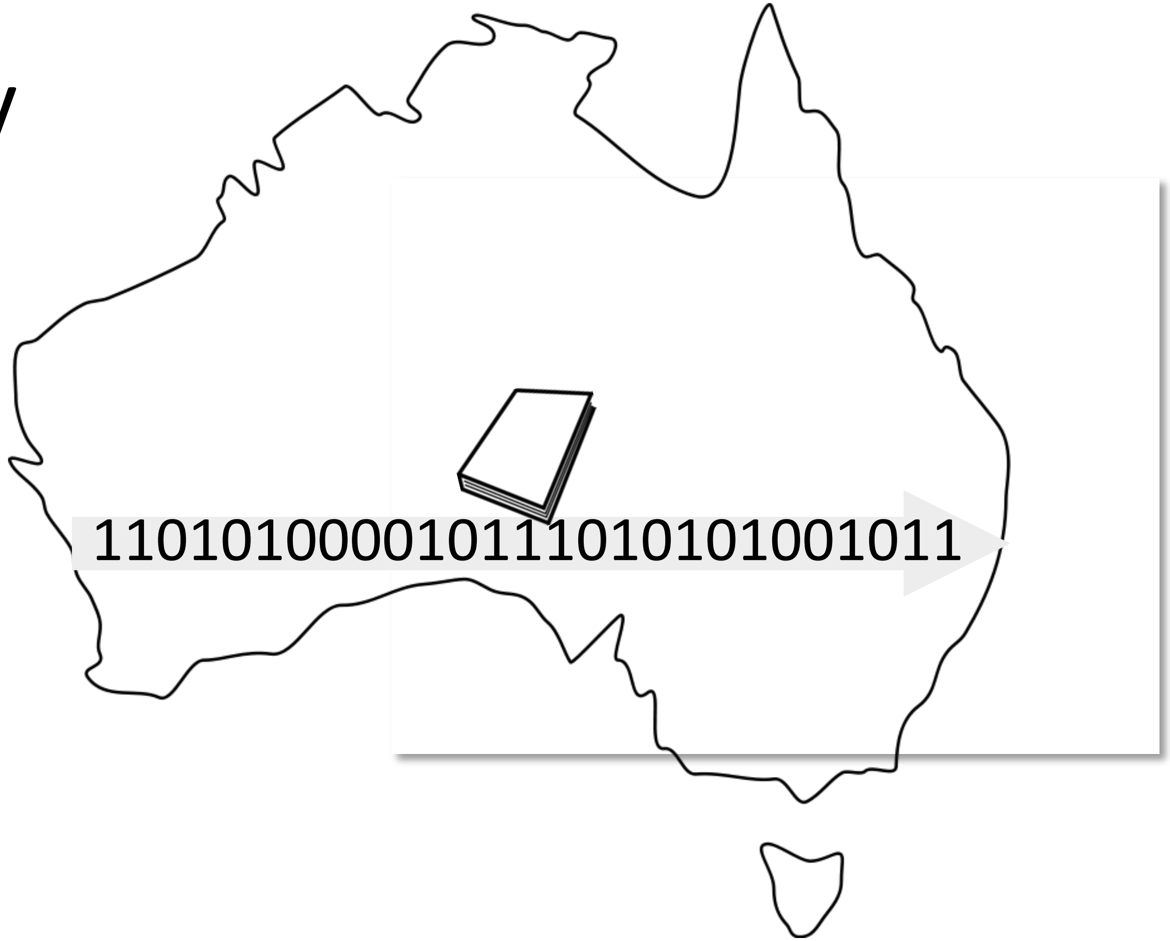
- The amount of data in flight is the <u>bandwidth-delay (BD) product</u>

$$BD = R \times D$$

  - 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 x 10^6 x 50 x 10^{-3} bits

  = 2000 Kbit

  = 250 KB

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