Physical Layer

Lecture Progression

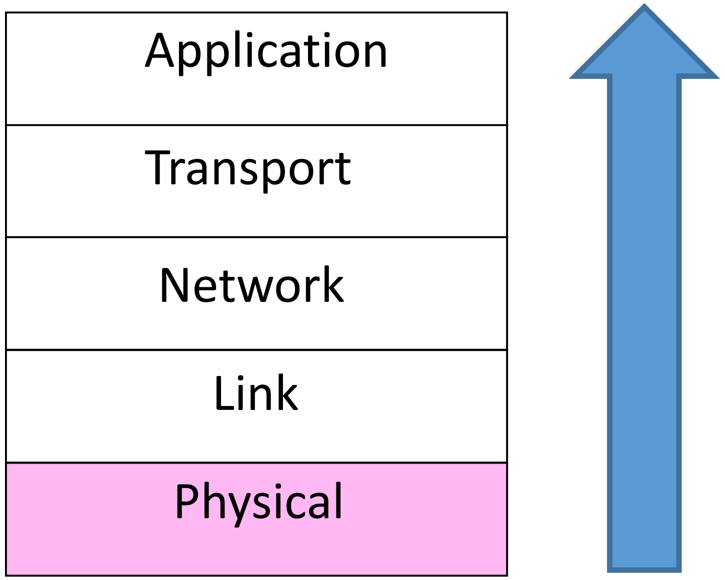
- Bottom-up through the layers:

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)

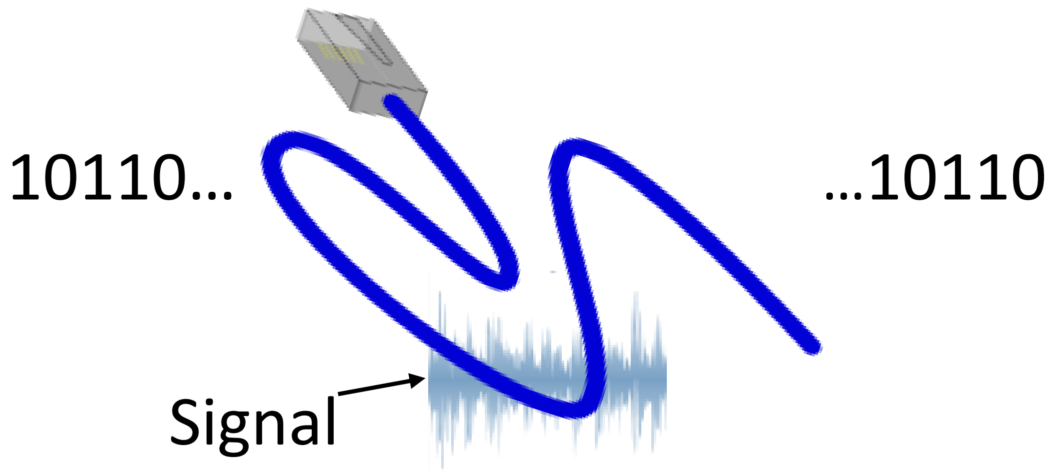
Where we are in the Course

- 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



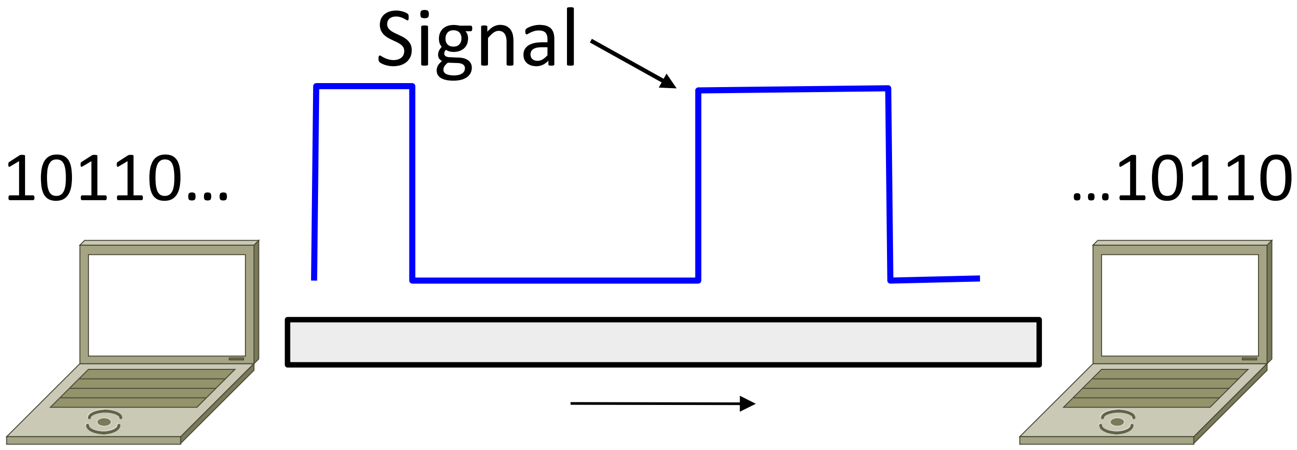
Topics

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

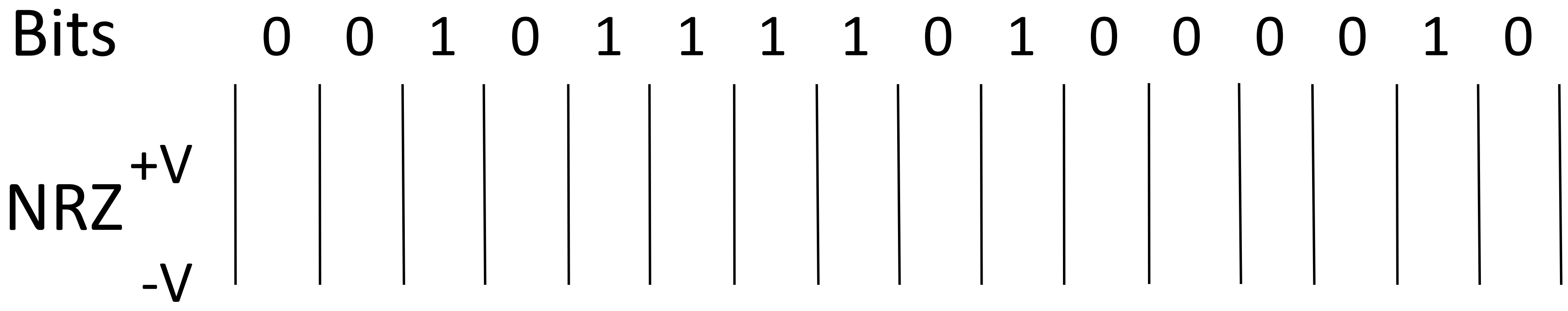
Topic

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



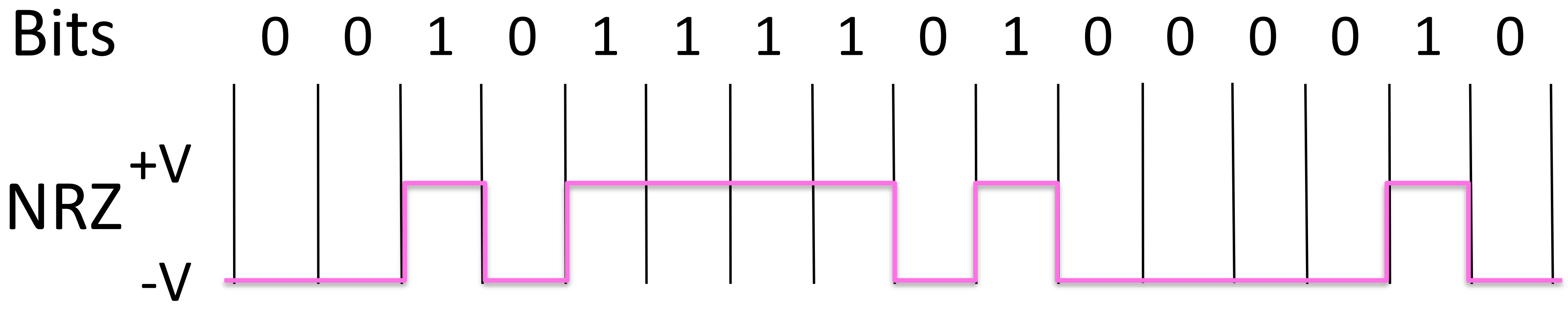
A Simple Coding

- 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

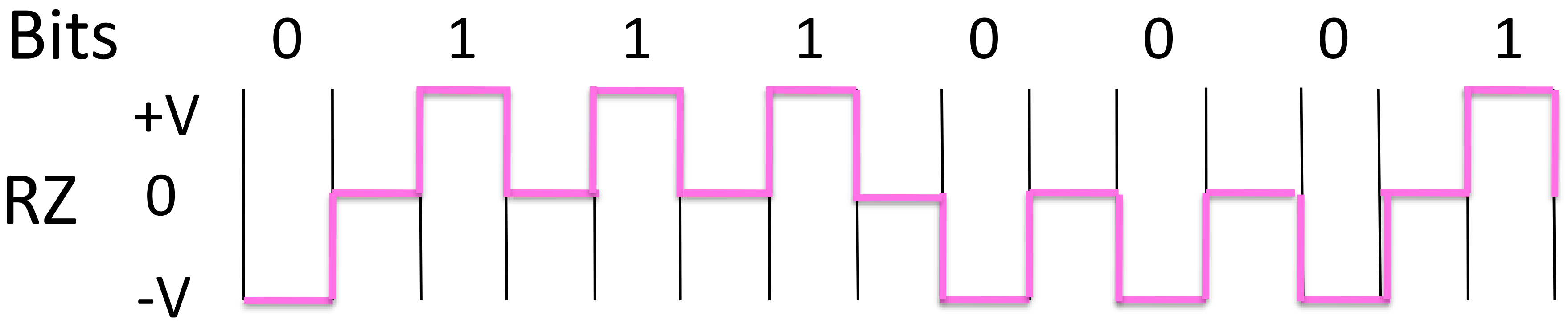
- Um, how many zeros was that?
  - Receiver needs frequent signal transitions to decode bits

- 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:

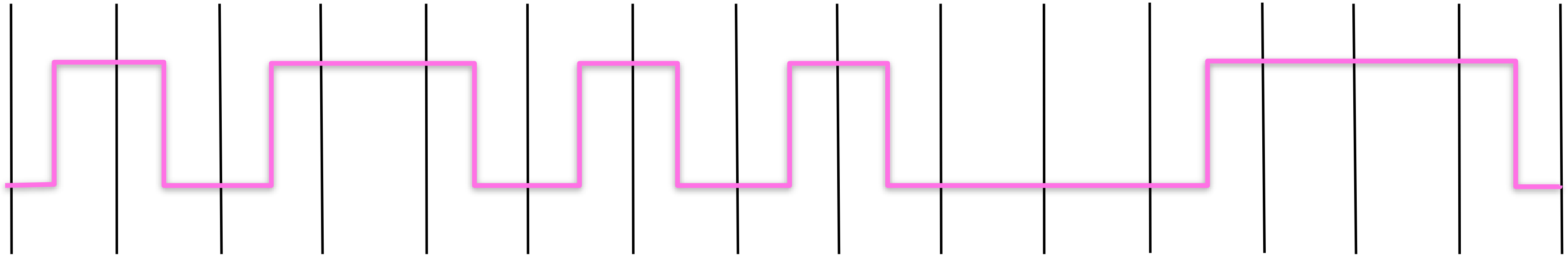
Signal:

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:

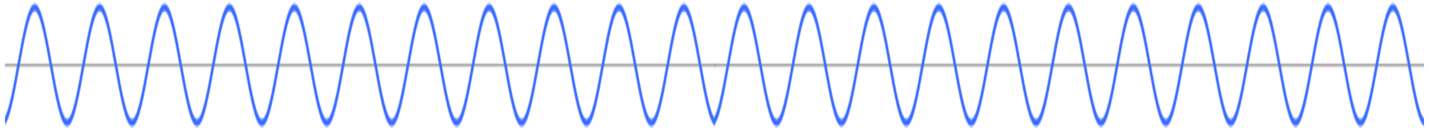


Modulation vs Coding

- 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

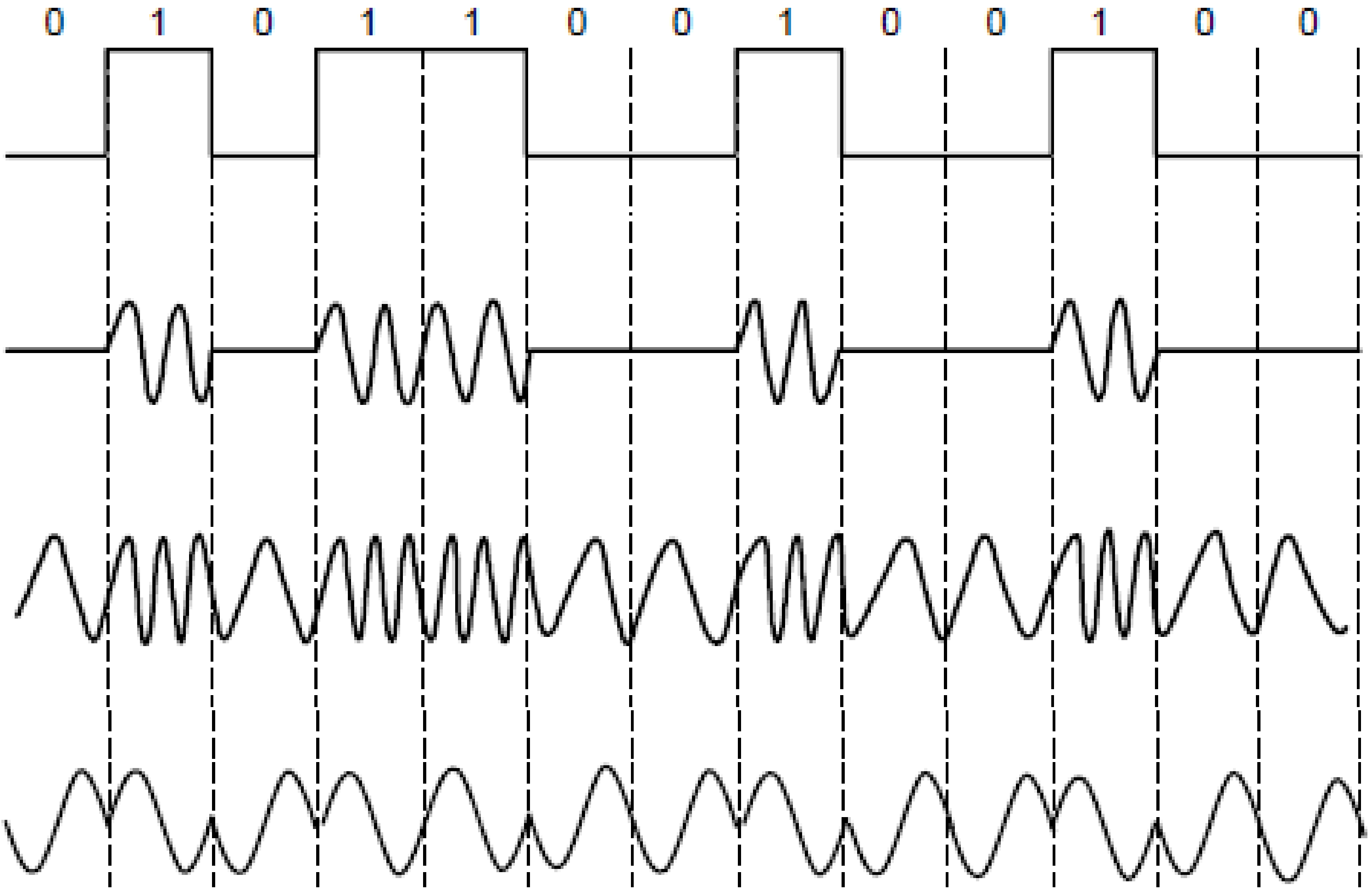
Comparisons

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying

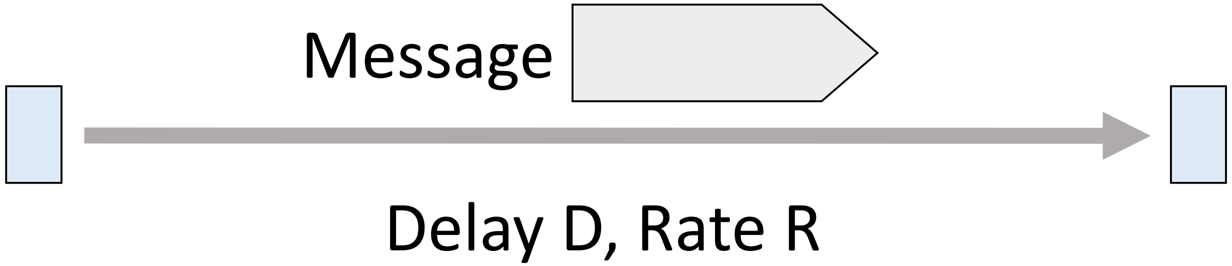


Philosophical Takeaways

- 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)

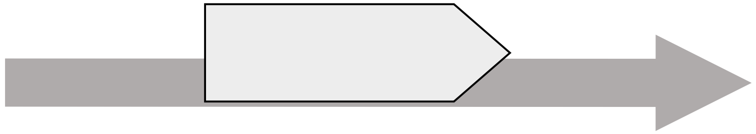
- “Dialup” with a telephone modem:
  - D = 5 ms, R = 56 kbps, M = 1250 bytes
  - L = (1250x8)/(56 x 10^3) sec + 5ms = 184 ms!

- 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 <u>bandwidth-delay (BD) product</u>

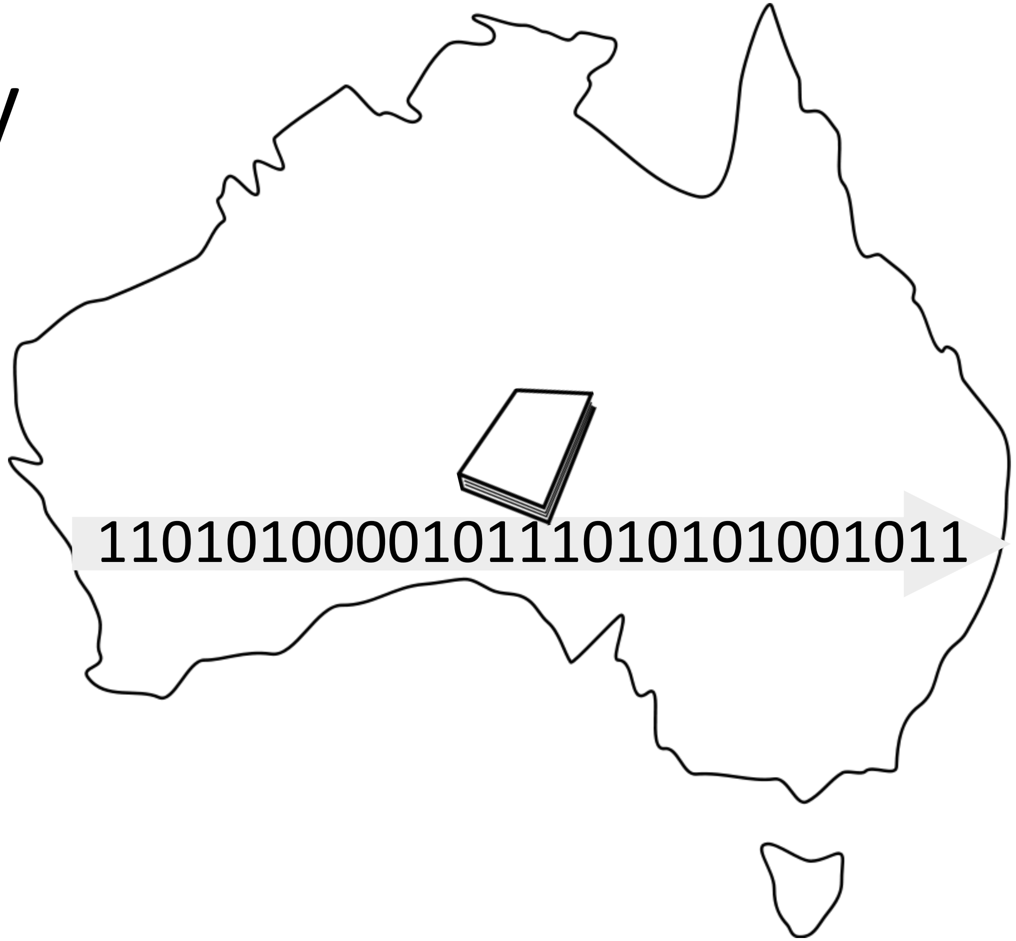
$$BD = R \times D$$

  - 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

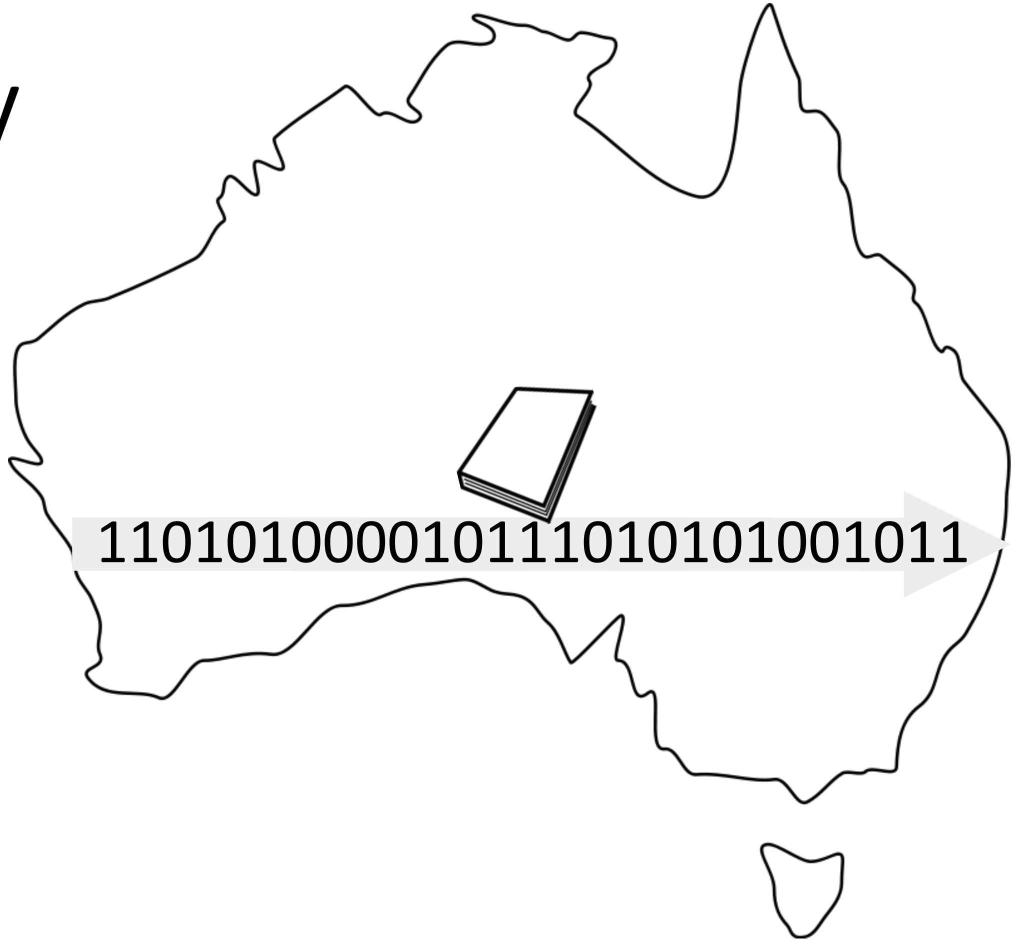
  R=40 Mbps, D=50 ms

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

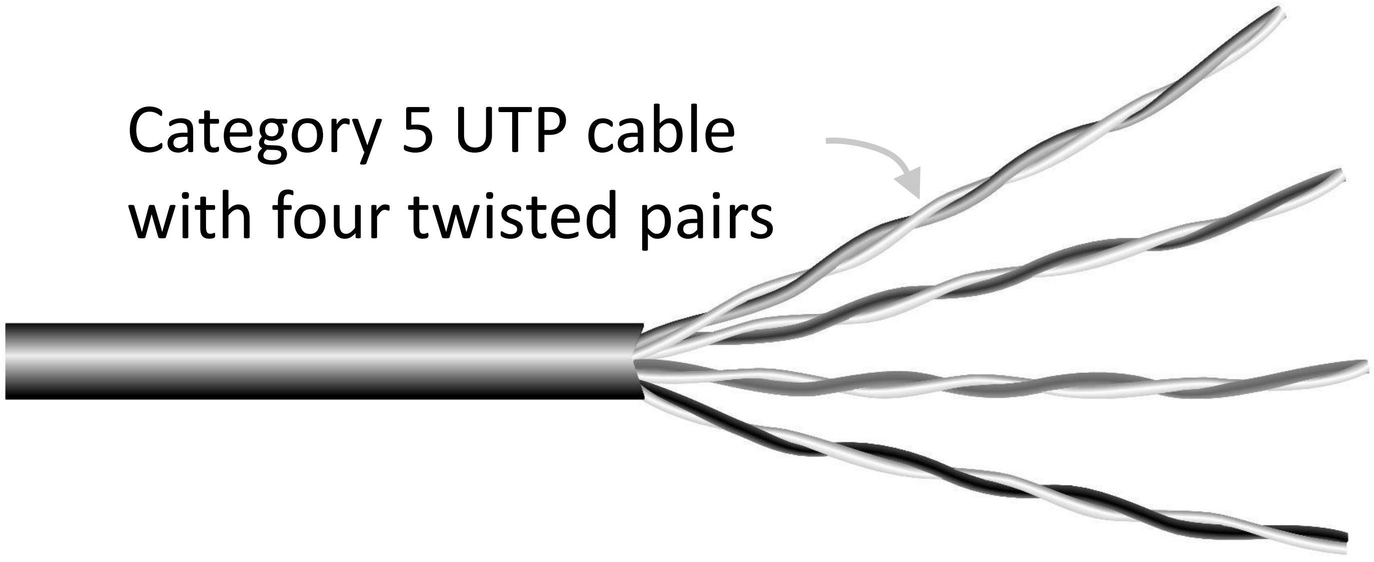
https://www.merriam-webster.com/dictionary/media

Types of Media

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

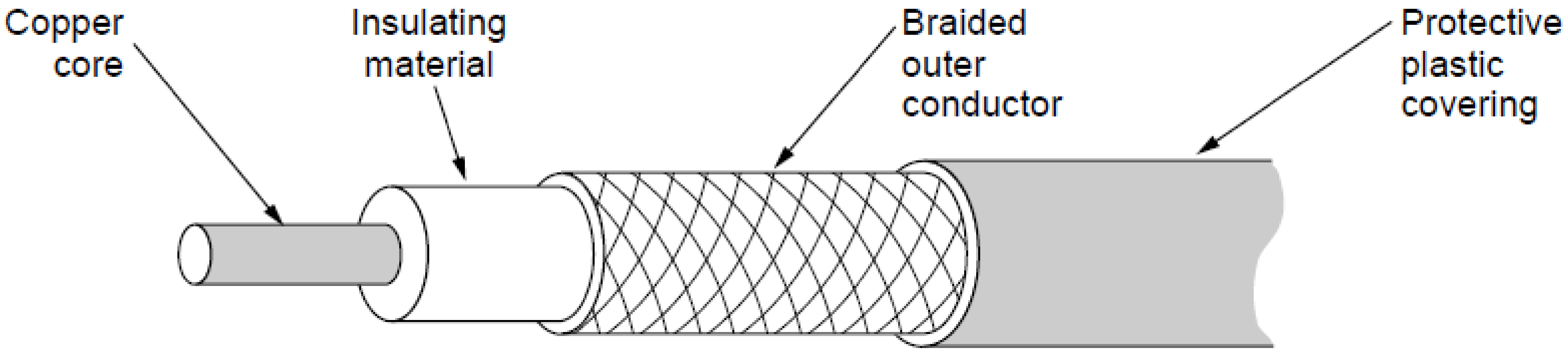
Wires – Twisted Pair

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



Wires – Coaxial Cable

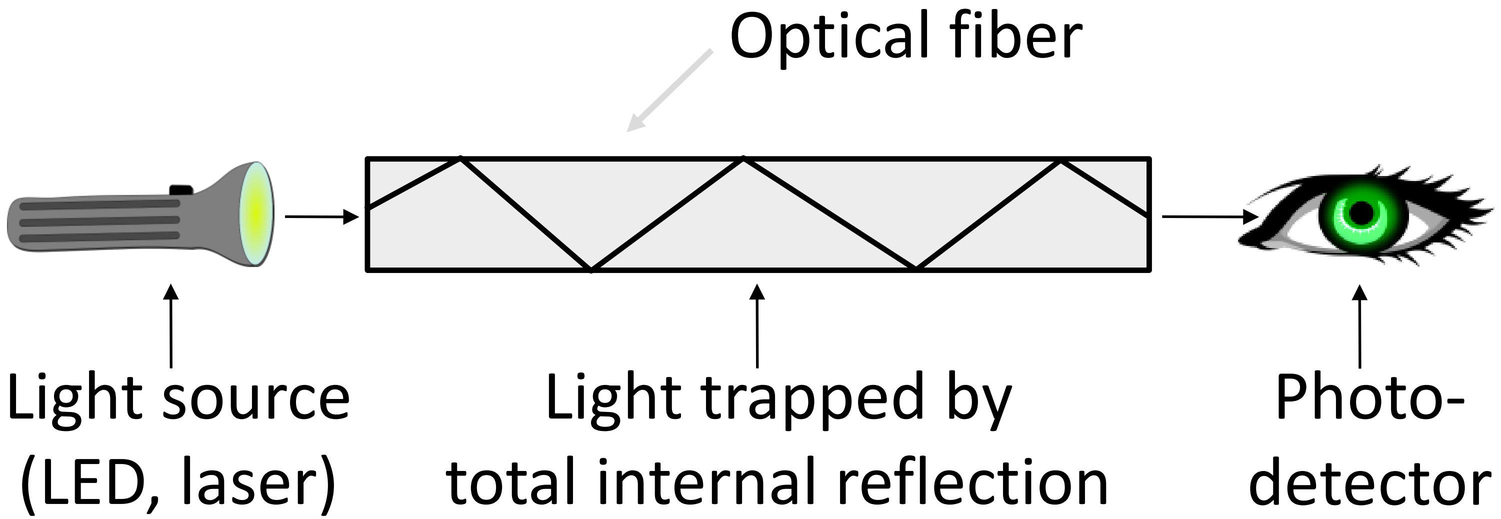
- Also common. Better shielding for better performance



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

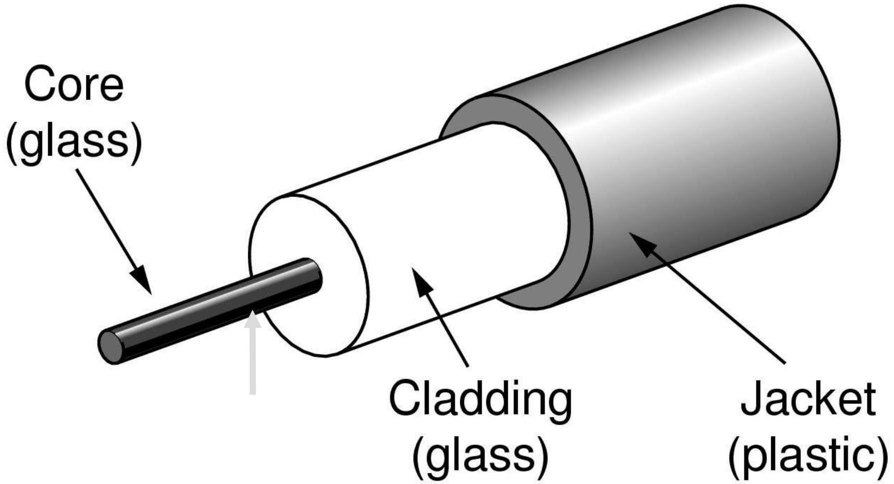
Fiber

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

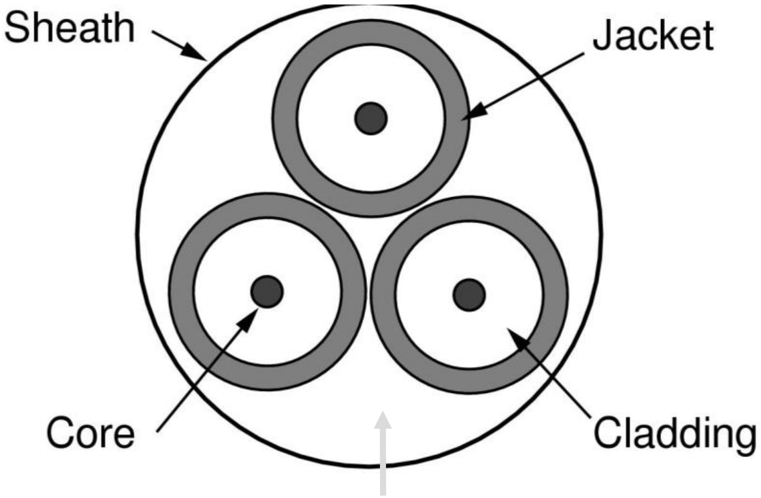


Fiber (2)

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



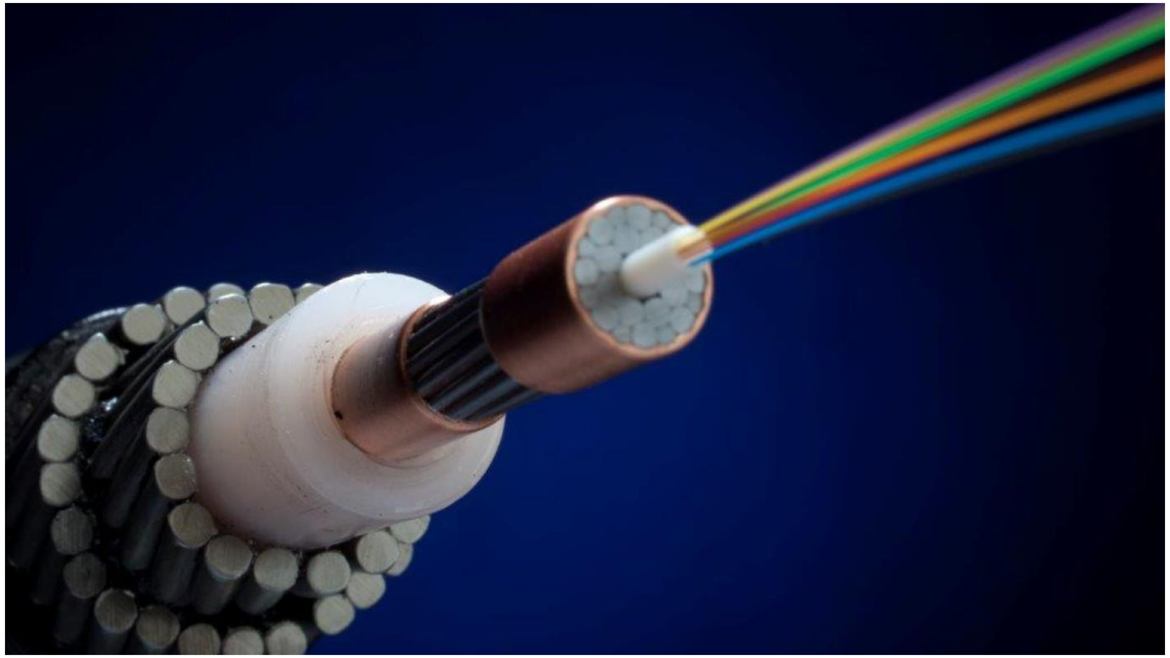
One fiber

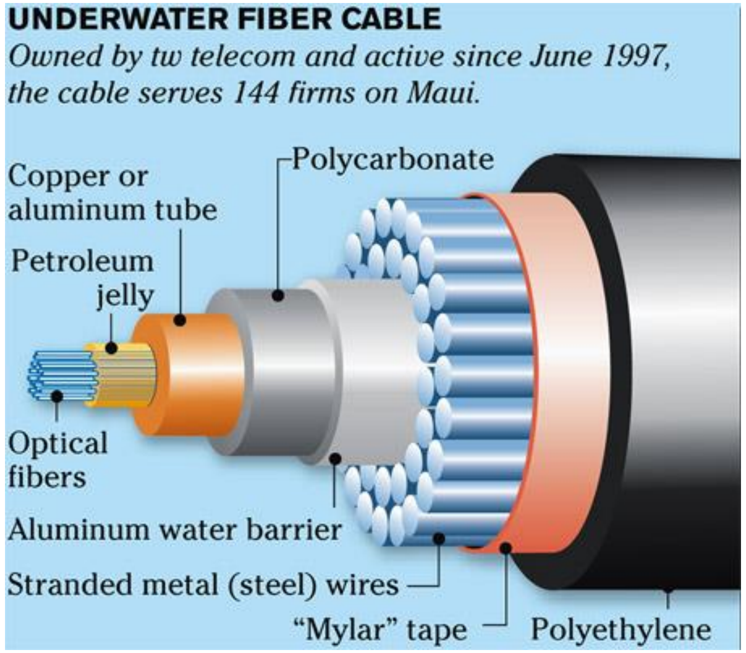


Fiber bundle in a cable

Fiber (3)

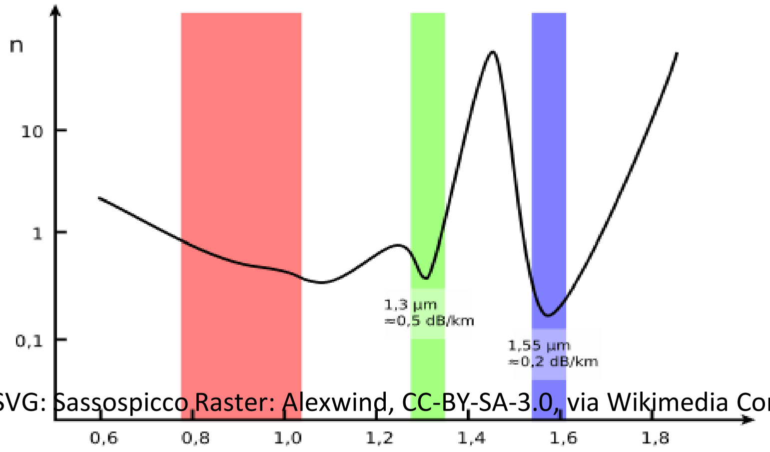
- Actual cables





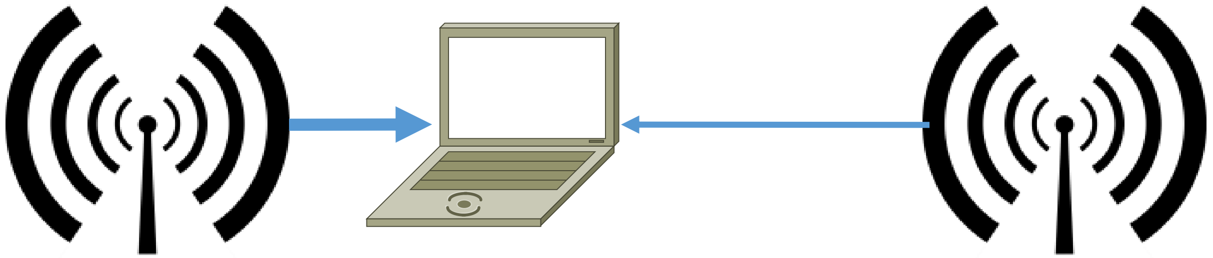
Signals over Fiber

- 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.) <u>interfere</u> at a receiver; need to coordinate use



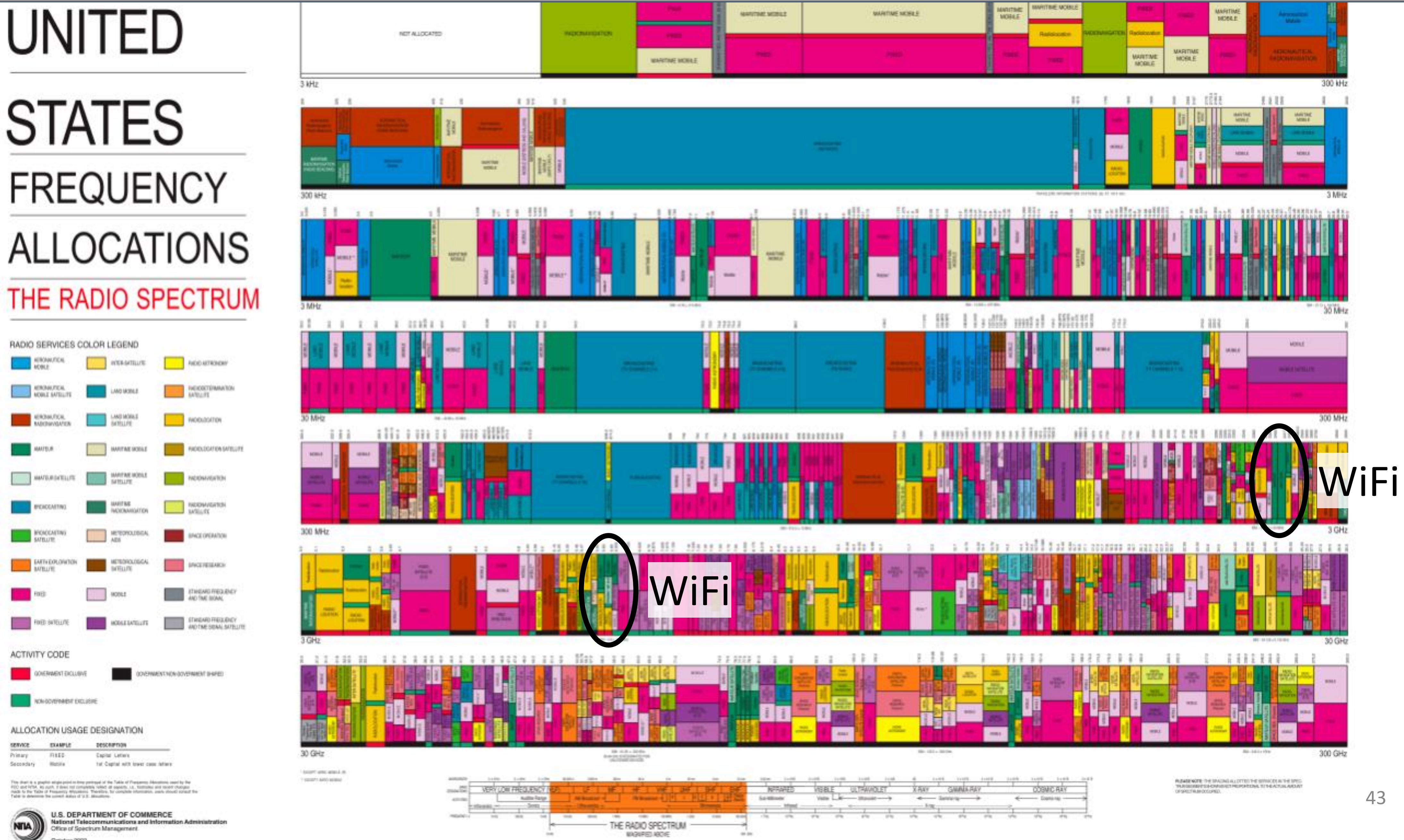
What is the difference between light, radio waves, and gamma radiation?

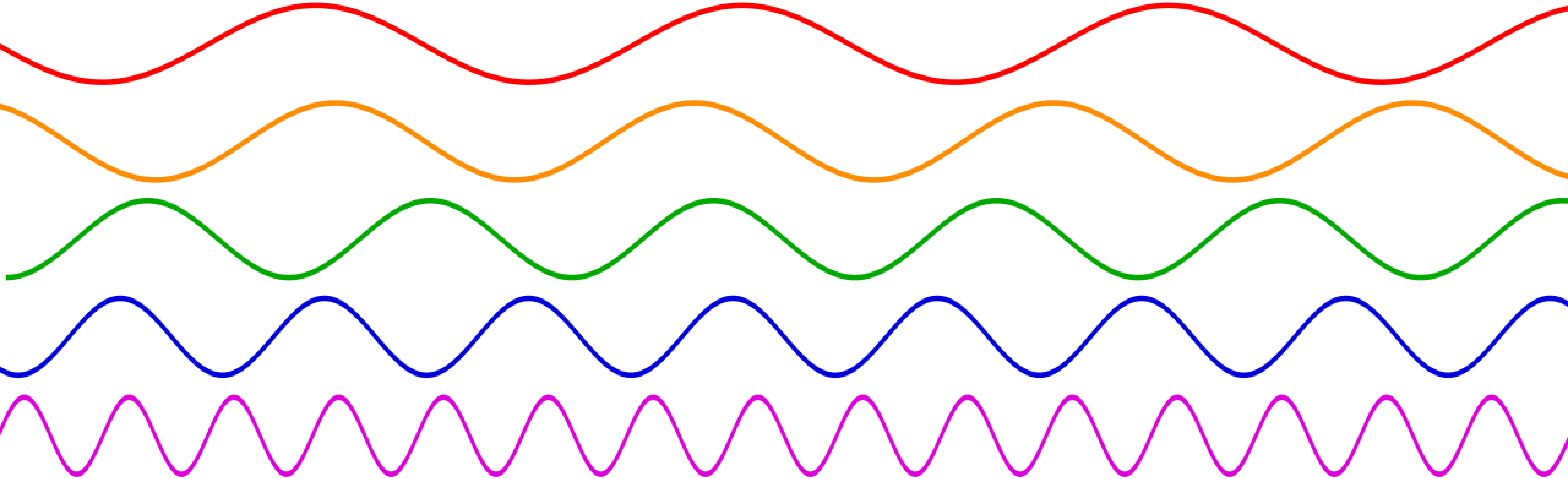
Well… only one makes the Hulk

Photo credit
Marvel via

They are all the same thing (electromagnetic radiation) at different frequencies…

Warning! Brief Review!





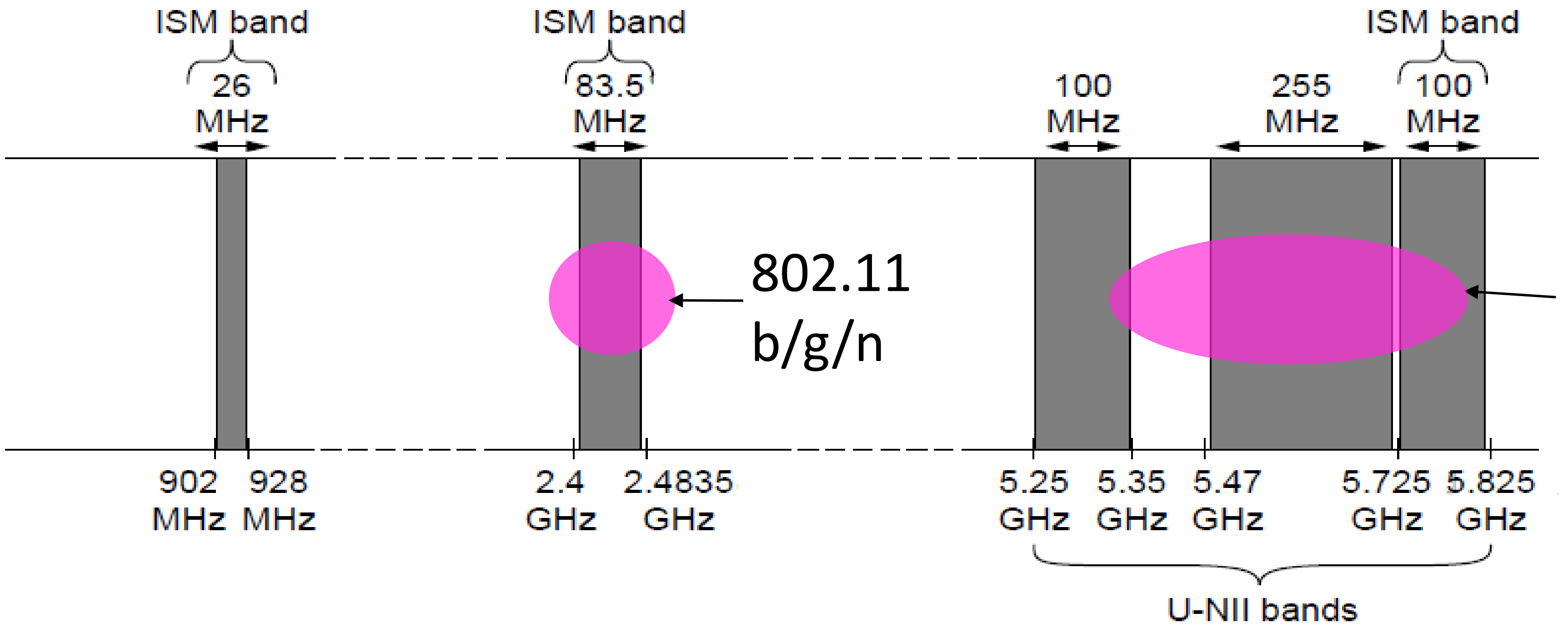
Different frequencies have different properties!

Not all frequencies are created equal...

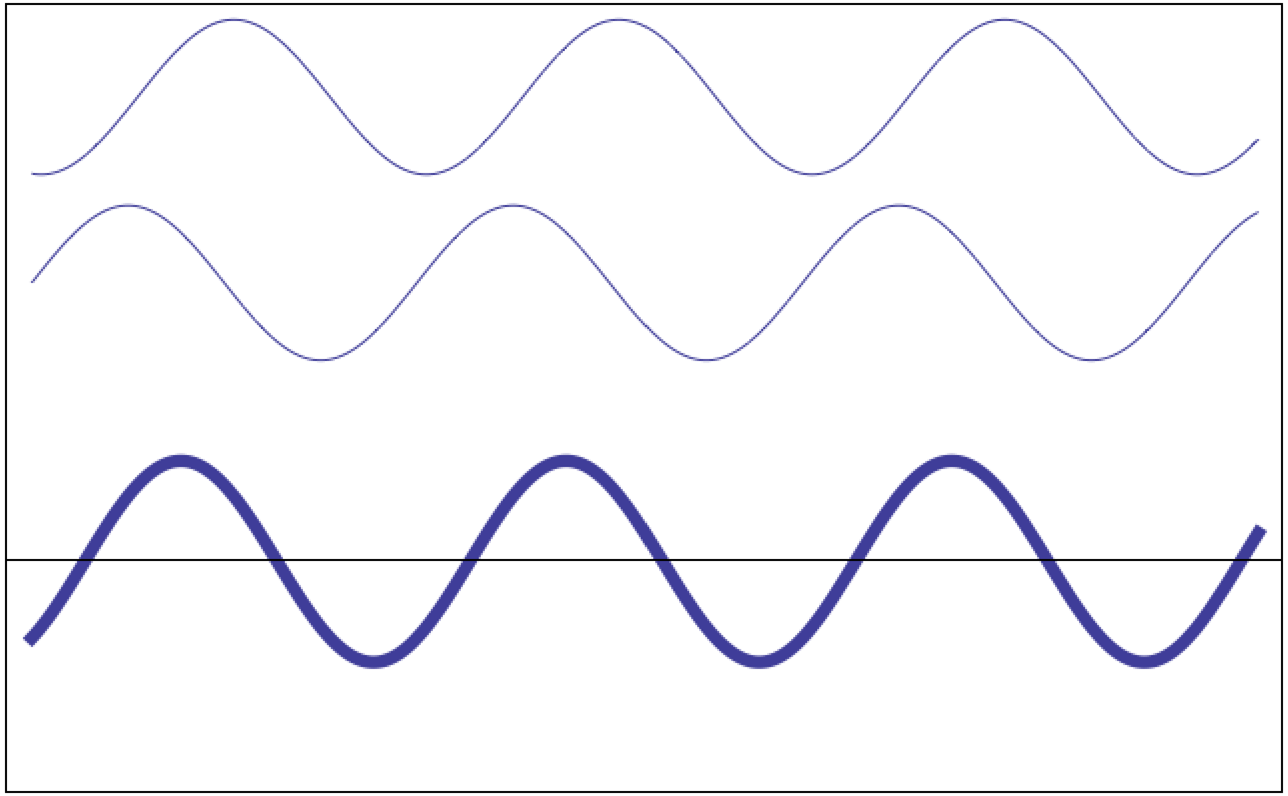
wikimedia

Wireless (2)

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

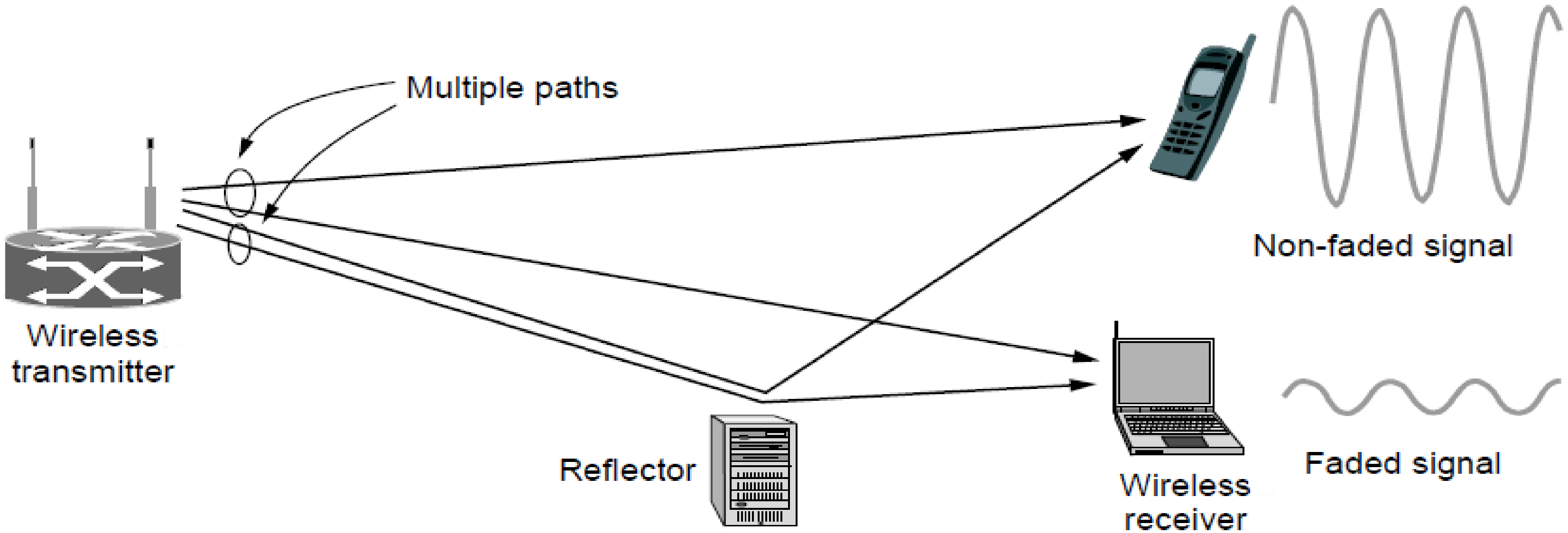


Wireless Interference



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

Theoretical Limits

“Information Theory”

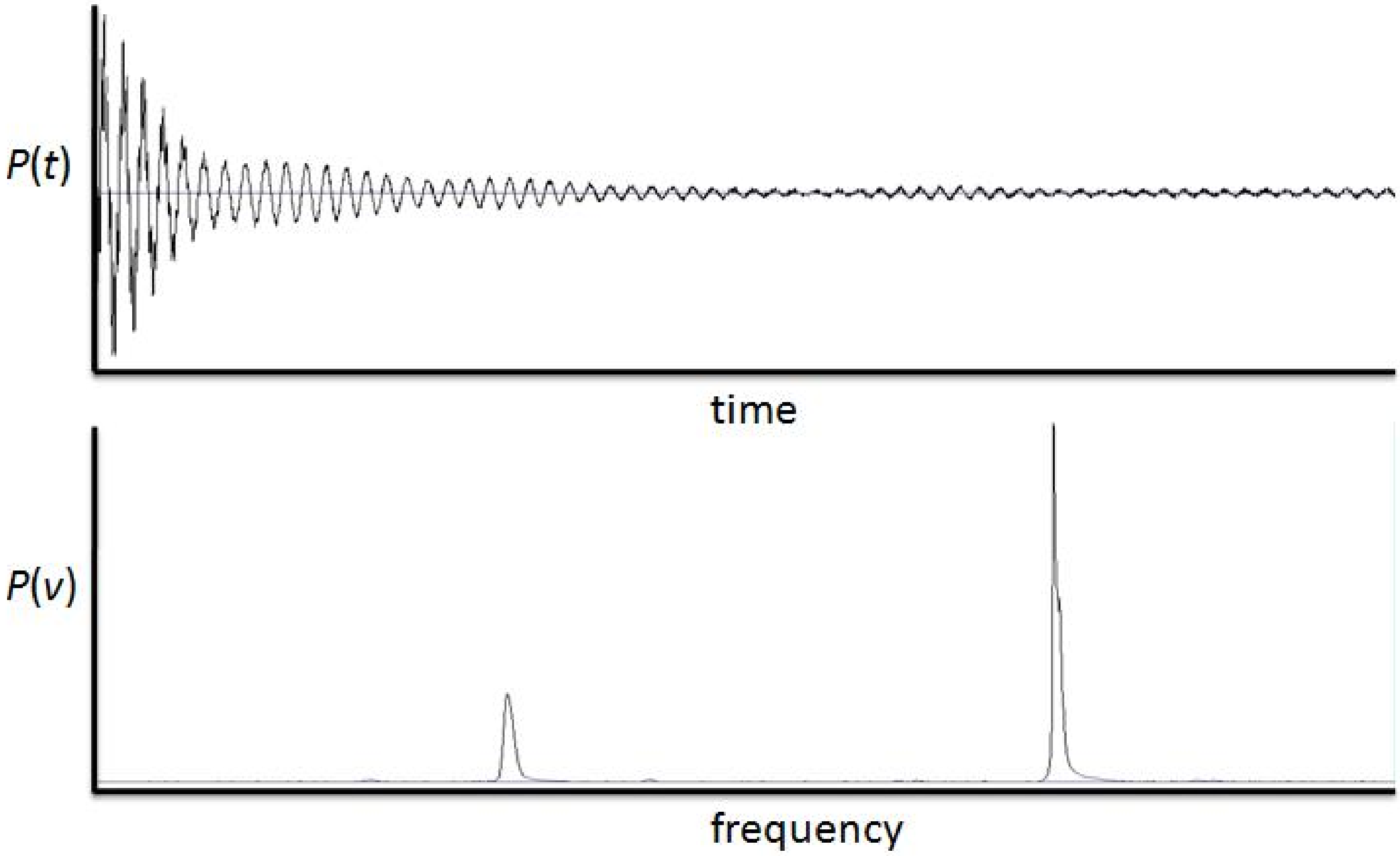
Real World Limits

- How rapidly can we send information over a link?
  - Nyquist limit (~1924)
  - Shannon capacity (1948)

- Practical systems (I.E. your cellphone) approach these limits! Pretty cool :)

Analog Vocabulary Again

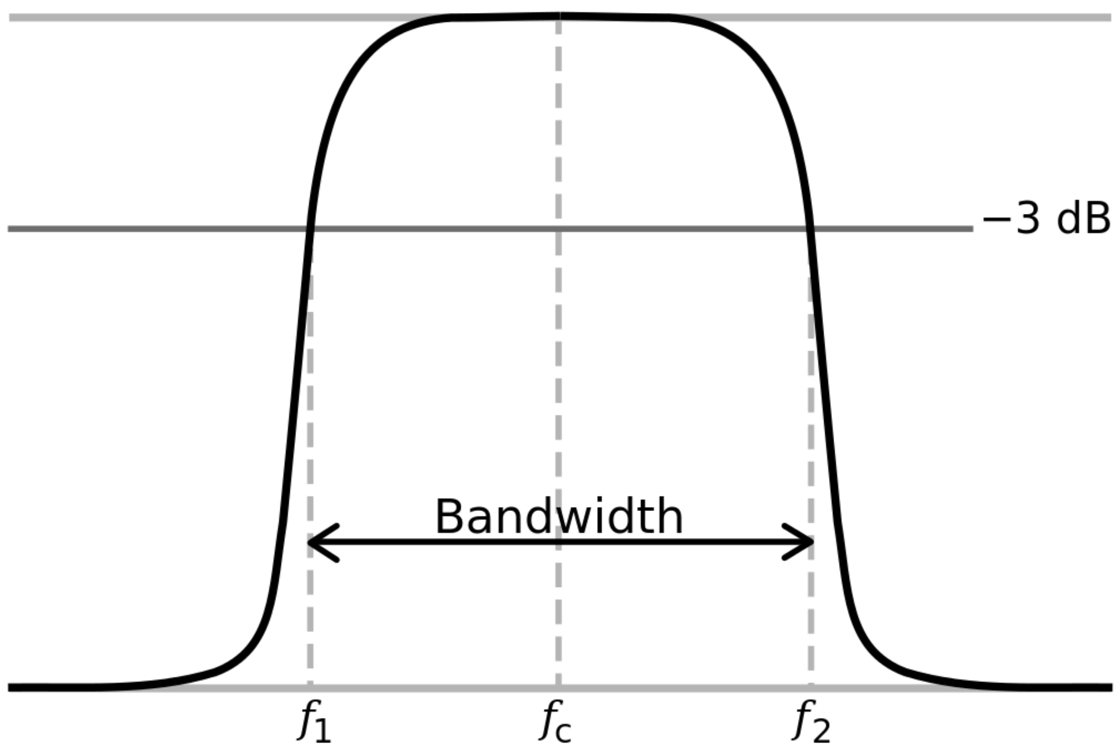
- Often easier to think about ***signals*** in ***frequency***



Attribution: Pbchem at en.wikipedia

Important Analog Vocabulary (2)

- Every analog ***signal*** has a given ***bandwidth***



Attribution: Henrikb4 at en.wikipedia

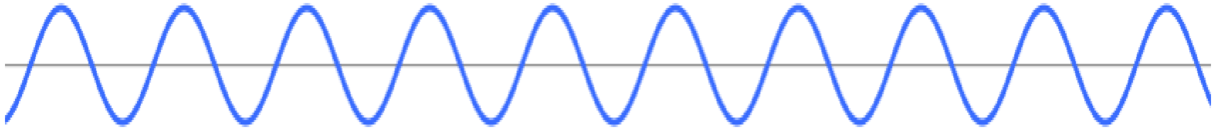
Key Channel Properties

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

Nyquist Limit

- The maximum symbol rate is 2*Bandwidth

1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1

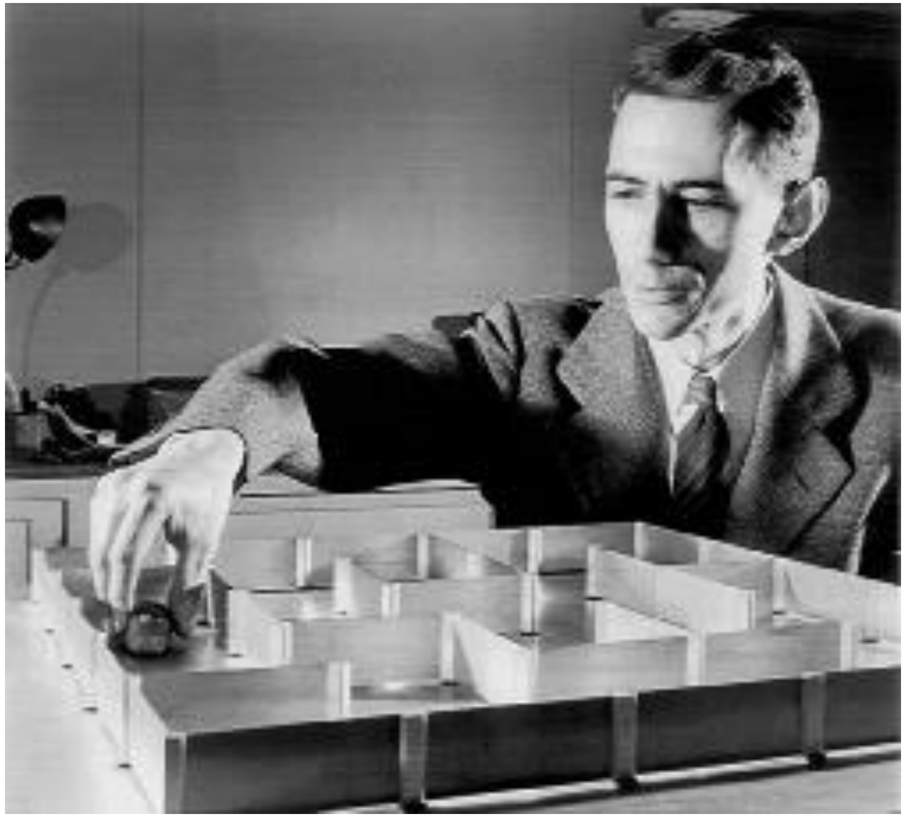


- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

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

Claude Shannon (1916-2001)

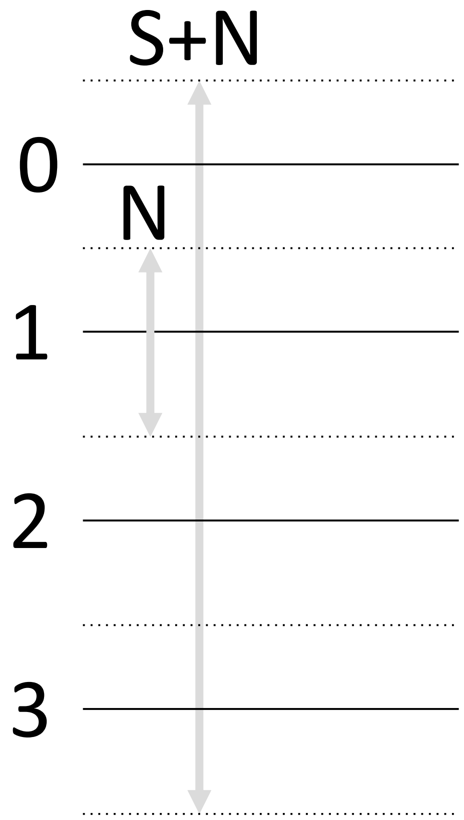
- Father of information theory
  - "A Mathematical Theory of Communication", 1948
- Fundamental contributions to digital computers, security, and communications


Credit: Courtesy MIT Museum

Electromechanical mouse that "solves" mazes!

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 ***lossless*** information carrying rate of the channel:

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

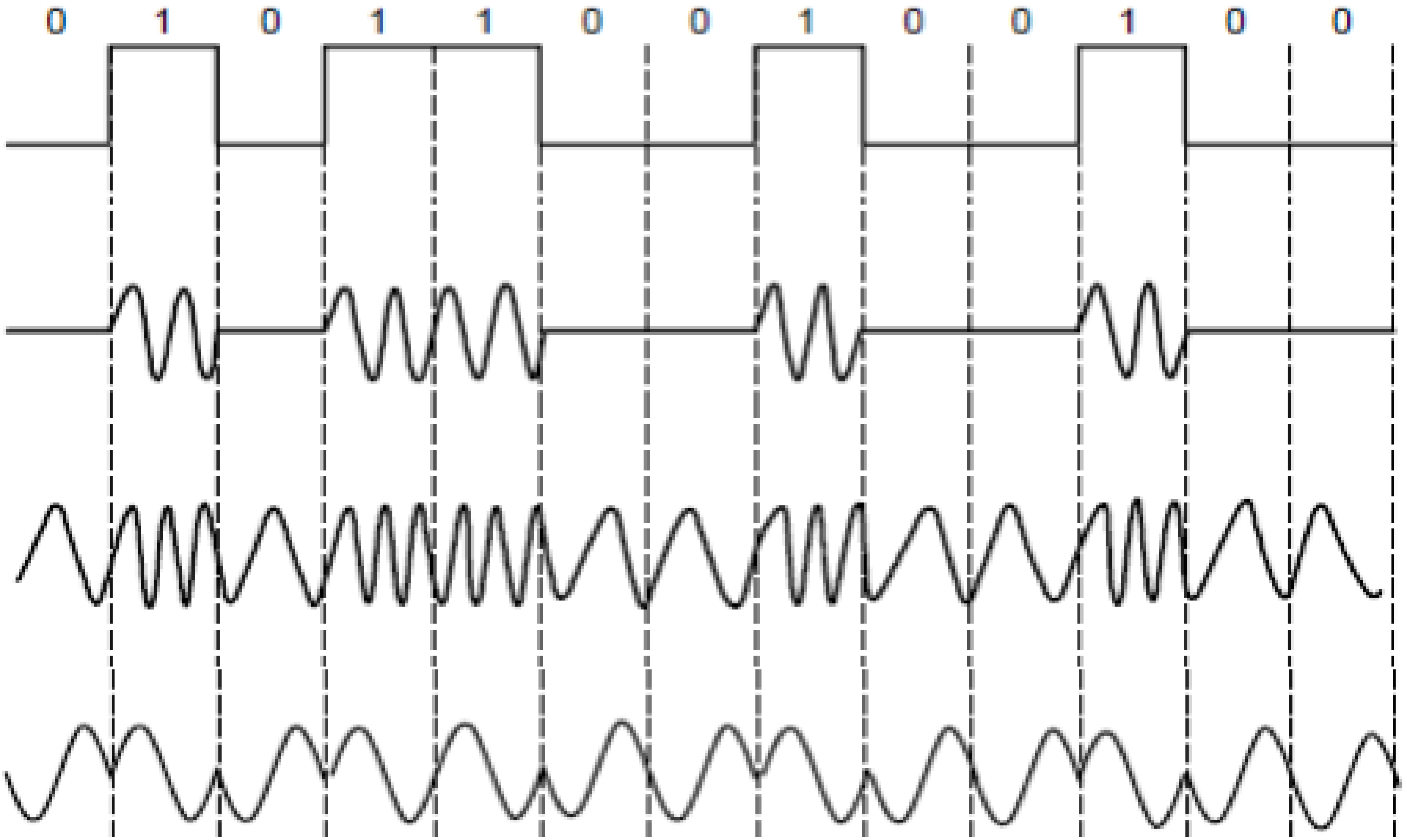
- Deriving this is outside the scope of this course, but it is an elegant result with incredible implications...

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 bandwidth increases capacity linearly!

No matter what fancy code you use, you can't beat Shannon (in AWGN)



NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying

Wired/Wireless Perspective

- 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

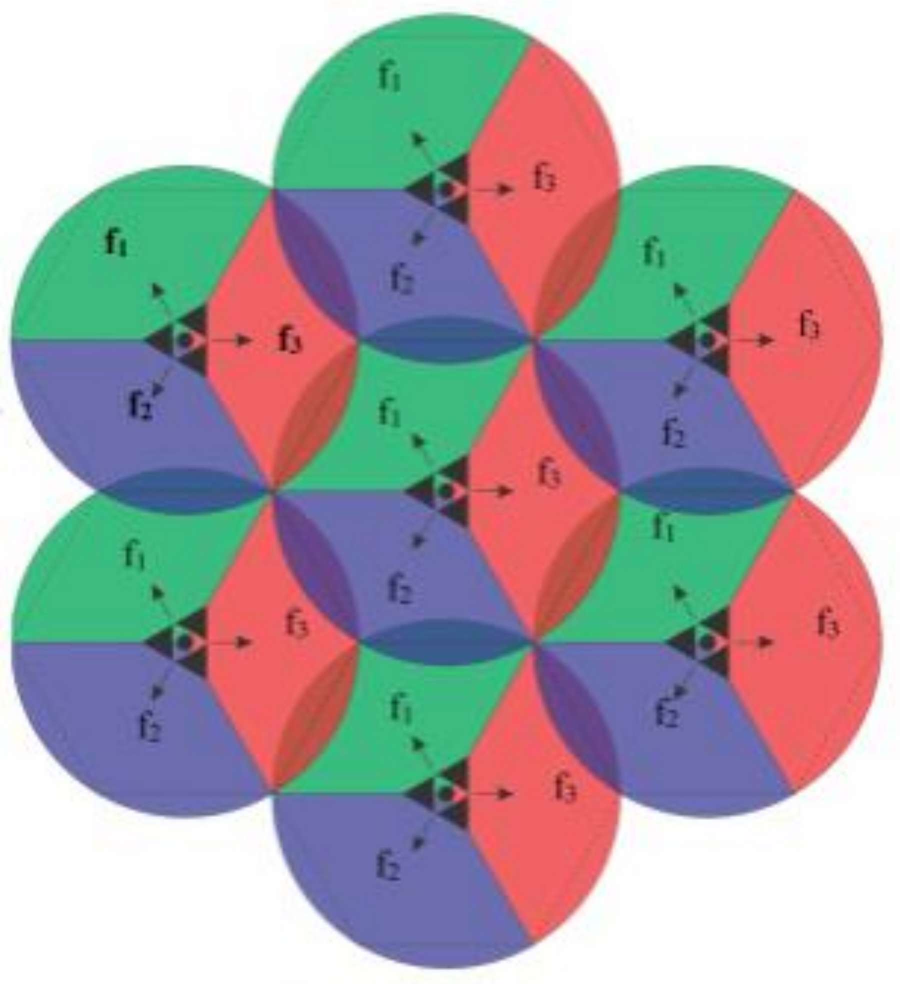
??? Which is better ???

5G... There is no magic

- To increase the data rate, you need either more spectrum or more power
- Both are limited by physics… how can we work around it???

Imaged by Heritage Auctions, HA.com

“Spatial Reuse”



Cellular Network

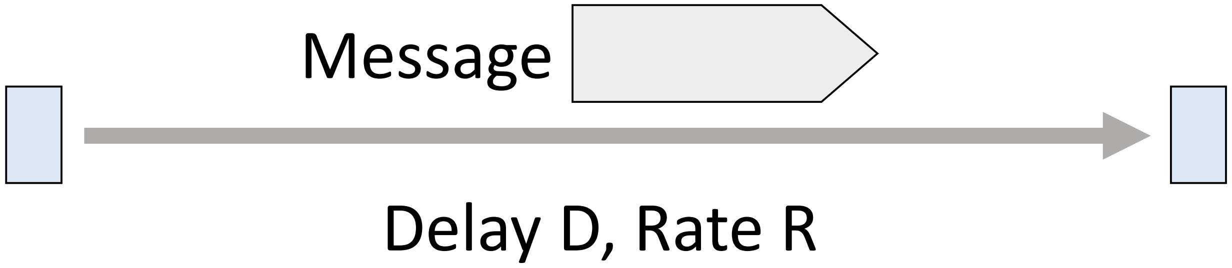
Make the cells smaller… so we can have more of them!

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
- 100 GbE in datacetners, etc.

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, its error rate, and its stability