The Physical Layer

Today's Objectives:

Describe how digital data can be encoded in analog signals

Design a functional data encoding scheme

Enumerate the Nyquist and Shannon limits governing data communication rates, and their physical intuitions.

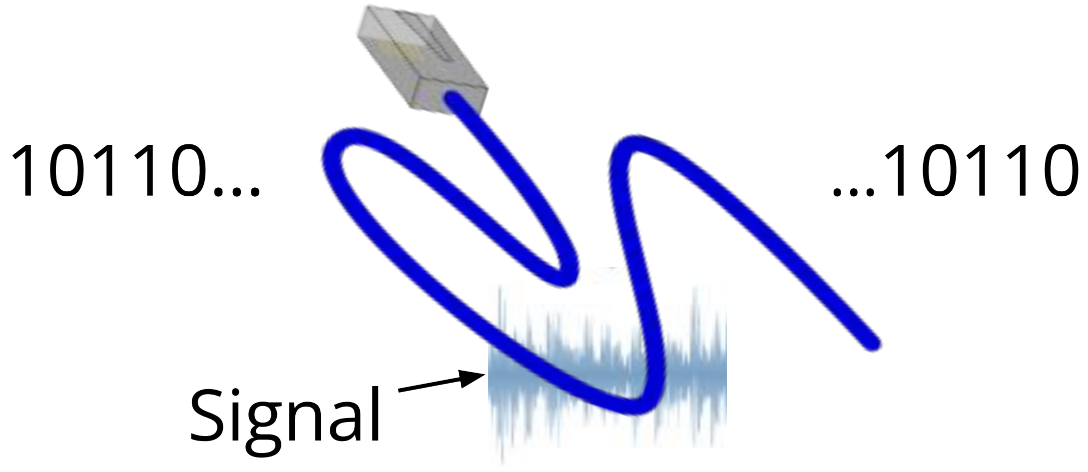
Course Reference Model

- We mostly follow the Internet
  - A little more about the Physical layer, and alternatives

5	Application	– Programs that use network service
4	Transport	– Provides end-to-end data delivery
3	Network	– Send packets over multiple networks
2	Link	– Send frames over one or more links
1	Physical	– Send bits using signals

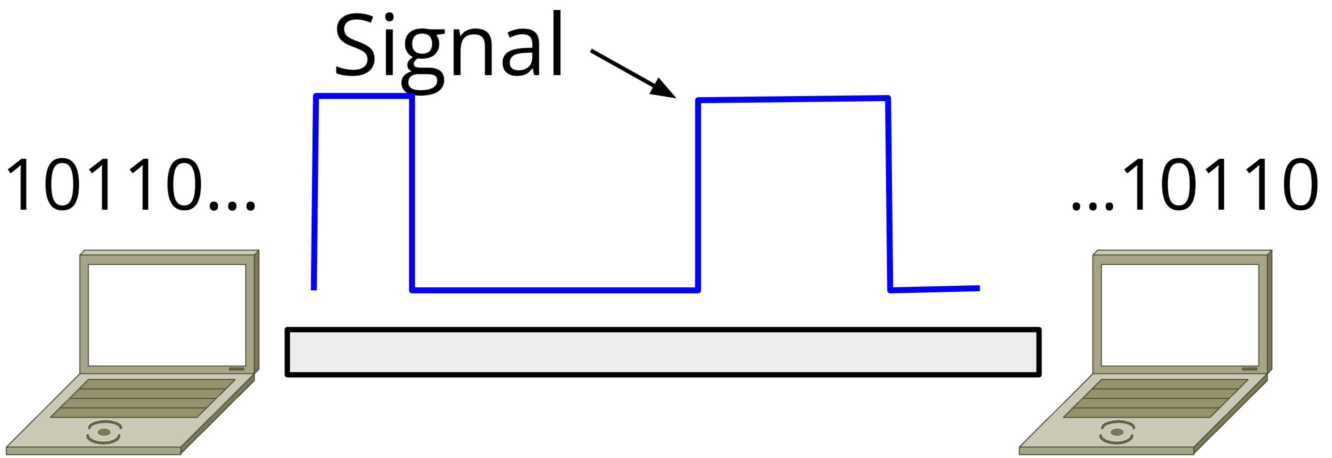
Scope of the Physical Layer

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



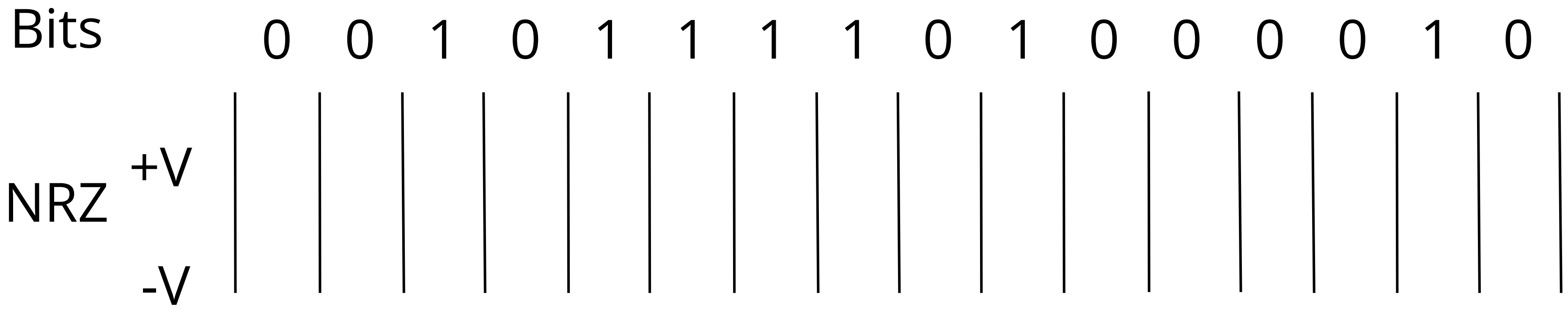
Topic

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



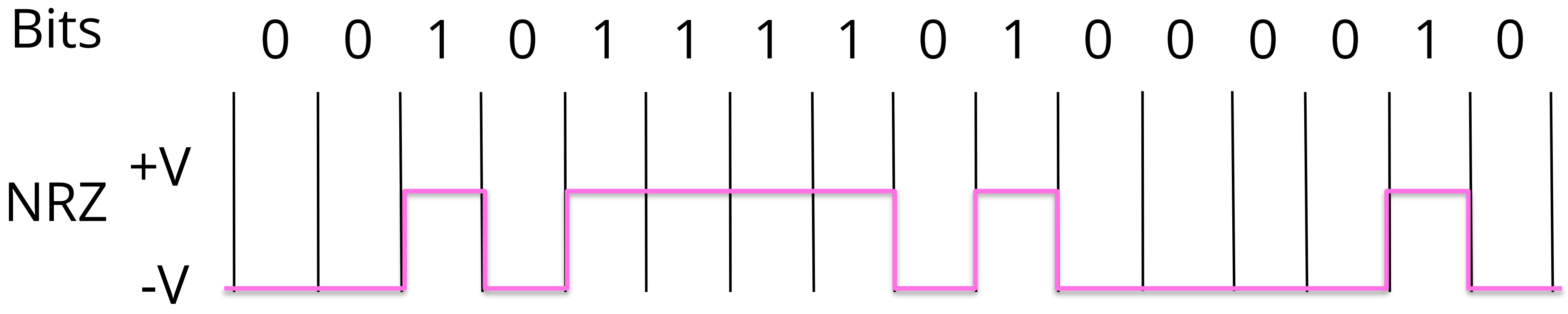
A Simple Coding

- 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 Coding (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 Coding (3)

- Problems?

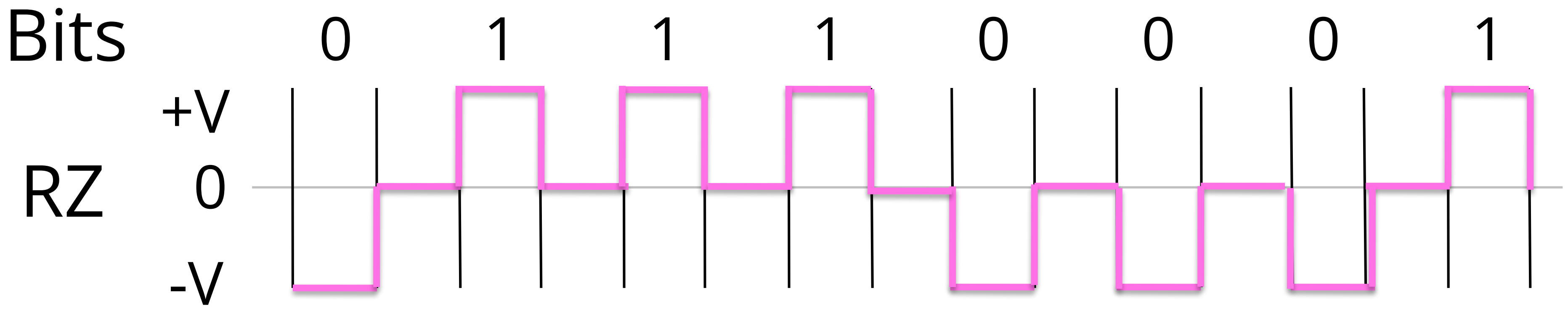
Clock Recovery

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

- Several other possible solutions we won't discuss
  - E.g., Manchester coding (§2.2.1), or scrambling

Answer 1: A Different 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)



But this is pretty wasteful! Takes twice as long! (Same as Manchester)

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!

- But what about long runs of 1s?
  - Also invert the signal level on each 1 to break up long runs of 1s
  - (called NRZI, §2.2.1)

Answer 2: Clock Recovery – 4B/5B (2)

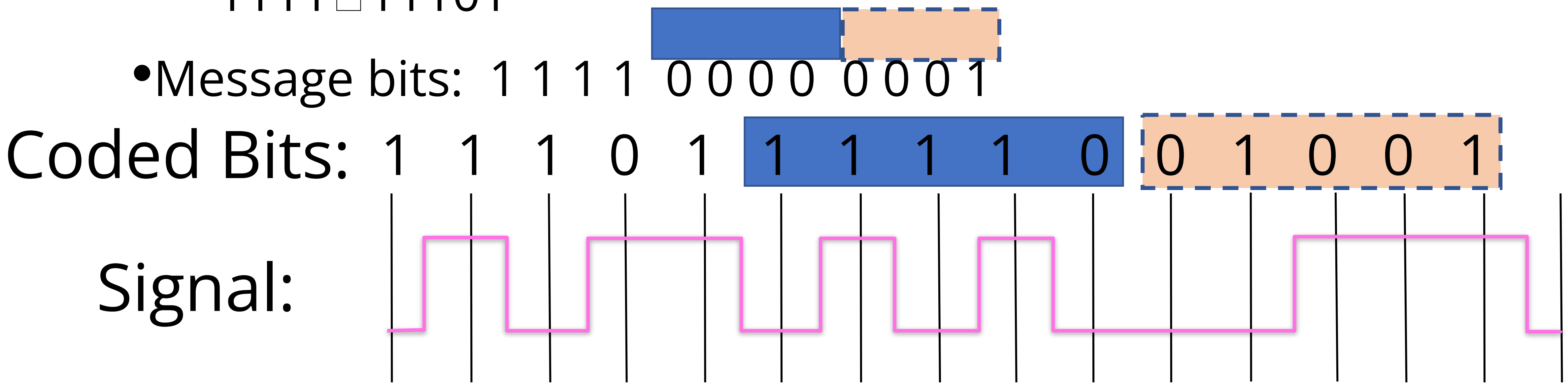
- 4B/5B code for reference:
  - 0000 □ 11110, 0001 □ 01001, 1110 □ 11100, … 1111□11101
- Message bits: 1 1 1 1 0 0 0 0 0 0 0 1

Coded Bits:

Signal:

Answer 2: 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



Many Other Schemes

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

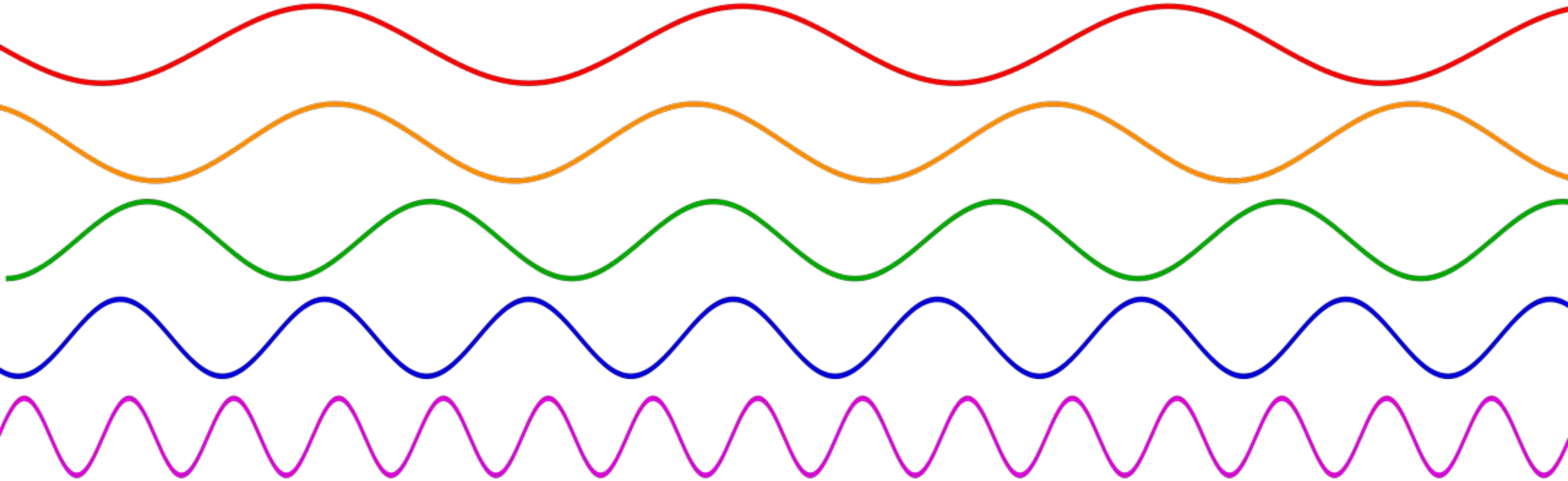
Pause for questions 💡

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)

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

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



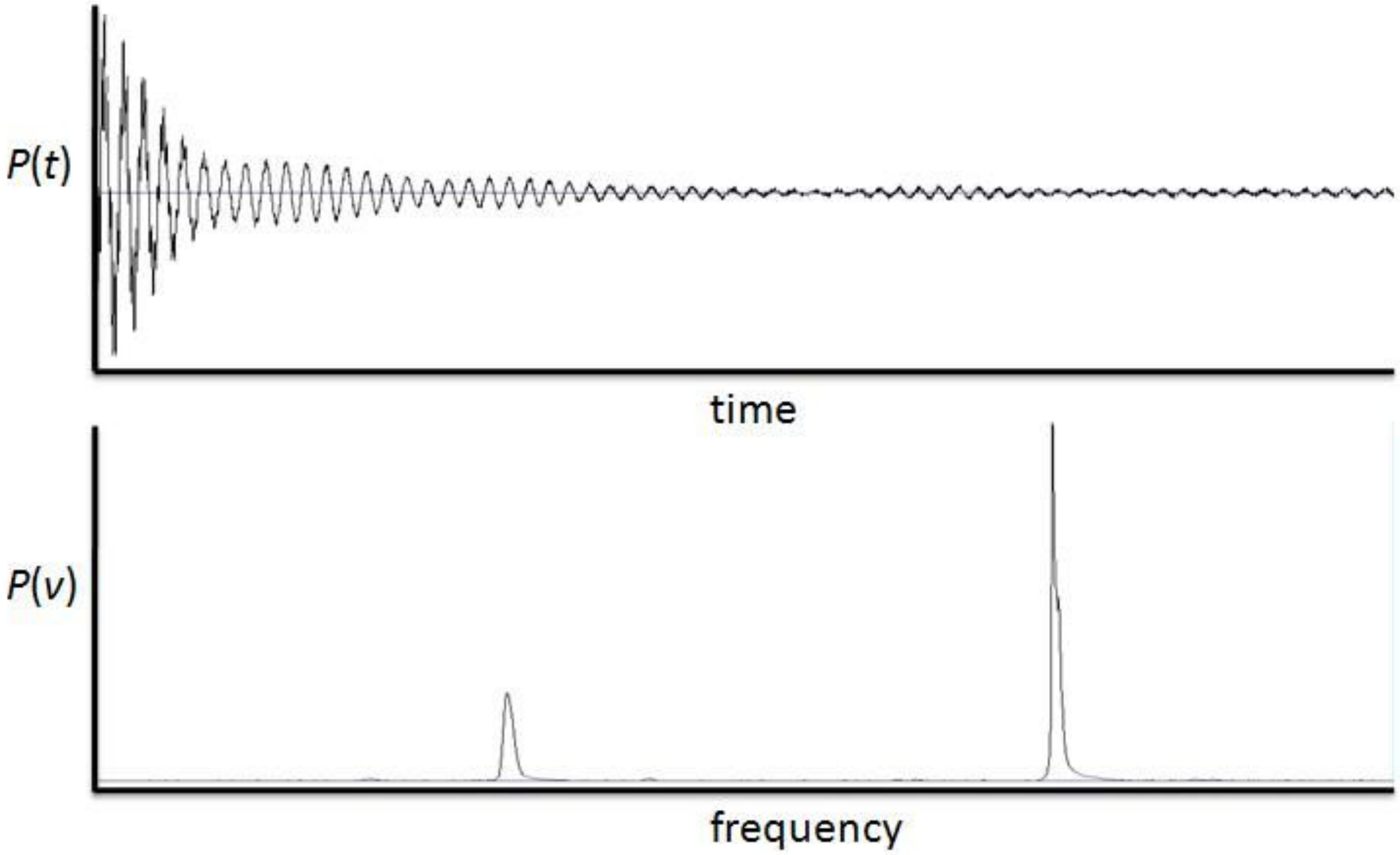
Img: wikimedia commons

Different frequencies have different properties!

Not all frequencies are created equal...

Analog Vocabulary Again

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

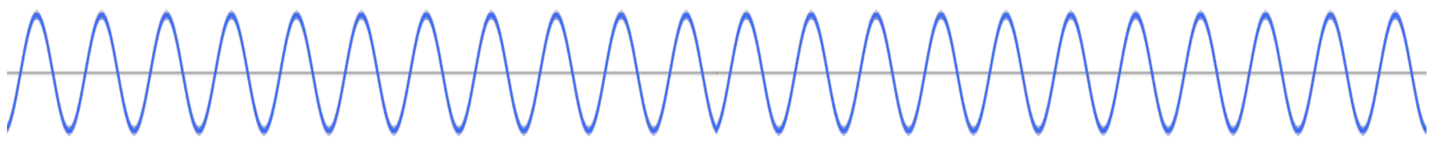


Modulation vs Coding

- What we have seen so far is called coding
  - Signal is sent directly on a wire
- These signals do not propagate well!
  - Need to send at higher frequencies (i.e. RF)
- Modulation carries a signal by modulating a carrier
  - To modulate comes from the same word root as “multiply”
  - “Baseband” is the 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

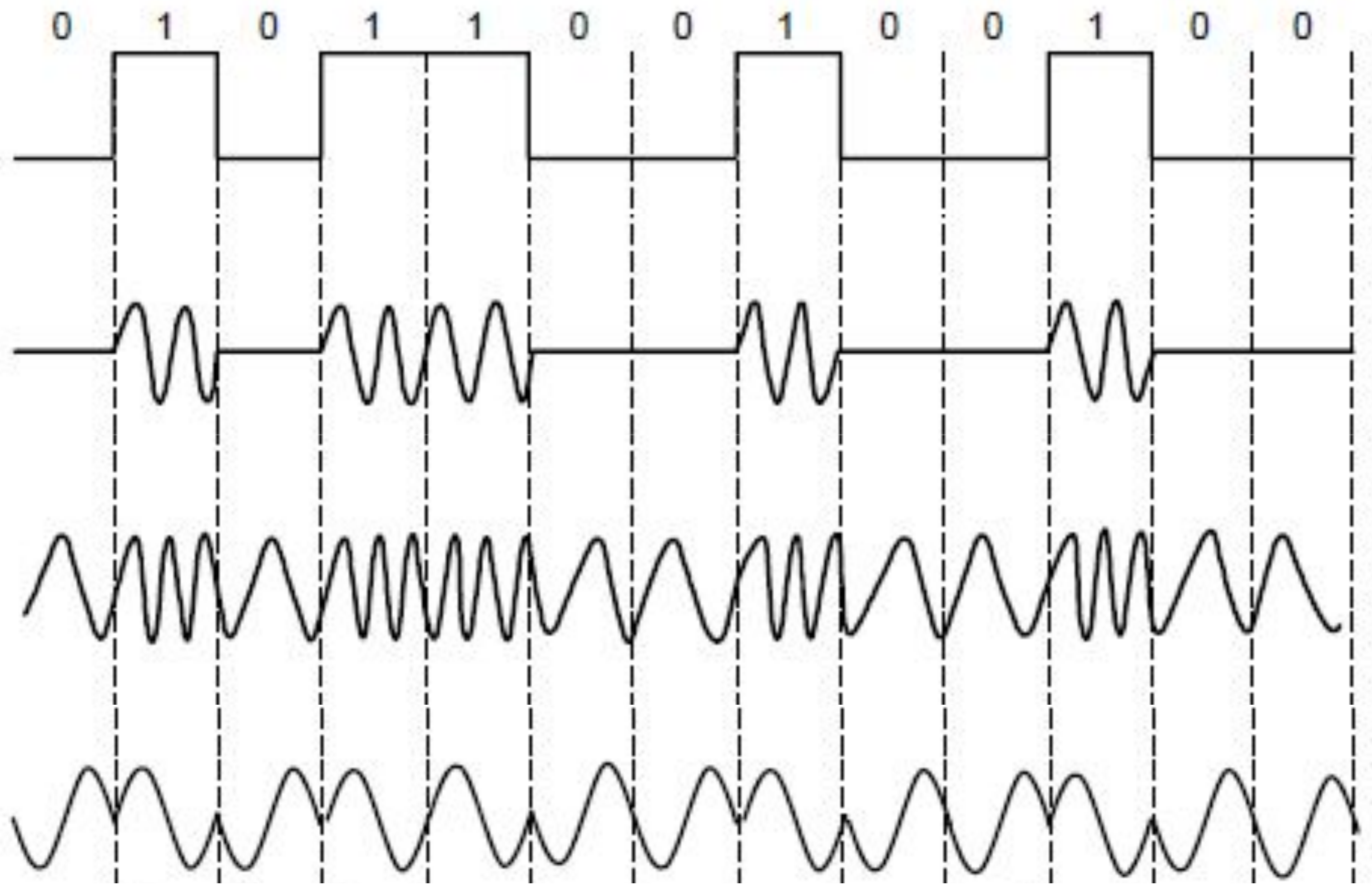
Comparisons

NRZ signal of bits

Amplitude shift keying

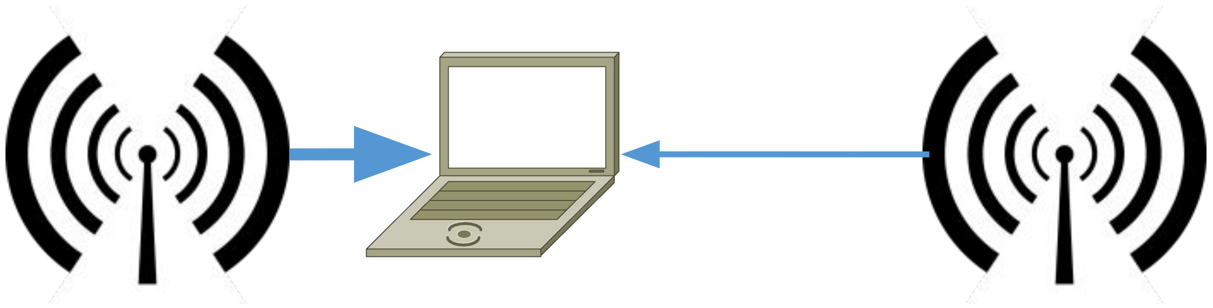
Frequency shift keying

Phase shift keying

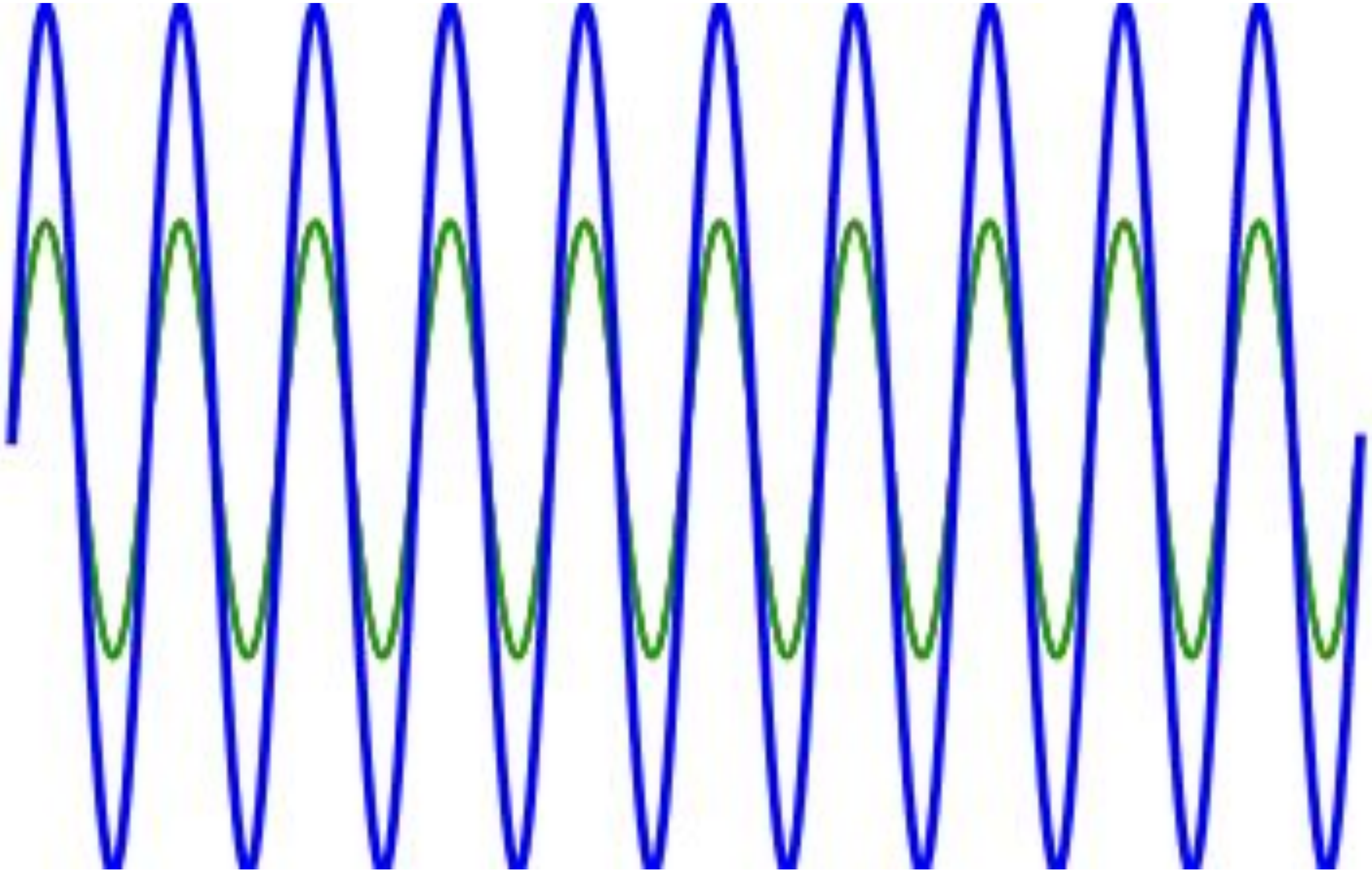


Wireless

- 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

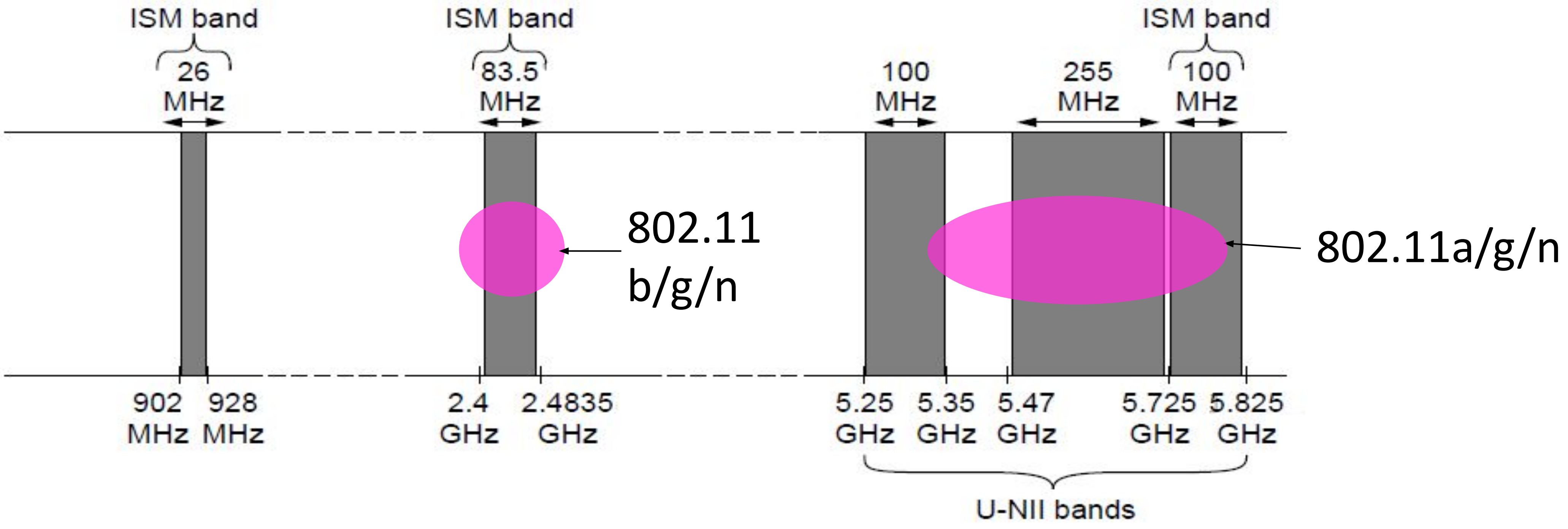


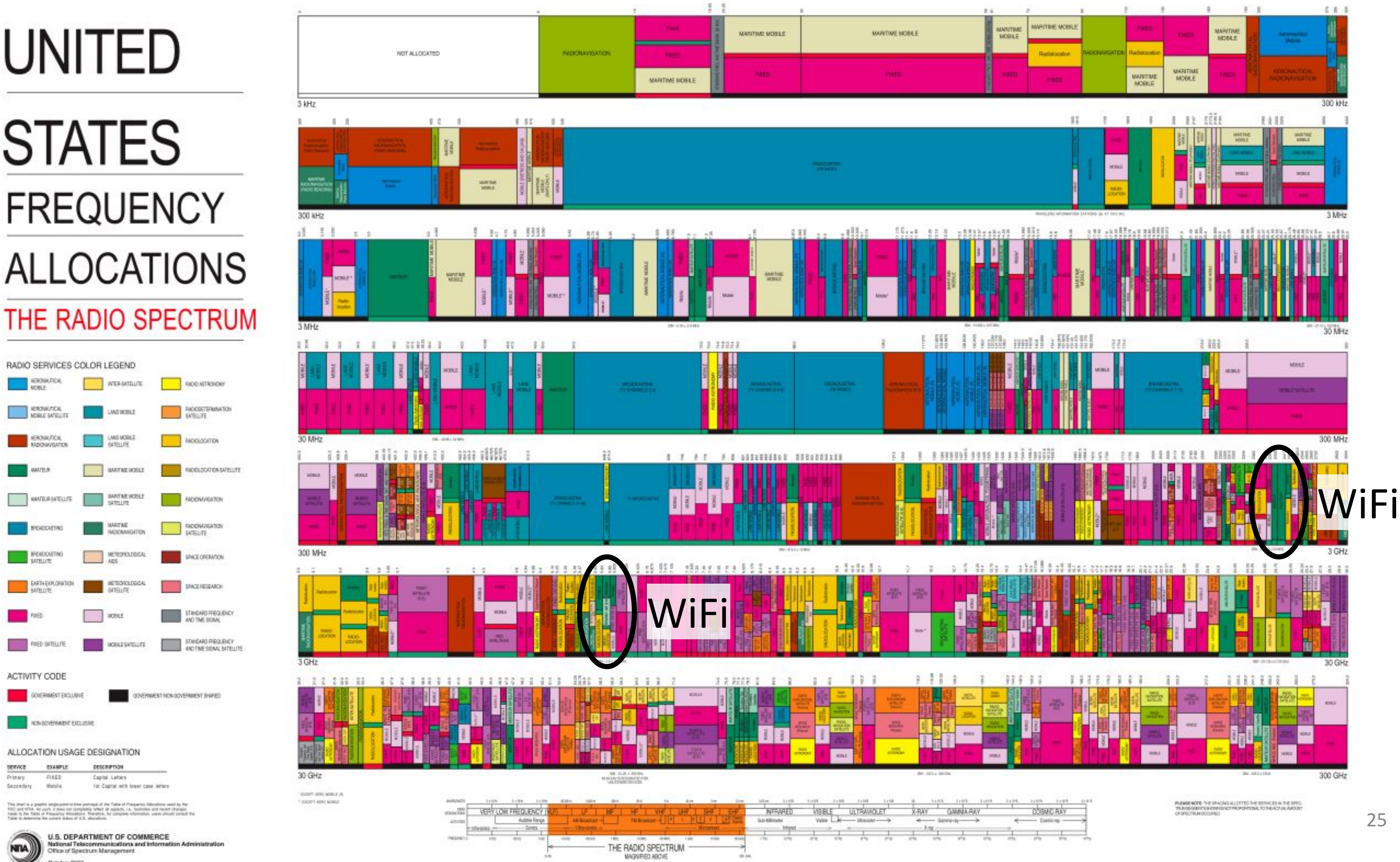
Wireless Interference



Wireless (2)

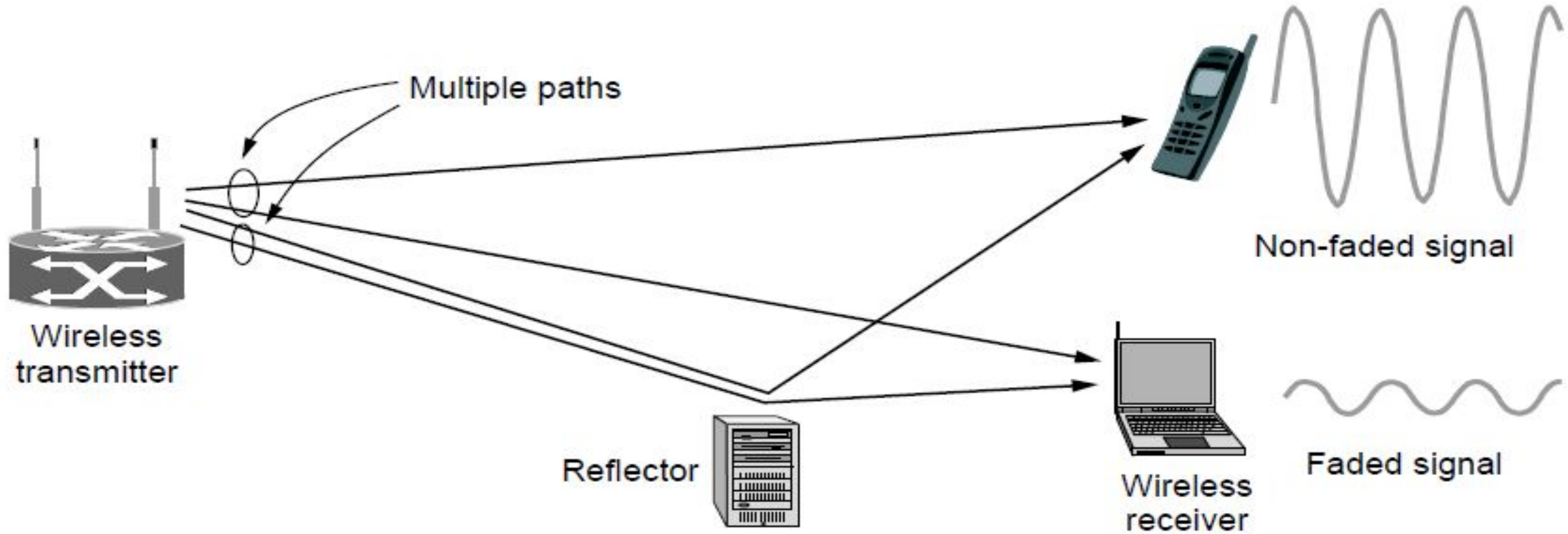
- Unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking




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
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
THE RADIO SPECTRUM

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”

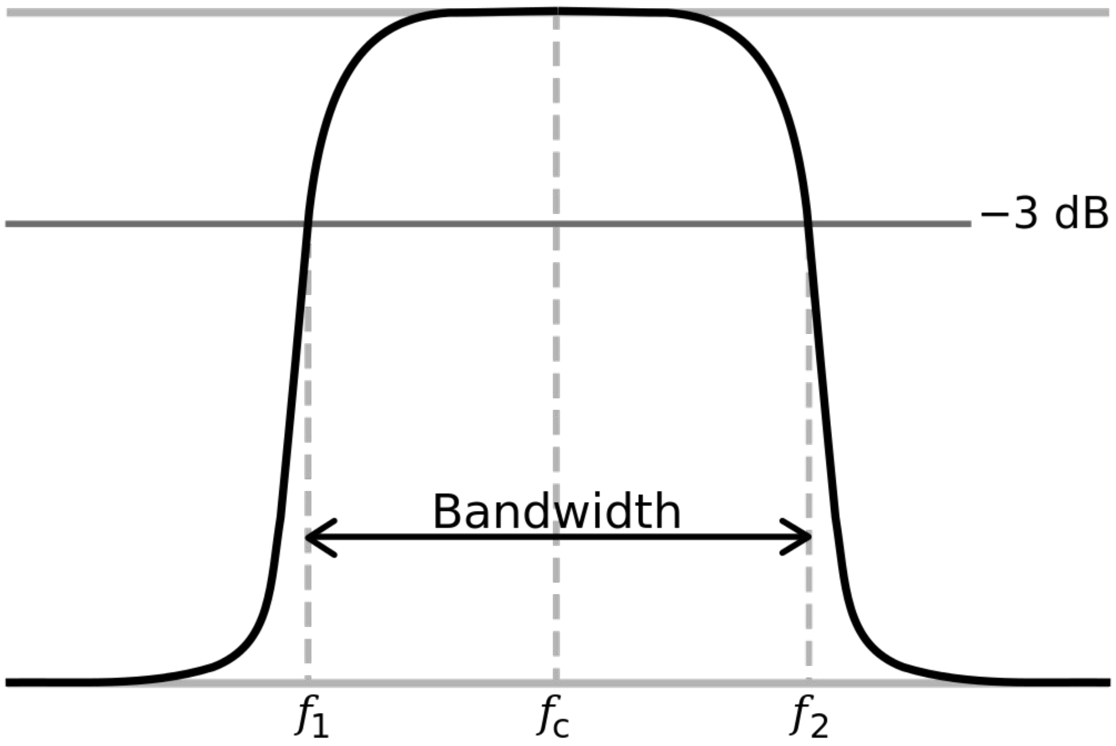
Real World Limits

- 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 :)

Important Analog Vocabulary (2)

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



This is not the same "bandwidth" as often used to describe the transmission rate of a connection!

The two terms are related (as you'll see in the following slides) but refer to different things!

Attribution: Henrikb4 at en.wikipedia

Key Physical Properties

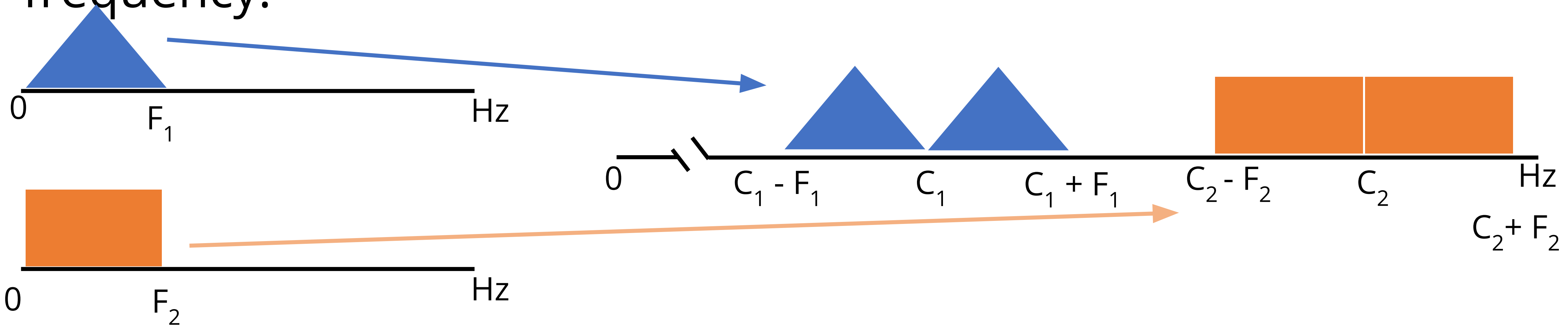
- The bandwidth (B), signal power (S), and noise power (N)
  - B (in hertz) limits the rate of transitions
  - S and N (in watts) limit how many signal levels we can distinguish

Some more context for bandwidth(Hz)

- The bandwidth of a given signal can be thought of loosely as how wiggly/sharp the signal is
  - The higher the bandwidth, the faster the signal can change from one value to another
- Bandwidths of some common things:
  - The main components of an analog human voice: ~3KHz
  - The limits of human hearing: ~20KHz
  - Analog TV channels: 5MHz
  - WiFi channels: 5/10/20/40MHz

Signals can be shifted via modulation

- If the music you hear on the radio exists from approximately 20Hz -> 20KHz, why do you tune to 90.3MHz to listen to it?
  - The unmodulated signal, aligned at 0Hz, is the “baseband” signal
- Modulation of the baseband signal up to different carriers allows multiple signals to coexist, differentiated by carrier frequency!



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

- The maximum symbol rate is 2 * Bandwidth
  - Can have multiple “levels” per symbol, so bit rate has $\log_2 V$

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

Takeaway:

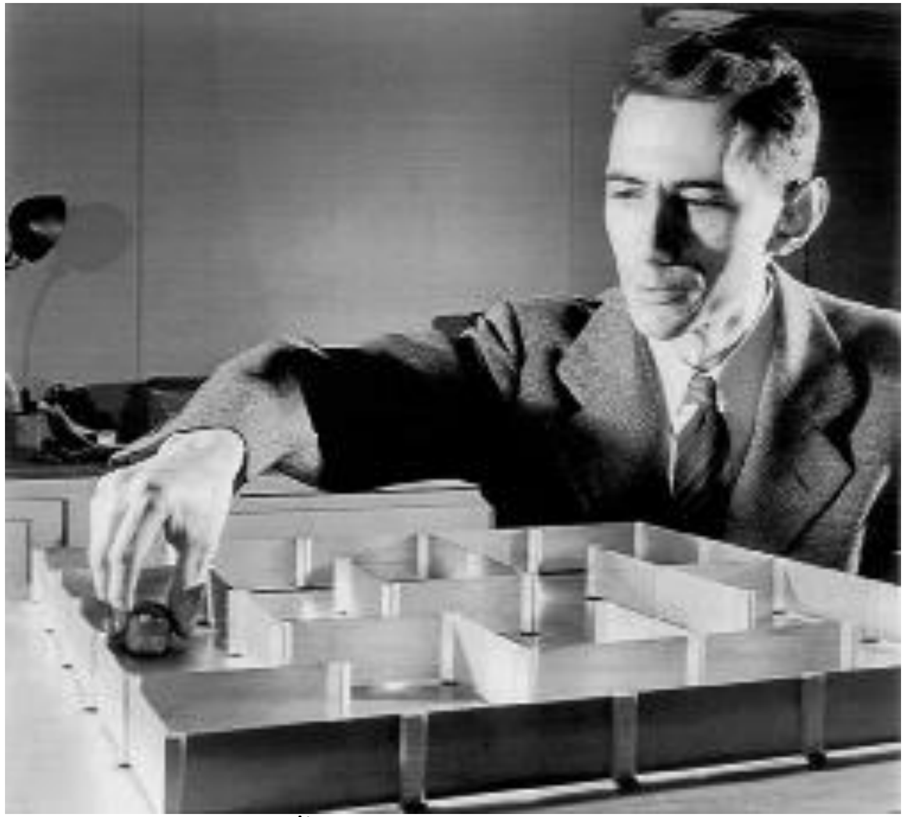
- This is why it's the ***bandwidth***, not the specific frequency, that determines how much information a signal carries

- Nyquist rate is all about how many digital symbols you can cram into a signal with a given bandwidth
- Shannon capacity is all about how much information you can communicate over a channel that's corrupted by noise…
  - And it turns out the information content is linearly related to the bandwidth!

Claude Shannon (1916-2001)

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

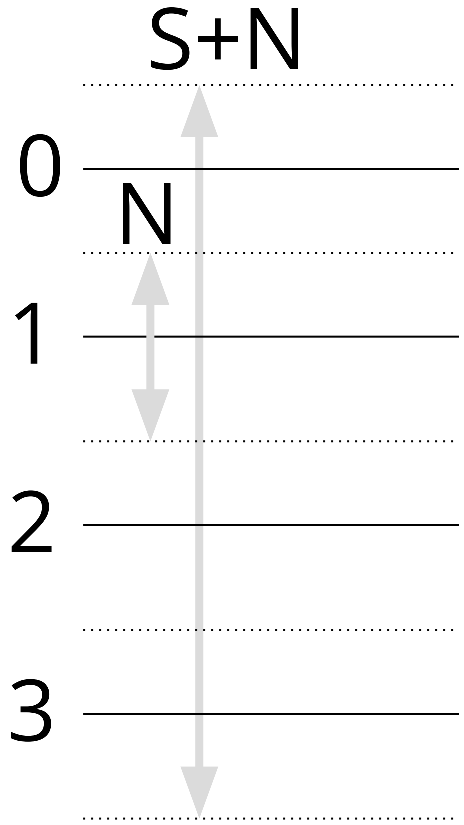
Electromechanical mouse that "solves" mazes!



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>
  - Note: noise is random, hence some errors
  - Note: there is a "noise floor" for any channel
- 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
  - Requires *error correction*, which we will cover next class :)
- Assuming noise power fixed, increasing the signal power yields diminishing returns : (
- Assuming signal/noise ratio is fixed, increasing bandwidth increases capacity linearly!

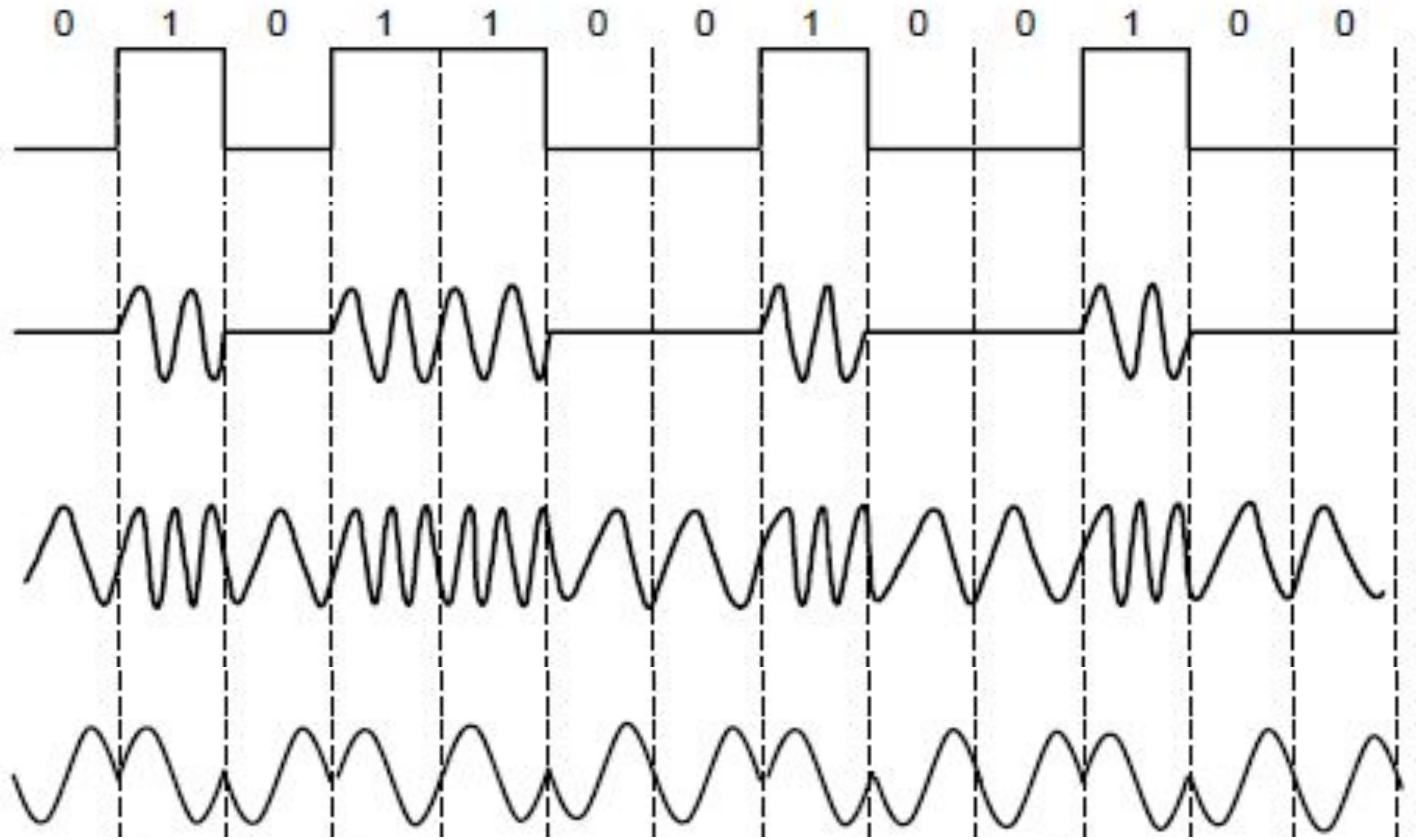
No matter what fancy code you use, you can't beat Shannon (in most channels)

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

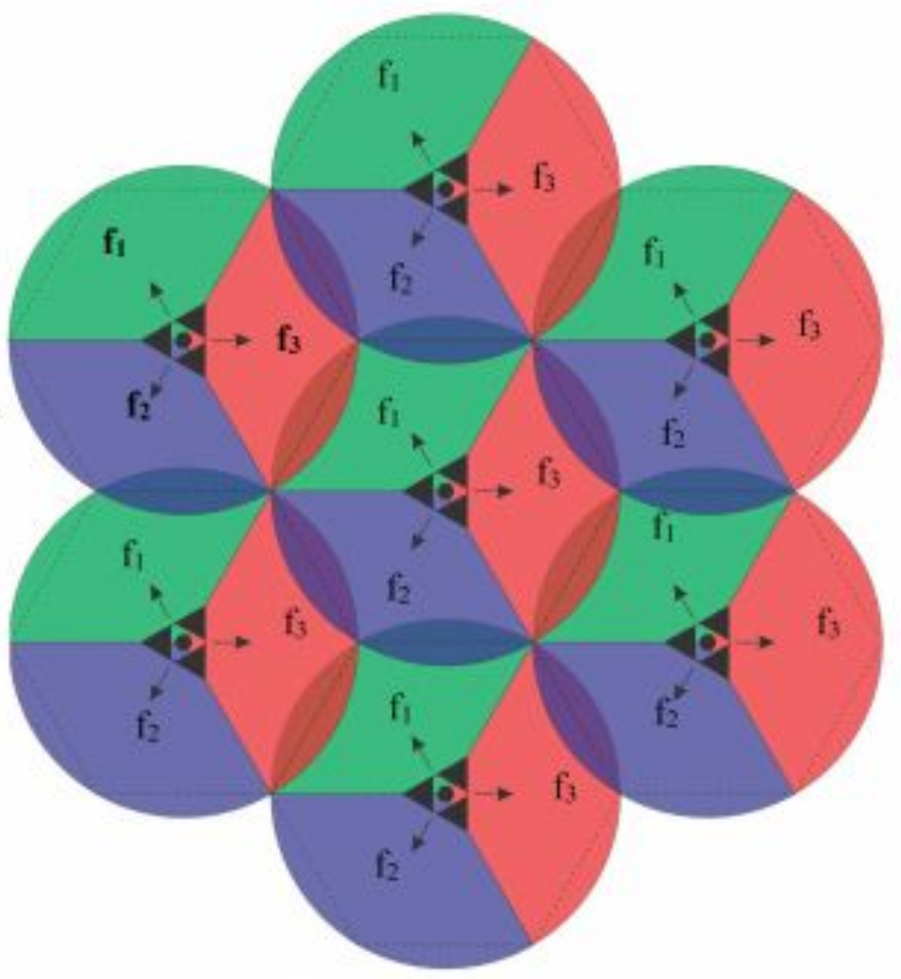
??? Which is better ???

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

medium.com/@artieda

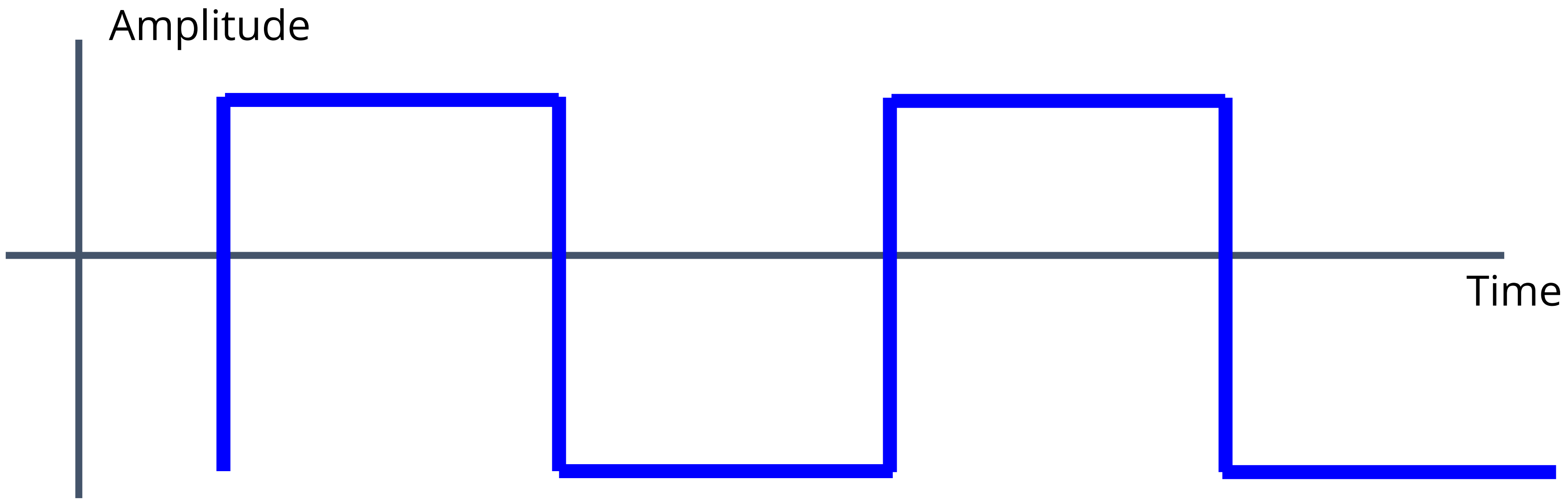
Make the cells smaller… so we can have more of them!

Phy Layer Innovation Still Happening!

- **Backscatter** “zero power” wireless
- **mm wave** 20GHz+ radio equipment
- Free space optical (**FSO**)
- Cooperative **interference management**
- **Massive MIMO** and beamforming
- Powerline Networking
- 100 GbE in datacetners, etc.

MATT STUFF

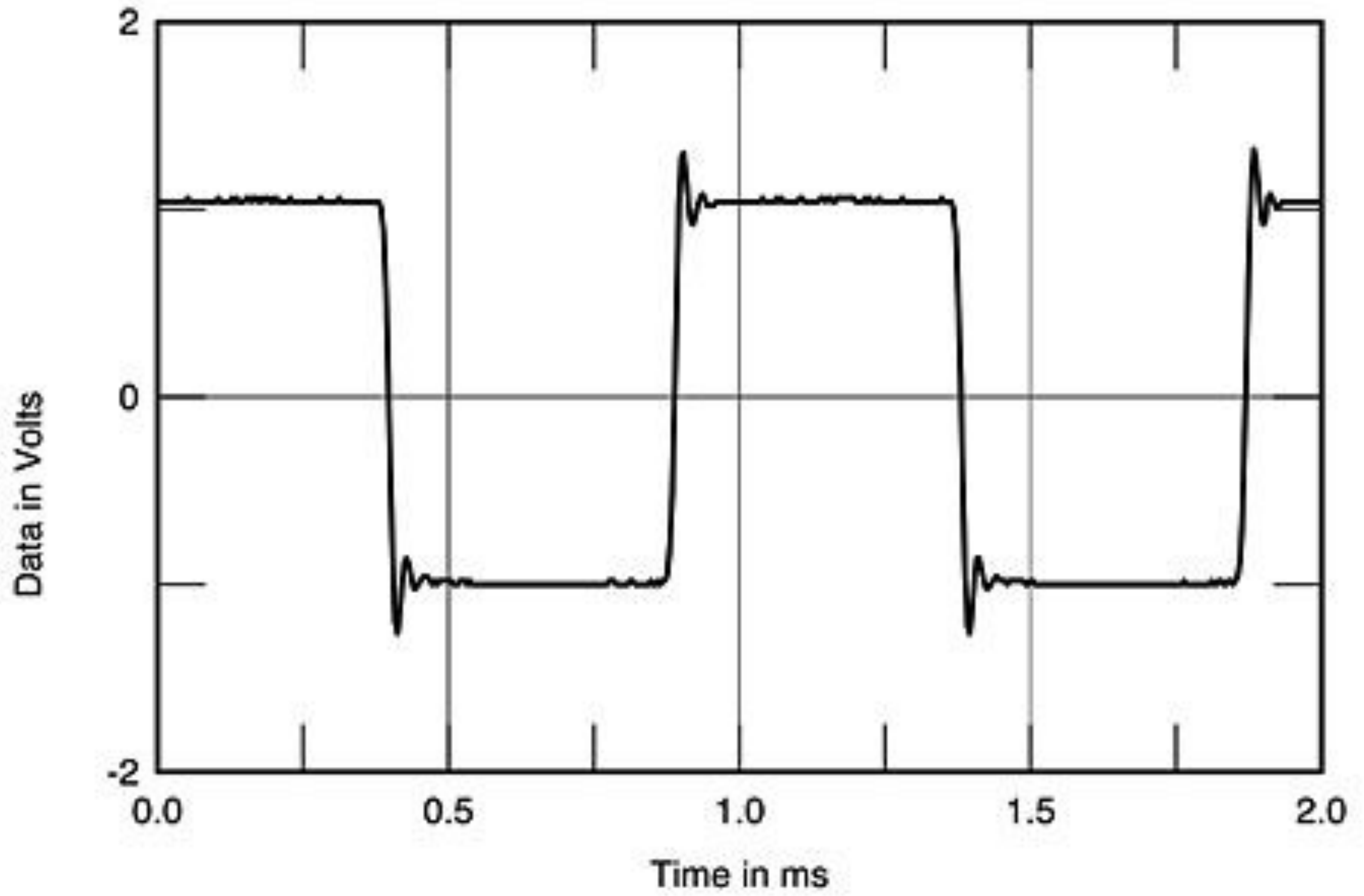
What is the bandwidth of a square wave?



Infinite! *No true square wave exists in the real world*

Attribution: Henrikb4 at en.wikipedia

Warning! Brief EE Moment!



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