CSE160: Computer Networks

Lecture #03 – Bits and Bandwidth

2020-09-03

Professor

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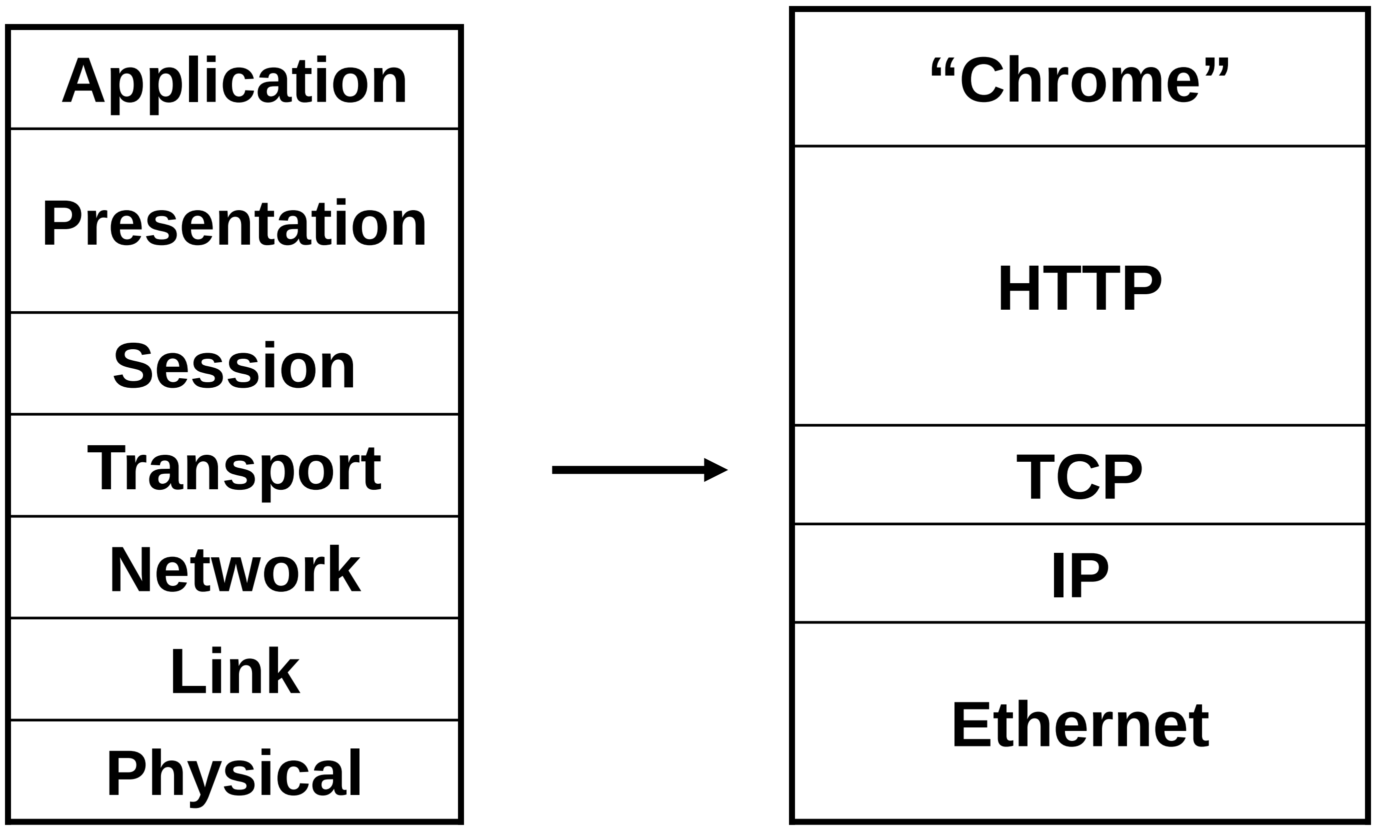
Last Time ...

- Protocols, layering and reference models



The OSI Model

Sample Protocol Stack

This Lecture

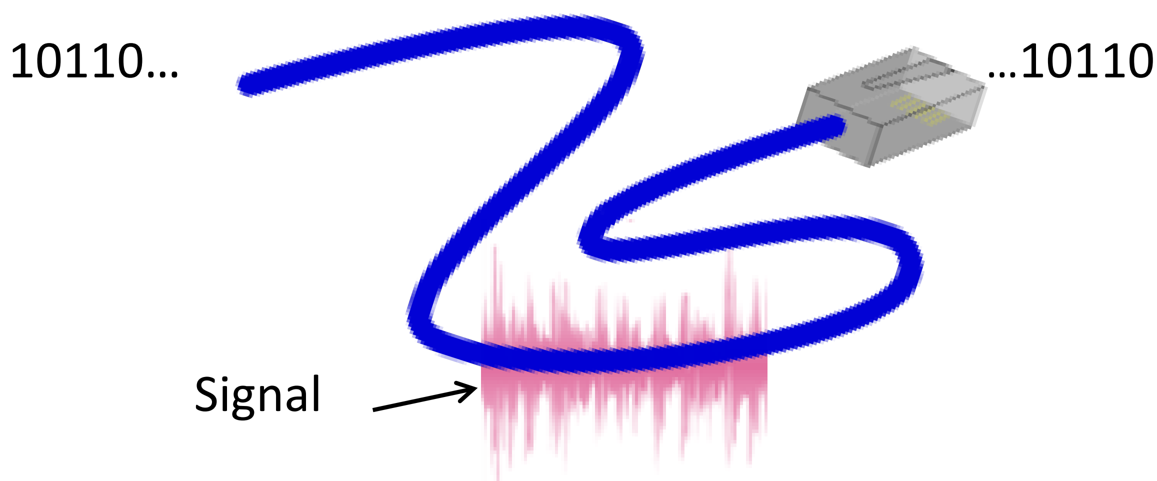
- Focus: ***How do we send a message across a wire?***

- The physical / link layers:
  1. Model of a link
  2. Different kinds of media, signals
  3. Encoding bits with signals
  4. Fundamental Limits

Application
Presentation
Session
Transport
Network
Data Link
Physical

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>

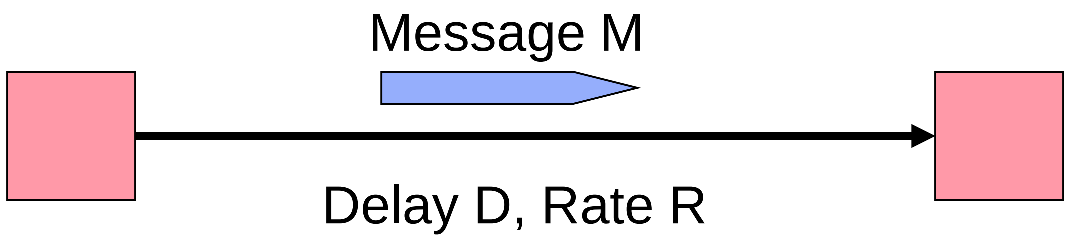


1. Simple Link Model

- Abstract model is typically all we will need
  - What goes in comes out altered by the model
- We'll end with an abstraction of a physical channel
  - Rate (or bandwidth, capacity, speed) in bits/seconds
  - Delay in seconds, related to length
- Other parameters that are important:
  - The kind and frequency of errors
  - Whether the media is broadcast or not

Message Latency

- How long does it take to send a message?



- Latency is the delay to send a message over a link
  - Transmission delay = message (bits) / rate (bps)
    - Time to put M-bit message “on the wire” (M/R seconds)
  - Propagation delay = length / speed of light in media
    - Time for bits to propagate across the wire (D seconds)
- Combining the two terms we have: **L = M/R + D**
- Later we will see queuing delay …

Relationships

- Latency (sec) =
  - Transmit (sec) + Propagation (sec) + Queue (sec)
- Transmit Time (sec) =
  - Message Size (bits) / Bandwidth (bits/sec) = M/R seconds
- Propagation Delay (sec) =
  - Length (mts) / Speed of signals (mts/sec) = L/(2/3c) = D seconds

Metric Units

- The main prefixes we use:

Prefix	Exp.	Prefix	Exp.
K(ilo)	10^3	m(illi)	10^{-3}
M(ega)	10^6	μ(micro)	10^{-6}
G(iga)	10^9	n(ano)	10^{-9}

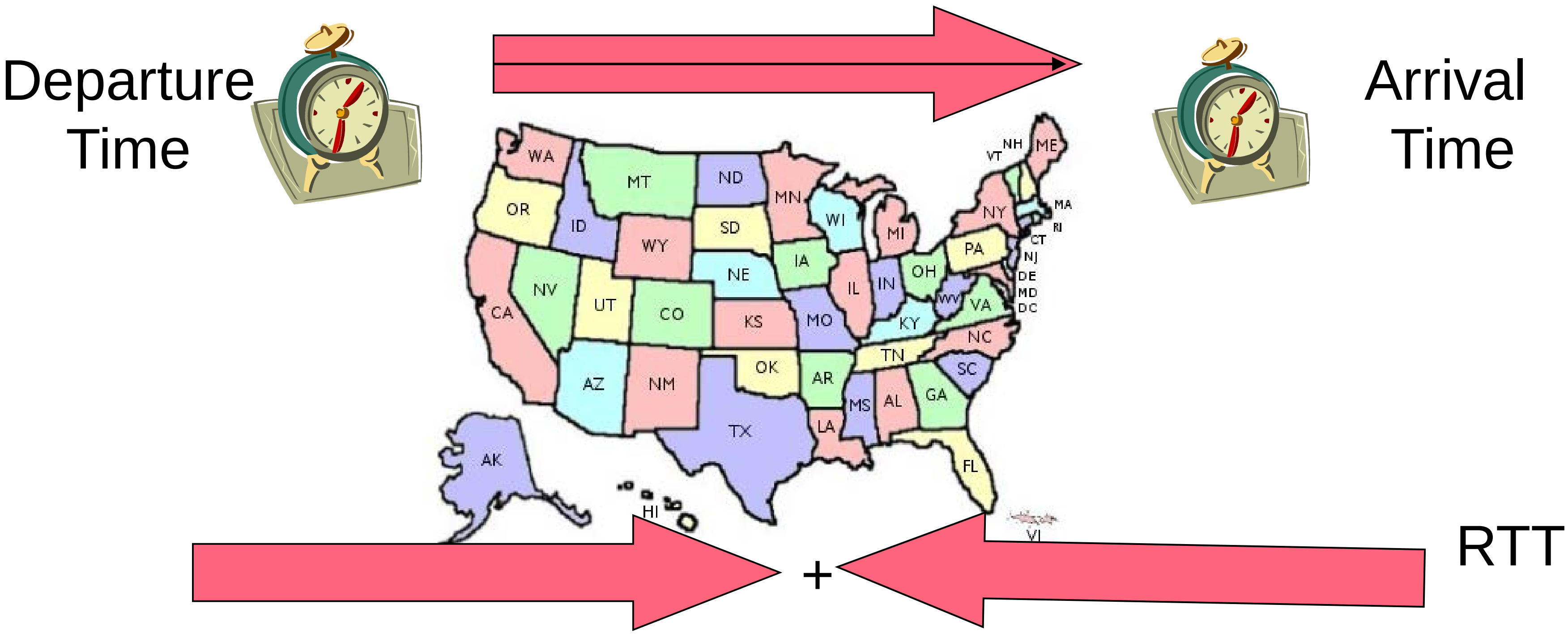
- Use powers of 10 for rates, 2 for storage
  - 1 Kbps = 1,000 bps, 1 KB = 2^{10} = 1024 bytes
  - 1 Mbps = 1,000,000 bps, 1 MB = 2^{20} = 1,048,576 bytes
- "B" is for bytes, "b" is for bits, 1B = 8b

One-way Latency

- "Dialup" with a telephone modem:
  - D = 10ms, R = 56Kbps, M = 1024 bytes
  - Latency = (1024 x 8)/(56 x 1,000) sec + 10ms = 153ms!
- Cross-country with T3 (45Mbps) line:
  - D = 50ms, R = 45Mbps, M = 1024 bytes
  - Latency = (1024 x 8) / (45 x 1,000,000) sec 50ms = 50ms!
- Either a slow link or long wire makes for large latency
  - Often, one delay components dominates

Latency and RTT

- Latency is typically the one way delay over a link
  - Arrival Time - Departure Time



- The round trip time (RTT) is twice the one way delay
  - Measure of how long to signal and get a response

Throughput

- Measure of system's ability to "pump out" data
  - NOT the same as bandwidth
- Throughput = Transfer Size / Transfer Time
  - Eg, "I transferred 1000 bytes in 1 second on a 100Mb/s link"
    - BW?
    - Throughput?
- Transfer Time = SUM OF
  - Time to get started shipping the bits
  - Time to ship the bits
  - Time to get stopped shipping the bits
- Throughput includes all protocols overheads

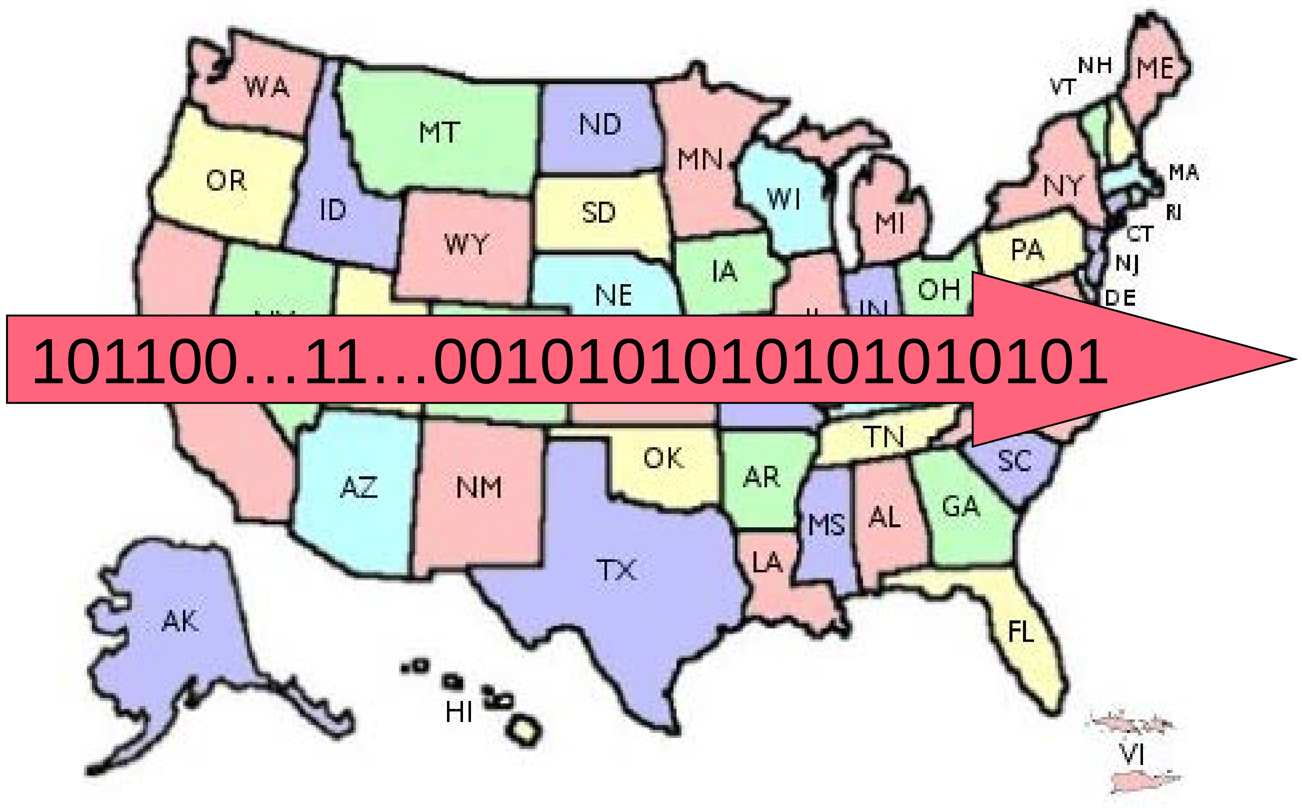
Messages Occupy “Space” On the Wire

- Consider a 1b/s network.
  – How much space does 1 byte take?
- Suppose latency is 16 seconds.
  – How many bits can the network “store”
  – This is the BANDWIDTH-DELAY product
  – Measure of “data in flight.”
  – 1b/s * 16s = 16b
- Tells us how much data can be sent before a receiver sees any of it.
  – Twice B.D. tells us how much data we could send before hearing back from the receiver something related to the first bit sent.
  – Implications?

A More Realistic Example

- Fiber at home, cross country

BD = 50ms * 45Mbps = 2.25 * 10^6 = 280KB



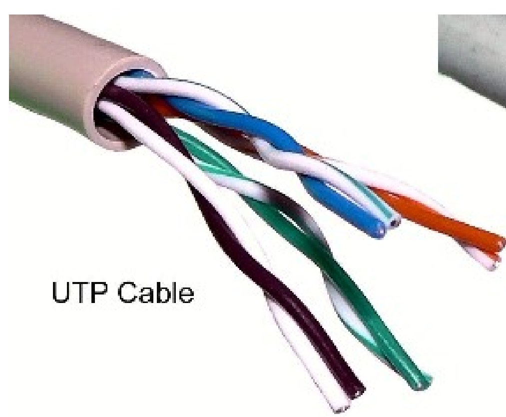
- That’s quite a lot of data in the network
  – Like a small novel

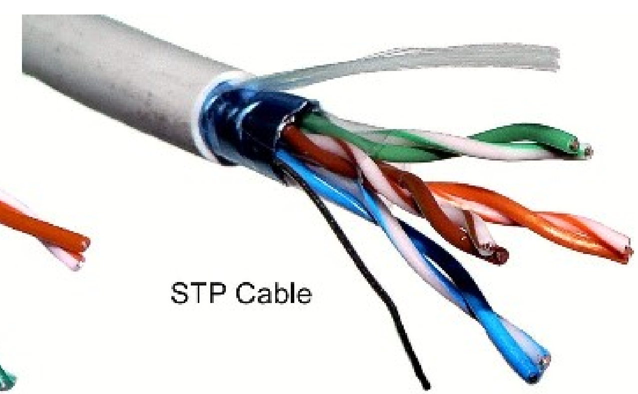
2. Types of Media

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

Wires – Twisted Pair

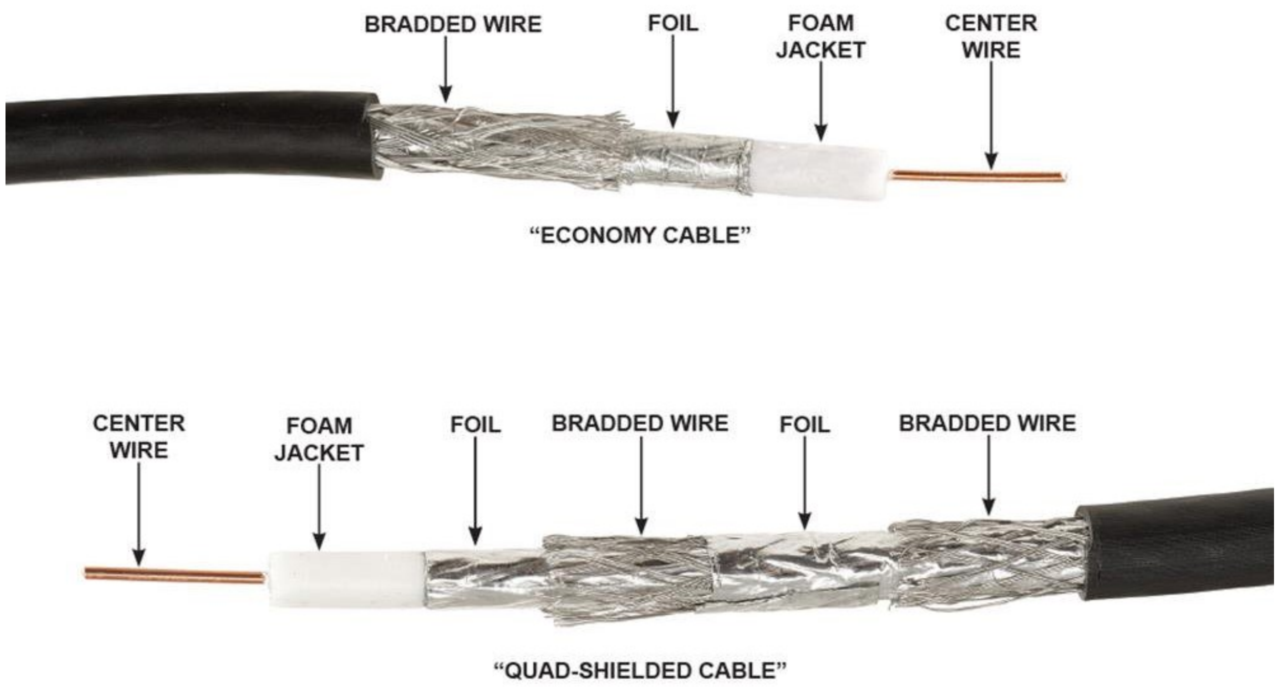
- Very common, used in LANs and telephone lines
  - Four twisted pairs
  - Twists reduce radiated signal
  - Category 5e or 6 (bandwidth and insertion loss)
  - Unshielded (UTP) or Shielded (STP)





Wires – Coaxial Cable

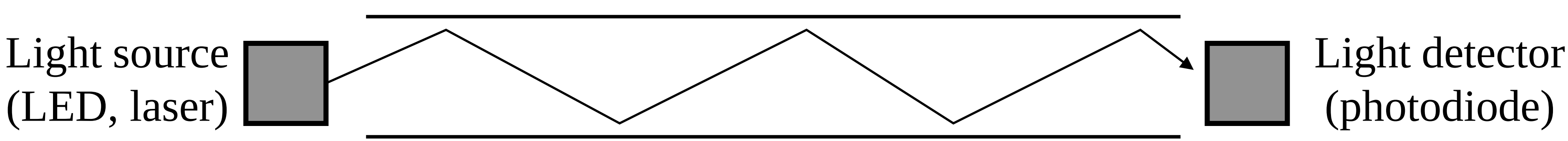
- Also common. Better shielding for better performance

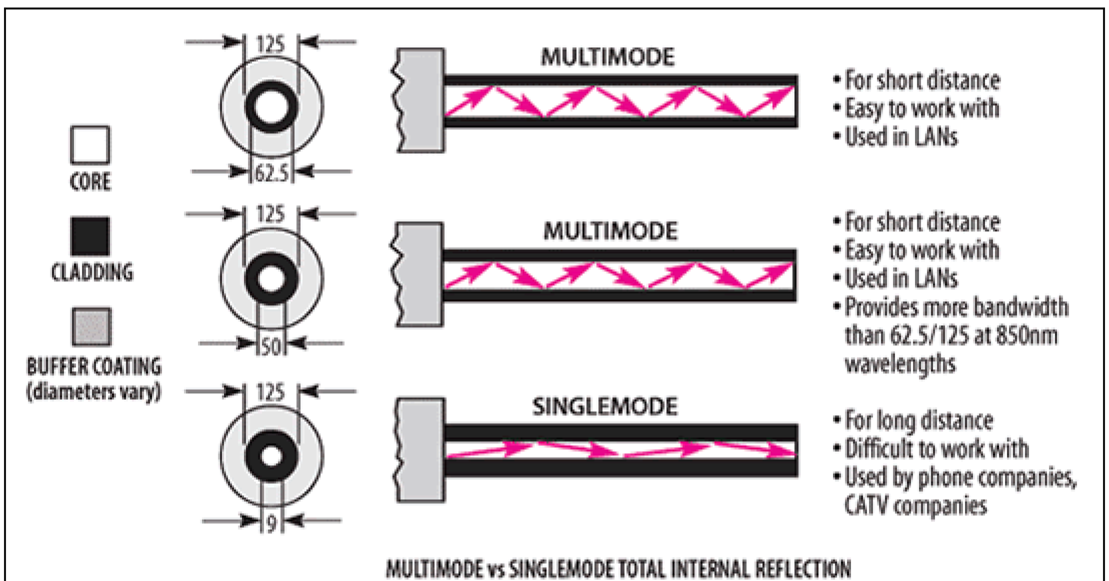


- Other kinds of wires too: e.g., electrical power

Fiber

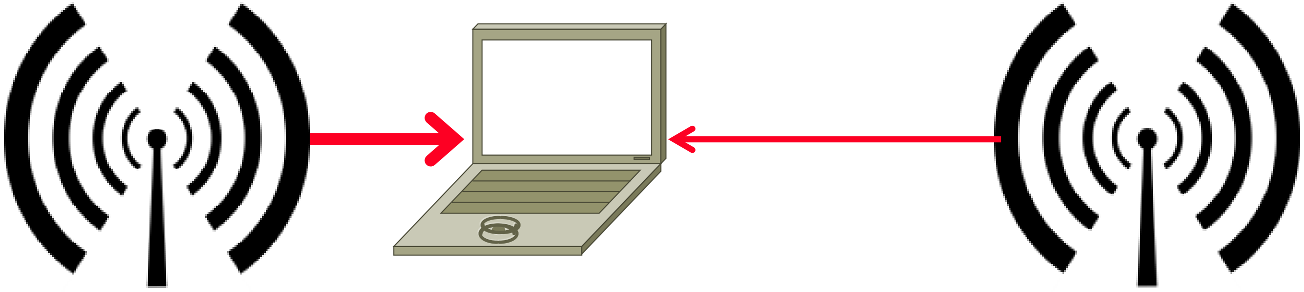
- Long, thin, pure strand of glass
  - light propagated with total internal reflection
  - enormous bandwidth available (terabits)
  - Multi-mode allows many different paths, limited by dispersion
  - Chromatic dispersion if multiple frequencies

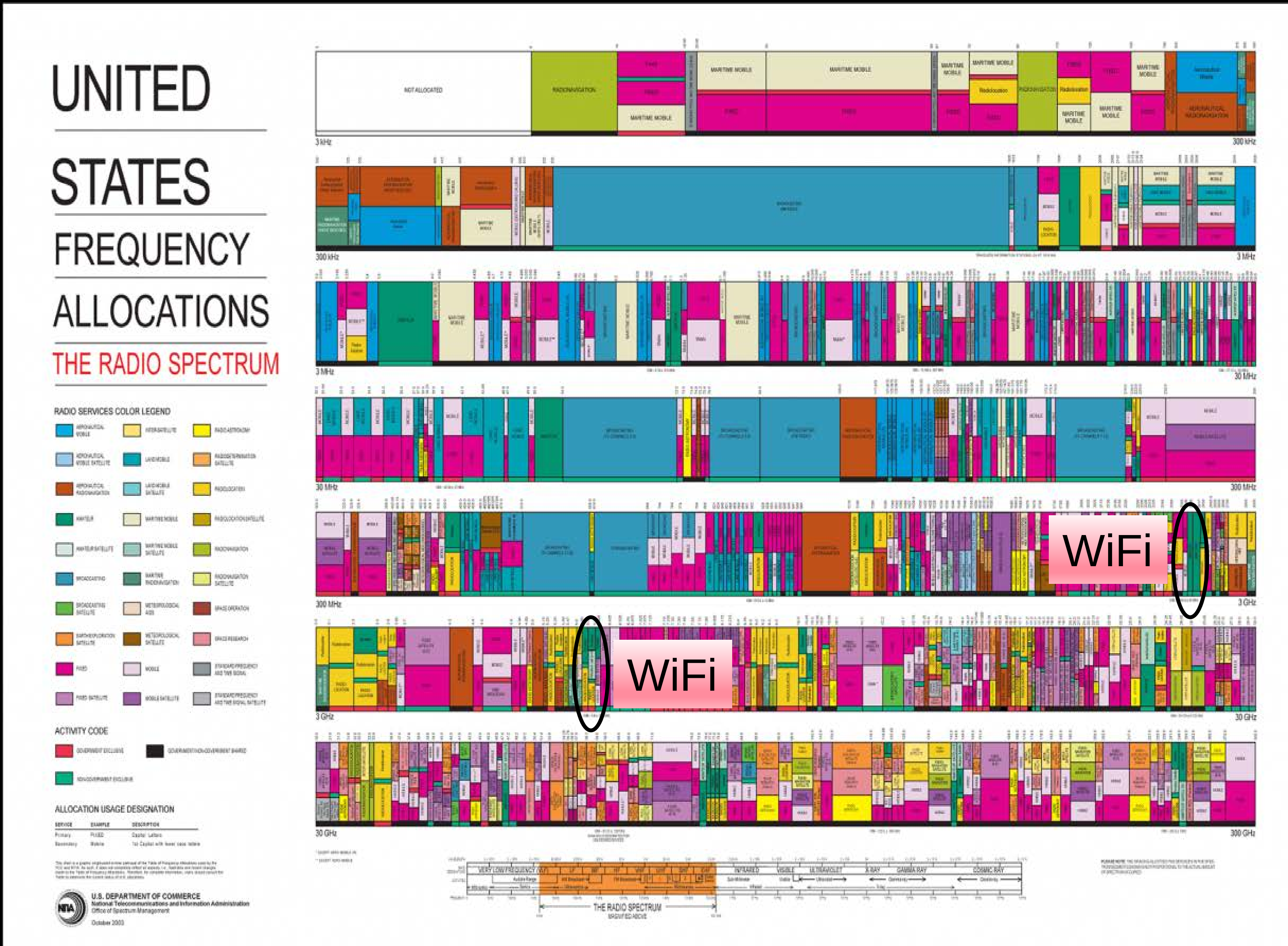




Wireless

- 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

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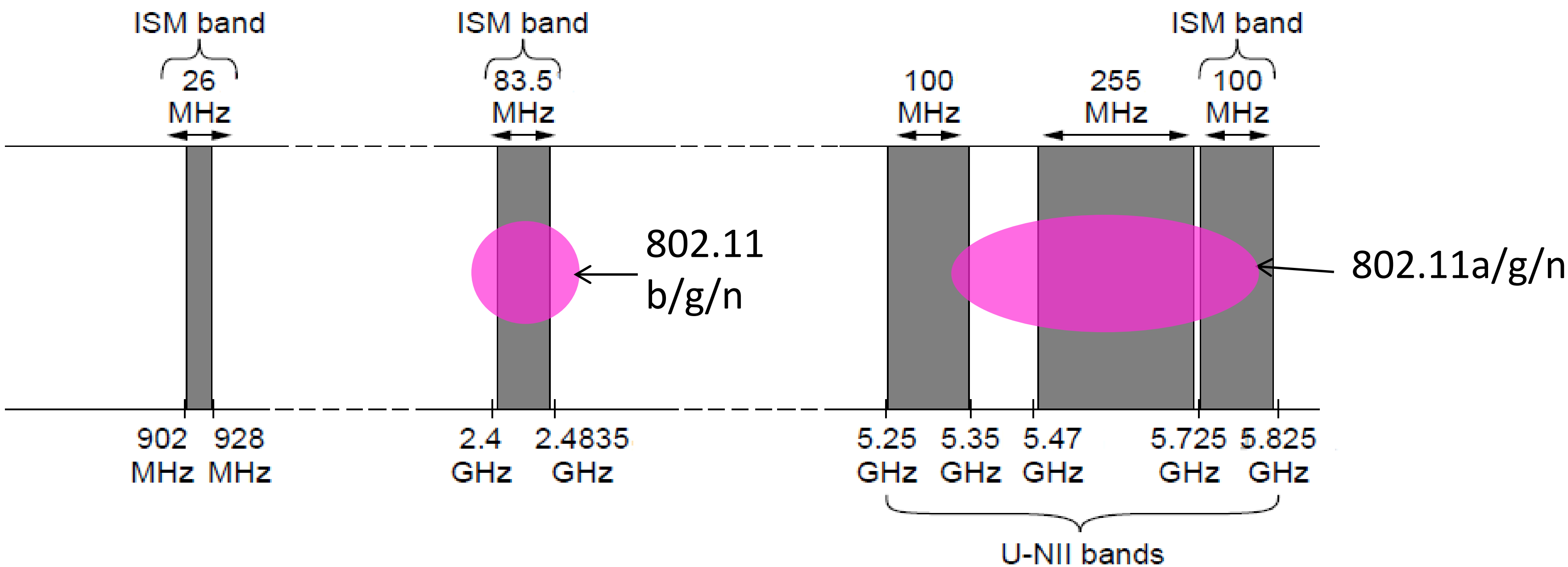
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
WiFi
WiFi
THE RADIO SPECTRUM

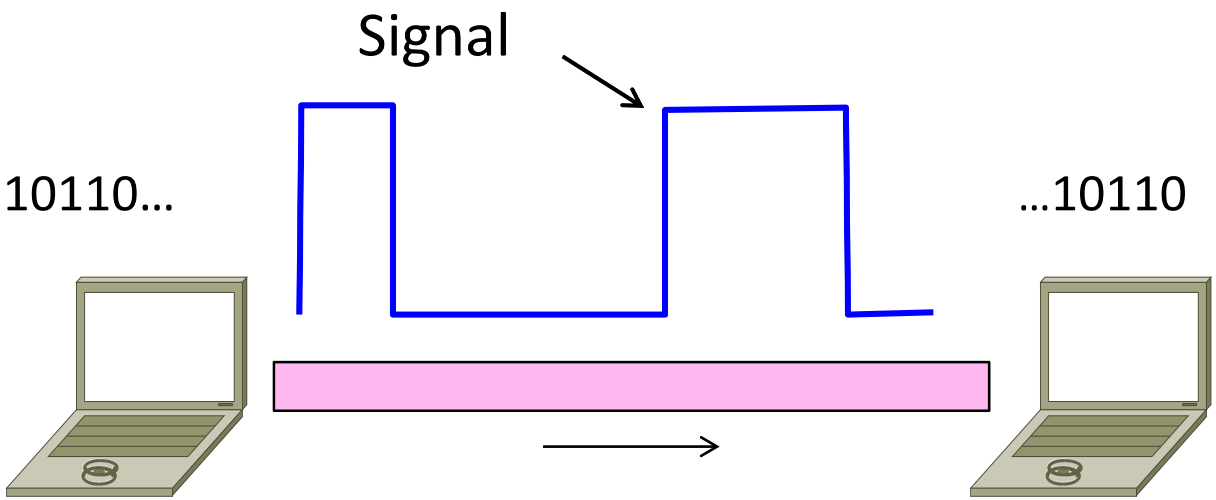
Wireless (2)

- Microwave, e.g., 3G, and unlicensed (ISM – Industrial, Scientific and Medical) frequencies, e.g. WiFi, are widely used for computer networking



3. Signals

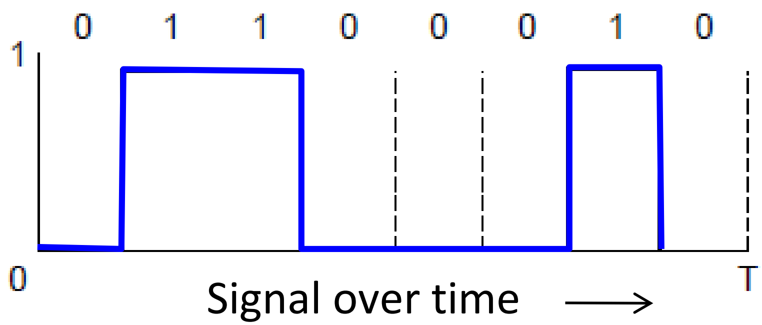
- Analog signals encode digital bits
- We want to know what happens as signals propagate over media



Frequency Representation

- A signal over time can be represented by its frequency components (called Fourier analysis)

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$



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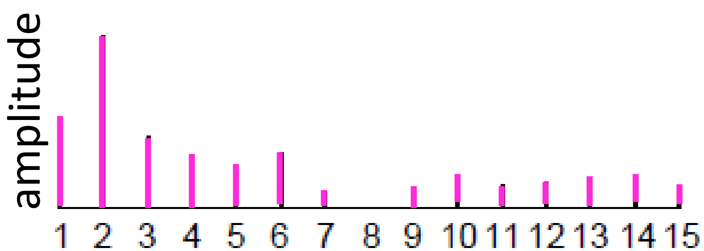
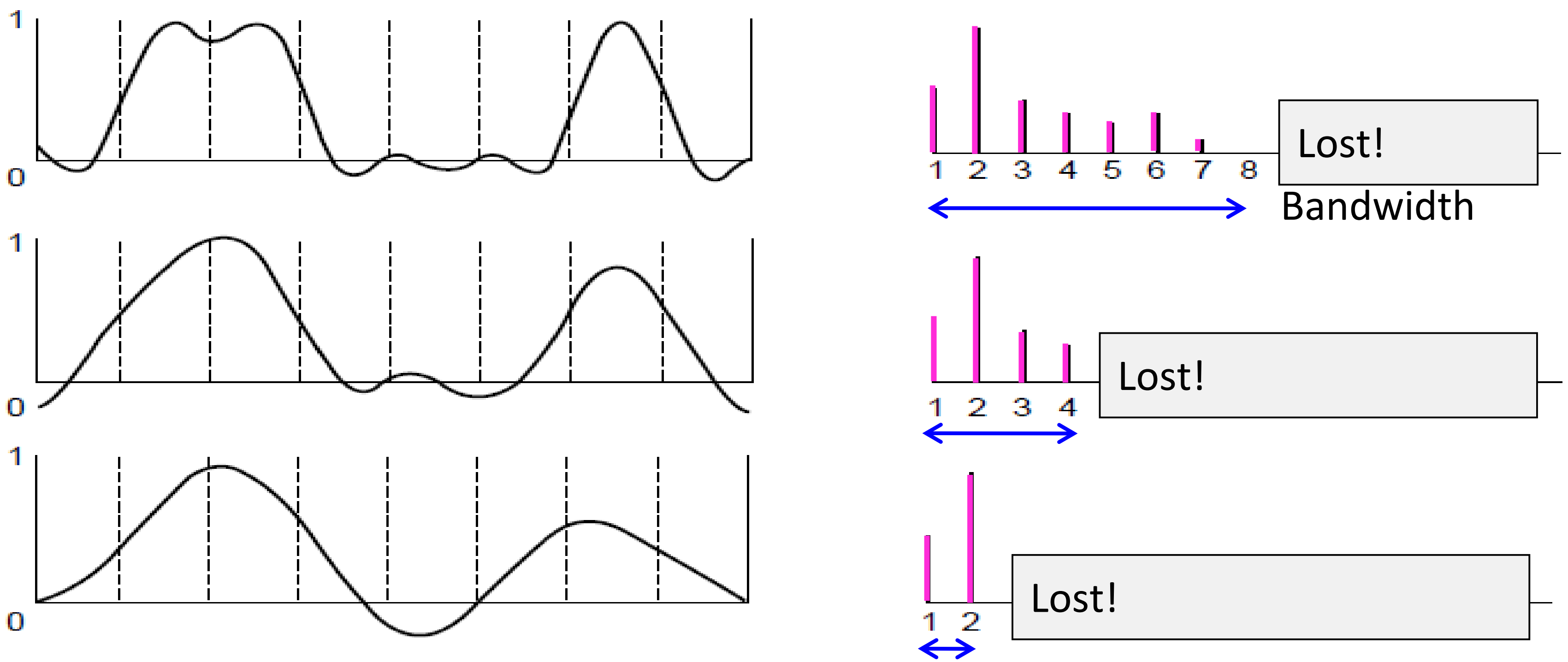


Effect of Less Bandwidth

- Fewer frequencies (=less bandwidth) degrades signal (less rapid transitions)



- Which one is good for data communication?

Signals over a Wire

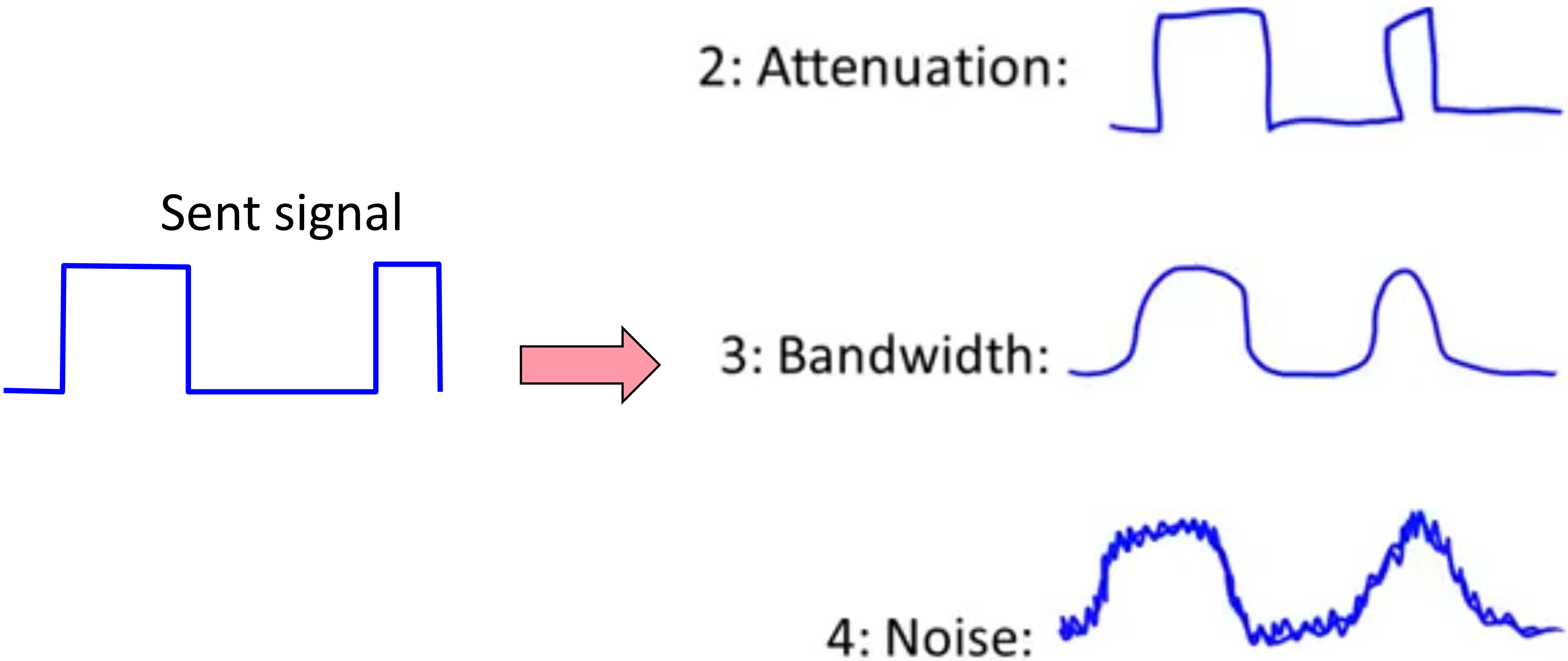
- What happens to a signal as it passes over a wire?
  1. The signal is delayed (propagates at 2/3 c)
  2. The signal is attenuated (goes for m to km)
  3. Frequencies above a cutoff are highly attenuated
  4. Noise is added to the signal (later, causes errors)

EE: Bandwidth = width of frequency band, measured in Hz

CS: Bandwidth = information carrying capacity, in bits/sec

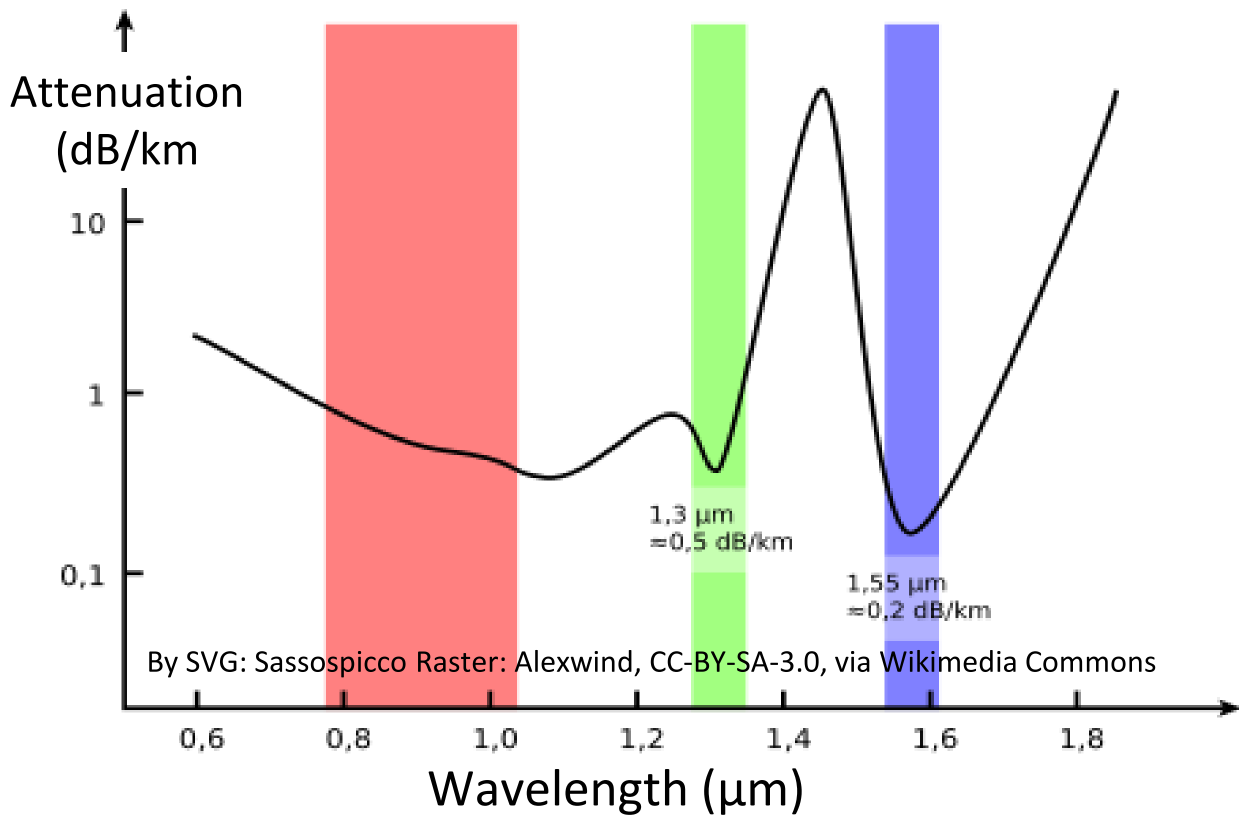
Signals over a Wire (2)

- Example:



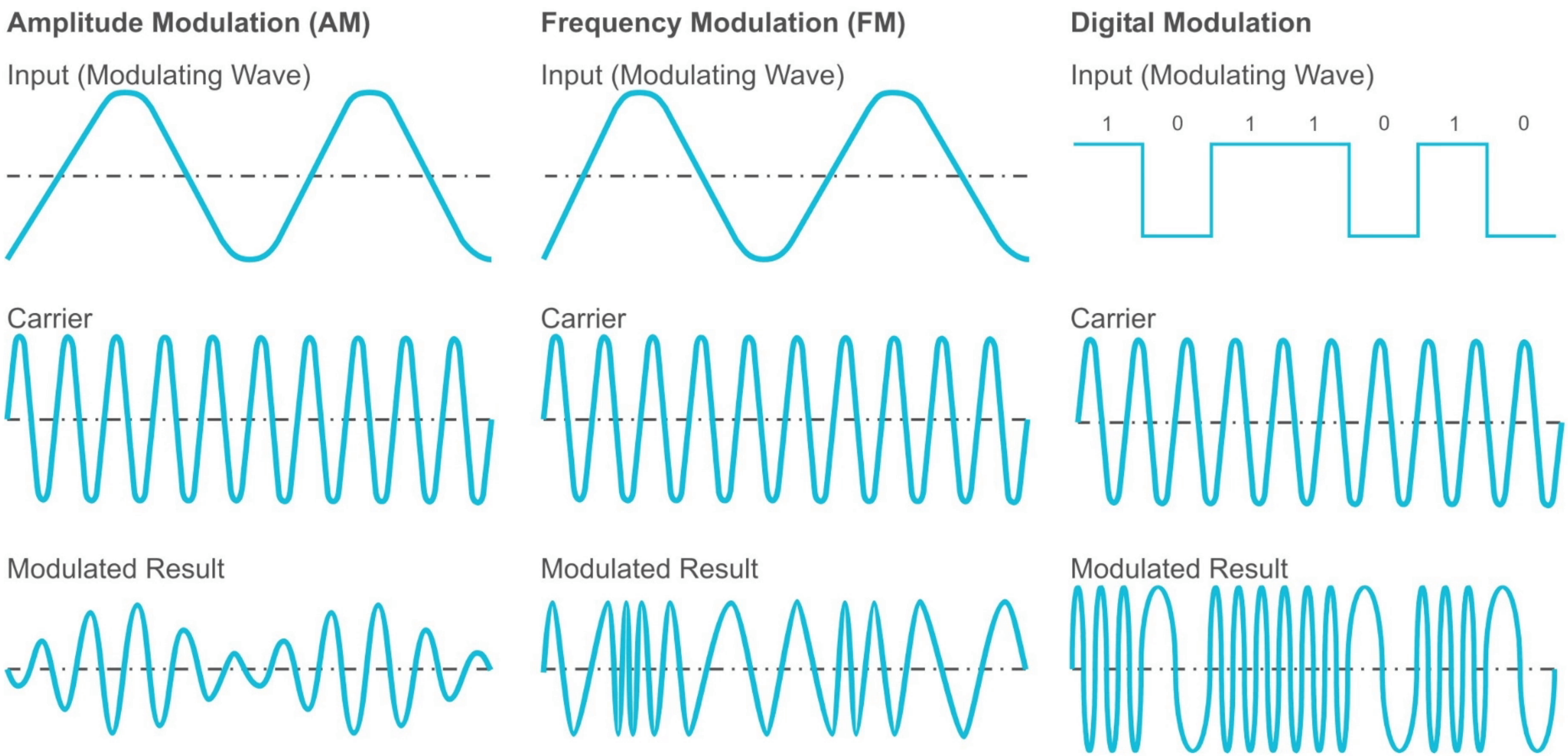
Signals over Fiber

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



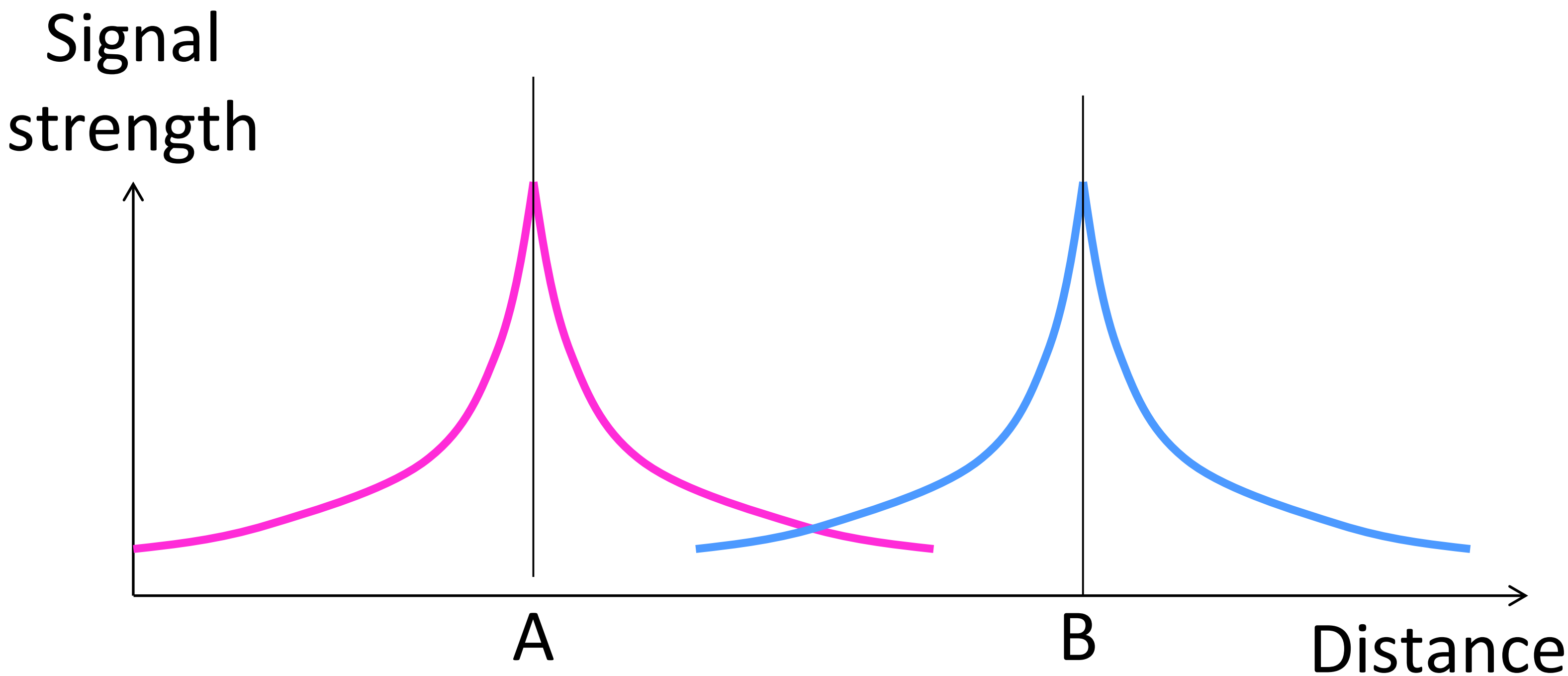
Signals over Wireless

- Signals transmitted on a carrier frequency, like fiber (more later)



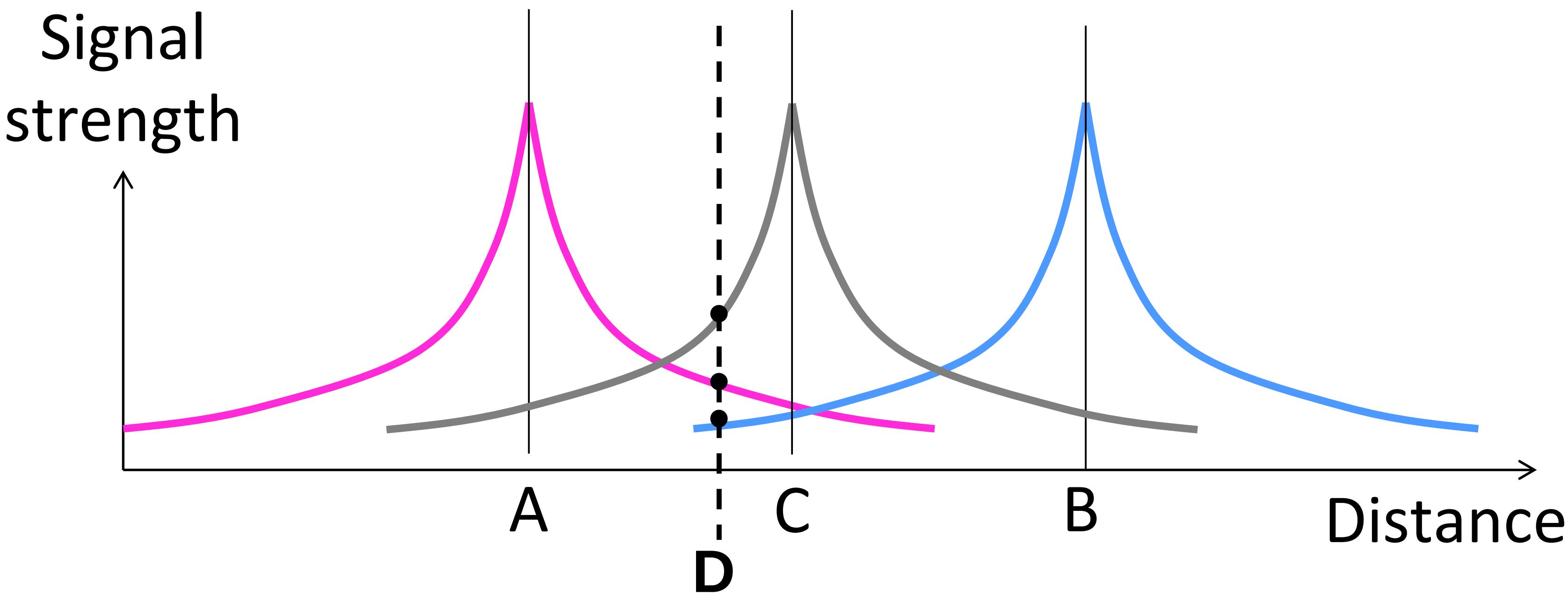
Signals over Wireless (2)

- Travel at speed of light, spread out and attenuate faster than $1/\text{dist}^2$



Signals over Wireless (3)

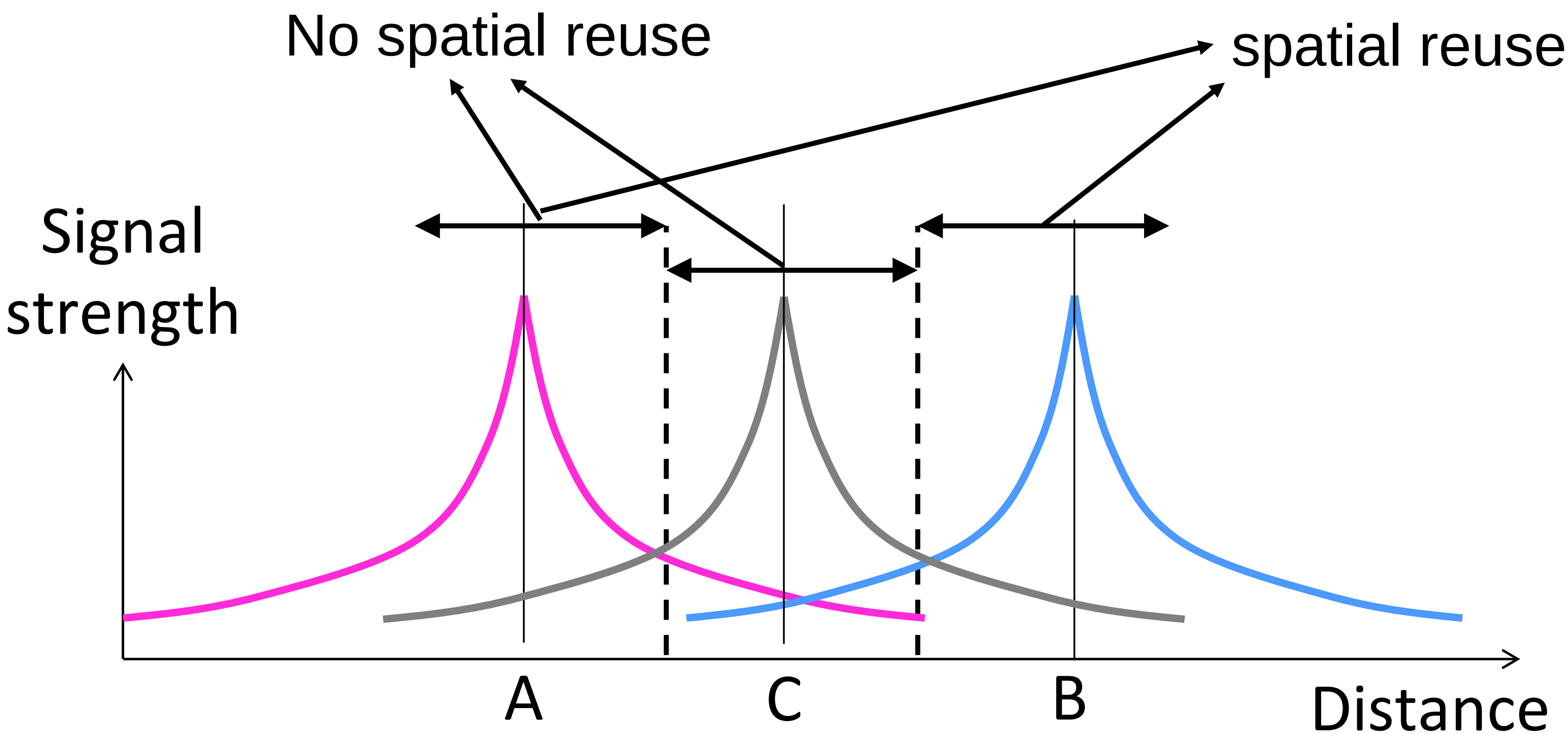
- Multiple signals on the same frequency interfere at a receiver



- D sees = strong C + weak A, B

Signals over Wireless (4)

- Interference leads to notion of <u>spatial reuse</u> (of same frequency)



Signals over a Wireless (5)

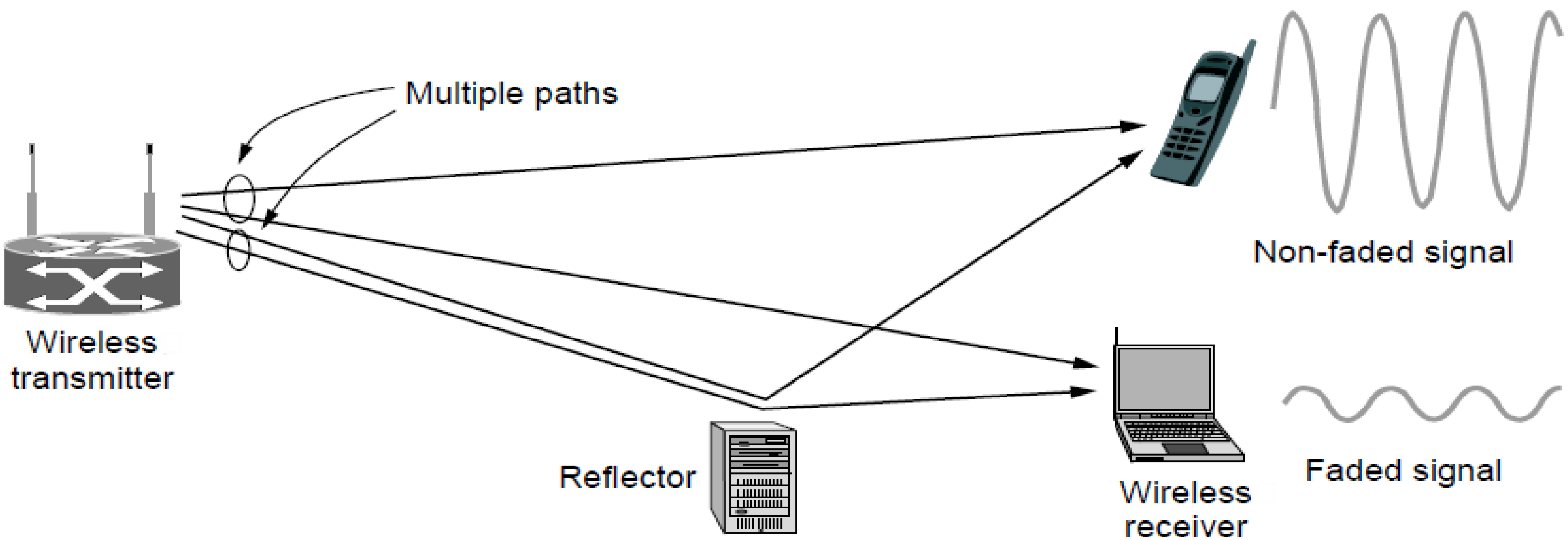
- Various other effects too!
  - Wireless propagation is complex, depends on environment

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

- More on this later when discussing Medium Access Control

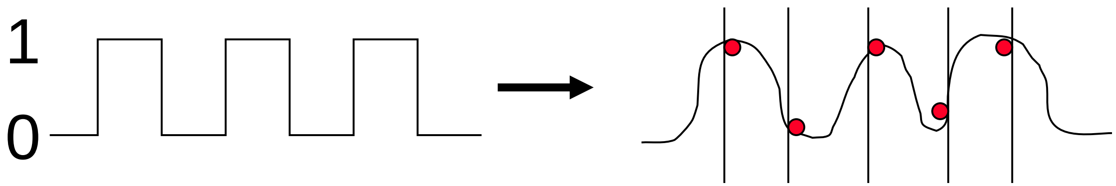
Wireless Multipath

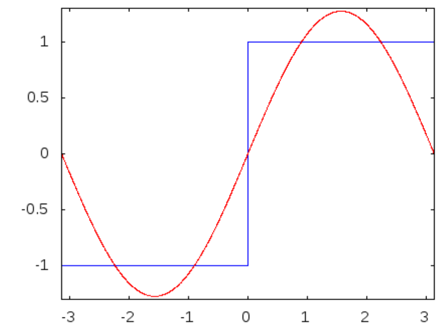
- Signals bounce off objects and take multiple paths
  - Some frequencies attenuated at receiver, varies with location
  - Messes up signal; handled with sophisticated methods



Modulation

- Generate analog waveform (e.g., voltage) from digital data at transmitter and sample to recover at receiver

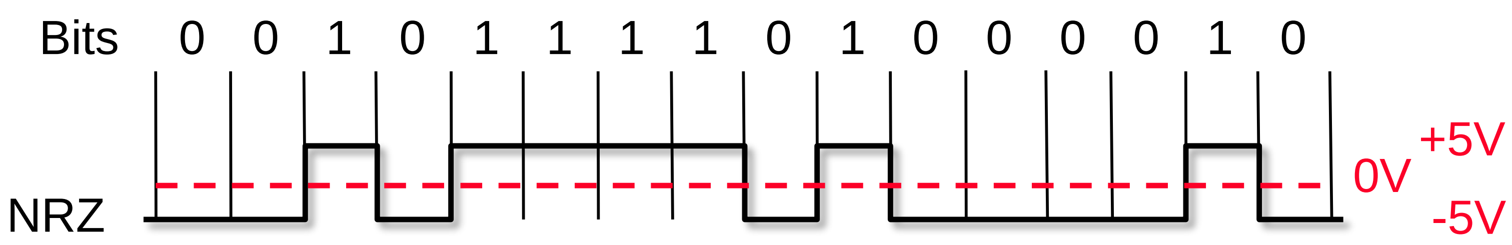




- We send/recover symbols that are mapped to bits
  - Signal transition rate = baud rate vs bit rate
- This is baseband transmission … for more details you need a signals course!

Simple Modulation

- What is the simplest encoding?
  - Use high voltage for 1, zero voltage for zero
  - What is the problem?
- To solve DC bias, NRZ (Non-return to zero)
  - Use high/low voltages, e.g., high=1, low=0
  - Use +/- voltages, e.g., +5V = 1 , -5V = 0



- Variation, NRZI (NRZ, invert on 1)
  - Use transition for 1s, no transition for 0s
- How do we sample a long sequence of 0s?

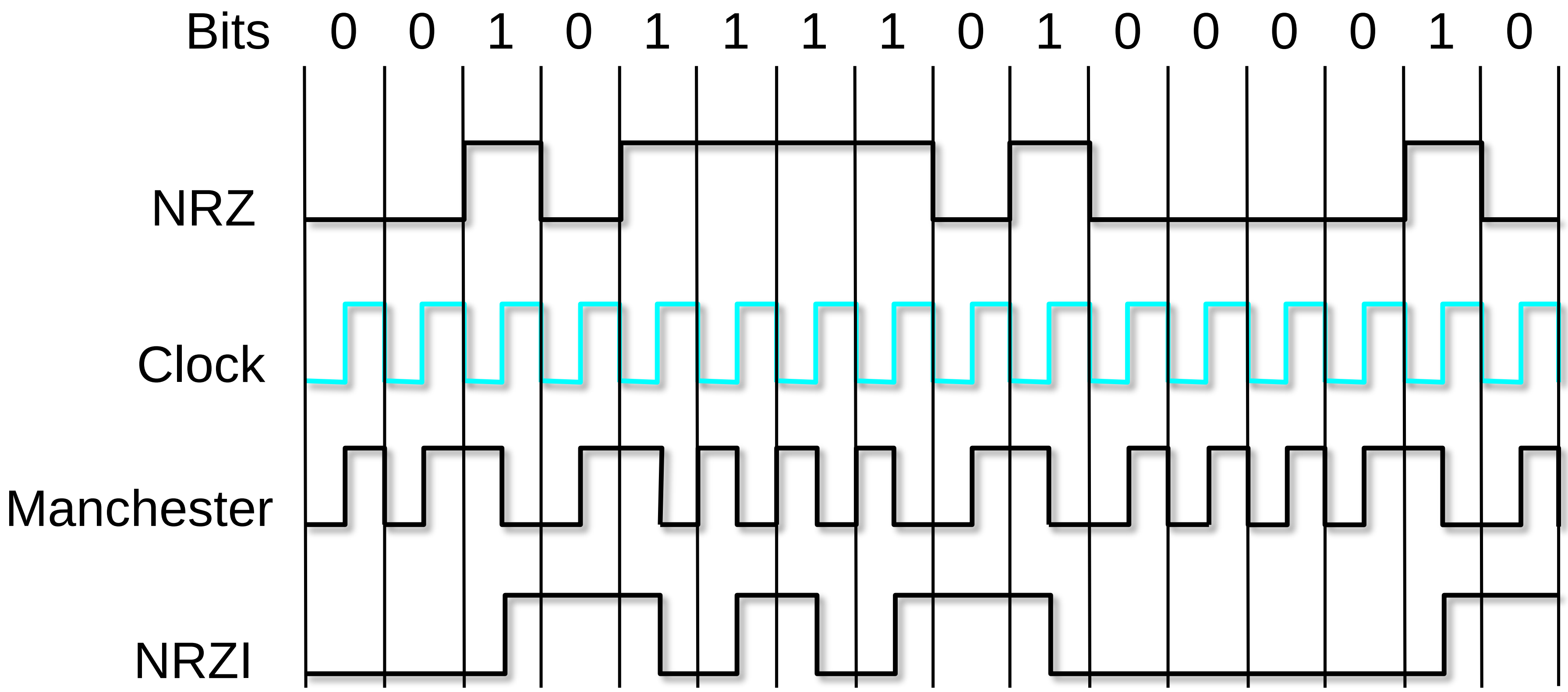
Clock Recovery

- How do we distinguish consecutive 0s or 1s?
- If we sample at the wrong time we get garbage
- If Tx and Rx have exact clocks no problem
  - But in practice they drift slowly
- This is the Clock Recovery problem
- Possible solutions:
  - Send separate clock signal
    - Expensive
  - Keep messages short
    - Limits data rate
  - Embed clock signal in data signal
    - Other codes

Manchester Coding

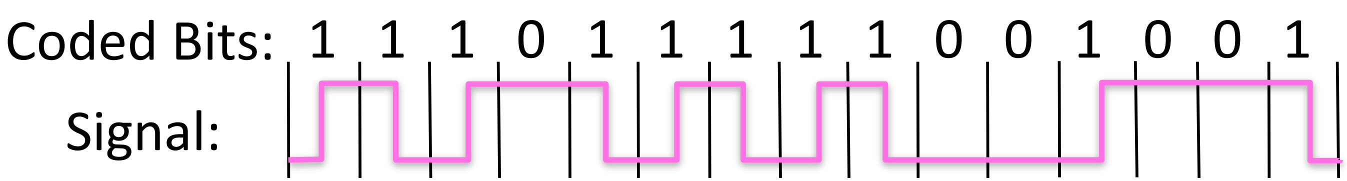
- Make transition in the middle of every bit period
  - Low-to-high is 0; high-to-low is 1
  - Signal rate is twice the bit rate
  - Used on 10 Mbps Ethernet
- Advantage:
  - self-clocking: clock is embedded in signal, and we re-sync with a phase-locked loop (PLL) every bit
- Disadvantage:
  - 50% efficiency

Coding Examples



4B/5B and 8B/10B Codes

- We want transitions *and* efficiency… how?
- Solution: map data bits (which may lack transitions) into code bits (which are guaranteed to have them)
- 4B/5B code:
  - 0000 → 11110, 0001 → 01001, … 1111 → 11101
  - Never more than three consecutive 0s back-to-back using NRZI or other codes (e.g. MLT-3)
  - 80% efficiency (used in 100Mbps Ethernet and FDDI)
  - Message bits: 1111 0000 0001



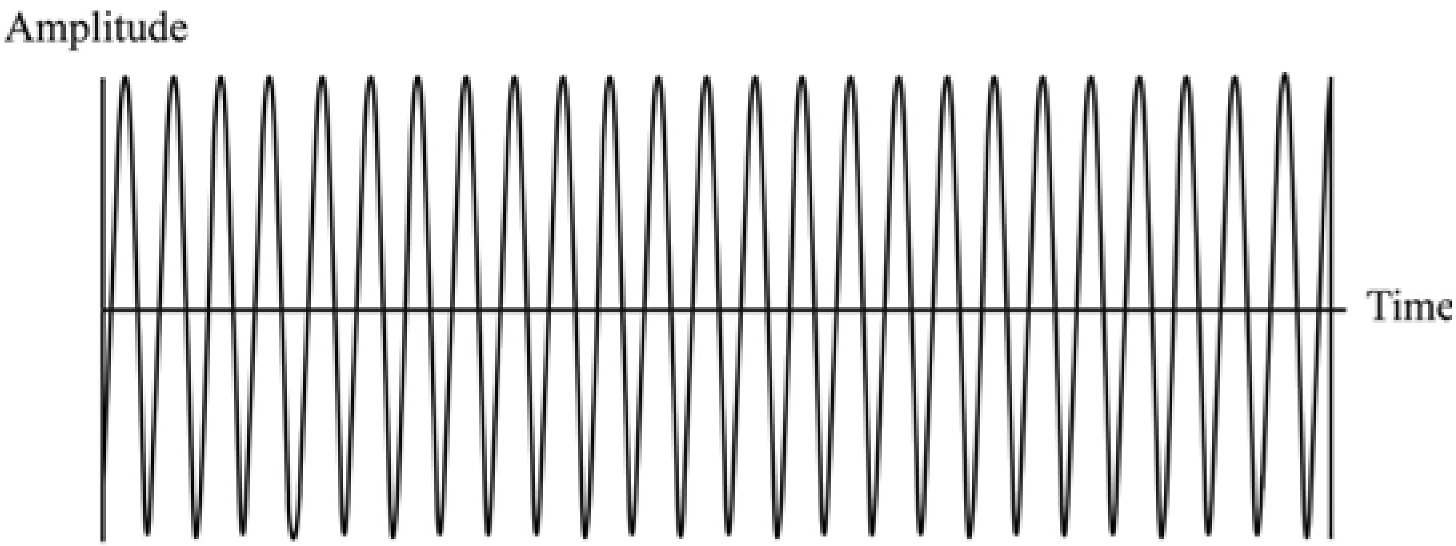
- 8B/10B encoding used for 1GB Ethernet (with NRZ)
  - never more than 5 consecutive 0s or 1s (clock recovery)
  - diff. bw counts of 1s/0s every 20 bits < 2 (DC-balance)

Passband Modulation

- What we have seen so far is baseband modulation for wires
  - Signal is sent directly on a wire
- These signals do not propagate well on fiber / wireless
  - Need to send at higher frequencies
- Passband modulation carries a signal by modulating a carrier

Passband Modulation (2)

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



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

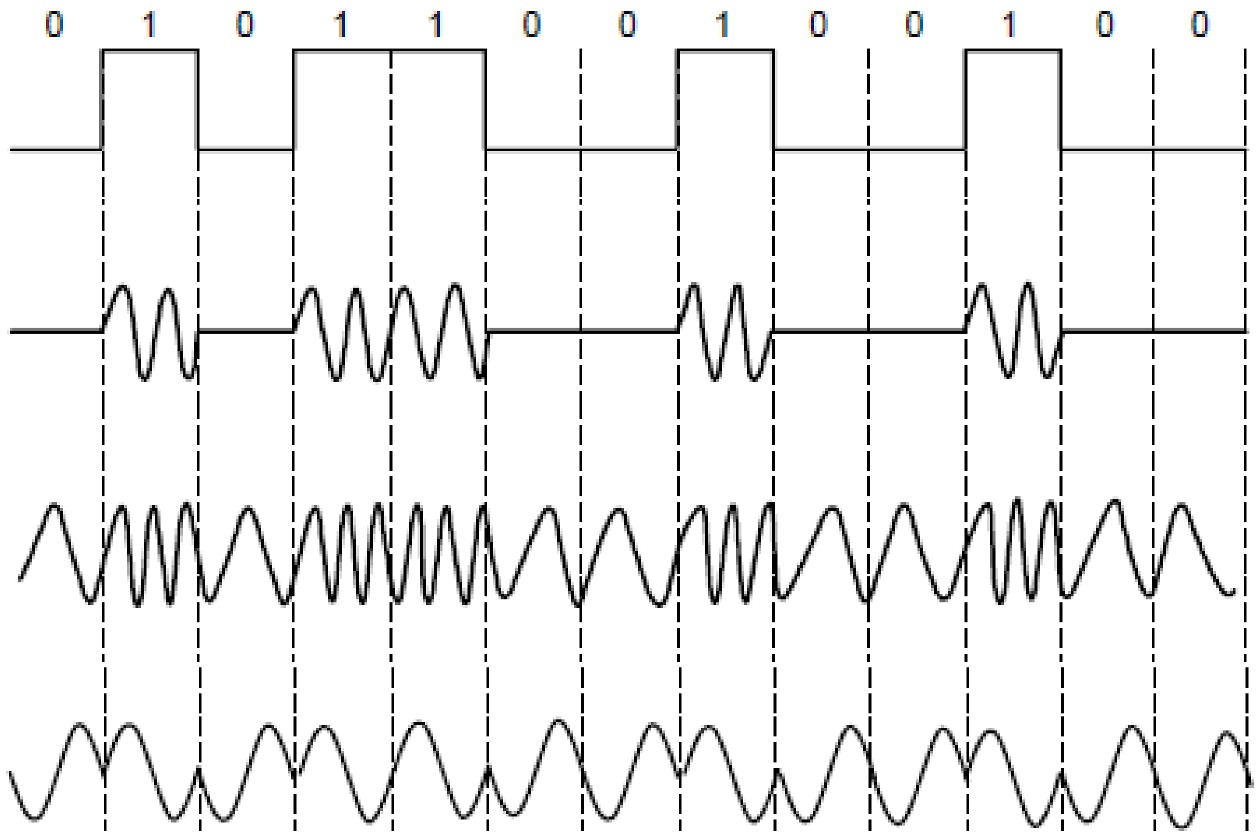
Passband Modulation (3)

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying



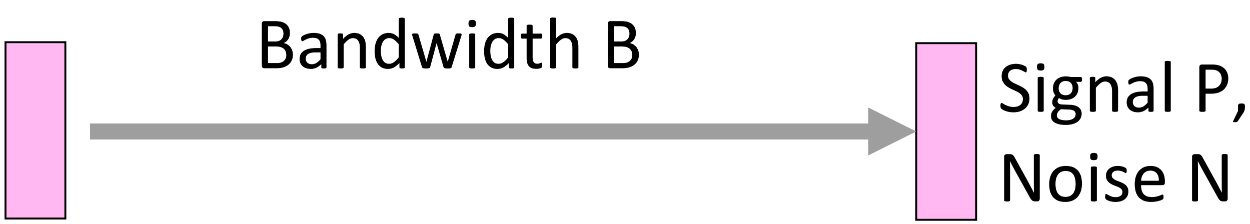
4. Fundamental Limits

- 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

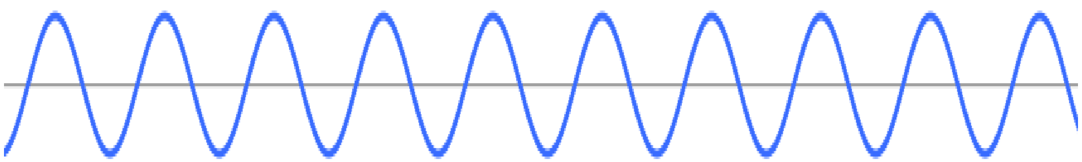
- The bandwidth (B), signal strength (S), and noise strength (N)
  - All measured at the receiver
  - B limits the rate of transitions
  - S and N limit how many signal levels we can distinguish



Nyquist Limit

- The maximum symbol rate is 2B
  - – Symbol is a waveform that it's used to represent information (bits)
    - It may represent 1 bit, more than 1bit if you have multiple signal levels

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

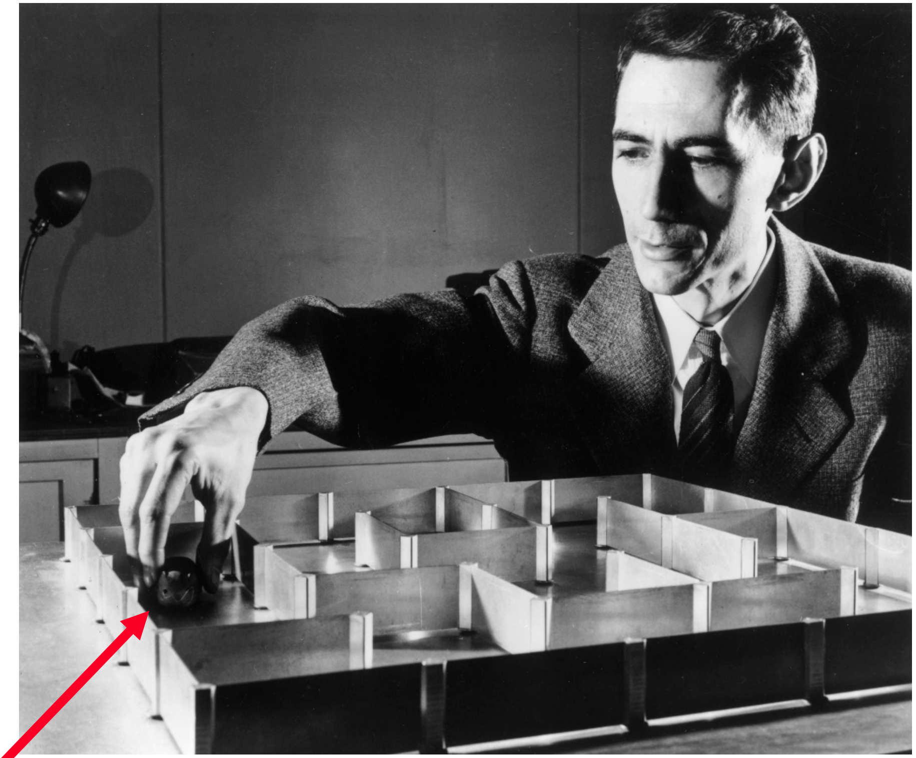


- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

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

Claude Shannon (1916-2001)

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



Credit: Courtesy MIT Museum

Electromechanical mouse that “solves” mazes!

Shannon Limit

- 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:
  - $SNR_{dB} = 10\log_{10}(S/N)$

S/N	dB
1000	30
100	20
10	10
2	3

Shannon Limit (2)

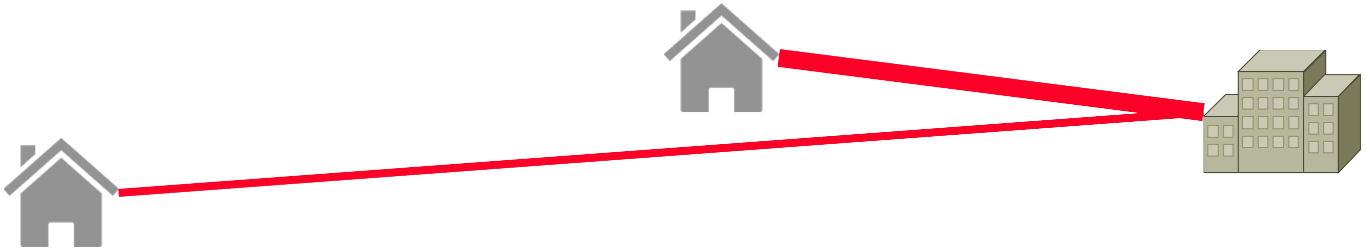
- Shannon limit is for capacity (C), the maximum information carrying rate of the channel:

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

  - Shannon showed that you can send information up to that rate, but not higher
  - Revolutionary at the time: there were many errors in the channels and the only way to cope with them was increasing signal strength
  - Shannon showed us that there might be coding schemes that would allow us to transmit the signal

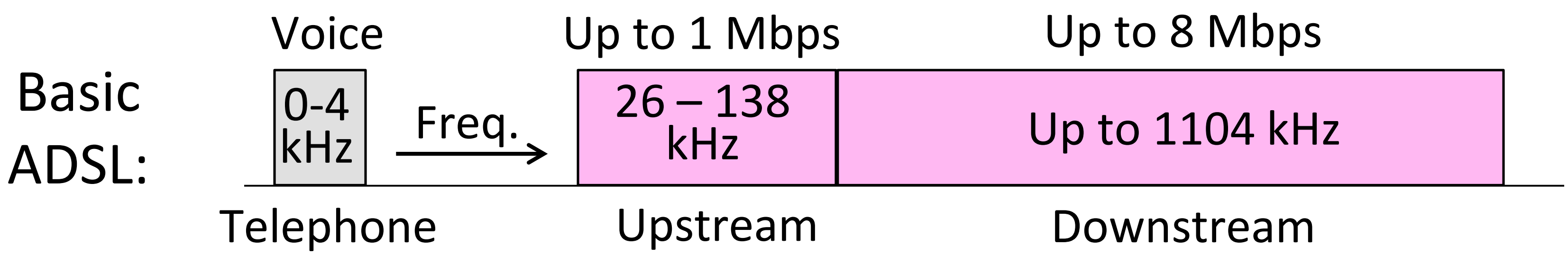
Putting it all together – DSL

- DSL (Digital Subscriber Line, see §2.1.1) 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
  - Separate bands for upstream and downstream (larger)
  - Modulation called QAM varies both amplitude and phase
  - High SNR, up to 15 bits/symbol, low SNR only 1 bit/symbol



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! (that's 1M times)
  - Can't design for worst case, must adapt data rate

Adapt data rate to SNR

Key Concepts

- We typically model links in terms of bandwidth and delay, from which we can calculate message latency
- Different media have different properties that affect their performance as links
- We need to encode bits into signals so that we can recover them at the other end of the channel
- Passband modulation allows us to transmit baseline signals in other higher frequencies for fiber and wireless
- Shannon showed us the limit of what is possible to transmit on any channel