15-441 Computer Networks

Physical Layer

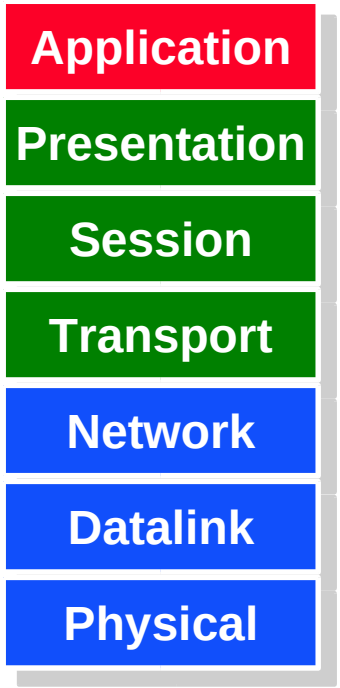
Dave Eckhardt

Many slides stolen from
Peter Steenkiste, Hui Zhang
Srini Seshan, David Andersen

Plus some new Spring '06 slides!!

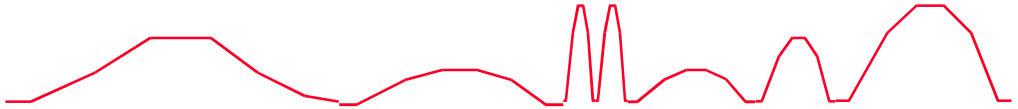
Lecture Plan

- **Physical layer**
- **What is the Data-Link layer?**
  - Framing, addressing, Medium Access Control
- **Lots of Ethernet**
- **Then switching**
  - Starting with Ethernet



Concept Plan: “Signals to Packets”

Analog Signal

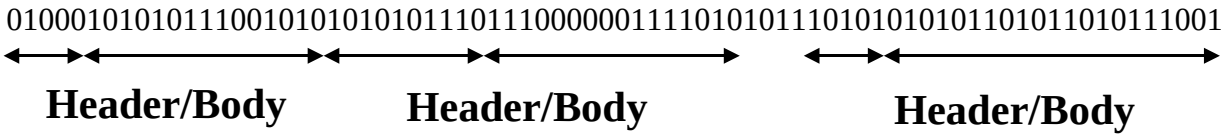


“Digital” Signal

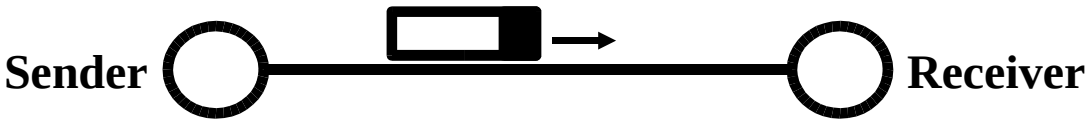
Bit Stream

0 0 1 0 1 1 1 0 0 0 1

Packets



Packet Transmission



Outline

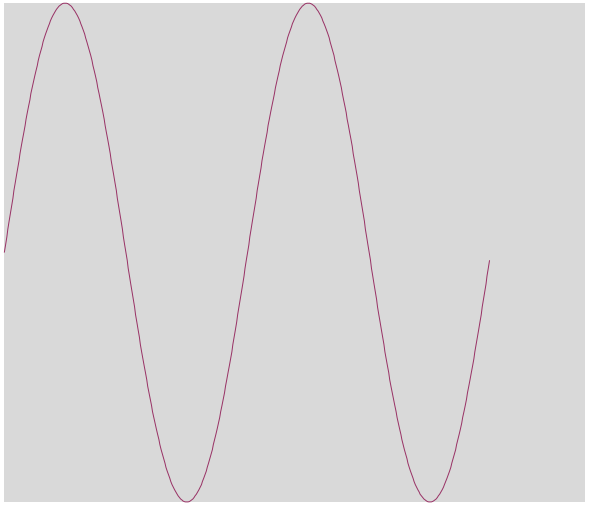
- Signals
- Modulation
- Baseband, Analog, Digital
- Limits
- Multiplexing
- POTS
- Wire and Fiber
- Wireless

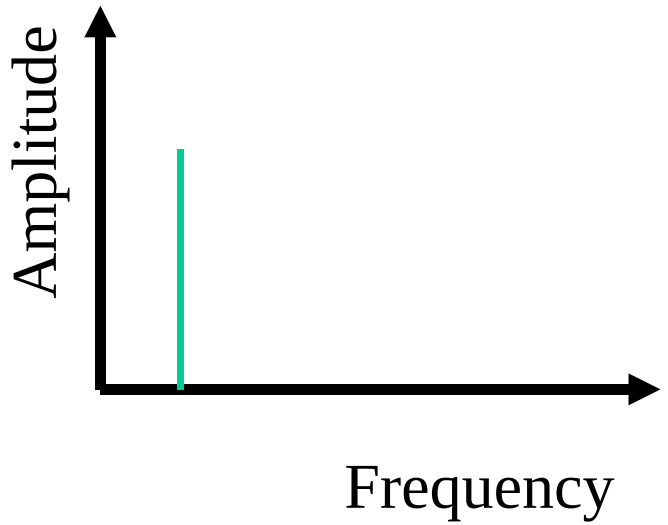
Signal

- What's a signal?

Base Case

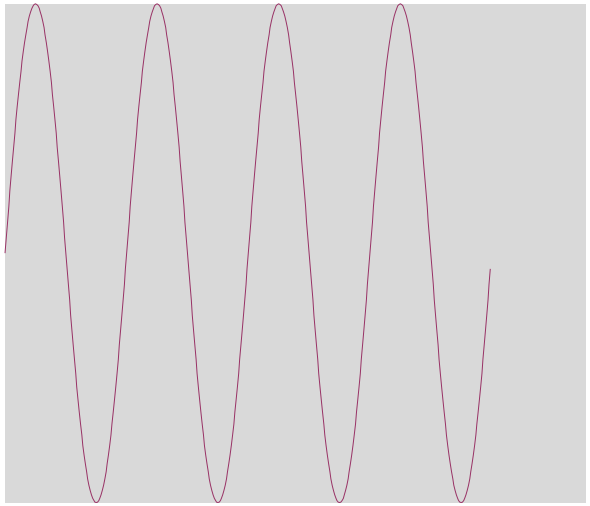
- **What's a signal?**
  - A sine wave is a simple signal
    - Varying amplitude-signal at a single frequency
      - Frequency measured in “cycles per second” aka “Hertz”

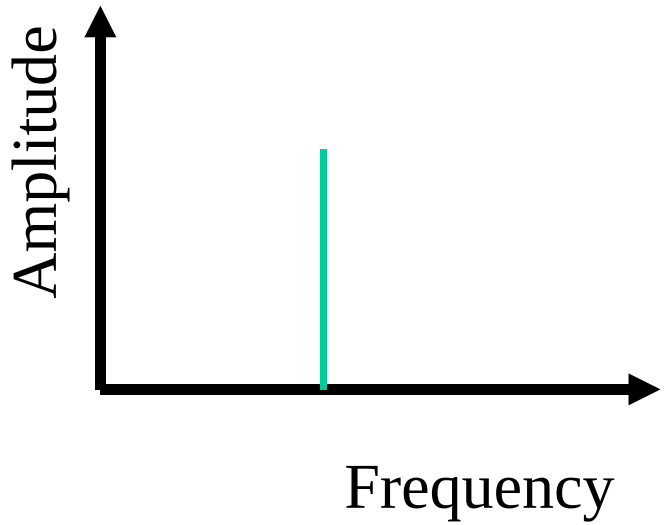




Another Base Case

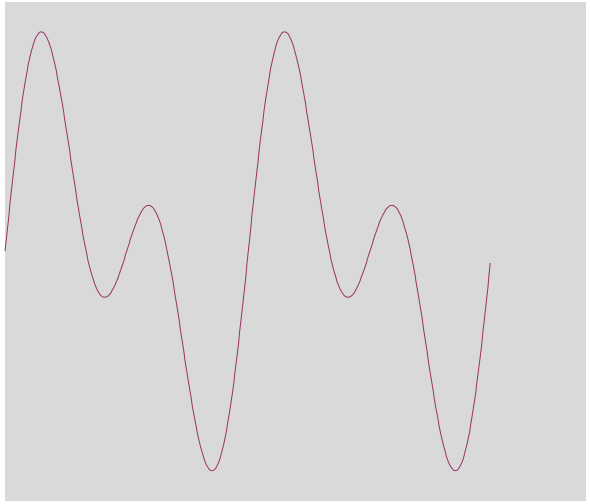
- **Here's a different sine wave**
  - Same maximum amplitude
  - Twice the frequency

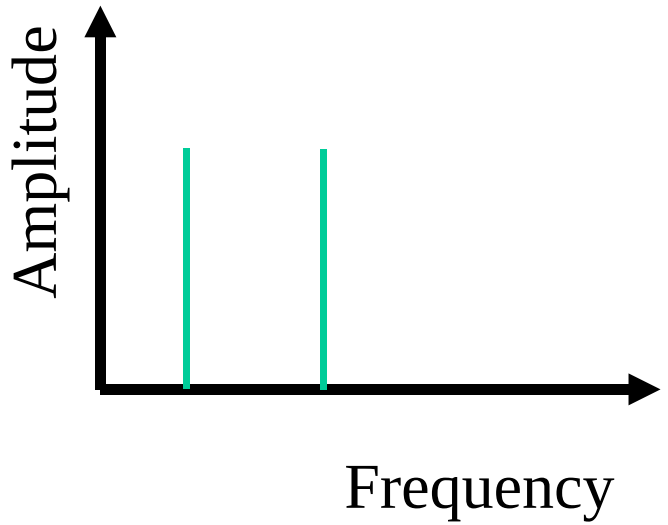




Induction

- **“Complicated” signals are sums of sine waves**
  - sin(x) + sin(2x)
  - The shape looks complicated but the frequency-domain plot is still clear





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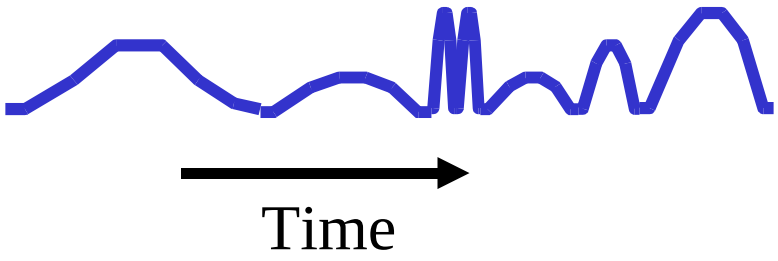
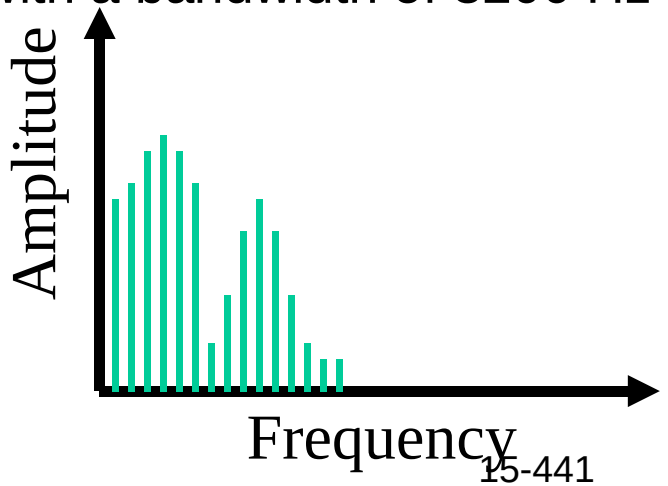
Frequency, Bandwidth of Signal

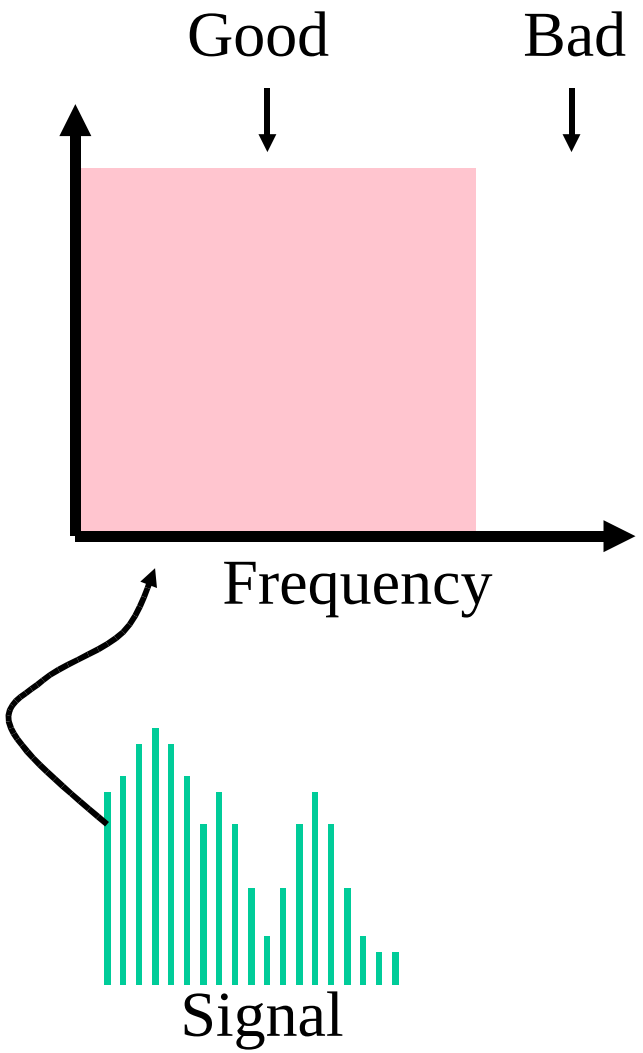
- **A signal can be viewed as a sum of sine waves of different strengths**
  - sin(x) + ¼sin(3x) + 17sin(42x) + ...
  - Each component contributes some energy at some frequency
- **Bandwidth: width of the frequency range**
  - Human voice: 100~3300 Hz, with a bandwidth of 3200 Hz





Bandwidth of Transmission Channels

- **Every medium supports transmission in a certain frequency range.**
  - Outside this range, effects such as attenuation degrade the signal too much
- **Transmission and reception hardware will try to maximize the useful bandwidth in this frequency band.**
  - Tradeoffs between cost, distance, bit rate
- **As technology improves, these parameters change, even for the same wire.**
  - Thanks to our EE friends



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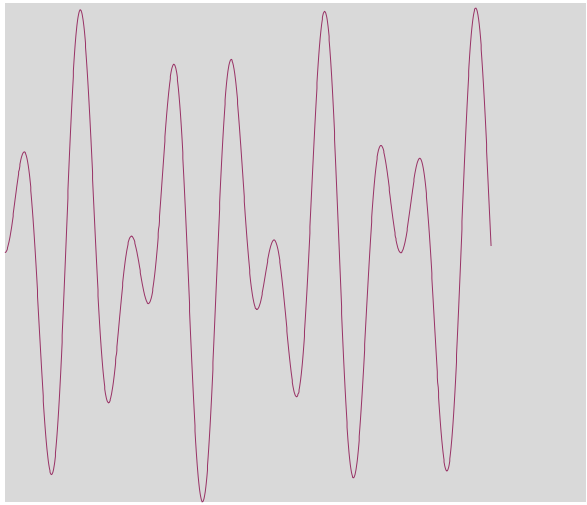
Modulation

- **What are signals good for?**
  - Carrying information!
    - Simple case: presence/absence of a sine wave
      - – Frequency, amplitude remain constant
      - – Sometimes it's on, sometimes it's off
    - “On/off keying” aka “CW”
    - One kind of “modulation”

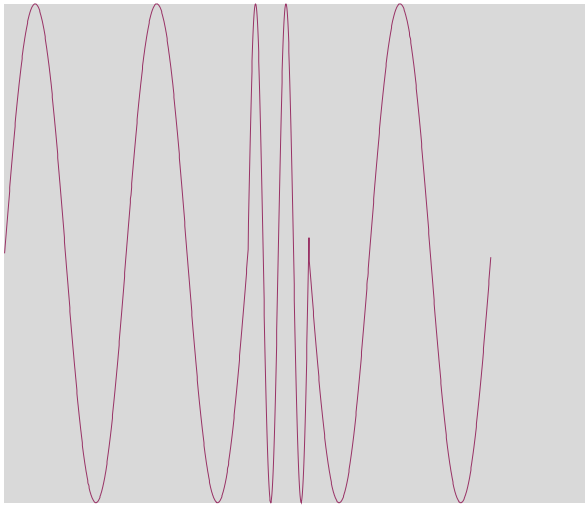
Amplitude Modulation

- We can control/adjust different properties of a signal
- On/off keying is a special case of varying the strength (amplitude)
- Amplitude Modulation = “AM”

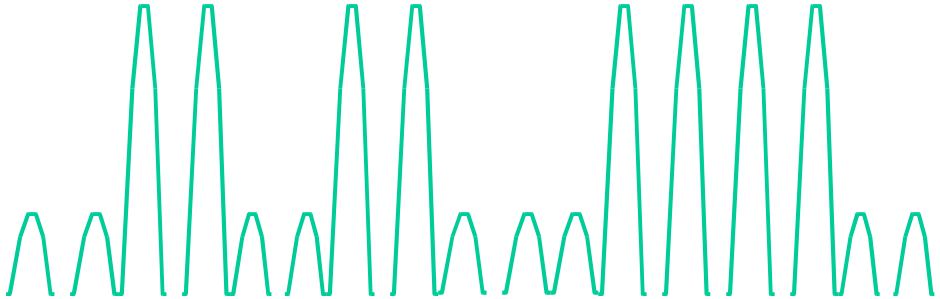


Frequency Modulation

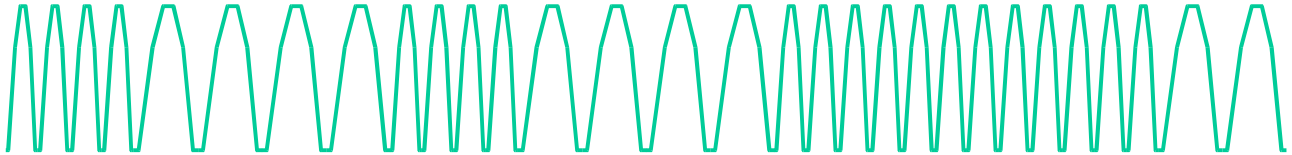
- **Another thing to adjust is frequency**
  - Switch between sin(x) and sin(2) from time to time
- **Harder to think about, but easier to detect by ear!**



Amplitude and Frequency Modulation



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



0 1 1 0 1 1 0 0 0 1

Analog vs. Digital

- Used in different contexts

	Analog	Digital
Data (something has meaning)	Voice, Image	Text, computer message
Signal (encoded data)	Continuously varying wave	Sequence of 1's and 0's
Transmission	Propogation of waves	Propogation of 1's and 0's

Data Encoding: Mapping Data Into Signal

- **Analog data encoded in analog signal**
  - Radio,TV, telephone
- **Analog data encoded in digital signal**
  - Digital voice (PCM sampling of analog phone line)
- **Digital data encoded in digital signal**
  - Ethernet (Manchester)
  - FDDI (NRZ 4B/5B)
  - (next lecture)

Analog vs. Digital Transmission

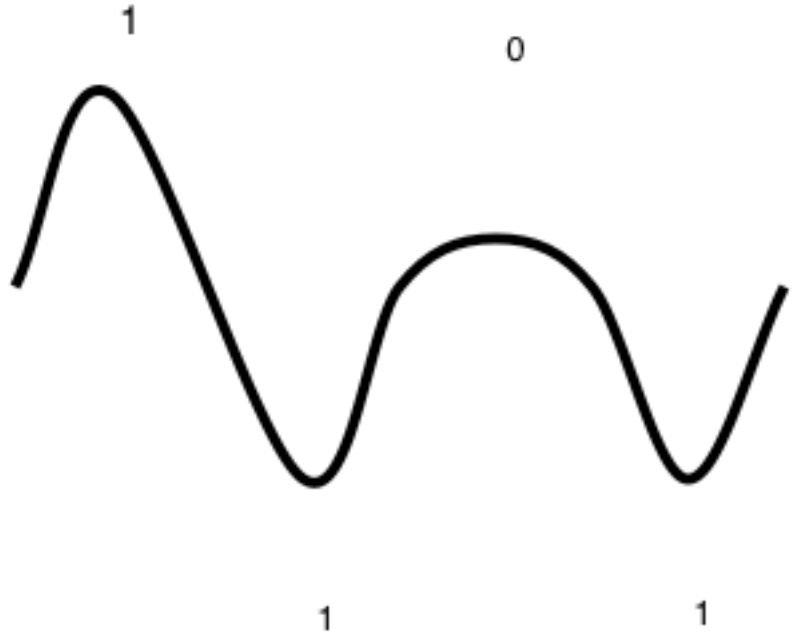
- **Digital transmission**
  - Interpret the signal as 1's and 0's
  - Use repeaters to reconstruct the signal
- **Analog transmission**
  - Do not interpret content
  - Use amplifiers to boost the strength of signal
- **Why do we increasingly use digital transmission?**

Digitalization of Analog Voice

- **Two steps:**
  - Sample the voice signal at certain frequency
  - “Quantize the sample” (assign it a number)
- **What should be the sampling frequency so that the original signal can be reconstructed losslessly?**
  - Nyquist’s sampling theorem: 2H, where H is the bandwidth of the signal
- **PCM coding:**
  - 3 KHz voice band
  - 8000 Hz sampling
  - 7 or 8 bits encoding of each sample (logarithmically spaced)
  - 56 or 64 kbps

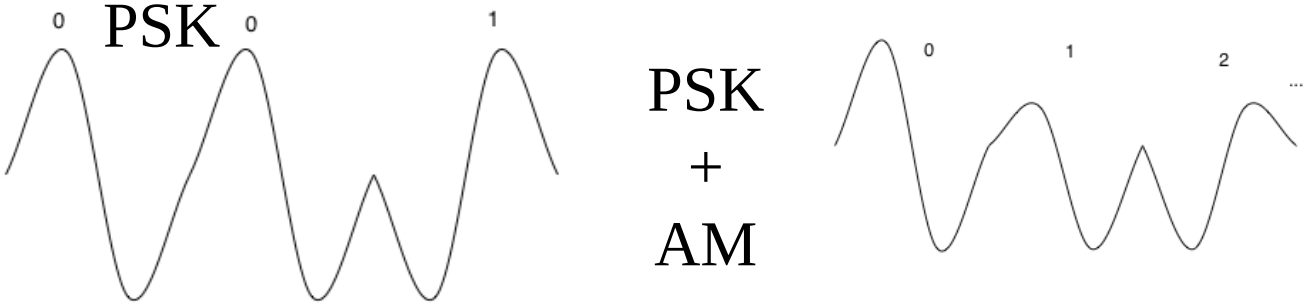
Nyquist Limit

- **A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.**
  - E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  - Assumes binary amplitude encoding



Expanding the Nyquist Limit

- **More aggressive encoding can increase the channel bandwidth.**
  - Example: modems
    - Same *sampling rate* - number of symbols per second
    - Symbols have more possible values



- **Every transmission medium supports transmission in a certain frequency range.**
  - The channel bandwidth is determined by the transmission medium and the quality of the transmitter and receivers
  - Channel capacity increases over time due to innovation

Channel Bandwidth and Capacity For Digital Signal

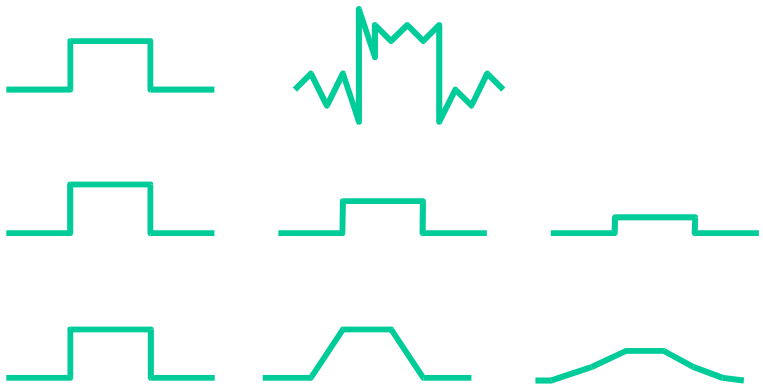
- **Question: given a channel with bandwidth H, what is the capacity of the channel for digital signal?**
- **How to measure channel capacity?**
  - Baud rate: number of symbols per second (Hz)
  - Bit rate: Baud rate x bits/symbol
- **Nyquist Theorem:**
  - a noiseless channel of width H can at most transmit a signal of rate 2H
- **Example**
  - Twisted pair long loop has channel bandwidth of 3200 Hz
  - Phase-Shift Modulation means 8 possible configurations per symbol
  - Channel bit rate?

Data over Telephone Network

- **Private line data service**
  - 56kbps, T1, T3
- **How to extend data service to home over analog subscriber loop?**
  - “Modem”: digital signal over analog transmission channel

Non-Ideal Channel

- **Noise: “random” energy is added to the signal.**
- **Attenuation: some of the energy in the signal leaks away.**
- **Dispersion: attenuation and propagation speed are frequency dependent.**
  - Changes the shape of the signal



Capacity of a Noisy Channel

- **Can't add infinite symbols - you have to be able to tell them apart. This is where noise comes in.**
- **Shannon's theorem:**
  - C = B x log(1 + S/N)
  - C: maximum capacity (bps)
  - B: channel bandwidth (Hz)
  - S/N: signal to noise ratio of the channel
    - Often expressed in decibels (db). 10 log(S/N).
- **Example:**
  - Local loop bandwidth: 3200 Hz
  - Typical S/N: 1000 (30db)
  - What is the upper limit on capacity?
    - Modems: Teleco internally converts to 56kbit/s digital signal, which sets a limit on B and the S/N.

Multiplexing

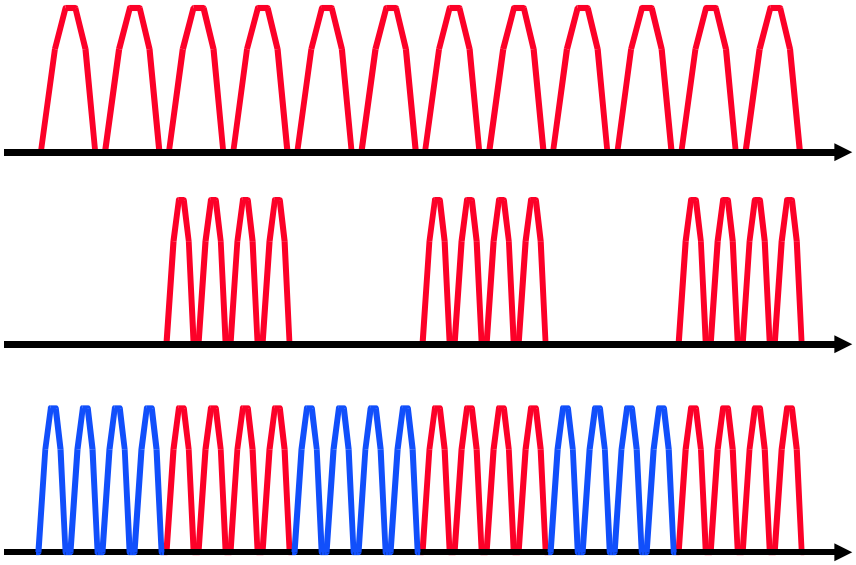
- **Transmit multiple signals on the same channel**
  - Frequency Division Multiplexing
  - Time Division Multiplexing

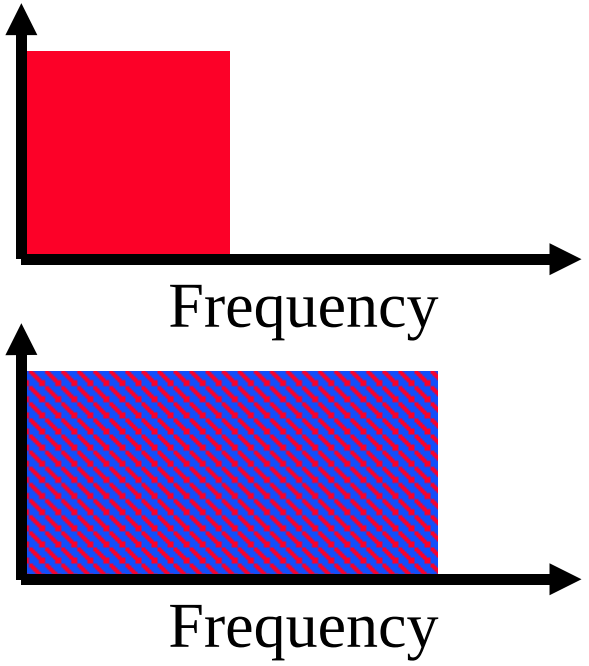
Supporting Multiple Channels

- **Multiple channels can coexist if they transmit at a different frequency, or at a different time, or in a different part of the space.**
  - Three dimensional space: frequency, space, time
- **Space can be limited using wires or using transmit power of wireless transmitters.**
- **Frequency multiplexing means that different users use a different part of the spectrum.**
  - Again, similar to radio: 95.5 versus 102.5 station
- **Controlling time is a Data Link protocol issue.**
  - Media Access Control (MAC): who gets to send when?

Time Division Multiplexing

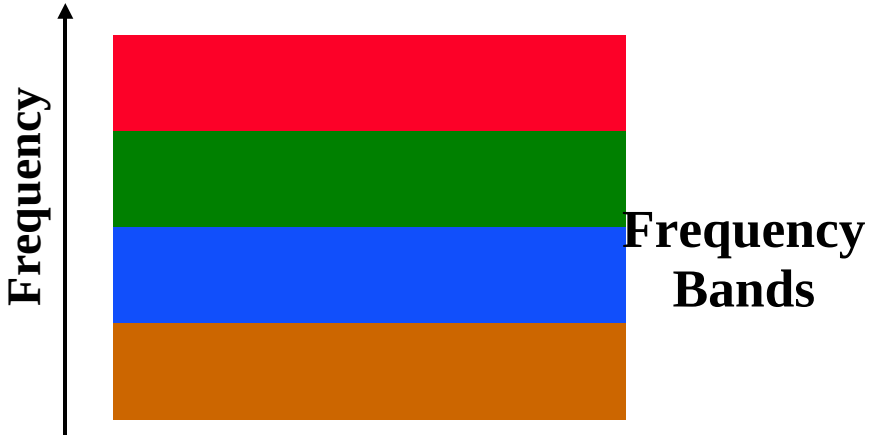
- Different users use the wire at different points in time.
- Aggregate bandwidth also requires more spectrum.

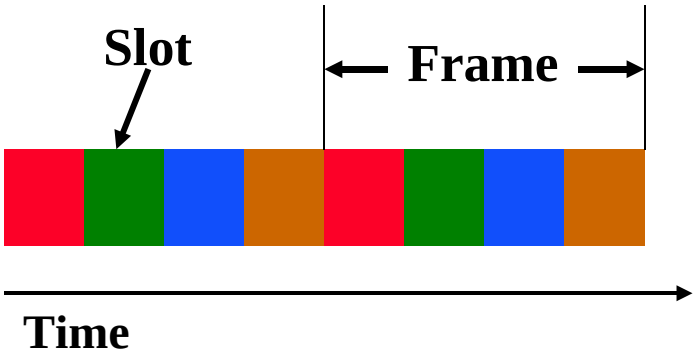




Frequency versus Time-division Multiplexing

- **With frequency-division multiplexing different users use different parts of the frequency spectrum.**
  - » Each user can send all the time, at a reduced rate
  - » Example: roommates
- **With time-division multiplexing different users send at different times.**
  - » Each user can sent at full speed some of the time
  - » Example: a time-share condo
- **The two solutions can be combined.**





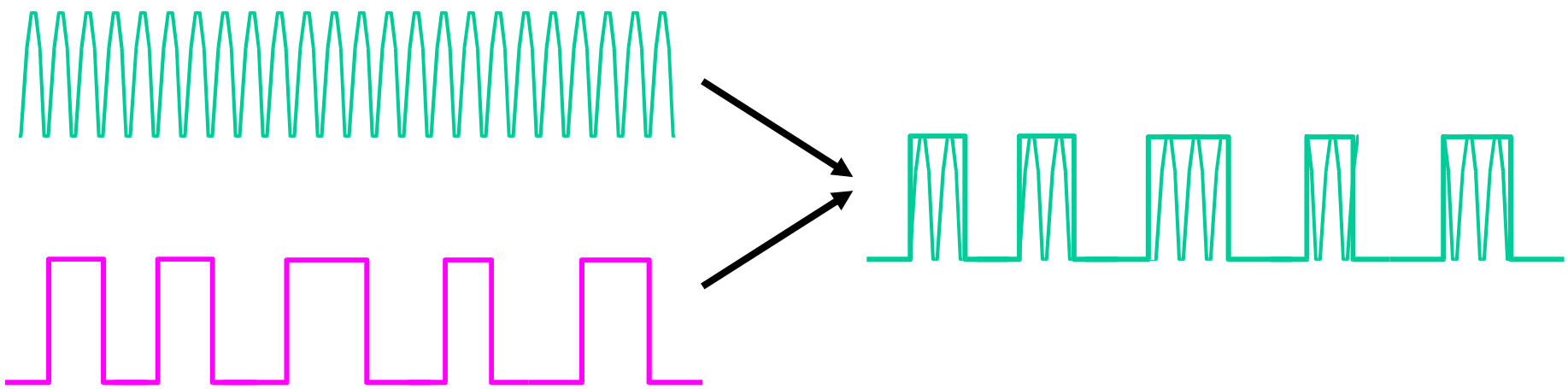
Modulation

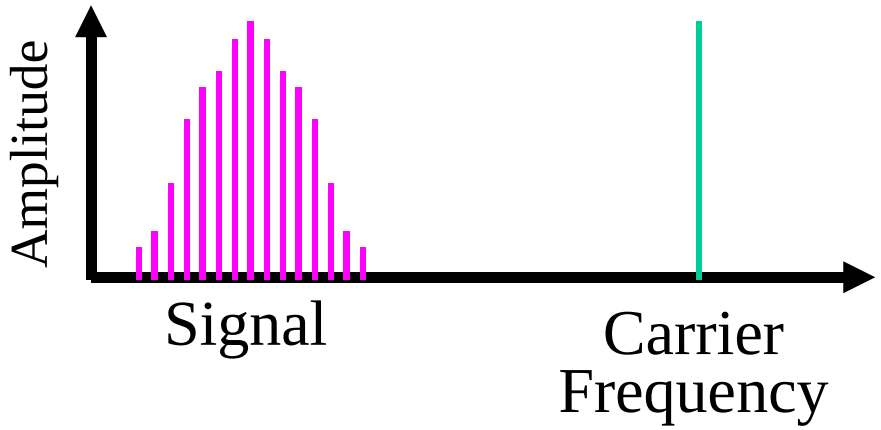
- **Sender changes the nature of the signal in a way that the receiver can recognize.**
- **Amplitude modulation: change the strength of the signal, typically between on and off.**
  - Sender and receiver agree on a “rate”
  - On means 1, Off means 0
- **Similar: frequency or phase modulation**

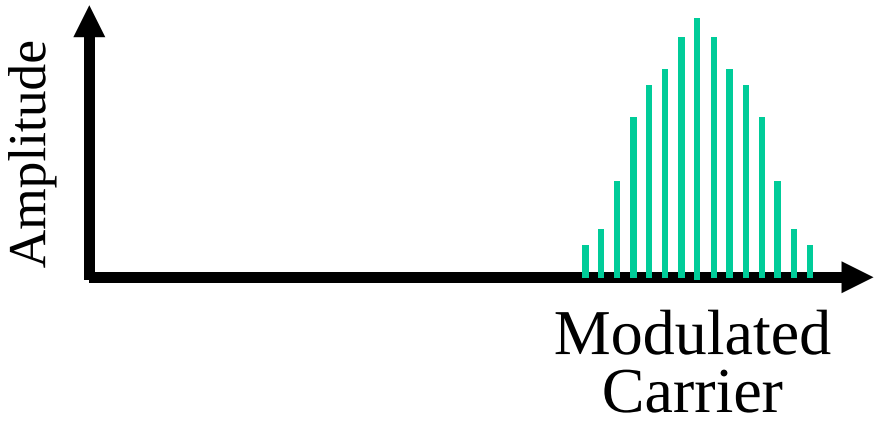
Baseband versus Carrier Modulation

- **Baseband modulation**
  - Convert some data to a signal
  - Send the “bare” signal.
- **Carrier modulation: use the signal to modulate a higher frequency signal (“carrier”).**
  - Can be viewed as the product of the two signals
  - Corresponds to a shift in the frequency domain
- **Important for Frequency Division Multiplexing**

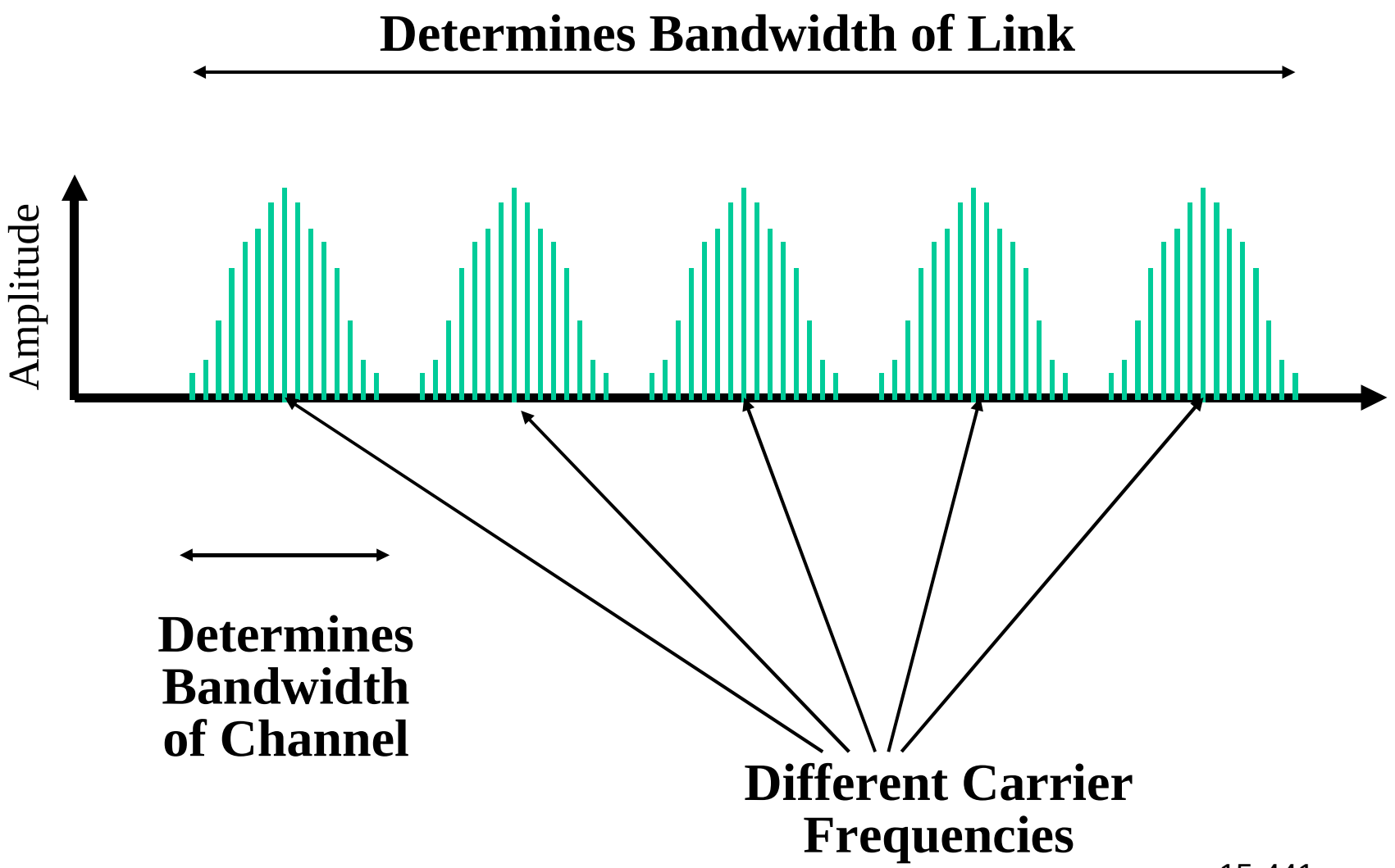
Amplitude Carrier Modulation







Frequency Division Multiplexing: Multiple Channels



Digital Transmission/Multiplexing Hierarchy

- **North America**
  - T1/DS1: 24 voice channels plus 1 bit per sample
    - (24 x 8 + 1) x 8000 = 1.544 Mbps
  - T3/DS3: another D2 hierarchy that is rarely exposed
    - 7 x 4 x 1.544 = 44.736 Mbps
- **Europe has different standard**
  - E1, E3

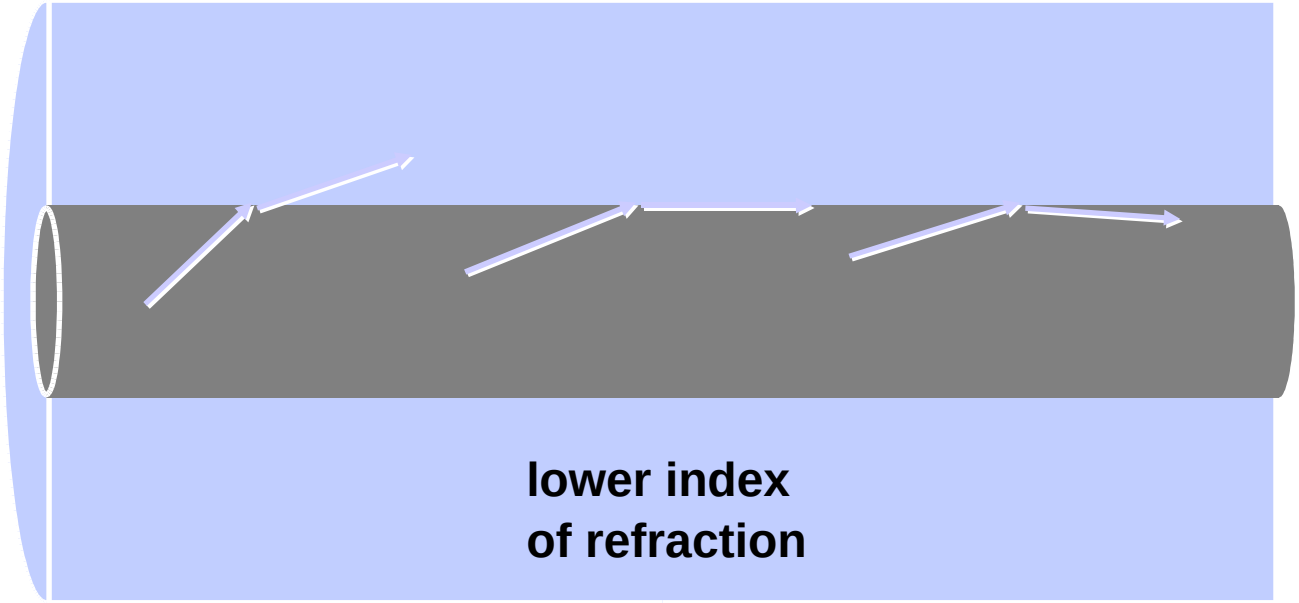
Copper Wire

- **Unshielded twisted pair**
  - Two copper wires twisted - avoid antenna effect
  - Grouped into cables: multiple pairs with common sheath
  - Category 3 (voice grade) versus Category 5
    - 100 Mbps up to 100 m
    - 1 Mbps up to a few km (assuming digital transmission)
- **Coaxial cables.**
  - One connector is placed inside the other connector
  - Holds the signal in place and keeps out noise
  - Gigabit up to a km
- **Signaling processing research pushes the capabilities of a specific technology**

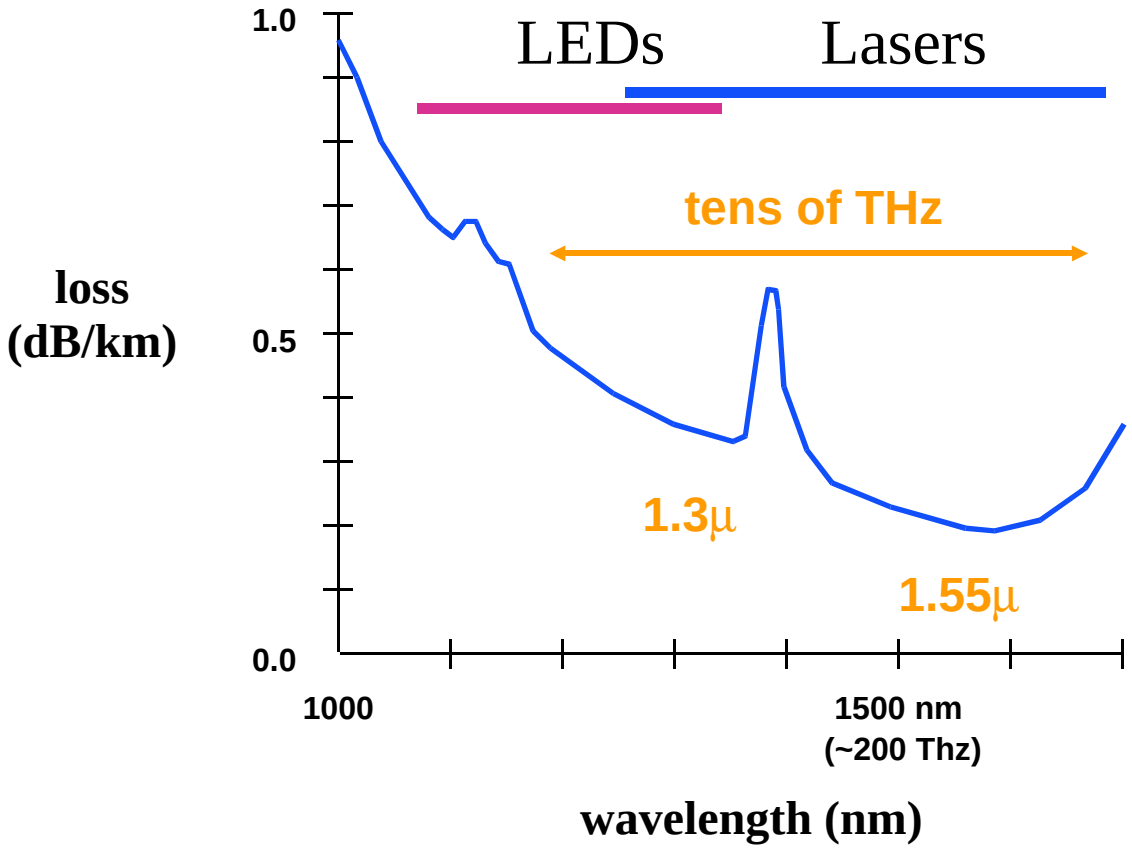
Age of Fiber and Optics

- **Enabling technology: optical transmission over fiber**
- **Advantages of fiber**
  - Huge bandwidth (TeraHz): huge capacity
  - Low attenuation: long distance

Ray Propagation



Light Transmission in Fiber



Fiber and Optical Source Types

- **Multi-mode fiber.**
  - 62.5 or 50 micron core carries multiple “modes”
  - used at 850 nm or 1310 nm, usually LED source
  - subject to mode dispersion: different propagation modes travel at different speeds
  - typical limit: 1 Gbps at 100m
- **Single-mode**
  - 8 micron core carries a single mode
  - used at 1.3 or 1.55 microns, usually laser diode source
  - typical limit: 10 Gbps at 40 km or more, rapidly improved by technology advances
  - still subject to chromatic dispersion

Gigabit Ethernet: Physical Layer Comparison

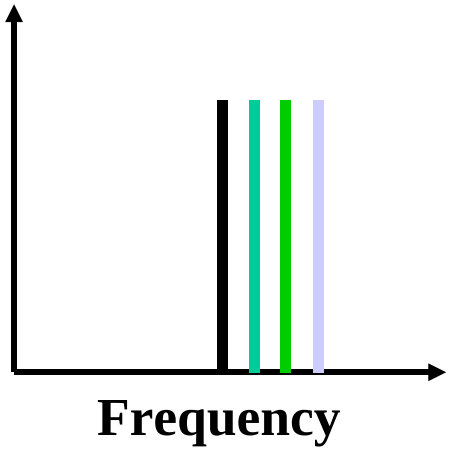
Medium	Transmit/receive	Distance	Comment
Copper	1000BASE-CX	25 m	machine room use
Twisted pair	1000BASE-T	100 m	
MM fiber 62 μm	1000BASE-SX	260 m	
	1000BASE-LX	500 m	
MM fiber 50 μm	1000BASE-SX	525 m	
	1000BASE-LX	550 m	
SM fiber	1000BASE-LX	5000 m	
Twisted pair	100BASE-T	100 m	2p of UTP5/2-4p of UTP3
MM fiber	100BASE-SX	2000m	

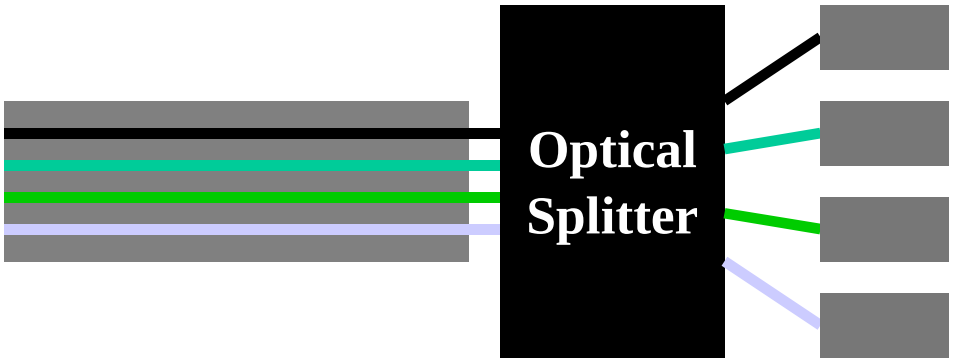
Optical Amplification

- At end of span, either regenerate electronically or amplify.
- Electronic repeaters are potentially slow, but can eliminate noise.
- Amplification over long distances made practical by erbium doped fiber amplifiers offering up to 40 dB gain, linear response over a broad spectrum. Ex: 10 Gbps at 500 km.

Wavelength Division Multiplexing

- **Send multiple wavelengths through the same fiber.**
  - Multiplex and demultiplex the optical signal on the fiber
- **Each wavelength represents an optical carrier that can carry a separate signal.**
  - ITU grid: 40 wavelengths around 1510 nm





“Wireless”

“You see, wire telegraph is a kind of a very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles. Do you understand this? And radio operates exactly the same way: you send signals here, they receive them there. The only difference is that there is no cat.”

– Albert Einstein

Wireless Technologies

- **Great technology: no wires to install, convenient mobility, ..**
- **High attenuation limits distances.**
  - » Wave propagates out as a sphere
  - » Signal strength reduces quickly $(1/\text{distance})^3$
- **High noise due to interference from other transmitters**
  - » Use MAC and other rules to limit interference
  - » Aggressive encoding techniques to make signal less sensitive to noise
- **Other effects: multipath fading, security, ..**
- **“Ether has limited bandwidth”**
  - » Try to maximize its use
  - » Government oversight to control use

Things to Remember

- **Bandwidth and distance of networks is limited by physical properties of media.**
  - Attenuation, noise, …
- **Network properties are determined by transmission medium and transmit/receive hardware.**
  - » Nyquist gives a rough idea of idealized throughput
  - » Can do much better with better encoding
    - – Low b/w channels: Sophisticated encoding, multiple bits per wavelength.
    - – High b/w channels: Simpler encoding (FM, PCM, etc.), many wavelengths per bit.
- **Multiple users can be supported using space, time, or frequency division multiplexing.**
- **Properties of different transmission media.**

Analog versus Digital Encoding

- **Digital transmissions.**
  - Interpret the signal as a series of 1's and 0's
  - E.g., data transmission over the Internet
- **Analog transmission**
  - Do not interpret the contents
  - E.g., broadcast radio
- **Why digital transmission?**