15-441 / 15-641 Computer Networking

Lecture 3: Physical layer

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Next Three Lectures …

1. Physical layer.
2. Datalink layer introduction, framing, error coding, switched networks.
3. Broadcast-networks, home networking.

- Application
- Presentation
- Session
- Transport
- Network
- Datalink
- Physical

Transferring Information

- Information transfer is a physical process
- In this class, we generally care about
  - Electrical signals (on a wire)
  - Optical signals (in a fiber)
  - More broadly, EM waves
- Information carriers can also be
  - Sound waves
  - Quantum states
  - Proteins
  - Ink & paper, etc.

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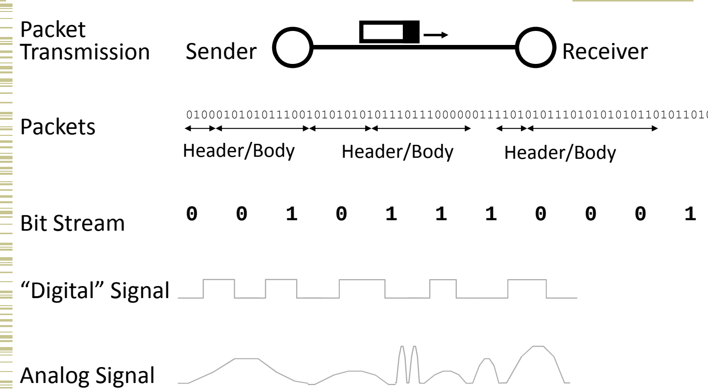
From Signals to Packets



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Today's Lecture

- Modulation.
- Bandwidth limitations.
- Multiplexing.
- Media: Copper, Fiber, Optical, Wireless.

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Why Do We Care?

- I am not an electrical engineer?
  - Well, most of you aren't
- Physical layer places constraints on what the network infrastructure can deliver
  - Reality check
  - Impact on system performance
  - Impact on the higher protocol layers
  - Some examples:
    - Fiber or copper?
    - Do we need wires?
    - Error characteristic and failure modes
    - Effects of distance on bandwidth?

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Modulation

- Changing a signal to convey information
- From Music:
  - Volume
  - Pitch
  - Timing

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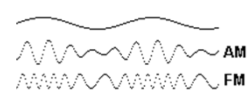
Modulation

- Changing a signal to convey information
- Ways to modulate a sinusoidal wave
  - Volume: Amplitude Modulation (AM)
  - Pitch: Frequency Modulation (FM)
  - Timing: Phase Modulation (PM)



- In our case, modulate signal to encode a 0 or a 1. (multi-valued signals sometimes)

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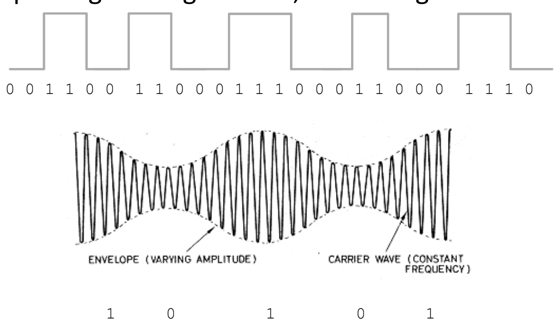
Amplitude Modulation

- AM: change the strength of the signal.
- Example: High voltage for a 1, low voltage for a 0



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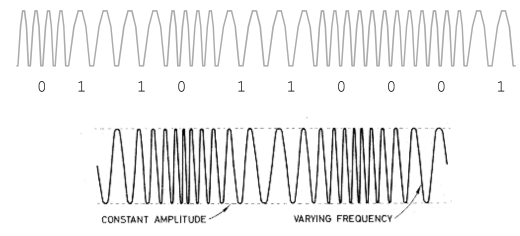
Frequency Modulation

- FM: change the frequency



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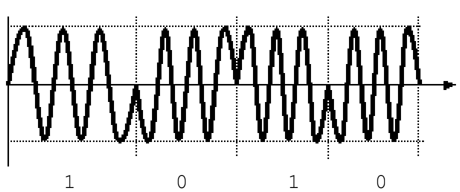
Phase Modulation

- PM: Change the phase of the signal



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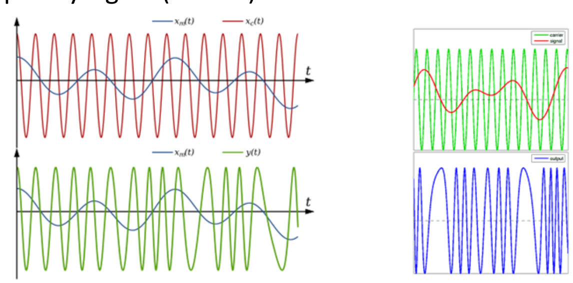
Carrier Modulation

- Baseband modulation: send the “bare” signal.
- Carrier modulation: use the signal to modulate a higher frequency signal (carrier).



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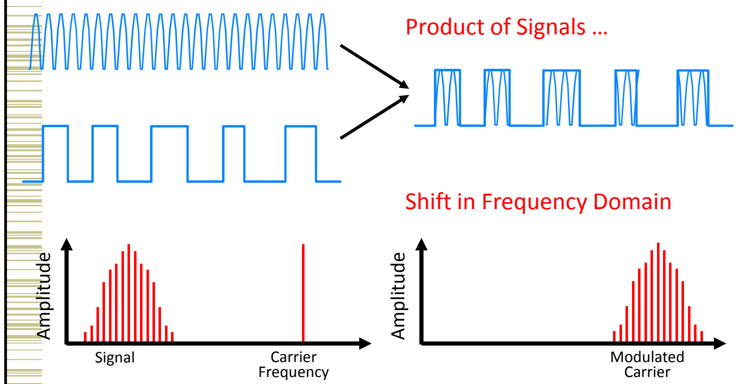
Amplitude Carrier Modulation



Why Different Modulation Methods?

Offers choices with different tradeoffs:

- Transmitter/Receiver complexity
- Power requirements
- Bandwidth
- Medium (air, copper, fiber, …)
- Noise immunity
- Range
- Multiplexing

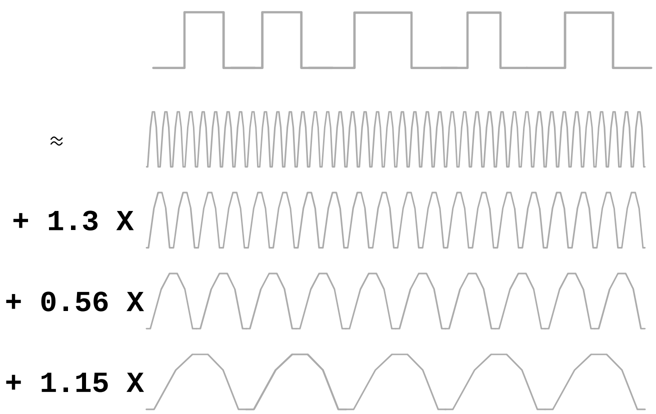
Let us Look at Some Quesions

- How much bandwidth can I get out of a specific wire (transmission medium)?
- What limits the physical size of the network?
- How can multiple hosts communicate over the same wire at the same time?
- How can I manage bandwidth on a transmission medium?
- How do the properties of copper, fiber, and wireless compare?

Bandwidth

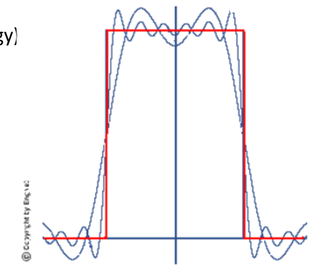
- Bandwidth is width of the frequency range in which the Fourier transform of the signal is non-zero.
- Sometimes referred to as the channel width
- Or, where it is above some threshold value (Usually, the half power threshold, e.g., -3dB)
- dB - short for decibel
  - Defined as 10 * $\log_{10}(P_1/P_2)$
  - When used for signal to noise: 10 * $\log_{10}(S/N)$
- Also: dBm – power relative to 1 milliwatt
  - Defined as 10 * $\log_{10}(P/1\ mW)$

Signal = Sum of Waves



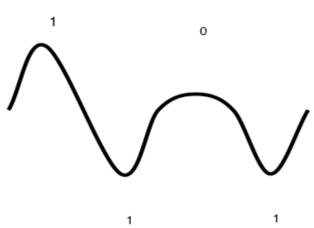
The Frequency Domain

- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
  - Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
  - What frequencies are present and what is their strength (energy)
- E.g., radio and TV signals



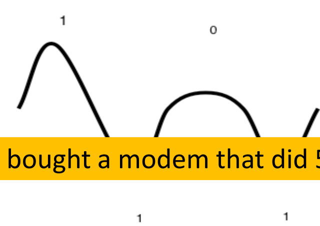
The Nyquist Limit

- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  - Assumes binary amplitude encoding



The Nyquist Limit

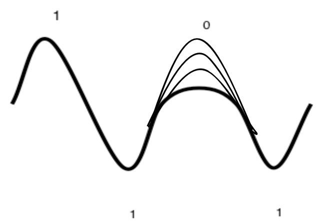
- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  - Assumes binary amplitude encoding
  - E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second



Hmm, I once bought a modem that did 54K????

How to Get Past the Nyquist Limit

- Instead of 0/1, use lots of different values.
- (Remember, the channel is noiseless.)
- Can we really send an infinite amount of info/sec?

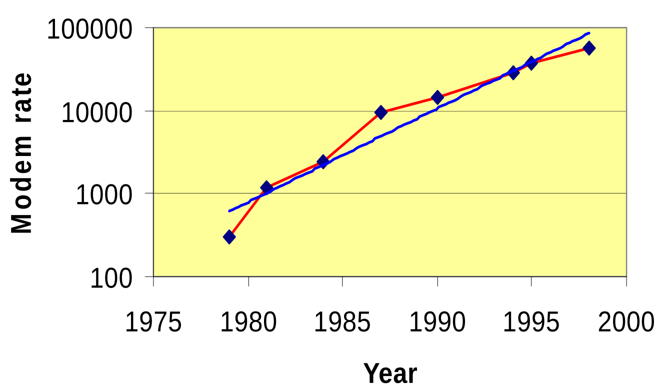


Past the Nyquist Limit

- More aggressive encoding can increase the bandwidth
- Example: modulate multi-valued symbols
  - Modulate blocks of “digital signal” bits, e.g, 3 bits = 8 values
  - Often combine multiple modulation techniques

- Problem? Noise!
  - The signals representing two symbols are less distinct
  - Noise can prevent receiver from decoding them correctly

Example: Modem Rates



Capacity of a Noisy Channel

- Places upper bound on channel capacity, while considering noise
- Shannon’s theorem:

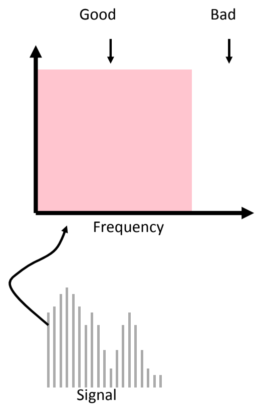
  $C = B \times \log_2(1 + S/N)$

  - 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?

$C = 3200 \times \log_2(1 + 1000) = 31.9$ Kbps

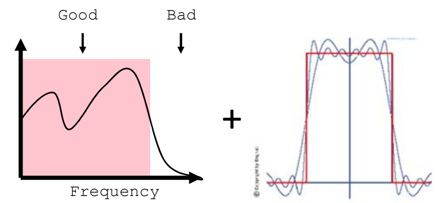
Transmission Channel Considerations

- Every medium supports transmission in a certain frequency range.
  - Outside this range, effects such as attenuation, .. degrade the signal too much
- Transmission and receive 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.



Attenuation & Dispersion

- Real signal may be a combination of many waves at different frequencies
- Why do we care?



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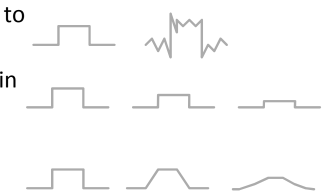
Limits to Speed and Distance

- 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)



- Effects limit the data rate that a channel can sustain.
  - » But affects different technologies in different ways
- Effects become worse with distance.
  - » Tradeoff between data rate and distance

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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.
  - Similar to radio: 95.5 versus 102.5 station
- Controlling time (for us) is a datalink protocol issue.
  - Media Access Control (MAC): who gets to send when?

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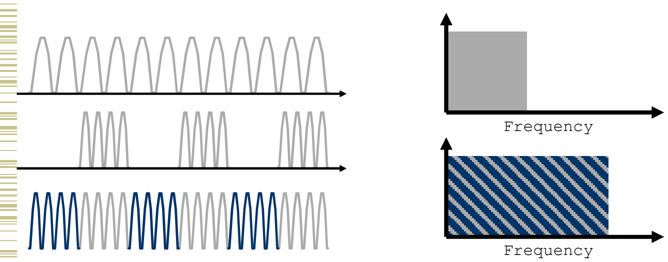
Time Division Multiplexing

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



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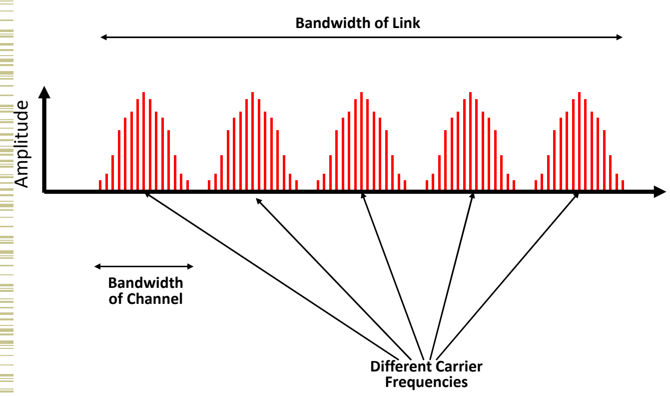
FDM: Multiple Channels



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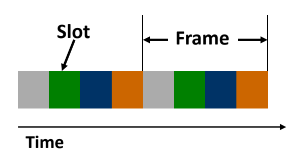
Frequency versus Time-division Multiplexing

- With FDM different users use different parts of the frequency spectrum.
  - I.e. each user can send all the time at reduced rate
  - Example: roommates
- With TDM different users send at different times.
  - I.e. each user can sent at full speed some of the time
  - Example: a time-share condo
- The two solutions can be combined.



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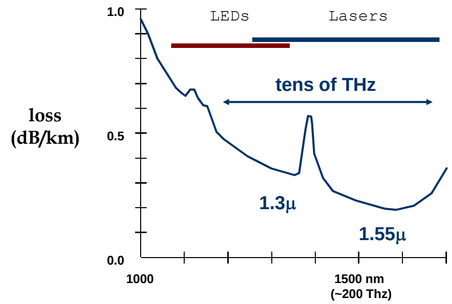
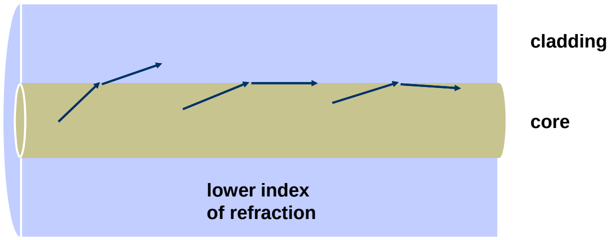
Copper Wire

- Unshielded twisted pair (UTP)
  - Two copper wires twisted - avoid antenna effect
  - Grouped into cables: multiple pairs with common sheath
  - Category 3 (voice grade) versus category 6
  - 100 Mbit/s up to 100 m, 1 Mbit/s up to a few km
  - Cost: ~ 10cents/foot
- Coax 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.
  - E.g. modems, use of cat 6

Light Transmission in Fiber



Ray Propagation



(note: minimum bend radius of a few cm)

Fiber Types

- Multimode fiber.
  - 62.5 or 50 micron core carries multiple “modes”
  - Used at 1.3 microns, 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: 10s of Gbps at 60 km or more
  - Still subject to chromatic dispersion

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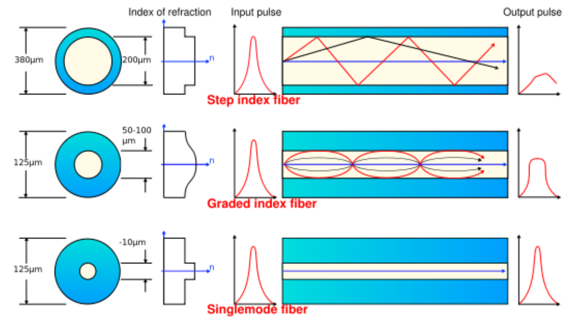
Fiber Types

Multimode

Single mode



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Can we Increase Distance? Regeneration and 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: 40 Gbps at 500 km.

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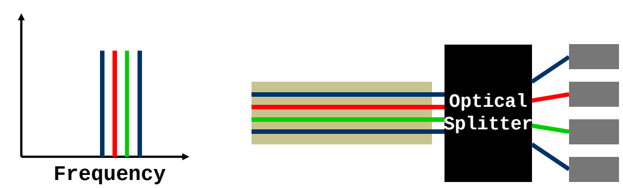
Wavelength Division Multiplexing

- 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.
  - E.g., 16 colors of 2.4 Gbit/second
- Like radio, but optical and much faster



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Things to Remember

- Bandwidth and distance of networks is limited by physical properties of media.
  - Attenuation, noise, dispersion, …
- 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.
  - Shannon: $C = B \times \log_2(1 + S/N)$
- Multiple users can be supported using space, time, or frequency division multiplexing.
- Properties of different transmission media.