15-441 15-641 Computer Networking

Lecture 3: Physical Layer

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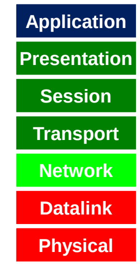
Fall 2016

www.cs.cmu.edu/~prs/15-441-F16

Back to Basics

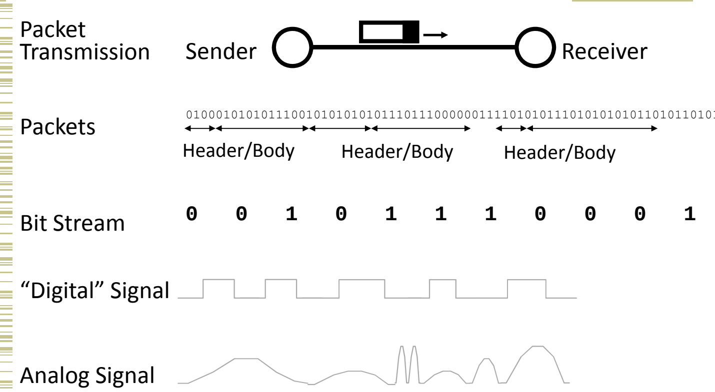
1. Physical layer.
2. Datalink layer introduction, framing, error coding, switched networks.
3. Contention-based networks, e.g., ethernet.



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)
  - Wireless signals
  - More broadly, EM waves
- Information carriers can also be
  - Sound waves
  - Quantum states
  - Ink & paper, etc.

From Signals to Packets



Today's Lecture

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

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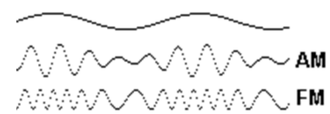
What is Modulation?

- The sender changes a signal in a way that the receiver can recognize - conveys information
- Ways to modulate a signal (think: sinusoidal wave)
  - Change frequency, phase, or amplitude
- Similar to AM/FM radio:
  - But we encode bits!
- Many forms of modulation!
  - Basic AM, FM, and PM - OK for "easy" environments
  - Wireless environments are very challenging – uses much more aggressive forms of modulation



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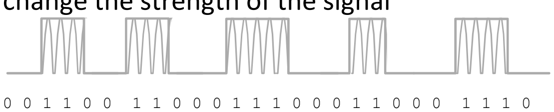
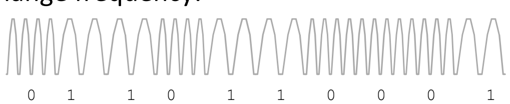
Binary Modulation

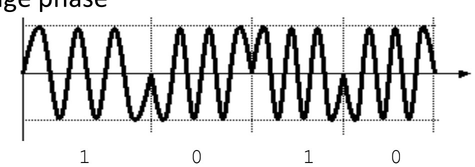
- AM: change the strength of the signal



- FM: change frequency:



- PM: change phase



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Let us Look at Some Quesions

- Is there a limit to the capacity of a wire?
- How do the properties of copper, fiber, and wireless compare?
  - Price, bandwidth, easy of deployment, …
- What limits the physical size of the network?
  - Or: how long can the wires be
- Does the modulation technique matter?
- How can multiple hosts communicate over the same wire at the same time?

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Why Different Modulation Methods?

Offers choices with different tradeoffs:

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

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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 $10 * \log_{10}(P/1\ mW)$

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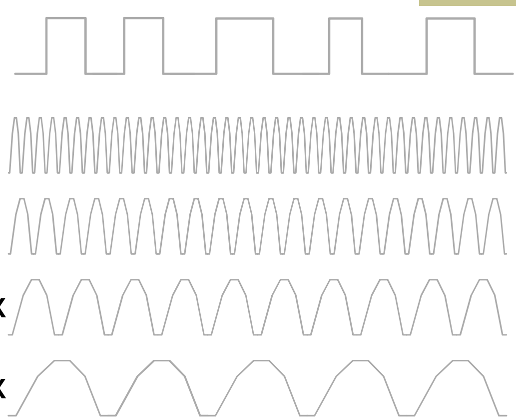
Signal = Sum of Waves



≈

+ 1.3 X

+ 0.56 X

+ 1.15 X

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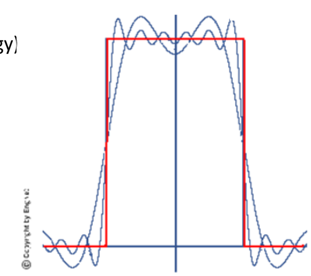
The Frequency Domain

- 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)
- Channel properties can be frequency dependent
  - E.g., attenuation



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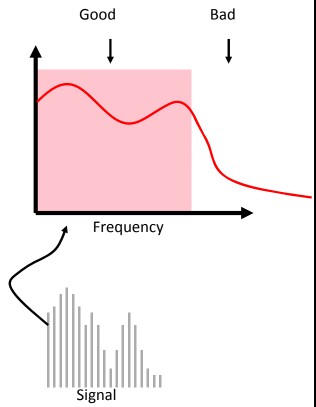
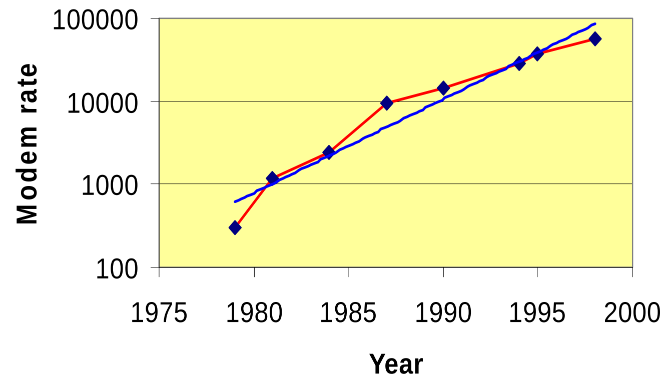
Transmission Channel Considerations

- Every medium supports transmission in a certain frequency range
  - Good transmission inside range
  - Outside this range, effects such as attenuation, .. degrade the signal significantly
- Transmit and receive hardware will try to maximize the useful bandwidth, given channel properties
  - Tradeoffs between cost, distance, bit rate
  - Very hard to do for wireless!
- As technology improves, these parameters change, even for the same the wire

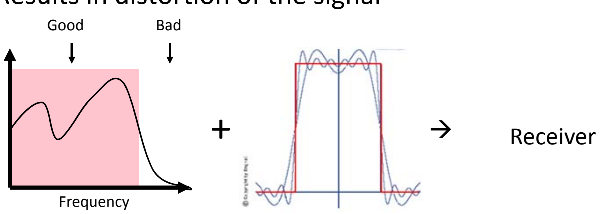


Example: Modem Rates



Attenuation & Dispersion

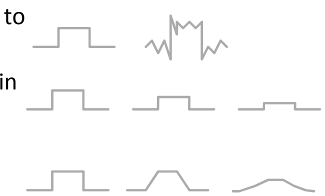
- Different frequencies in the signal are “abused” differently
- Especially bad in wireless
  - Changes over time – frequency selective fading (bad!)
- Results in distortion of the signal



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.

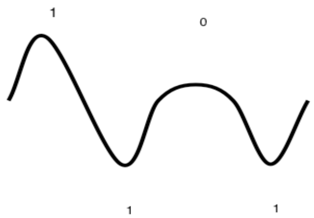
(Changes the shape of the signal)



- 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

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



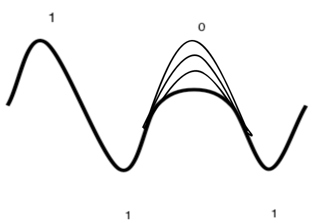
The Nyquist Limit

- 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????

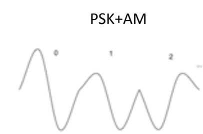
How to Get Past the Nyquist Limit

- 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

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

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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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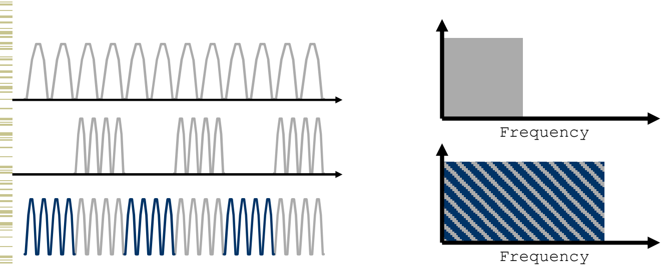
Time Division Multiplexing

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



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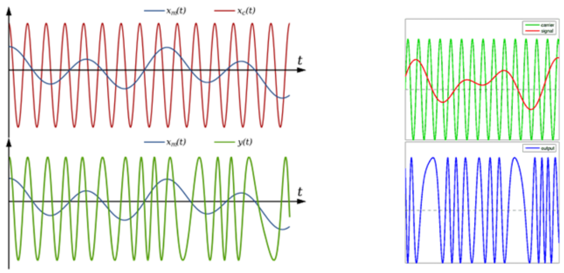
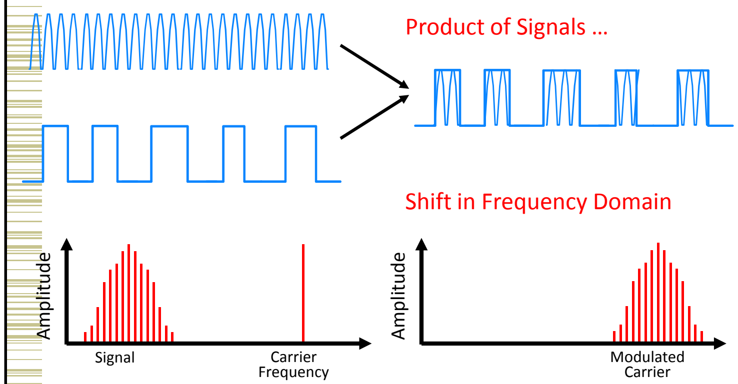
Carrier Modulation

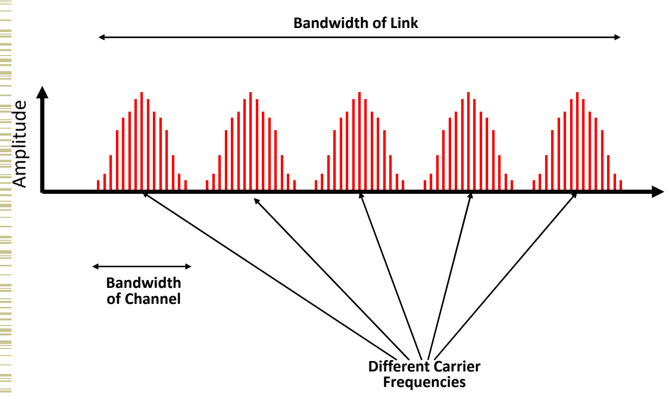
- Baseband modulation: send the “bare” signal.
- Carrier modulation: use the signal to modulate a higher frequency signal (carrier).



Amplitude Carrier Modulation

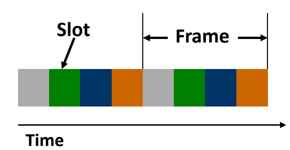


FDM: Multiple Channels



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

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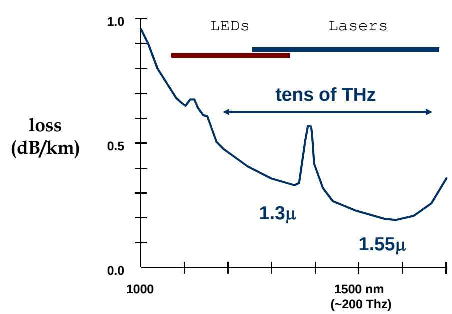
Light Transmission in Fiber



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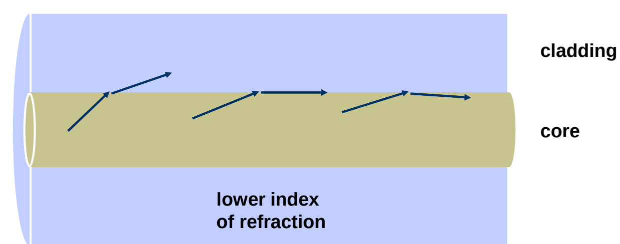
Ray Propagation



(note: minimum bend radius of a few cm)

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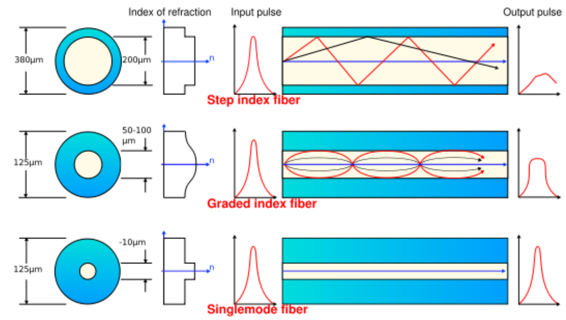
Fiber Types

- 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

Fiber Types

Multimode

Single mode

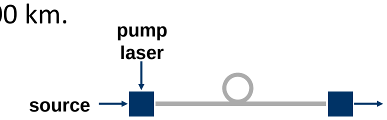


Gigabit Ethernet: Physical Layer Comparison (old chart)

Medium	Transmit/ receive	Distance	Comment
Copper	1000BASE-CX	25 m	machine room use
Twisted pair	1000BASE-T	100 m	not yet defined; cost? Goal:4 pairs of UTP5
MM fiber 62 mm	1000BASE-SX	260 m	
	1000BASE-LX	500 m	
MM fiber 50 mm	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	

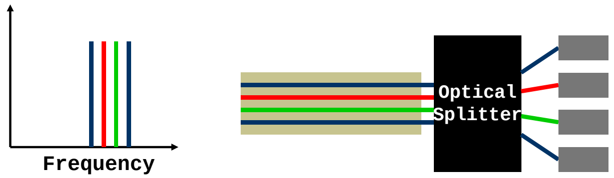
Can we Increase Distance? Regeneration and Amplification

- 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.



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



Things to Remember

- Bandwidth and distance of network links 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.