15-441/641: Physical and Datalink Layers

15-441 Spring 2019

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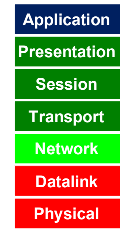
https://computer-networks.github.io/sp19/

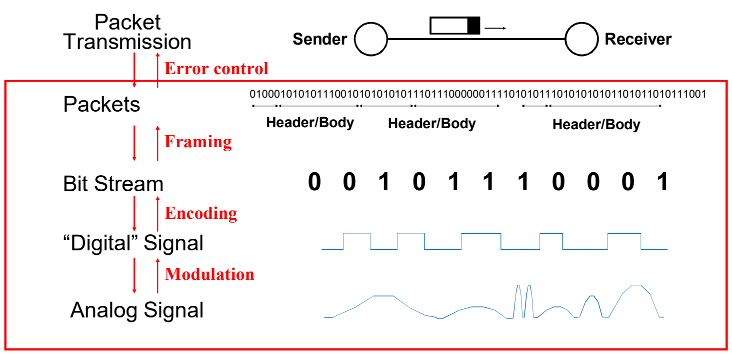
Carnegie Mellon University

Back to Basics

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



From Signals to Packets



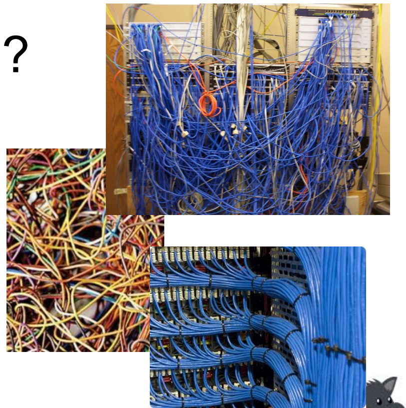
Today's Lecture

- Modulation
- Signal propagation
- Throughput limits
- Multiplexing
- Media: Copper, Fiber, Optical, Wireless
- Coding and framing

Wires – Boring?

- You are responsible for installing the networking in a new office building. What wires will you use:

1. Inside each office?
2. Connecting offices to the wiring closet?
3. Between floors?
4. Between buildings?

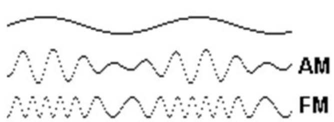


Transferring Information

- Information transfer is a <u>physical</u> process
- In this class, we generally care about
  - Electrical signals (on a wire)
  - Optical signals (in a fiber)
  - Wireless signals (over the "ether")
  - More broadly, electromagnetic waves
- Information carriers can also be
  - Sound waves
  - Quantum states
  - Ink & paper, etc.

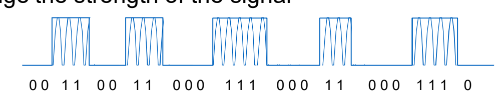
What is Modulation?

- The sender sends an EM signal and changes in a way that the receiver can recognize – this conveys information
- Ways to modulate a signal (think: sinusoidal wave)
  - Change frequency, phase, or amplitude
- Similar to AM/FM radio:
  - But digital: 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

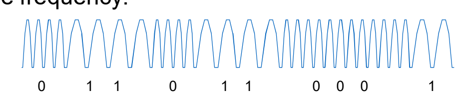


Binary Modulation

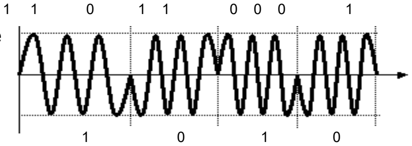
- AM: change the strength of the signal



- FM: change frequency:



- PM: change phase



Why Different Modulation Methods?

Offers choices with different tradeoffs:

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

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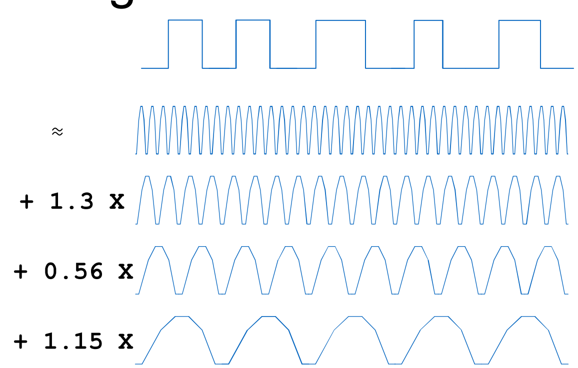
Some “Wire” Questions

- 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?

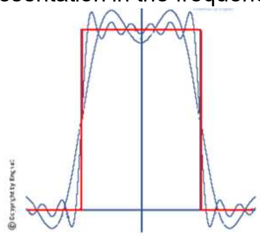
→ How does signal propagation affect the signal quality and bitrate?

Signal = Sum of Waves

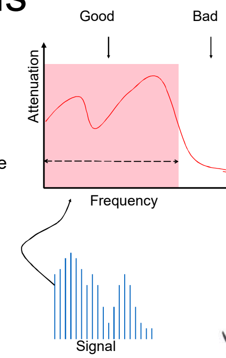


The Frequency Domain

- 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)
  - Use Fourier transform to translate between frequency and time view
- Channel properties can be frequency dependent
  - E.g., attenuation



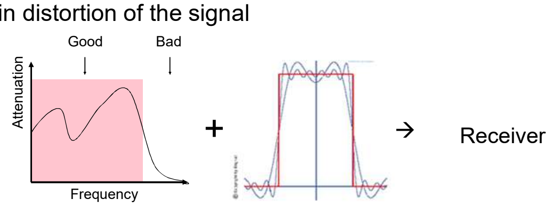
Transmission Channel Considerations



- Every medium supports transmission in a certain frequency range
  - Good transmission inside some range – “channel width”
  - Question: is channel width (Hz) related to throughput (MHz)?
  - Outside this range, effects such as attenuation, .. degrade the signal significantly
- Transmit and receive hardware tries to maximize the useful bandwidth, given channel properties
  - Tradeoffs between cost, distance, bit rate
- As technology improves, these parameters change, even for the same the wire

Attenuation & Distortion

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

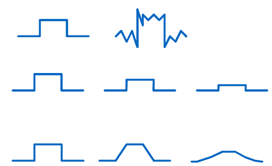


Spectral Bandwidth

- Bandwidth is width of the frequency range in which the Fourier transform is above some threshold
  - For example, the half power threshold
- Sometimes referred to as the signal width
- Power levels are often specified in 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 * $\log_{10}(P/1\ mW)$

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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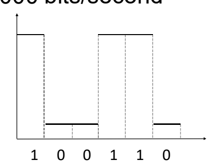
The Nyquist Limit

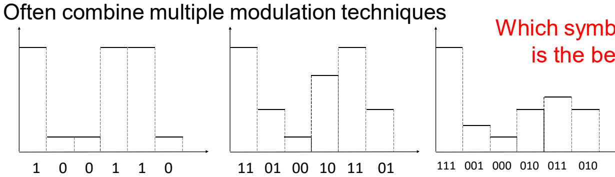
- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  - Assumes binary amplitude modulation
- Example: a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second



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

Which symbol size is the best?



- 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 (not in dB)
    S/N 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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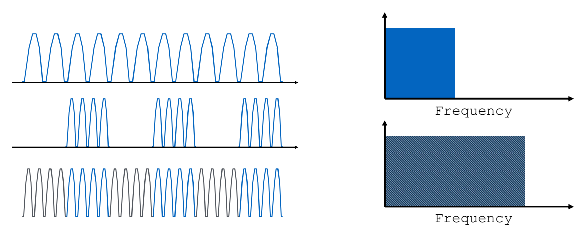
Supporting Multiple Channels

- What do we do if a transmission medium has a very large (spectral) bandwidth?
  - Example: fiber has several THz of usable bandwidth
  - Good news: we can send at Tbits/second!
  - Bad news: would be very expensive!
  - Also: user do not need that much bandwidth
- Frequency multiplexing means that different users use a different part of the spectrum.
  - Very common for fiber, wireless, and coax cable
  - Similar to radio: 95.5 FM versus 102.5 FM radio station

Time Division Multiplexing

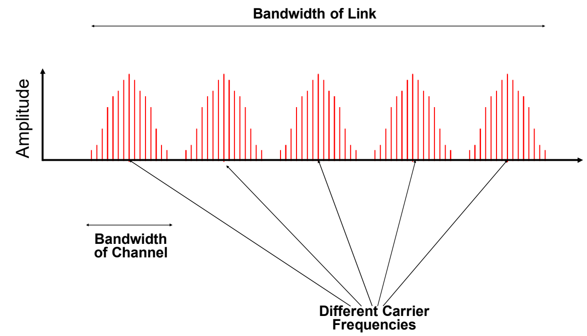
- Different users use the wire at different points in time.
- Aggregate bandwidth also requires more spectrum.



Frequency Multiplexing

- Remember: we send data by modulating a carrier signal with a certain (high) frequency
- How about if different users use carriers with a different frequency?
  - Moves the signal around in the spectrum
  - There are relatively simple EE techniques to do this ("mixing")
- This is called Frequency Division Multiplexing (FDM)
- The alternative is Time Division Multiplexing (TDM)
  - Multiple users share the same carrier (i.e., on same frequency)
- Tradeoffs are complex (out of scope)

FDM: Multiple Channels



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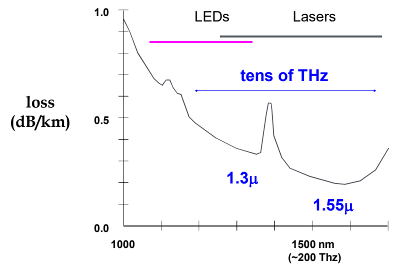
Copper Wire

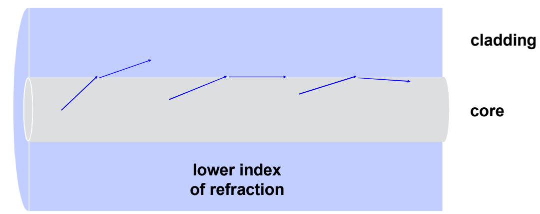
Attribute	Category 5e	Category 6	Category 6A	Category 7/7$_A$	Category 8
Frequency	100 MHz	250 MHz	500 MHz	1000 MHz	2000 MHz
Maximum Data Rate	1000Base-T	1000Base-T	10GBase-T	10GBase-T	25GBase-T 40GBase-T
Distance	100 meters	100 meters	100 meters	100 meters	30 meters
Number of Connectors in Channel	4	4	4	4	2
Cable Construction	UTP or Shielded	UTP or Shielded	UTP or Shielded	Shielded	Shielded
Connector Type	RJ45	RJ45	RJ45	Non-RJ45	Class I: RJ45 Class II: Non-RJ45

- 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 7
  - Cheapest technology
- Coax cables.
  - One connector is placed inside the other connector
  - Holds the signal in place and keeps out noise
  - Gigabitd up to a km

Light Transmission in Fiber



Ray Propagation



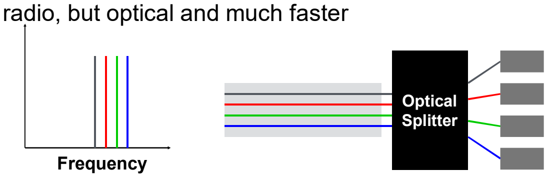
Example – there are many types of fiber!

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 dispersion

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



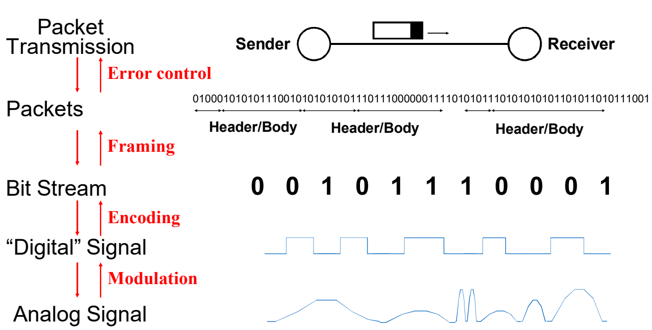
Wires: Things to Remember

- 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
    - Especially important in wireless
  - 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.

Outline

- Encoding and decoding
  - Translate between bits and digital signal
- Framing
  - Bit stream to packets
- Dealing with errors
  - Error detection and correction

From Signals to Packets

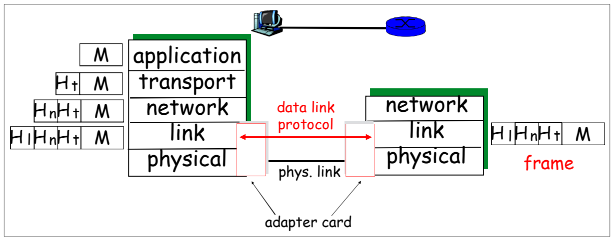


Datalink Functions

- Encoding: change bit stream before transmission
- Framing: encapsulating a network layer datagram into a bit stream.
  - Add header, mark and detect frame boundaries
- Error control: error detection and correction to deal with bit errors.
  - May also include other reliability support, e.g. retransmission
- Flow control: avoid that sender outruns the receiver
- Media access: controlling which frame should be sent over datalink.
- Hubbing, bridging: extend the size of the network

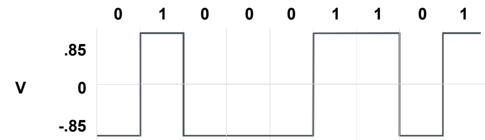
Link Layer: Implementation

- Implemented most in in the network interface
  - Typically includes: RAM, DSP chips, host bus interface, and link interface
  - Some control logic in the network device driver



Do We Need Coding?

- Of course not – why waste time on this? Just modulate the signal!



But:

- How easily can the receiver retrieve the bit stream?
- What happens when there are errors: a bit gets flipped
- Many solutions have been proposed – not a focus of this course

How about the Poor Receiver?

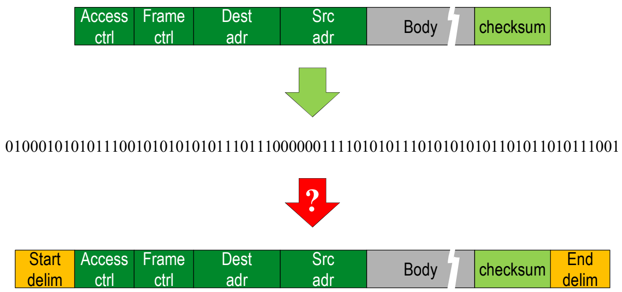
0 1 0 1 How many more ones?

- Sender needs to help the receiver by "shaping" the digital bit stream so it easy to correctly interpret
  - Applies to combination of modulation and coding
- Problem in this case: not enough transitions

Why Do We Need Encoding?

- Keep receiver synchronized with sender.
- Create control symbols, in addition to regular data symbols.
  - E.g. start or end of frame, escape, ...
- Error detection or error corrections.
  - Some codes are illegal so receiver can detect certain classes of errors
  - Minor errors can be corrected by having multiple "adjacent" bit sequences mapped to the same data symbol
- Encoding can be done one bit at a time or in multi-bit blocks, e.g., 4 or 8 bits.
- Encoding can be very complex, e.g. wireless

Why Framing?



Example: Ethernet

- Uses Manchester encoding, which turns each bit into two bits: 10 or 01
  - Very robust with a transition for every bit but doubles spectrum use!
- Uses preamble of 7 bytes (10101010 - 5 MHz square wave) followed by one byte of 10101011
- Allows receivers to recognize start of transmission after idle channel

preamble	datagram	length	more stuff

- Challenge: what happens if the user data includes of the above bit sequences?
- Bit stuffing: sender inserts extra bit in sequence (details omitted)

Example: 4B/5B Encoding

- Symbols of 4 data bits are encoded as 5 line bits, so 100 Mbps (data) results in 125 Mbps on the wire (25% overhead)
- Encoding ensures there are no more than 3 consecutive 0's
  - Allows the use of an efficient modulation scheme
- Provides 16 data codes (4 data bits), 8 control codes
  - Data codes: represent 4 data bits each
  - Control codes: idle, begin frame, etc.
  - Other 8 codes are invalid
- Example: FDDI.

4B/5B Encoding

Data	Code	Data	Code
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

From datalink

To modulator

Other Encodings

- 8B/10B: Fiber Channel and Gigabit Ethernet
- 64B/66B: 10 Gbit Ethernet (& 40 and 100 Gb/S)
- Trend: efficiency improves over time

- Rule of thumb:
  - Little bandwidth → complex encoding
    - Example: wireless
  - Lots of bandwidth → simple encoding
    - Example: fiber