Physical Layer &
Link Layer Basics

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Today (& Tomorrow (& Tmrw))

1. Physical layer.
2. Datalink layer introduction, framing, error coding, switched networks.

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 carrier can also be?
Transferring Information

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  - Electrical signals (on a wire)
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- Information carriers can also be
  - Sound waves
  - Quantum states
  - Proteins
  - Ink & paper, etc.

From Signals to Packets

Today's Lecture

- Modulation.
- Bandwidth limitations.
- Frequency spectrum and its use.
- Multiplexing.
- Media: Copper, Fiber, Optical, Wireless.

- Coding.
- Framing.
Why Do We Care?

- I am not an electrical engineer?
- 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

Modulation

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

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)
**Frequency Modulation**

- FM: change the frequency

**Phase Modulation**

- PM: Change the phase of the signal

**Baseband vs Carrier Modulation**

- Baseband modulation: 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

**Amplitude Carrier Modulation**
Why Different Modulation Methods?

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

What Do We Care About?

- 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: $10 \log_{10}(S/N)$
Signal = Sum of Waves

\[ \text{Signal} = 1 + 1.3 \times + 0.56 \times + 1.15 \times \]

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 \( 2 \times H \).
  - 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 channel bandwidth.
  - Example: modems
    • Same frequency - 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

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.
**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:
  \[ C = B \times \log_2(1 + \frac{S}{N}) \]
  - \( C \): maximum capacity (bps)
  - \( B \): channel bandwidth (Hz)
  - \( S/N \): signal to noise ratio of the channel
  Often expressed in decibels (db) \( \equiv 10 \log(S/N) \)

**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.

**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?

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?

Time Division Multiplexing

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

FDM: Multiple Channels

- Determines Bandwidth of Link
- Determines Bandwidth of Channel
- Different Carrier Frequencies
- 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.

Frequency versus Time-division Multiplexing
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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 5
  - 100 Mbit/s up to 100 m, 1 Mbit/s up to a few km
  - Cost: ~ 10 cents/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 5

UTP

- Why twist wires?
  - Provide noise immunity
  - Combine with Differential Signaling
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: 10 Gbps at 60 km or more
  - still subject to chromatic dispersion

Ray Propagation

- cladding
- core
- lower index of refraction

(light transmission in fiber)
# Gigabit Ethernet: Physical Layer Comparison

<table>
<thead>
<tr>
<th>Medium</th>
<th>Transmit/ receive</th>
<th>Distance</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1000BASE-CX</td>
<td>25 m</td>
<td>machine room use</td>
</tr>
<tr>
<td>Twisted pair</td>
<td>1000BASE-T</td>
<td>100 m</td>
<td>not yet defined; cost?</td>
</tr>
<tr>
<td>MM fiber 62 mm</td>
<td>1000BASE-SX</td>
<td>260 m</td>
<td>Goal: 4 pairs of UTP5</td>
</tr>
<tr>
<td></td>
<td>1000BASE-LX</td>
<td>500 m</td>
<td></td>
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<tr>
<td>MM fiber 50 mm</td>
<td>1000BASE-SX</td>
<td>525 m</td>
<td></td>
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<tr>
<td></td>
<td>1000BASE-LX</td>
<td>550 m</td>
<td></td>
</tr>
<tr>
<td>SM fiber</td>
<td>1000BASE-LX</td>
<td>5000 m</td>
<td></td>
</tr>
<tr>
<td>Twisted pair</td>
<td>100BASE-T</td>
<td>100 m</td>
<td>2p of UTP5/2-4p of UTP:</td>
</tr>
<tr>
<td>MM fiber</td>
<td>100BASE-SX</td>
<td>2000 m</td>
<td></td>
</tr>
</tbody>
</table>

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## How to increase distance?

- Even with single mode, there is a distance limit.
- I.e.: How do you get it across the ocean?

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## 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

Wireless Technologies

- Great technology: no wires to install, convenient mobility, ...
- High attenuation limits distances.
  - Wave propagates out as a sphere
  - Signal strength attenuates quickly $\rightarrow 1/d^3$
- 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, 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.