15-441/641: Physical and Datalink Layers

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

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

Packet Transmission

Sender → Receiver

Error control

Packets
Framing
Bit Stream
“Digital” Signal
Analog Signal

01000101010111001010101010111011... (Header/Body) (Header/Body)

0 0 1 0 1 1 0 0 0 1

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 physical 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

$\approx + 1.3 x + 0.56 x + 1.15 x$
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 \text{ 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): \[ S/N \text{ (db)} : = 10 \log(S/N) \]
- Example:
  - Local loop bandwidth: 3200 Hz
  - Typical S/N: 1000 (30db)
  - What is the upper limit on capacity?
  \[ C = 3200 \times \log_2(1 + 1000) = 31.9 \text{ Kbps} \]

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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

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

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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 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

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>10 MHz</td>
<td>30 MHz</td>
<td>50 MHz</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Maximum Data Rate</td>
<td>100Base-T</td>
<td>100Base-T</td>
<td>100Base-T</td>
<td>100Base-T</td>
</tr>
<tr>
<td>Distance</td>
<td>100 meters</td>
<td>100 meters</td>
<td>100 meters</td>
<td>100 meters</td>
</tr>
<tr>
<td>Number of Generations in a Cable</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Data Commitment</td>
<td>UTP or Shielded</td>
<td>UTP or Shielded</td>
<td>UTP or Shielded</td>
<td>UTP or Shielded</td>
</tr>
</tbody>
</table>

Connector Type: Cat. 6A, Cat. 7, Cat. 7A, Cat. 8, Cat. 8A
Light Transmission in Fiber

Ray Propagation

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: $C = B \cdot \log_2(1 + S/N)$
- 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

Outline

From Signals to Packets

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<tr>
<td>Bit Stream</td>
<td>Encoding</td>
</tr>
<tr>
<td>“Digital” Signal</td>
<td>Modulation</td>
</tr>
<tr>
<td>Analog Signal</td>
<td></td>
</tr>
</tbody>
</table>

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 next over datalink.
- Hubbing, bridging: extend the size of the network
Link Layer: Implementation

- Implemented most 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!

  \[ V = \frac{1}{2} \left( 0, 1, 0, 0, 1, 1, 0, 1 \right) \]

  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?

- 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?

- The start delimiter (01001010) can be recognized after an idle channel.
- Manchester encoding 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.
- Challenge: what happens if the user data includes any of the above bit sequences?
- Bit stuffing: sender inserts an extra bit in sequence (details omitted).

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.
- 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

<table>
<thead>
<tr>
<th>Data</th>
<th>Code</th>
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</thead>
<tbody>
<tr>
<td>0000</td>
<td>11110</td>
</tr>
<tr>
<td>0001</td>
<td>01001</td>
</tr>
<tr>
<td>0010</td>
<td>10100</td>
</tr>
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<tr>
<td>0110</td>
<td>01110</td>
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<tr>
<td>0111</td>
<td>01111</td>
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</table>

<table>
<thead>
<tr>
<th>Data</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
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<td>1001</td>
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</tr>
<tr>
<td>1101</td>
<td>11011</td>
</tr>
<tr>
<td>1110</td>
<td>11100</td>
</tr>
<tr>
<td>1111</td>
<td>11101</td>
</tr>
</tbody>
</table>
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 $\rightarrow$ complex encoding
    • Example: wireless
  • Lots of bandwidth $\rightarrow$ simple encoding
    • Example: fiber