Where we are in the Course

- Beginning to work our way up starting with the Physical layer
Scope of the Physical Layer

• Concerns how signals are used to transfer message bits over a link
  – Wires etc. carry analog signals
  – We want to send digital bits

10110...  ...10110
Topics

1. Properties of media
   – Wires, fiber optics, wireless
2. Simple signal propagation
   – Bandwidth, attenuation, noise
3. Modulation schemes
   – Representing bits, noise
4. Fundamental limits
   – Nyquist, Shannon
Simple Link Model

• We’ll end with an abstraction of a physical channel
  – Rate (or bandwidth, capacity, speed) in bits/second
  – Delay in seconds, related to length

• Other important properties:
  – Whether the channel is broadcast, and its error rate
Message Latency

• **Latency** is the delay to send a message over a link
  – **Transmission delay**: time to put M-bit message “on the wire”

  – **Propagation delay**: time for bits to propagate across the wire

  – Combining the two terms we have:
Message Latency (2)

• **Latency** is the delay to send a message over a link
  – **Transmission delay:** time to put M-bit message “on the wire”
    \[ T\text{-delay} = \frac{M \text{ (bits)}}{\text{Rate (bits/sec)}} = \frac{M}{R} \text{ seconds} \]
  – **Propagation delay:** time for bits to propagate across the wire
    \[ P\text{-delay} = \frac{\text{Length}}{\text{speed of signals}} = \frac{\text{Length}}{\frac{2}{3}c} = D \text{ seconds} \]
  – Combining the two terms we have: \( L = \frac{M}{R} + D \)
Metric Units

- The main prefixes we use:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Exp.</th>
<th>prefix</th>
<th>exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>K(ilo)</td>
<td>$10^3$</td>
<td>m(illi)</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>M(ega)</td>
<td>$10^6$</td>
<td>μ(micro)</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>G(iga)</td>
<td>$10^9$</td>
<td>n(ano)</td>
<td>$10^{-9}$</td>
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</table>

- Use powers of 10 for rates, 2 for storage
  - 1 Mbps = 1,000,000 bps, 1 KB = $2^{10}$ bytes
- “B” is for bytes, “b” is for bits
Latency Examples

• “Dialup” with a telephone modem:
  – $D = 5 \text{ ms}$, $R = 56 \text{ kbps}$, $M = 1250 \text{ bytes}$

• Broadband cross-country link:
  – $D = 50 \text{ ms}$, $R = 10 \text{ Mbps}$, $M = 1250 \text{ bytes}$
Latency Examples (2)

- “Dialup” with a telephone modem:
  \[ D = 5 \text{ ms}, \quad R = 56 \text{ kbps}, \quad M = 1250 \text{ bytes} \]
  \[ L = 5 \text{ ms} + \frac{1250 \times 8}{56 \times 10^3} \text{ sec} = 184 \text{ ms}! \]

- Broadband cross-country link:
  \[ D = 50 \text{ ms}, \quad R = 10 \text{ Mbps}, \quad M = 1250 \text{ bytes} \]
  \[ L = 50 \text{ ms} + \frac{1250 \times 8}{10 \times 10^6} \text{ sec} = 51 \text{ ms} \]

- A long link or a slow rate means high latency
  - Often, one delay component dominates
Bandwidth-Delay Product

• Messages take space on the wire!

• The amount of data in flight is the bandwidth-delay (BD) product
  \[ BD = R \times D \]
  – Measure in bits, or in messages
  – Small for LANs, big for “long fat” pipes
Bandwidth-Delay Example

- Fiber at home, cross-country
  R=40 Mbps, D=50 ms
Bandwidth-Delay Example (2)

- Fiber at home, cross-country
  \[ R = 40 \text{ Mbps}, \ D = 50 \text{ ms} \]
  \[ \text{BD} = 40 \times 10^6 \times 50 \times 10^{-3} \text{ bits} = 2000 \text{ Kbit} = 250 \text{ KB} \]

- That’s quite a lot of data “in the network”!
Types of Media

- **Media** propagate **signals** that carry **bits** of information
- We’ll look at some common types:
  - Wires »
  - Fiber (fiber optic cables) »
  - Wireless »
Wires – Twisted Pair

- Very common; used in LANs and telephone lines
  - Twists reduce radiated signal

Category 5 UTP cable with four twisted pairs
Wires – Coaxial Cable

• Also common. Better shielding for better performance

• Other kinds of wires too: e.g., electrical power (§2.2.4)
Fiber

- Long, thin, pure strands of glass
  - Enormous bandwidth (high speed) over long distances

![Diagram of optical fiber with light source, optical fiber, and photo-detector]

- Light source (LED, laser)
- Light trapped by total internal reflection
- Photo-detector
Fiber (2)

- Two varieties: multi-mode (shorter links, cheaper) and single-mode (up to \(~100\) km)
Wireless

- Sender radiates signal over a region
  - In many directions, unlike a wire, to potentially many receivers
  - Nearby signals (same freq.) interfere at a receiver; need to coordinate use
UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

WiFi

WiFi

WiFi
Wireless (2)

- Microwave, e.g., 3G, and unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking.
Topic

- Analog signals encode digital bits. We want to know what happens as signals propagate over media.
A signal over time can be represented by its frequency components (called Fourier analysis)

\[ g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n ft) + \sum_{n=1}^{\infty} b_n \cos(2\pi n ft) \]

Frequency Representation
Effect of Less Bandwidth

- Fewer frequencies (=less bandwidth) degrades signal
Signals over a Wire

What happens to a signal as it passes over a wire?

1. The signal is delayed (propagates at $\frac{2}{3}c$)
2. The signal is attenuated (goes for m to km)
3. Frequencies above a cutoff are highly attenuated
4. Noise is added to the signal (later, causes errors)

EE: Bandwidth = width of frequency band, measured in Hz
CS: Bandwidth = information carrying capacity, in bits/sec
Signals over a Wire (2)

• Example:

2: Attenuation:

3: Bandwidth:

4: Noise:
Signals over Fiber

- Light propagates with very low loss in three very wide frequency bands
  - Use a carrier to send information

![Attenuation vs Wavelength](image-url)
Signals over Wireless

- Signals transmitted on a carrier frequency, like fiber (more later)
Signals over Wireless (2)

• Travel at speed of light, spread out and attenuate faster than $1/\text{dist}^2$
Signals over Wireless (3)

- Multiple signals on the same frequency interfere at a receiver
Signals over Wireless (4)

- Interference leads to notion of **spatial reuse** (of same freq.)
Signals over Wireless (5)

• Various other effects too!
  – Wireless propagation is complex, depends on environment

• Some key effects are highly frequency dependent,
  – E.g., multipath at microwave frequencies
Wireless Multipath

- Signals bounce off objects and take multiple paths
  - Some frequencies attenuated at receiver, varies with location
  - Messes up signal; handled with sophisticated methods (§2.5.3)