Introduction to Computer Networks

Overview of the Physical Layer
Where we are in the Course

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

<table>
<thead>
<tr>
<th>Application</th>
<th>Transport</th>
<th>Network</th>
<th>Link</th>
<th>Physical</th>
</tr>
</thead>
</table>
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 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
    
    \[ P\text{-delay} = \frac{\text{Length}}{\text{speed of signals}} = \frac{L}{\frac{2}{3}c} = D \text{ seconds} \]

- Combining the two terms we have: \( \text{Latency} = \frac{M}{R} + D \)
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>
</tr>
</tbody>
</table>

• Use powers of 10 for rates, 2 for storage
  – 1 Mbps = 1,000,000 bps, 1 KB = 1024 bytes
• “B” is for bytes, “b” is for bits
Latency Examples

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

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

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

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

- 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**
  - 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=50ms
  BD = 40 x 50 x 10^3 bits
  = 250 KB

• That’s quite a lot of data
  the network”!

• Question: What is the implication of a
  high BDP?

1101010000101110101001011

“in
Announcements

- Homework 1 due today
- Project 0 released today
  - Due in 11 days
- Focuses on socket programming
- Looking forward:
  - Project 1: HTTP proxy
  - Project Tor461: Implement Tor
Project 0

• Use Datagrams (UDP) to implement the POP protocol
• Client-server programming
• Client sends:
  – Hello message
  – Data message(s) with sequence numbers
  – Closes connection
• Server:
  – Maintains state regarding the client
  – Sends response messages to received data
Project 0

• Two programming styles:
  – Thread based programming
  – Event based single-thread programming

• Goal: provide an understanding of the different models
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
Fiber

- Long, thin, pure strands of glass
  - Enormous bandwidth over long distances

![Diagram of fiber optic communication](image)

- 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

RADIO SERVICES COLOR LEGEND

WiFi

ACTIVITY CODE:

GOVERNMENT MILITARY
GOVERNMENT NONMILITARY

ALLOCATION USAGE DESIGNATION

GOVERNMENT MILITARY
GOVERNMENT NONMILITARY

CSE 461 University of Washington
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.
Frequency Representation

- A signal over time can be represented by its frequency components (called Fourier analysis)

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

Signal over time

weights of harmonic frequencies

amplitude
Effect of Less Bandwidth

- Less bandwidth degrades signal (less rapid transitions)
Signals over a Wire

- What happens to a signal as it passes over a wire?
  - The signal is delayed (propagates at \( \frac{2}{3}c \))
  - The signal is attenuated (goes for m to km)
  - Noise is added to the signal (later, causes errors)
  - Frequencies above a cutoff are highly attenuated

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

• Example:

1: Attenuation:

Sent signal

2: Bandwidth:

3: Noise:
Signals over Fiber

- Light propagates with very low loss in three very wide frequency bands
  - Use a carrier to send information
Signals over Wireless (§2.2)

- Signals transmitted on a carrier frequency
- Travel at speed of light, spread out and attenuate faster than $1/\text{dist}^2$
- Multiple signals on the same frequency interfere at a receiver
- Other 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)
Topic

• We’ve talked about signals representing bits. How, exactly?
  – This is the topic of modulation
A Simple Modulation

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)

<table>
<thead>
<tr>
<th>Bits</th>
<th>0 0 1 0 1 1 1 1 0 1 0 0 0 0 1 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ</td>
<td>+V</td>
</tr>
<tr>
<td></td>
<td>-V</td>
</tr>
</tbody>
</table>

CSE 461 University of Washington
A Simple Modulation (2)

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)
Many Other Schemes

• Can use more signal levels, e.g., 4 levels is 2 bits per symbol

• Practical schemes are driven by engineering considerations
  – E.g., clock recovery »
Clock Recovery

• Um, how many zeros was that?
  – Receiver needs frequent signal transitions to decode bits
  
  1 0 0 0 0 0 0 0 0 0 0 … 0

• Several possible designs
  – E.g., Manchester coding and scrambling (§2.5.1)
Clock Recovery – 4B/5B

- Map every 4 data bits into 5 code bits with a transition that are sent
  - 0000 $\rightarrow$ 11110, 0001 $\rightarrow$ 01001,
    1110 $\rightarrow$ 11100, ... 1111 $\rightarrow$ 11101
  - Has at most 3 zeros in a row
Clock Recovery – 4B/5B (2)

- 4B/5B code for reference:
  - 0000→11110, 0001→01001, 1110→11100, ... 1111→11101

- Message bits: 1 1 1 1 0 0 0 0 0 0 1

Coded Bits:

Signal:
Passband Modulation

- What we have seen so far is **baseband** modulation for wires
  - Signal is sent directly on a wire
- These signals do not propagate well on fiber/wireless
  - Need to send at higher frequencies
- **Passband** modulation carries a signal by modulating a carrier
Passband Modulation (2)

- Carrier is simply a signal oscillating at a desired frequency:

- We can modulate it by changing:
  - Amplitude, frequency, or phase
Passband Modulation (3)

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying
Introduction to Computer Networks

Fundamental Limits (§2.2)

Computer Science & Engineering
UNIVERSITY of WASHINGTON
Topic

• How rapidly can we send information over a link?
  – Nyquist limit (~1924)
  – Shannon capacity (1948)

• Practical systems are devised to approach these limits
Key Channel Properties

• The bandwidth (B), signal strength (S), and noise strength (N)
  – B limits the rate of transitions
  – S and N limit how many signal levels we can distinguish
Nyquist Limit

• The maximum symbol rate is $2B$

  \[ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \ \]

• Thus if there are $V$ signal levels, ignoring noise, the maximum bit rate is:

  \[ R = 2B \log_2 V \text{ bits/sec} \]
Claude Shannon (1916-2001)

• Father of information theory
  – “A Mathematical Theory of Communication”, 1948
• Fundamental contributions to digital computers, security, and communications

Electromechanical mouse that “solves” mazes!

Credit: Courtesy MIT Museum
Shannon Limit

• How many levels we can distinguish depends on S/N
  – Or SNR, the Signal-to-Noise Ratio
  – Note noise is random, hence some errors

• SNR given on a log-scale in deciBels:
  – $\text{SNR}_\text{dB} = 10\log_{10}(S/N)$
Shannon Limit (2)

• Shannon limit is for capacity (C), the maximum information carrying rate of the channel:

\[
C = B \log_2(1 + S/N) \text{ bits/sec}
\]
Putting it all together – DSL

• DSL (Digital Subscriber Line, see §2.6.3) is widely used for broadband; many variants offer 10s of Mbps
  – Reuses twisted pair telephone line to the home; it has up to ~2 MHz of bandwidth but uses only the lowest ~4 kHz
**DSL (2)**

- DSL uses passband modulation
  - Separate bands for upstream and downstream (larger)
  - Modulation called QAM varies both amplitude and phase
  - High SNR, up to 15 bits/symbol, low SNR only 1 bit/symbol

<table>
<thead>
<tr>
<th>Basic ADSL</th>
<th>Voice (0-4 kHz)</th>
<th>Up to 1 Mbps  (26 – 138 kHz)</th>
<th>Up to 8 Mbps (Up to 1104 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telephone</td>
<td></td>
<td>Upstream</td>
<td>Downstream</td>
</tr>
<tr>
<td>Freq.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Wired/Wireless Perspective

- **Wires, and Fiber**
  - Engineer link to have requisite SNR and B
  - Can fix data rate

- **Wireless**
  - Given B, but SNR varies greatly, e.g., up to 60 dB!
  - Can’t design for worst case, must adapt data rate
Wired/Wireless Perspective (2)

- **Wires, and Fiber**
  - Engineer link to have requisite SNR and B
  - Can fix data rate

- **Wireless**
  - Given B, but SNR varies greatly, e.g., up to 60 dB!
  - Can’t design for worst case, must adapt data rate