CS455: Computer Networks

Data Communications Link Technology
Transmission Media and Coding
(Physical Layer)

These slides were written by Dr. Mark Pullen with updates and changes by Dr. Charles Snow, both of George Mason University. Students registered in Computer Science networking courses at GMU may make a single machine-readable copy and print a single copy of each slide for their own reference, so long as each slide contains the copyright statement, and GMU facilities are not used to produce paper copies. Permission for any other use, either in machine-readable or printed form, must be obtained from the authors in writing.

Class 2
16:30 to 19:10
28 Jan 2004

CS455: Computer Networks

Data Representation

- binary numbers (integers)
  - each bit represents a power of 2
  - start with $2^0$ at right: e.g., $10011_2 = 2^4 + 2^1 + 2^0 = 19_{10}$
- One byte (a.k.a. an “octet”) = 8 bits
  - allows 256 distinct values

OSI 7-layer Reference Model

- Today we look at the physical layer

Data Representation

- binary values: 0/1, off/on, true/false

- codes: specific sequences of binary digits (bits) represent symbols, e.g.,
  
  'A' = 1000001
  
  in American Standard Code for Information Interchange (ASCII)

- how many bits do you need for text?

Transmission Basics

- bits are state values on the transmission medium
  - the medium is sampled over time
  - exist for some detectable time

- the state value may be
  - electrical charge (flow of charge = current)
  - presence/absence of photons in a fiber

- number of samples of medium per second is measured in baud
  - e.g., 1000 samples per second = 1000 baud

ASCII

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<td>DEL</td>
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</tbody>
</table>
Data Transmission Units

- Information Rate (a.k.a., data rate, bit rate)
  - bits/second or bps
  - bytes/second = \( \frac{\text{bits/sec}}{8} \)

Signaling rate: baud = samples / second
- e.g., with 4 bits/sample, 2400 baud = 9600 bps

Analog vs. Digital Signals
- analog signals change continuously:
  - digital signals take on discrete values:

Analog Signal Characteristics

- \[ S(t) = A \sin(2\pi ft + \phi) \]
- \( A \) is amplitude
- \( P \) is period (time per cycle)
- \( f \) is frequency in cycles/second or Hertz (\( f = 1 / P \))
- \( \phi \) is phase angle in degrees (or radians)
- \( \lambda \) is wavelength \( \lambda = \frac{v}{f} \)  
  - e.g., \( f = 3000 \text{ Hz}, \lambda = \frac{(3 \times 10^8)}{(3 \times 10^3)} = 10^5 \text{ m} \)

Analog Signal Characteristics
- may have offset: DC component

Analog Signal Characteristics
- may have more than 1 sine wave
  - frequencies may be multiples of each other
  - \( f_0 \) is fundamental frequency; multiples are harmonics
Analog Signal Characteristics

- signals can have different phase angles from one another

Signal Power
- e.g., if $S(t)$ is a voltage, $P = \frac{A^2}{2Z}$
- where $Z$ is a characteristic of load called impedance.
- power is measured in watts

Fourier Analysis

- consider a periodic function $g(t)$.
  - $f_0$ is fundamental frequency of periodic change,
  - $d$ is the DC component (may be 0)
  - $g(t)$ can be described to any level of accuracy by a Fourier Series
    $$g(t) = d + \sum_{n=1}^{\infty} a_n \sin \left( \frac{2\pi f_0 t}{180} \right)$$
- how many terms of the series do you need?
  - as $n$ grows, $a_n$ values become small
  - generally use only a few terms to obtain satisfactory approximation

Bandwidth: Analog Channel Capacity

- to communicate, the signal must go from sender to receiver across some medium
- what can we get the signal to do so as to communicate the message?

Bandwidth: Analog Channel Capacity

- to communicate, the signal must go from sender to receiver across some medium
- what can we get the signal to do so as to communicate the message?
- if signal is DC? (i.e., same voltage at all times)
**Bandwidth: Analog Channel Capacity**

- A signal that changes value over time is an AC (alternating current) signal.

- **Information capacity**, $C$, of a signal is related to range of frequencies in the signal.

- That range of frequencies is signal's bandwidth $W = f_H - f_L$.
  - e.g., a signal contains frequencies from 1000 to 5000 Hz: $W = 5000 - 1000 = 4000$ Hz ($4$ kHz).

- If $f_H \gg f_L$, $W$ is approximated by $f_H$.
  - e.g., 20 - 20,000 Hz means bandwidth of $\approx 20$ kHz.

**Spectrum**

- The 'spread' of frequency values in a signal is the spectrum of the signal.

- A signal has $f_L = 2$ MHz, $f_H = 10$ MHz:
  - its bandwidth is 8 MHz.
  - its spectrum is 2 MHz to 10 MHz.

- Range of frequencies used in signals covers wide range:
  - From DC.
  - To $10^{15}$ Hz (today, anyway).

**About Units**

- Commonly used (metric) prefixes for frequencies and wavelengths:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>1,000,000,000</td>
<td>Tera</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>1,000,000</td>
<td>Giga</td>
<td>$10^{9}$</td>
</tr>
<tr>
<td>1,000</td>
<td>Mega</td>
<td>$10^{6}$</td>
</tr>
<tr>
<td>1,000</td>
<td>Kilo</td>
<td>$10^{3}$</td>
</tr>
<tr>
<td>.001</td>
<td>Milli</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>.000 001</td>
<td>Micro</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>.000 000 001</td>
<td>Nano</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

- Remember! 'Kilo' here is 1000 not 1024; all these prefixes are true powers of 10.

**Human Voice**

- **Bandwidth of Human Voice**
  - Human voice spectrum = 100 to 7000 Hz.
  - Older telephone systems pass frequencies between 300 and 3300 Hz.
  - $\Rightarrow$ Bandwidth is?
  - This bandwidth is sufficient for clearly understood human speech.
  - But lose high-frequency friction (e.g., 'f', 's').
  - High fidelity audio systems reproduce range of human hearing, 20 to 20000 Hz (in young people).
Channel Noise

- all channels have noise
- major categories of noise:
  - thermal: evenly distributed across all frequencies (white noise): function of temperature (agitated electrons)
  - intermodulation (IM): artifacts from multiple frequencies sharing transmission medium (+, −, ×)
  - crosstalk (xtalk): artifacts from other, ‘nearby’ signals
  - impulse: bursty, irregular, non-continuous, short duration

Shannon’s Law Example

- suppose, for a channel:
  - signal power = 1024 × noise power (on average)
  - W = 10 kHz
- what is maximum channel capacity?
  \[ C = W \log_2 (1 + \frac{S}{N}) \text{ bps} \]

What Noise Can Do

Figure 3.13 from Data & Computer Communications, Stallings © 2000, 1996 Prentice-Hall Inc.

Relating Digital and Analog Signals: Shannon’s Law

- maximum channel capacity given by Shannon’s Law:
  \[ C = W \log_2 (1 + \frac{S}{N}) \text{ bps} \]
  where:
  - S is signal power,
  - N is noise power,
  - W is bandwidth
- in practice, very good channels can support a few bps per Hz:
  - e.g., a high-quality voice-grade line handles 33.6 kbps with W = 4 kHz
- note: \[ \log_b x = \left( \frac{\log_{10} x}{\log_{10} b} \right) \]

SNR

- Shannon’s Law uses ratio of signal power to noise power
- generally, the signal to noise ratio (SNR) is:
  \[ \text{SNR}_{\text{dB}} = 10 \log_{10} \left( \frac{\text{signal power}}{\text{noise power}} \right) \]
  in units called decibels (dB).
Transmission Media: Twisted Pair

- telephone signals have been transmitted over wire pairs for many years
- two wires allow a closed circuit path
- twisting wires with right number of twists-per-meter reduces sensitivity to noise (especially xtalk)
- pairs often used in "balanced mode" where signal phase, φ on one wire is the inverse of that on the other
  - receiver inverts again; what does this achieve?

Transmission Media: Twisted Pair

- to be used for digital data, twisted pair wiring should be category 3 or category 5 ("CAT3" or "CAT5")
  - both have 4 pairs of wires grouped into 1 plastic sleeve
  - CAT5 has more twists per unit length than CAT3
  - CAT5 has better insulation than CAT3
  - sometimes called UTP: unshielded twisted pair
- 10 Mbps Ethernet uses 2 pairs
- 100 Mbps Ethernet uses all 4 pairs simultaneously

Transmission Media: Twisted Pair

- cancellation of electrical noise picked up along wire

 Transmission Media: Coaxial Cable

- coaxial cable (coax) consists of:
  - a central conductor
  - surrounded by an insulating layer
  - surrounded by a braided shield; the shield gives good immunity to noise (xtalk, external noise; much better than TP)
  - surrounded by insulating sleeve
  - familiar example: cable TV

Transmission Media: Coaxial Cable

- data rates up to 500 Mbps at distances ≤ 2 miles (= 3 km)
- beyond that distance need amplification: use repeater
- "baseband" mode carries signal in digital form
- "broadband" mode, such as cable TV, carried multiple channels but requires more complex receiver

Transmission Media: Twisted Pair

- twisted pairs can be used with digital signals
- distance varies with signaling rate:
  - 10 Mbps ↔ 300 ft (= 90 m)
  - 10 Mbps: recently announced up to 1500 feet (= 455 m)
  - 1.5 Mbps ↔ about 3 miles/5 km
  - 9.6 kbps at 10 miles (= 15 km)
- recent building construction practice has been to install several twisted pairs to each work area
  - terminate in a "wiring closet" for ease of connection
  - connect to network equipment in closet, fiber backbones, etc.
### Transmission Media: Optical Fiber

- **optical fiber** is a fine strand of ultra-clear silicon (like glass) that transmits light
- a bit is a pulse of light
- optical fiber is immune to noise that is normally present in wire conductors due to stray EM fields
- light-emitting diodes (LEDs) or lasers create light pulses passed through the fiber
- fiber normally enclosed in protective jacket, often in bundles
  - fiber relatively cheap, so save$ to install many at once

### Transmission Media: Microwave Radio

- radio operating at frequencies in GHz range can pass digital signals in range of 200 – 300 Mbps, or more
- digital microwave was developed to carry many voice channels simultaneously (but can also be used for digital data)

### Transmission Media: Optical Fiber

- works by *total internal reflection* of light at outside edge of medium
- comes in two major forms:
  - multimode
  - single mode
  - see figures 2.7 to 2.9 in Shay

### Transmission Media: Microwave Radio

- at microwave frequencies, radio is limited to *line of sight*
  - obstacles block transmission
  - how big do obstacles have to be? (consider $\lambda$)
- microwave is typically limited to ~ 20 miles (~ 33 km) due to curvature of the earth

### Transmission Media: Communications Satellites

- a satellite orbiting at altitude ~ 22,300 miles (~ 36,000 km) revolves around the earth at same rate as earth rotates
- if satellite orbits over equator at that altitude, it will be stationary with respect to earth surface: called “geosynchronous” or “geostationary”
Transmission Media: Communications Satellites

- A communications satellite typically has multiple transponders on board (digital microwave receiver/transmitter).
- A typical transponder handles ≥ 3 Mbps; rate improves with bandwidth increases in transponder (but noise vulnerability increases along with it).

Transmission Media: Undersea Cable

- First optical fiber cable 1988 (coax wire before); first “all optical” in 1996.
- Current std like STM-16: 2.5 Gbps per wavelength x 4 - 8 λ per fiber pair.
- Can go up to 400 km without repeater.
- New York ↔ London: 5,600 km
- Tokyo ↔ Seattle: 7,800 km.
- Lay, by special ship, up to 15 km/hr at 7 km depth.
- Not always sure where cable ends up.

Transmission Media: Communications Satellites

- Satellite earth stations expensive because:
  - Need to transmit high power.
  - Receive low power.
- Frequency bands for satellite transponders are letter coded:
  - C-band: ≈ 4 to 6 GHz (7.5 cm to 5.0 cm).
  - Ku-band: ≈ 12 to 14 GHz (2.5 cm to 2.14 cm).
- Ku-band transmissions may be affected by heavy rain; need more power at earth station in ‘rainy’ areas.

Transmission Media: Undersea Cable

- No longer do point-to-point; usually do as looped, e.g.,
- Size of dish antenna depends on band:
  - Can be as much as 10 m diameter.
  - Smaller antenna for a given band → need more power at satellite → leasing transponder more $$.
- Very Small Aperture Terminal (VSAT) are ∼ 2 m across:
  - Easy to mount on roof (or on ground).
- Receive-only antennas of 18” to 24” (∼ 45 – 60 cm) diameter used for receiving TV broadcasts.
Transmission Media: Undersea Cable

- need repeaters for long runs
- currently, repeaters are pure-optical: no signal conversions
- repeaters need electrical power (~ 40 V per repeater)
  - so typical 7500 km cable requires ~ 10,000 Volts
- built to run 25 years without repair at depths of down to 7000 m
- deeper is better: 20% of all repairs are in deep ocean
  - 1 repair/3 yrs in North Atlantic
  - 1 repair/5 wks in North Sea

Transmission Media: Wireless Systems

- infrared (IR) is line-of-sight (but bounces), allows great mobility in limited area; see, e.g., http://www.irda.org
- radio frequency (RF) signals good for several hundred feet, can pass through walls
  - eliminates need to install wires
  - can use “spread spectrum” technique that limits power in any one band; thus doesn’t interfere with existing radio systems
  - if popularity increases, users could start to interfere with each other, as with cordless phones

Transmission Media: Undersea Cable

- transmission media (particularly wires) have a loss in signal intensity called attenuation that is proportional to distance
- normally, compensate for attenuated signal by amplifying at intervals along link
  - what else gets amplified at these intervals?
- calculations involving attenuation and amplification in an upcoming class

Link Performance: Attenuation

- to find time needed to transmit a unit of information \( i \), divide by link capacity, \( C \):
  \[ t = \frac{i}{C} \]
  - e.g., to xmit a floppy (1.44 Mb) over a 19.2 kbps link:
    \[ t = \frac{1.44 \times 10^2}{19.2 \times 10^3} = 629 \text{ seconds} \]
- this figure holds if we disregard:
  - errors
  - synchronization overhead
  - flow control
- what determines how fast bits move?

Link Performance: Transmission Time

- in a vacuum, EM energy travels at speed of light, \( c \).
- light travels more slowly in glass, electrical signals travel more slowly in wire
  - reasonable estimate: ~30% slower: 130,000 miles/s (2.1 \times 10^8 m/sec)
- propagation delay:
  \[ D = \frac{\text{distance}}{V_{\text{medium}}} \]
  \[ D = \frac{130,000}{2.1 \times 10^8} \text{ m} = \frac{\text{distance in miles}}{2.1 \times 10^8} \text{ m/sec} \]
Link Performance: Propagation Delay

- propagation delay is most significant in satellite links:
  - one-hop delay is: \((2 \times 22,300) / 186,000 = 0.24\) seconds
- round-trip delay is double, nearly \(1/2\) second

Synchronous Transmission: Framing

- in synchronous transmission, sender must provide full block of information to be sent at once, together
- each such block is called a **frame** and is identified by a beginning and ending **flag**: a special "framing" character
- a commonly used flag is \(01111110\) (0x7E)
- on flag detection, receiver "syncs up" with the frame and begins receiving bits, continuing until next flag is seen
- in this way, synchronization occurs in every frame, not every character: overhead once per frame, not per byte
- but what if 0x7E is part of the message to be sent?

Link Performance: Synchronization

- data moves fastest if each character follows another, with no space between, as a stream
- such transmission is called "**synchronous**"
- synchronous transmission requires special equipment because sender and receiver must have precise timing relationship, a "**clock**"
- for high-capacity leased circuits a good solution often is to let the company providing the circuit provide the clock or timing pulses

Synchronous Transmission: Framing

- the flag pattern must not appear in the frame data, else receiver detects premature end of frame
- to prevent flag being seen where not intended (i.e., within frame data), transmitter **stuff**s in extra bits as needed
  - requires receiver to detect & remove (unstuff) the extra bits

Link Performance: Synchronization

- on lower-cost and lower-capacity circuits, clock is discarded in favour of "start" and "stop" bits that a receiver can use to generate its own synchronizing pulses
- this is called "**asynchronous**" transmission

Synchronous Transmission: Framing

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<th><strong>Sender:</strong></th>
<th><strong>Receiver:</strong></th>
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<tbody>
<tr>
<td>transmits an opening flag</td>
<td>detects and discards opening flag</td>
</tr>
<tr>
<td>begins xmit of frame data</td>
<td>begins receiving data bits</td>
</tr>
<tr>
<td>if have 5 consecutive 1-bits, <strong>stuff</strong> in extra 0 bit</td>
<td>remove every 0-bit following 5 consecutive 1-bits</td>
</tr>
<tr>
<td>when done frame, send closing flag</td>
<td>detect closing flag, stop receiving data bits</td>
</tr>
</tbody>
</table>
Bit Stuffing/Unstuffing Example

original data frame

transmitted data frame

received data frame

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Leased Lines

- at speeds of ≥ 56 kbps, a "CSU/DSU" is used in place of a modem because interface is digital, not analog
- some acronyms:
  - user equipment is DTE (data terminal equipment)
  - modem or CSU/DSU (channel/digital service unit) is DCE (data circuit terminating equipment)

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Link Performance: Duplexity

- data flows: only one, one-at-a-time, or both directions simultaneously
  - A  simplex  B
  - A  half duplex  B
  - A  full duplex  B
- can be achieved using two wire pairs or fibers, or by assigning different frequency bands to "send" and "receive"

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Homework

1. Do the following exercises:
   - Graph the function \( S(t) = 6 \sin(800 \pi t + 0.125) \) volts. Make sure your graph has grid lines (use graph paper or draw your own grid), and remember to label the graph appropriately. What is the frequency of this function? what phase? State how is \( S(t) \) related to \( S_1(t) = 4 \sin(1200 \pi t - 0.375) \) (don't draw \( S_1(t) \))?
   - A channel has intended capacity of 30 Mb/s. The bandwidth of the channel is 10 MHz. When no signal is present, the noise is 60 milliwatts. What signal power is required in order to achieve this capacity?
   - Given an audio CD with a total playing time of 42:38, how long will it take to transmit the digital audio data over a perfect 56 kbps link? Note that audio CD's have 44,100 16-bit integers per channel per second of data.
   - Depict the transmitted frame, including opening and closing flags and stuffed bits, for the following message (first bit to send is rightmost):

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Leased Lines

- company providing service is called the carrier
  - not to be confused with unmodulated signal in analog circuit of same name
- switched or "dial-up" lines require signaling for call setup
- leased lines generally have fewer errors
- high-capacity ("high speed") leased lines are inherently digital

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Project DLC1

- Purpose: understand how bit stuffing/unstuffing works by programming them using NW
- see UIP Chapter 3: “Data-Link Control: Framing”
Project DLC1

• Assignment:
  • create bit stuffing/unstuffing routines. There is a stub function in code/stuff.cpp with correct interfaces.
  • test your routines in NW using dlc1.cpp
  • document your code with adequate and suitable comments
  • submit your results to TA using facilities in NEW see http://netlab.gmu.edu/NEW