

CSC458 - Lecture 2

Bits and Bandwidth Error Detection and Correction

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<http://www.cs.toronto.edu/syslab/courses/csc458>

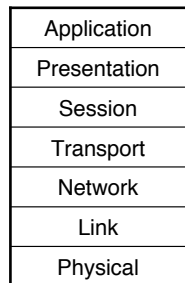
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Administrivia

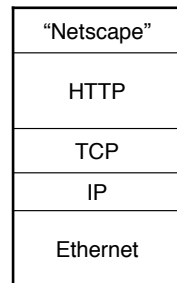
- Project 1 is due in one week (Monday Jan 23)
 - If you have trouble finding a teammate, come talk to me *today*
- Homework 1 is due in two weeks (Monday Jan 30)

Last Time ...

- Protocols, layering and reference models



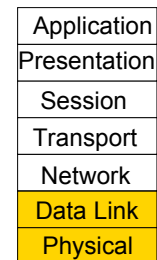
The OSI Model



Sample Protocol Stack

Part 1

- Focus: How do we send a message across a wire?
- The physical / link layers:
 1. Different kinds of media
 2. Encoding bits, messages
 3. Model of a link

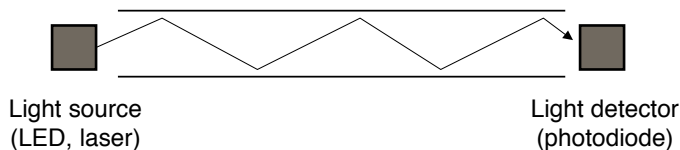


1. Different kinds of media

- Wire
 - Twisted pair, e.g., CAT5 UTP, 10 → 100Mbps, 100m
 - Coaxial cable, e.g., thin-net, 10 → 100Mbps, 200m
- Fiber
 - Multi-mode, 100Mbps, 2km
 - Single mode, 100 → 2400 Mbps, 40km
- Wireless
 - Infra-red, e.g., IRDA, ~1Mbps
 - RF, e.g., 802.11 wireless LANs, Bluetooth (2.4GHz)
 - Microwave, satellite, cell phones, ...

Fiber

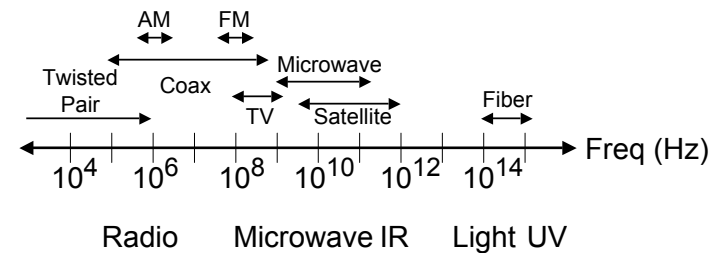
- Long, thin, pure strand of glass
 - light propagated with total internal reflection
 - enormous bandwidth available (terabits)



- Multi-mode allows many different paths, limited by dispersion
- Chromatic dispersion if multiple frequencies

Wireless

- Different frequencies have different properties
- Signals subject to atmospheric/environmental effects



Aside: bandwidth of a channel

- EE: bandwidth (B, in Hz) is the width of the pass-band in the frequency domain
- CS: bandwidth (bps) is the information carrying capacity (C) of the channel
- Shannon showed how they are related by noise
 - noise limits how many signal levels we can safely distinguish
 - geekspeak: “cannot distinguish the signal from the noise”

2. Encoding Bits with Signals

- Generate analog waveform (e.g., voltage) from digital data at transmitter and sample to recover at receiver



- We send/recover symbols that are mapped to bits
 - Signal transition rate = baud rate, versus bit rate
- This is baseband transmission ...

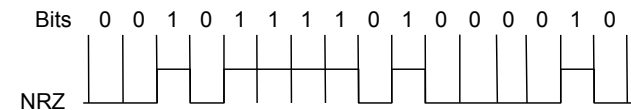
Clock Recovery

- Problem: How do we distinguish consecutive 0s or 1s?
- If we sample at the wrong time we get garbage ...
- If sender and receiver have exact clocks no problem
 - But in practice they drift slowly
- This is the problem of clock recovery

- Possible solutions:
 - Send separate clock signal → expensive
 - Keep messages short → limits data rate
 - Embed clock signal in data signal → other codes

NRZ and NRZI

- Simplest encoding, NRZ (Non-return to zero)
 - Use high/low voltages, e.g., high = 1, low = 0
- Variation, NRZI (NRZ, invert on 1)
 - Use transition for 1s, no transition for 0s



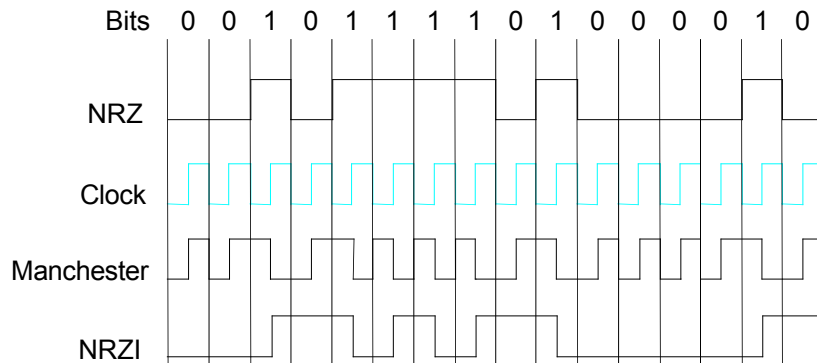
Manchester Coding

- Make transition in the middle of every bit period
 - Low-to-high is 0; high-to-low is 1
 - Signal rate is twice the bit rate
 - Used on 10 Mbps Ethernet

- Advantage: self-clocking
 - clock is embedded in signal, and we re-sync with a phase-locked loop every bit

- Disadvantage: 50% efficiency

Coding Examples



3. Framing

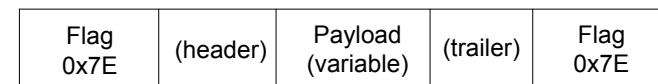
- Need to send message, not just bits
 - Requires that we synchronize on the start of message reception at the far end of the link
 - Complete Link layer messages are called frames
- Common approach: Sentinels
 - Look for special control code that marks start of frame
 - And escape or “stuff” this code within the data region

4B/5B Codes

- We want transitions *and* efficiency ...
- Solution: map data bits (which may lack transitions) into code bits (which are guaranteed to have them)
- 4B/5B code:
 - 0000 → 11110, 0001 → 01001, ... 1111 → 11101
 - Never more than three consecutive 0s back-to-back
 - 80% efficiency
- This code is in LANs such as FDDI, 100Mbps Ethernet

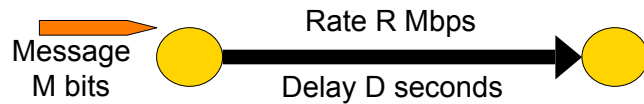
Example: Point-to-Point Protocol (PPP)

- IETF standard, used for dialup and leased lines



- Flag is special and indicates start/end of frame
- Occurrences of flag inside payload must be “stuffed”
 - Replace 0x7E with 0x7D, 0x5E
 - Replace 0x7D with 0x7D, 0x5D

4. Model of a Link



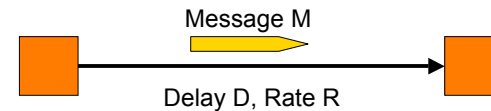
- Abstract model is typically all we will need
 - What goes in comes out altered by the model
- Other parameters that are important:
 - The kind and frequency of errors
 - Whether the media is broadcast or not

Relationships

- Latency = Propagation + Transmit + Queue
- Propagation Delay = Distance/SpeedOfLight
- Transmit Time = MessageSize/Bandwidth

Message Latency

- How long does it take to send a message?



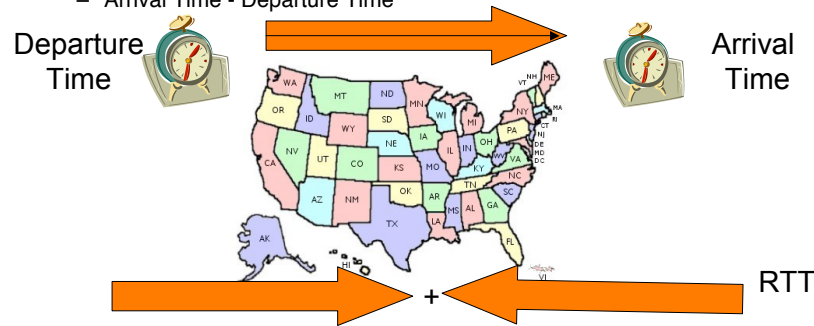
- Two terms:
 - Propagation delay = distance / speed of light in media
 - How quickly a message travels over the wire
 - Transmission delay = message (bits) / rate (bps)
 - How quickly you can inject the message onto the wire
- Later we will see queuing delay ...

One-way Latency

- Dialup with a modem:
 - $D = 10\text{ms}$, $R = 56\text{Kbps}$, $M = 1000$ bytes
 - Latency = $10\text{ms} + (1024 \times 8) / (56 \times 1024)$ sec = 153ms!
- Cross-country with T3 (45Mbps) line:
 - $D = 50\text{ms}$, $R = 45\text{Mbps}$, $M = 1000$ bytes
 - Latency = $50\text{ms} + (1024 \times 8) / (45 \times 1000000)$ sec = 50ms!
- Either a slow link or long wire makes for large latency

Latency and RTT

- Latency is typically the one way delay over a link
 - Arrival Time - Departure Time



- The round trip time (RTT) is twice the one way delay
 - Measure of how long to signal and get a response

Messages Occupy “Space” On the Wire

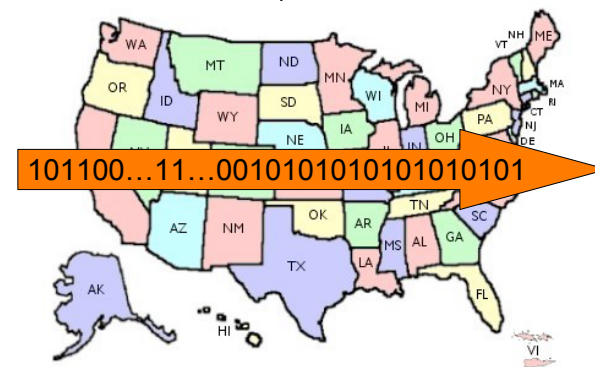
- Consider a 1b/s network.
 - How much space does 1 byte take?
- Suppose latency is 16 seconds.
 - How many bits can the network “store”
 - This is the BANDWIDTH-DELAY product
 - Measure of “data in flight.”
 - $1\text{b/s} * 16\text{s} = 16\text{b}$
- Tells us how much data can be sent before a receiver sees any of it.
 - Twice B.D. tells us how much data we could send before hearing back from the receiver something related to the first bit sent.
 - Implications?

Throughput

- Measure of system’s ability to “pump out” data
 - NOT the same as bandwidth
- Throughput = Transfer Size / Transfer Time
 - Eg, “I transferred 1000 bytes in 1 second on a 100Mb/s link”
 - BW?
 - Throughput?
- Transfer Time = SUM OF
 - Time to get started shipping the bits
 - Time to ship the bits
 - Time to get stopped shipping the bits

A More Realistic Example

$$BD = 50\text{ms} * 45\text{Mbps} = 2.25 * 10^6 = 280\text{KB}$$



Part 1: Key Concepts

- We typically model links in terms of bandwidth and delay, from which we can calculate message latency
- Different media have different properties that affect their performance as links
- We need to encode bits into signals so that we can recover them at the other end of the channel.
- Framing allows complete messages to be recovered at the far end of the link

Part 2

- Error detection and correction
- Focus: How do we detect and correct messages that are garbled during transmission?
- The responsibility for doing this cuts across the different layers

Application
Presentation
Session
Transport
Network
Data Link
Physical

Errors and Redundancy

- Noise can flip some of the bits we receive
 - We must be able to detect when this occurs!
 - Why?
 - Who needs to detect it? (links, routers, OSs, or apps?)
- Basic approach: add redundant data
 - Error detection codes allow errors to be recognized
 - Error correction codes allow errors to be repaired too

Motivating Example

- A simple error detection scheme:
 - Just send two copies. Differences imply errors.
- Question: Can we do any better?
 - With less overhead
 - Catch more kinds of errors
- Answer: Yes – stronger protection with fewer bits
 - But we can't catch all inadvertent errors, nor malicious ones
- We will look at basic block codes
 - K bits in, N bits out is a (N,K) code
 - Simple, memoryless mapping

Detection vs. Correction

- Two strategies to correct errors:
 - Detect and retransmit, or Automatic Repeat reQuest. (ARQ)
 - Error correcting codes, or Forward Error Correction (FEC)
- Satellites, real-time media tend to use error correction
- Retransmissions typically at higher levels (Network+)

- Question: Which should we choose?

The Hamming Distance

- Errors must not turn one valid codeword into another valid codeword, or we cannot detect/correct them.
- Hamming distance of a code is the smallest number of bit differences that turn any one codeword into another
 - e.g, code 000 for 0, 111 for 1, Hamming distance is 3
- For code with distance $d+1$:
 - d errors can be detected, e.g, 001, 010, 110, 101, 011
- For code with distance $2d+1$:
 - d errors can be corrected, e.g., 001 \rightarrow 000

Retransmissions vs. FEC

- The better option depends on the kind of errors and the cost of recovery
- Example: Message with 1000 bits, Prob(bit error) 0.001
 - Case 1: random errors
 - Case 2: bursts of 1000 errors
 - Case 3: real-time application (teleconference)

Parity

- Start with n bits and add another so that the total number of 1s is even (even parity)
 - e.g. 0110010 \rightarrow 01100101
 - Easy to compute as XOR of all input bits
- Will detect an odd number of bit errors
 - But not an even number
- Does not correct any errors

2D Parity

- Add parity row/column to array of bits
- Detects all 1, 2, 3 bit errors, and many errors with >3 bits.
- Corrects all 1 bit errors

		↓
	0101001	1
	1101001	0
	1011110	1
	0001110	1
	0110100	1
	1011111	0
→	1111011	0 ←
		↑

CRCs (Cyclic Redundancy Check)

- Stronger protection than checksums
 - Used widely in practice, e.g., Ethernet CRC-32
 - Implemented in hardware (XORs and shifts)
- Algorithm: Given n bits of data, generate a k bit check sequence that gives a combined n + k bits that are divisible by a chosen divisor C(x)
- Based on mathematics of finite fields
 - “numbers” correspond to polynomials, use modulo arithmetic
 - e.g, interpret 10011010 as $x^7 + x^4 + x^3 + x^1$

Checksums

- Used in Internet protocols (IP, ICMP, TCP, UDP)
- Basic Idea: Add up the data and send it along with sum
- Algorithm:
 - checksum is the 1s complement of the 1s complement sum of the data interpreted 16 bits at a time (for 16-bit TCP/UDP checksum)
- 1s complement: flip all bits to make number negative
 - Consequence: adding requires carryout to be added back

How is C(x) Chosen?

- Mathematical properties:
 - All 1-bit errors if non-zero x^k and x^0 terms
 - All 2-bit errors if C(x) has a factor with at least three terms
 - Any odd number of errors if C(x) has $(x + 1)$ as a factor
 - Any burst error < k bits
- There are standardized polynomials of different degrees that are known to catch many errors
 - Ethernet CRC-32: 100000100110000010001110110110111

Reed-Solomon / BCH Codes

- Developed to protect data on magnetic disks
- Used for CDs and cable modems too
- Property: $2t$ redundant bits can correct $\leq t$ errors
- Mathematics somewhat more involved ...

Part 2: Key Concepts

- Redundant bits are added to messages to protect against transmission errors.
- Two recovery strategies are retransmissions (ARQ) and error correcting codes (FEC)
- The Hamming distance tells us how much error can safely be tolerated.