CSE/EE 461 – Lecture 2

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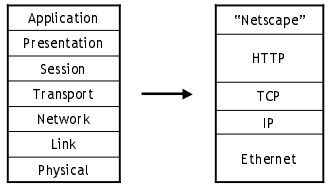
Last Time …

- We covered protocols, layering and reference models



The OSI Model Sample Protocol Stack

This Time

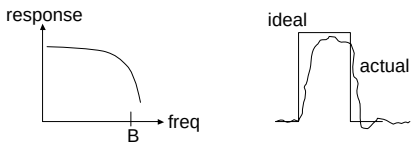
- A look at the physical/link layers:
  1. Media
  2. Limits to transmission
  3. Encoding bits/messages into signals
  4. Error detection and correction
- Key Focus:
  - How do we send a message across a wire?

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, …

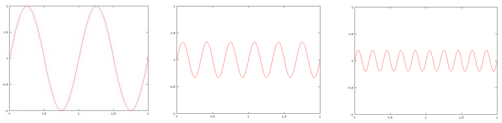
Wires

- Signal subject to:
  - Attenuation (repeaters)
  - Distortion (frequency and delay)
  - Noise (thermal, crosstalk, impulse)



Example: Square Wave

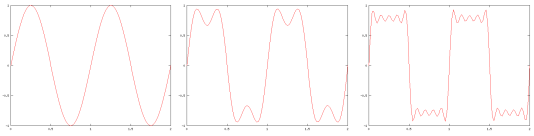
- Square wave can be decomposed into a sum of sines by a technique called Fourier analysis



sin(x) + sin(3x)/3 + sin(5x)/5 …

Example: Square Wave

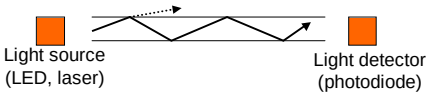
- Adding components back together gives successively better representations allowed by higher bandwidths



fundamental | 1st + 3rd harmonic | 5 terms ...

Fiber

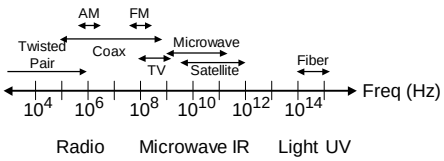
- Long, thin, pure strand of glass
  - Enormous bandwidth available (terabits)



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

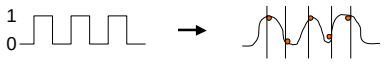
Wireless

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



Transmission of Digital Data

- Digital = discrete; Analog = continuous
- Generate analog waveform (e.g., voltage) from data at transmitter and sample to recover at receiver



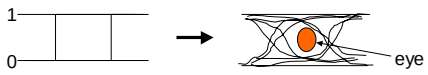
- We send/recover symbols that are mapped to bits (coming later)
  - Signal transition rate = baud rate, versus bit rate
- This is baseband transmission. Data modulated onto carriers for broadband transmission, e.g., AM/FM radio
- I've omitted "tons". Take a signals course!

2. Limits to Transmission

- How fast can we send bits down a wire?
  - Limited by bandwidth → Nyquist
  - Limited by noise → Shannon
- These are two fundamental results

Nyquist Limit (~1924)

- For a noiseless channel with bandwidth B
- Symbols will be distorted, and sending too fast leads to inter-symbol interference (ISI)



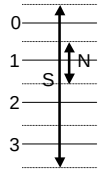
- The maximum rate at which it is possible to send is:

  R = 2B symbols/sec

  e.g., 3KHz → 6Ksym/sec

Taking Noise into Account

- Noise limits how many signal levels we can safely distinguish between
  - S = max signal amp., N = max noise amp.
- The number of bits per symbol depends on the number of signal levels
  - E.g, 4 levels implies 2 bits / symbol

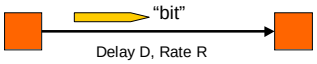


Shannon Limit (1948)

- Noise expressed as Signal to Noise Ratio (SNR)
  $SNR = 10\log_{10}(signal / noise)$ decibels (dB)
  - e.g, 30 dB means signal 1000 times as powerful as noise
- For a noisy channel with given SNR and bandwidth B, the maximum rate at which it is possible to send is:
  $C = B \log_2(1 + SNR)$ bits/sec
  e.g 3KHz and 30dB SNR → 30Kbps
- This is the information carrying capacity of the channel. Bandwidth is often a loosely used term.

A Note on Latency

- How long does it take to send a message?



- Two terms:
  - Propagation delay is a function(length of wire)
    - D = distance / speed of light in media
  - Transmission delay is a function(encoding, message length)
    - TX = message (bits) / rate (bps)
    - In effect, slow links stretch bits out in time/space
  - Later we will see queuing delay …

One-way Latency Examples

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

3. Encoding Bits

- How to represent bits as signals?
- We will look at two problems:
  - Clock recovery
    - When to sample the signal to recover bits
  - Framing
    - How to recognize the when a message starts

NRZ and NRZI

- Simplest scheme, 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
- (example following)

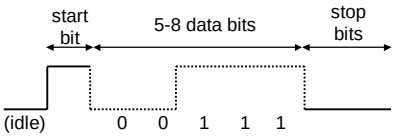
Clock Recovery

- 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

"Asynchronous" Transmission

- Avoid timing problem by sending short, delimited data
  - E.g., UARTs (typically used to connect your keyboard)



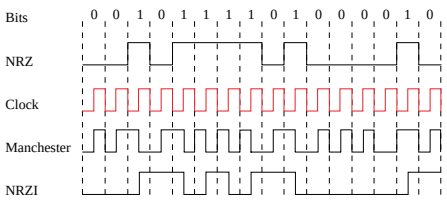
Manchester Coding

- 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

- (example following)

- Advantage: self-clocking
- Disadvantage: 50% efficiency

Coding Examples



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 used by LANs such as FDDI

Framing

- Need to send message, not just bits
  - Even if we know where the bits are we still need to synchronize on the start of the message
  - Complete Link layer messages are called frames

- Common approach: Sentinels
  - Look for special control code that marks start of frame

Point-to-Point Protocol (PPP)

- IETF standard, used for dialup and leased lines

Flag 01111110	(header)	Payload (variable)	(trailer)	Flag 01111110

- Flag indicates start/end of frame
- Occurrences of flag inside payload must be "stuffed"
  - Replace "flag" with "flag flag"
  - Length of payload is data-dependent!

Other Approaches

- Use explicit byte count after preamble
  - More susceptible to errors?
- Use "invalid" codeword
  - E.g., pick non-data 4B/5B symbol, used for FDDI
- SONET: "clock"-based framing
  - Periodic sync bits plus very accurate clock
  - Used extensively in the telecommunications industry

4. Error Detection/Correction

- Noise can flip some of the bits we receive
  - At a minimum we must be able to detect when this occurs
- Basic approach: add redundant data
  - Error detection codes allow errors to be recognized
  - Error correction codes allow some errors to be repaired too

Motivating Example

- Let's 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 versus Correction

- Two strategies to correct errors:
  - Error correcting codes and retransmissions (ARQ)
- Question: Which should we choose?
- Answer: Depends on errors and cost of recovery!
- Example: Message with 1000 bits, Prob(bit error) 0.001
  - If random errors, most messages likely to have an error
  - If bursts of 1000 errors typical, only 1 or 2 per 1000 messages
- Satellites, real-time media tend to use error correction
  - Called Forward Error Correction (FEC) in some contexts
- Retransmissions typically at the frame/packet level

The Hamming Distance

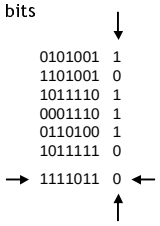
- To detect/correct bit errors, errors must not turn one valid codeword into another valid codeword
- Hamming distance is the number of bit differences
  - E.g, code 000 for 0, 111 for 1, Hamming distance is 3
  - This is the number of errors needed to turn one into the other
  - Hamming distance of the entire code is minimum of pairs
- 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 → 000 iff one error

Parity

- Start with n bits and add another so that the total number of 1s is even (even parity)
  - e.g. 0110010 → 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
- Corrects all 1 bit errors



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

Checksum Example

- Message is e3 4f 23 96 44 27 99 f3
- 2s complement sum is 1e4ff
- So 1s complement sum is e500 (add back carry)
- So checksum is 1aff (flip all bits)
- Advantages: fast to compute; incremental
- Disadvantage: error detection isn't strong

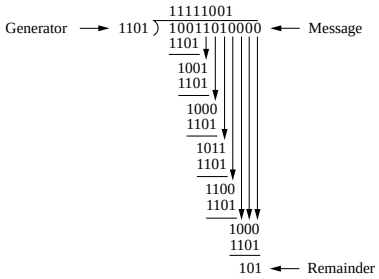
CRCs (Cyclic Redundancy Check)

- Stronger protection than checksums
  - Used widely in practice, e.g., Ethernet CRC-32
  - Easily 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 pre-defined number
- Based on mathematics of finite fields
  - "numbers" correspond to polynomials, use modulo arithmetic
  - e.g, interpret 10011010 as $x^7 + x^4 + x^3 + x^1$

CRC Example

- How do we generate the check sequence?
  - Have our message, e.g., 10011010 (m=8)
  - Have the divisor polynomial, e.g., C(x)=1110 ($x^3 + x^2 + x^1$; k=3)
  - Want to make m + k bits divisible by this divisor …
  - First, add k zeros to end of message
  - Then, divide by C(x) to find the remainder …

Example – Polynomial Division



Example – Remainder to CRC

- So we see the remainder is 101
- Thus the zero extended message - 101 must be evenly divisible by C(x)!
- So perform the subtraction to discover the check bits
  - Subtraction/addition is XOR in modulo 2 arithmetic
  - E.g., we get 10011010000 - 101 = 1011010101
  - The check bits are 101

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 degree that are known to catch many errors

Standard CRC Polynomials

- CRC-8 100000111
- CRC-10 11000110011
- CRC-12 110000000111
- CRC-16 1000100000100000
- CRC-32 10000010011000001000111011011 0111

Reed-Solomon / BCH Codes

- Reed-Solomon codes developed to protect data on magnetic disks
- Used for CDs and cable modems too
- Property: 2t redundant bits can correct <= t errors
- Mathematics somewhat more involved …

Key Concepts

- Different media have different properties
  - Affects higher layer protocols
- There are fundamental limits to transmission
  - Nyquist and Shannon limits
- To send messages in practice we must solve the problems of clock recovery and framing
- And we must be able to at least detect errors