CS 755 – System and Network Architectures and Implementation

Module 1 - Channels

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Overview

• Signal Transmission
• Framing
• Error Detection / Correction
• Medium Access Control
• Principles
  • Encapsulation
  • Performance
Signal Transmission

• encode/decode binary information as
  • electrical signals
  • acoustic signals
  • optical signals
  • radio signals
  • etc.

• discrete vs. continuous signals
Signals

• challenge: signal fading
  • signal level
  • transition edge
• binary vs. n-ary signals?
  • robustness vs. efficiency

• communication -> reconstruct original signal
Physical Media

• properties
  • capacity
  • shielding
  • propagation

• cable
  • cost & quality: twisted pair < coax < fiber
Radio Transmission

- medium: electromagnetic spectrum
  - public good: regulated vs. unregulated bands
- no wire – no shielding
- propagation effects
  - obstruction (path loss)
  - reflection (multipath)
  - interference
- typical pattern: base station – mobile
Radio Transmission – Adaption

- SNR: signal-to-noise ratio
- BER: bit error rate
- SNR vs. BER trade-offs
  - increase power -> increase SNR -> decrease BER
  - for fixed SNR: choose appropriate coding, such that BER is reasonable
Radio – Power Management

• radio ~ battery-powered devices
  • sending / receiving consumes significant power
• power savings mode: disable receiving
  • maybe hibernate device
• coordinate wake/sleep cycles with neighbour
  • fixed schedule or announce sleep periods
  • simple for base station scenarios, else difficult
• also: control sending power / interference
Optical Transmission

- computers are built using electrical components vs. much more efficient optical signals
  - “more efficient” -> more transitions per time
- electrical circuits (especially memory) have difficulty with keeping up...
- transmission pattern: point-to-point
- optical switches?
  - optical memory? optical delay lines
Binary Coding

- simplest coding: unipolar, non-return-to-zero

- clock synchronization?
- direct current (DC) bias?
Self-Clocking

- bipolar, return-to-zero

- transition in middle of interval -> clock signal
  - but: only 50% efficient
Manchester Encoding

- direction of transition in middle of signal period
- no DC bias at all
- inversion (cable swapped)?
  - both versions exist in literature and standards
Differential Manchester Encoding

- presence of transition at start of period
- transition easier to detect than level
- robust against inversion
4B/5B Encoding

- encode 4 bits in 5 NRZ transitions
- fixed mapping dictionary
  - each code word encoded with at least 2 transitions
  - coding room for 'idle' and other control signals
- more recent: 64B/66B
  - use scrambler instead of dictionary
  - first two bits: preamble, guarantee transition
- dictionary and scrambling also limit DC bias
Framing

- split bit stream in discrete units
- signal start and end of message
  - basis for any kind of reliable communication
  - define unit for basic error detection and correction

- signal/code for 'idle'?
  - yes: can use frame length field
  - no: must use frame delimiter
Frame Delimiter

- example: PPP
- Point-to-Point Protocol (PPP)
  - transparency: transmit binary data over anything
  - assume 0- and 1-signal, but no 'idle' signal
  - operates on bytes

- designate special bit pattern as delimiter
  - e.g., 01111110 (for both start and end)
- what if 01111110 appears in data stream?
Byte Stuffing

- PPP sender algorithm
  if 01111110 appears in data stream:
  insert another 01111110 before

- PPP receiver algorithm
  if 01111110 appears in communication stream:
  followed by 01111110 -> remove one of them
  else -> 01111110 is a delimiter
Notes

• can have different start/end delimiters for robustness

• generalized sender algorithm
  insert escape pattern before any occurrence of control patterns in data (including escape itself)

• generalized receiver algorithm
  if escape pattern in stream:
  remove and treat next symbol as data
Escape Character

• e.g., in many programming languages:
  print “Tom said “Hello” to me.”;
  ... is a syntax error, because double quotation mark is the string delimiter token

• use escape character (backslash):
  print “Tom said "Hello" to me.”;

• same for regular expressions and related tools
Framing with Idle-Signal

- with 'idle'-signal: delimiters not strictly needed
- use 'length' field in message for robustness

but: why does Ethernet define 'preamble'?
- for channel cleanup (see medium access control),
- ...and clock synchronization
  - self-clocking code
Error Control

- error detection: append parity bit to bit string
  - bit string can be codeword, message, etc.
  - add bit, such that number of 1s is odd
    - 'even' variant exists, as well

- 0111000110101011 -> append 0
- receiver can detect single-bit errors
- correction: Automatic Repeat reQuest (ARQ)
  - hold back ACK or send NAK
Forward Error Correction

- matrix of parity bits

\[
\begin{array}{cccc|ccc}
  d_{1,1} & \cdots & d_{1,j} & d_{1, j+1} \\
  d_{2,1} & \cdots & d_{2,j} & d_{2, j+1} \\
  \vdots & \ddots & \vdots & \vdots \\
  d_{i,1} & \cdots & d_{i,j} & d_{i, j+1} \\
  d_{i+1,1} & \cdots & d_{i+1,j} & d_{i+1, j+1} \\
\end{array}
\]

- no errors

\[
\begin{array}{c}
  1010111 \\
  1111000 \\
  0111011 \\
  1010100 \\
\end{array}
\]

- correctable single bit error

\[
\begin{array}{c}
  1010111 \\
  1011000 \\
  0111011 \\
  1010100 \\
\end{array}
\]

- parity error
Error Control: Redundancy

● what are we actually doing?
  ● add redundancy to message (cf. natural language)
  ● opposite of compression!

● data <-> code mapping
  ● code properties determine error control capabilities
    -> Hamming Distance
Hamming Distance

- number of positions in which two strings of equal length are different
  \[ h(a, b) \text{ for strings } a, b \]
- assume code / set of fixed-length bit strings
- Hamming Distance of code \( C \)
  \[ H(C) = \min( h(a, b) \quad \forall \ a, b \in C ) \]
Hamming Distance

- $H(C) > n \implies$ n-bit errors can be detected
- $H(C) > 2n \implies$ n-bit errors can be corrected

previous examples
- simple Parity scheme: $H(C) = 2 > 1$
  - 1-bit errors can be detected
- matrix Parity scheme: $H(C) = 3 > 2 \times 1$
  - 1-bit errors can be corrected

challenge: dictionary not feasible for messages
Internet Checksum

one's complement of sum of one's complements
  - process data as stream of 16-bit words
  - one's complement sum: add carry bit
  - not very strong: errors might go undetected

- why this format?
  - implementation in software
  - incremental update
  - independent of byte ordering
  - see RFC 1071 for discussion
Advanced Error Control

- Cyclic Redundancy Check (CRC)
  - error detection with small, fixed message overhead
  - simple in hardware – used, e.g., in Ethernet
- Erasure Codes
  - consider loss, instead of changes
  - parity -> e.g., in RAID systems
- Fountain Codes
  - any suitable subset of encoded symbols can recreate original message
Medium Access Control (MAC)

Goals

1. high channel utilization for single/few nodes
2. fair sharing for many nodes
3. decentralized, robust
4. simple
Medium Access Control Schemes

- channel partitioning
  - pessimistic: split channel into sub-channels
- random access
  - optimistic: uncoordinated access
  - distributed: handle collisions, resolve contention
- taking turns
  - distributed coordinated: avoid collisions
  - high complexity
Partitioning – Frequency

- Frequency Division Multiple Access (FDMA)
- channel spectrum divided into frequency bands
- each station assigned fixed frequency band
- unused capacity goes idle – utilization?
Partitioning – Time

- Time Division Multiple Access (TDMA)
- channel divided into “rounds”
- each station gets fixed length time slot

- unused slots go idle
Partitioning – Code

- Code Division Multiple Access (CDMA)
- ultimately uses multi-level signals
- each station is assigned chipping sequence
  - set of binary code vectors that are orthogonal
- downlink (from base station)
  - synchronous: signals add up, but can be decoded
- uplink (from mobile stations)
  - asynchronous: add pseudo-random “noise” signal
Partitioning

- need control functionality to manage channels
  - assign frequency or time slot or codes
  - mobile registration with base station
    - rare event (compared to message transmission)
  - ultimately: random access (bootstrapping problem)
    - truly global codes without collision not feasible

=> control overhead

- centralized
- utilization with few stations?
Random Access

- assumption: signal overlap detectable as error
- potential collision not avoidable
- first approach: send any time (ALOHA)
  - fixed message length
  - detect collisions, random wait time, retransmit
  - best-case utilization: 18%
- next: send at slot intervals (slotted ALOHA)
  - best-case utilization: 36%
Carrier Sensing

- Carrier-Sense Multiple Access (CSMA)
  - listen to channel before transmission
  - if channel busy, wait
    - persistency – when to send after channel is sensed free?
- collisions? still possible...
  - non-zero propagation delay
CSMA – Collisions

- propagation delay gap: two nodes do not hear each other
  - propagation speed
  - distance
- collision
  - entire message corrupt
Collision Detection

• compare signal on channel with own message
• detect collision locally -> abort transmission
  • reduce channel wastage
• easy in wired medium
  • similar signal strengths of transmitted/received signal
• difficult in radio networks
  • received signal strength overwhelmed by local transmission
Collision Detection
Minimum Message Size

- carrier sensing and minimum message size -> effective channel reservation scheme
- assume maximum distance $d$, prop speed $v$ => maximum travel time: $d/v$
- remote station could transmit just before $d/v$
- if no collision after $2 \times d/v$ -> channel reserved
- assume transmission rate $b$ => minimum message size: $b \times 2 \times d/v$
Ethernet

- 1-persistent CSMA/CD, no ACKs
- minimum message size -> channel reservation
- but: message simply lost, if no receiver present
- collision -> randomized exponential backoff
  - increase wait time during continuous collisions
  - adaptive to level of load/contention
- modern versions: not much need for MAC; star topology & network forwarding
Collision Avoidance

• radio: local collision detection not feasible
  • single radio cannot transmit/receive at same time
  • two radios: local signal would drown out remote
• hidden terminal problem

-> more conservative collision avoidance
  • exponential backoff during CSMA
  • RTS/CTS mechanism to mitigate collision effect
  • ACKs to confirm successful transmission
Priorities

- wait time counts down when medium is idle
- wait time priorities built into CSMA mechanism
  - SIFS – last receiver / ACK
  - PIFS – base station / control
  - DIFS – any station / data
- wait time includes backoff if applicable
Hidden Terminal

- obstruction
  - A, B hear each other
  - B, C hear each other
  - A, C can not hear each other

- signal attenuation
  - A, B hear each other
  - B, C hear each other
  - A, C can not hear each other

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RTS/CTS

time

RTS(A)

CTS(A)

DATA (A)

ACK(A)

RTS(B)

reservation collision

defer
Taking Turns

- channel partitioning protocols:
  - static, coordinated
  - very efficient at high load
  - low utilization at low load

- random access
  - little a-priori coordination
  - very efficient at low load
  - collision overhead at high load

-> try dynamic, coordinated
Centralized Polling

- master node “invites” slave nodes to transmit
- traditional scenario: host/terminal networks
- concerns
  - polling overhead
  - latency to send
  - single point of failure (master)
Token Passing

- control *token* passed from one station to next
- examples: Token Bus, Token Ring
- concerns
  - token overhead
  - latency
  - single point of failure (token)
Taking Turns

- efficient at low and high load
- manageability / control
  - minimum transmission rate
  - maximum latency
- but:
  - complexity
    - token passing: complexity in each station
  - obsolescence by point-to-point/switched Ethernet
Encapsulation

- wrap payload data into message format
- message header/trailer for control
- payload might be message itself
  -> encapsulation / layering
- typical header/trailer:
  - type, length, addresses, contro, checksum
Performance

- throughput vs. delay vs. loss (later)
- example: Tim Hortons
  - number of served customers per hour
  - throughput
  - vs. time to wait for coffee
  - delay
- high throughput does not guarantee low delay
  - synchronous vs. asynchronous execution of job
  - high level of multiplexing: good for throughput
Throughput

• transfer rate in bits/time

• always an average
  • different time scales relevant in different scenarios
    – streaming: minimum throughput needed “continuously”
      • i.e., over short time periods
    – download: average throughput
      • i.e., overall average throughput relevant

• capacity sharing: fairness vs. utility
  • consider two identical file downloads
  • sequential vs. concurrent download – utilities?
Throughput

• “width” of pipe
• multiple transmission segments
  • minimum throughput segment is *bottleneck*

\[ R_s \text{ bits/sec} \quad \text{vs.} \quad R_c \text{ bits/sec} \]
Delay

- processing delay
  - local processing at communication node
- queueing delay
  - later
- transmission delay (packetization)
  - message size / link throughput
- propagation delay
  - propagation speed / distance
Delay

- speed / length of pipe
- multiple transmission segments
  - total delay is sum of delays