Housekeeping

- Homework 2 handout
- Homework 1 questions

Point-to-Point Links (continued)

Outline
- Error Detection
- Reliable Transmission
  - Stop and wait
  - Sliding window algorithm

Cyclic Redundancy Check

- Add $k$ bits of redundant data to an $n$-bit message
  - want $k << n$
  - e.g., $k = 32$ and $n = 12,000$ (1500 bytes)
- Represent $n$-bit message as $n$-1 degree polynomial
  - e.g., MSG=10011010 as $M(x) = x^7 + x^4 + x^3 + x^1$
- Let $k$ be the degree of some divisor polynomial
  - e.g., $C(x) = x^3 + x^2 + 1$

CRC (cont)

- Transmit polynomial $P(x)$ that is evenly divisible by $C(x)$
  - shift left $k$ bits, i.e., $M(x)x^k$
  - subtract remainder of $M(x)x^k / C(x)$ from $M(x)x^k$
- Received polynomial $P(x) + E(x)$
  - $E(x) = 0$ implies no errors
- Divide ($P(x) + E(x)$) by $C(x)$; remainder zero if:
  - $E(x)$ was zero (no error), or
  - $E(x)$ is exactly divisible by $C(x)$
Selecting $C(x)$

- All single-bit errors, as long as the $x^k$ and $x^0$ terms have non-zero coefficients.
- All double-bit errors, as long as $C(x)$ contains a factor with at least three terms.
- Any odd number of errors, as long as $C(x)$ contains the factor $(x + 1)$.
- Any ‘burst’ error (i.e., sequence of consecutive error bits) for which the length of the burst is less than $k$ bits.
- Most burst errors of larger than $k$ bits can also be detected.
- See Table 2.6 on page 102 for common $C(x)$.

Shift Register Implementation of CRC

- Class: demonstrate that it works

Acknowledgements, Timeouts & Retransmissions

Stop-and-Wait

- Problem: keeping the pipe full
- Example
  - 1.5Mbps link x 45ms RTT = 67.5Kb (8KB)
  - 1KB frames implies 1/8th link utilization
Sliding Window

- Allow multiple outstanding (un-ACKed) frames
- Upper bound on un-ACKed frames, called window

SW: Sender

- Assign sequence number to each frame (SeqNum)
- Maintain three state variables:
  - send window size (SWS)
  - last acknowledgment received (LAR)
  - last frame sent (LFS)
- Maintain invariant: LFS - LAR <= SWS
- Advance LAR when ACK arrives
- Buffer up to SWS frames

SW: Receiver

- Maintain three state variables
  - receive window size (RWS)
  - largest frame acceptable (LAF)
  - last frame received (LFR)
- Maintain invariant: LAF - LFR <= RWS
- Frame SeqNum arrives:
  - if LFR < SeqNum <= LAF accepted
  - if SeqNum < LFR or SeqNum > LAF discarded
- Send cumulative ACKs

Sequence Number Space

- SeqNum field is finite; sequence numbers wrap around
- Sequence number space must be larger than number of outstanding frames
- SWS <= MaxSeqNum - 1 is not sufficient
  - suppose 3-bit SeqNum field (0..7)
  - SWS=RWS=7
  - sender transmit frames 0..6
  - arrive successfully, but ACKs lost
  - sender retransmits 0..6
  - receiver expecting 7, 0..5, but receives second incarnation of 0..5
- SWS < (MaxSeqNum+1) / 2 is correct rule
- Intuitively, SeqNum “slides” between two halves of sequence number space
Concurrent Logical Channels

- Multiplex 8 logical channels over a single link
- Run stop-and-wait on each logical channel
- Maintain three state bits per channel
  - channel busy
  - current sequence number out
  - next sequence number in
- Header: 3-bit channel num, 1-bit sequence num
  - 4-bits total
  - same as sliding window protocol
- Separates \textit{reliability} from \textit{order}