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 $C(x)$

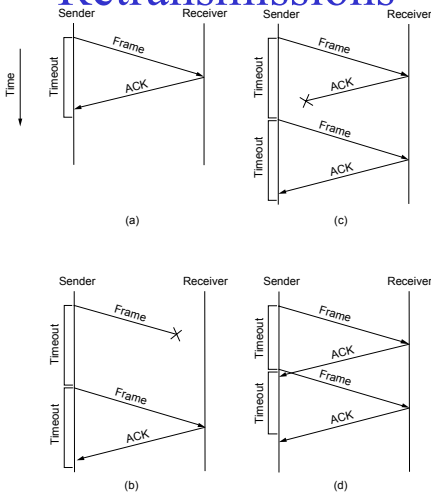
Selecting $C(x)$

- 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)*

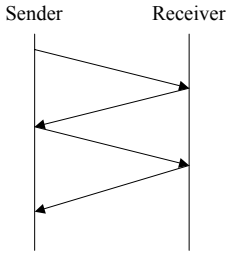
Shift Register Implementation of CRC

- Class: demonstrate that it works

Acknowledgements, Timeouts & Retransmissions



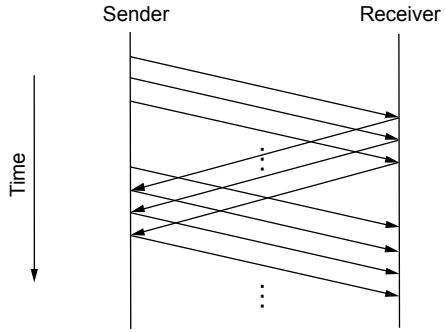
Stop-and-Wait



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

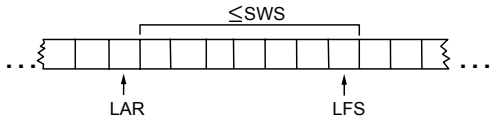
Sliding Window

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



SW: Sender

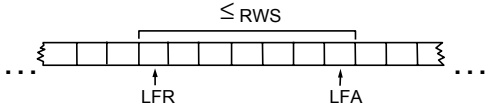
- Assign sequence number to each frame (**SeqNum**)
- Maintain three state variables:
  - send window size (**SWS**)
  - last acknowledgment received (**LAR**)
  - last frame sent (**LFS**)
- Maintain invariant: **LFS** - **LAR** <= **SWS**



- 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 then 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 *reliability* from *order*