

CSCI-1680

Link Layer Reliability

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- **Last time**

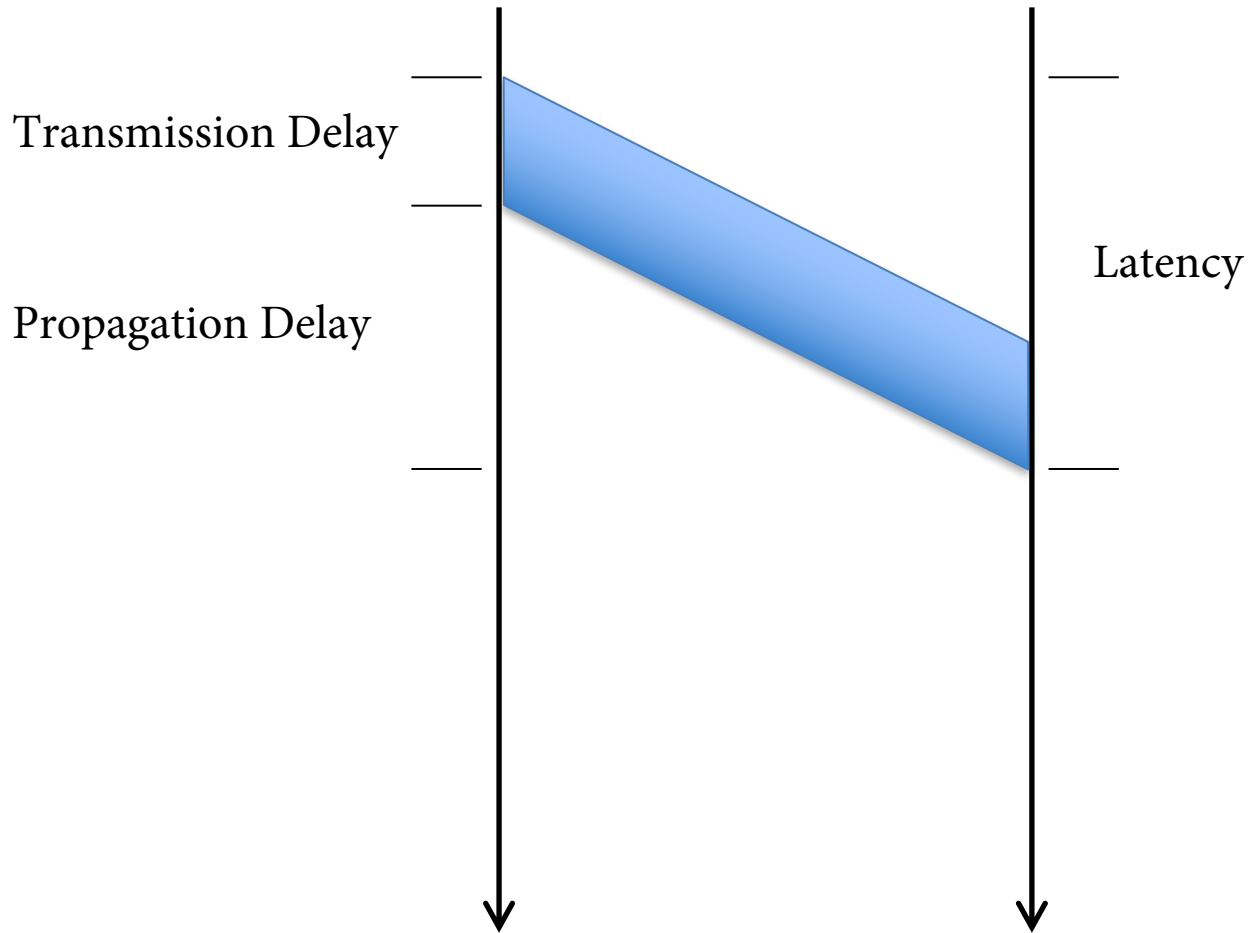
- Physical layer: encoding, modulation
- Link layer framing

- **Today**

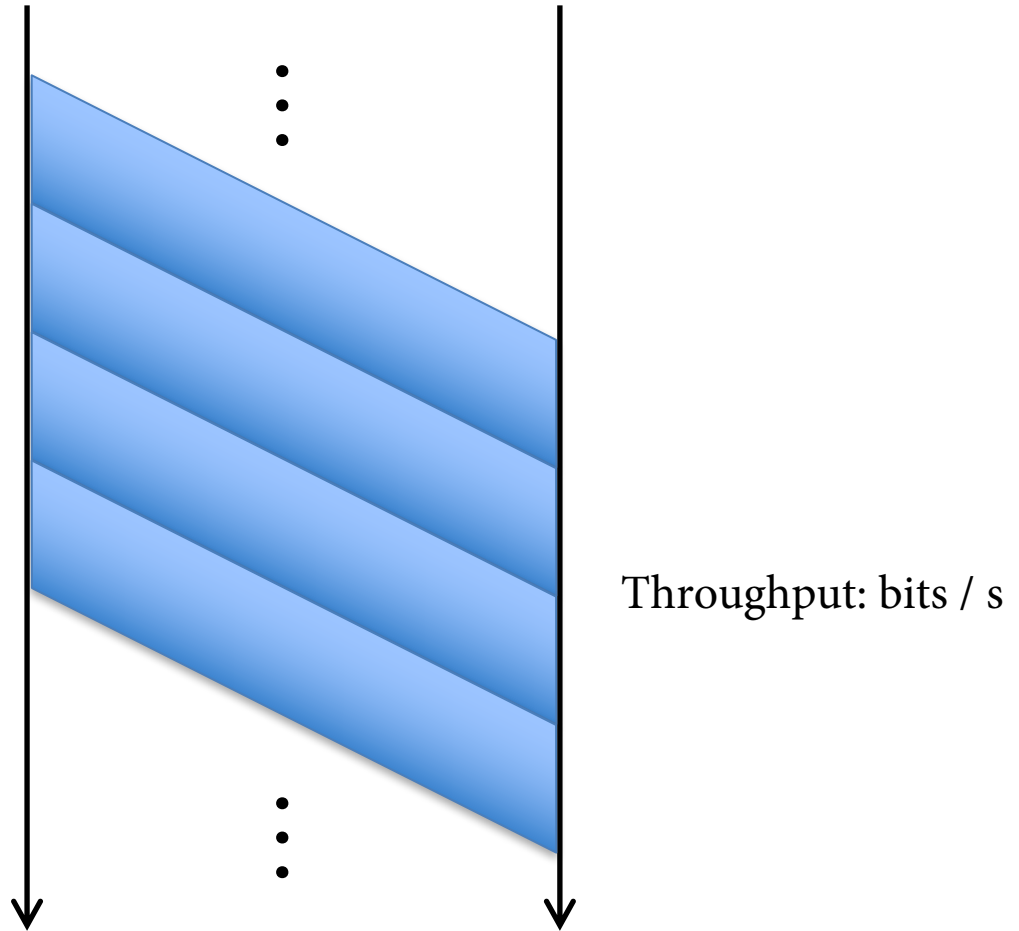
- Getting frames across: reliability, performance



Sending Frames Across

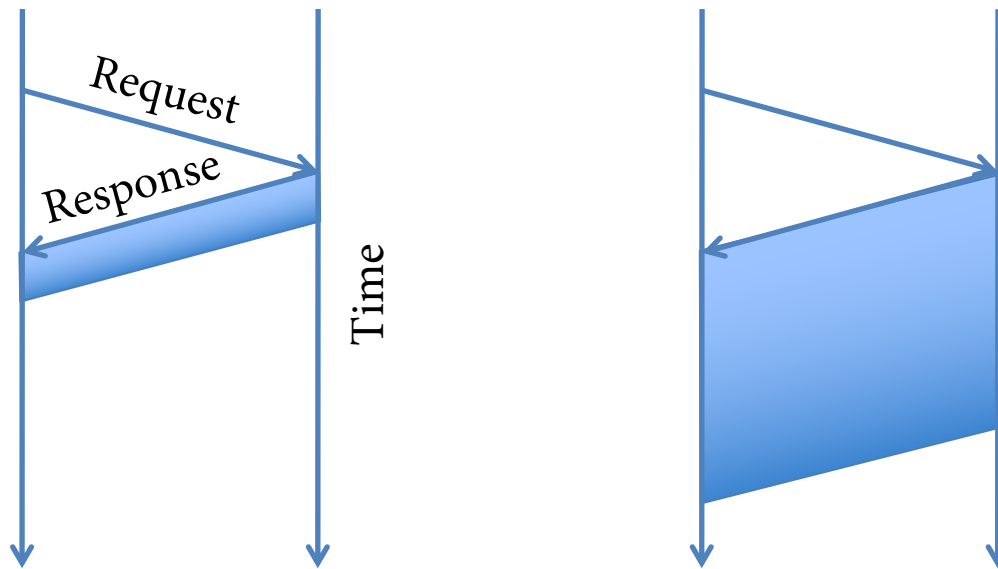


Sending Frames Across



Which matters most, bandwidth or delay?

- How much data can we send during one RTT?
- *E.g.*, send request, receive file



- For small transfers, latency more important, for bulk, throughput more important



Performance Metrics

- **Throughput** - Number of bits received/unit of time
 - e.g. 10Mbps
- **Goodput** - *Useful* bits received per unit of time
- **Latency** – How long for message to cross network
 - Process + Queue + Transmit + Propagation
- **Jitter** – Variation in latency



Latency

- **Processing**

- Per message, small, limits throughput

- *e.g.* $\frac{100Mb}{s} \times \frac{pkt}{1500B} \times \frac{B}{8b} \approx 8,333pkt/s$ or $120\mu s/pkt$

- **Queue**

- Highly variable, offered load vs outgoing b/w

- **Transmission**

- Size/Bandwidth

- **Propagation**

- Distance/Speed of Light



Reliable Delivery

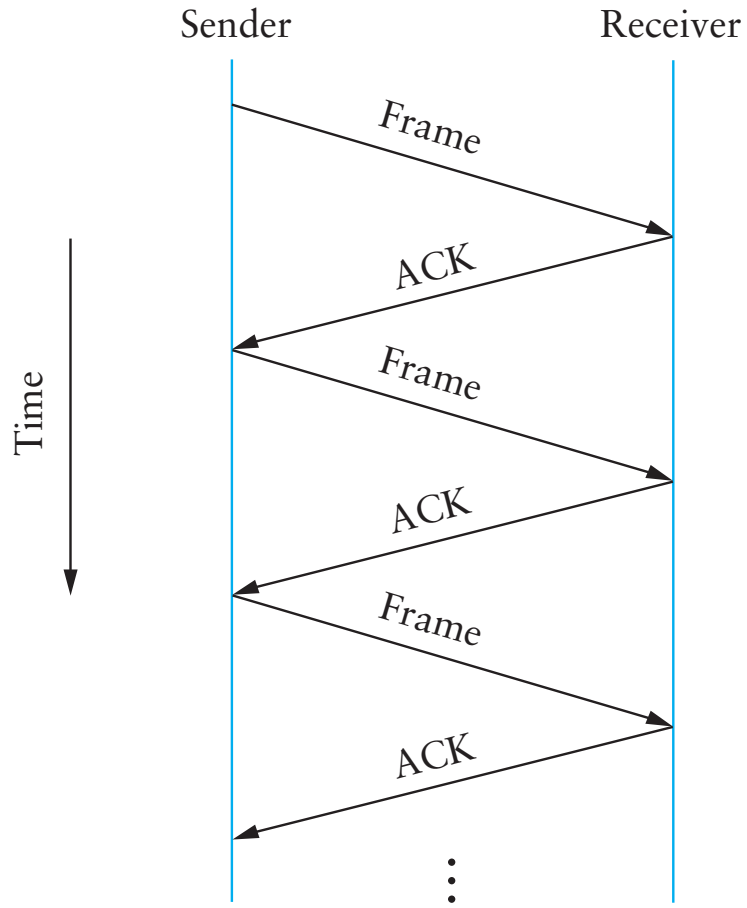
- **Several sources of errors in transmission**
- **Error detection can discard bad frames**
- **Problem: if bad packets are lost, how can we ensure reliable delivery?**
 - Exactly-once semantics = at least once + at most once

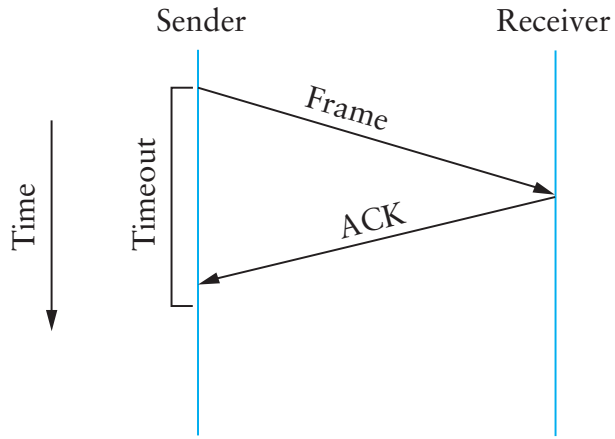


At Least Once Semantics

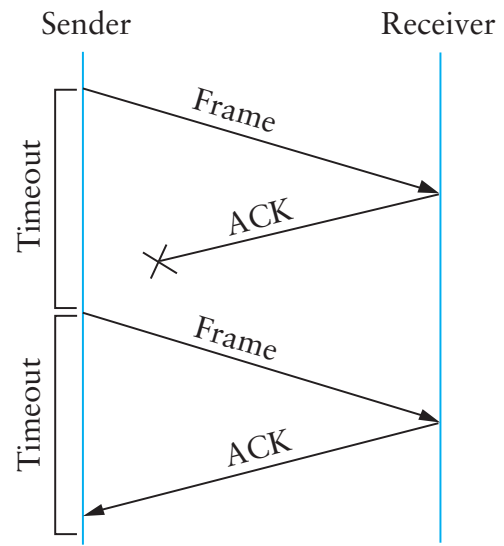
- **How can the sender know packet arrived *at least once*?**
 - Acknowledgments + Timeout
- **Stop and Wait Protocol**
 - S: Send packet, wait
 - R: Receive packet, send ACK
 - S: Receive ACK, send next packet
 - S: No ACK, timeout and retransmit



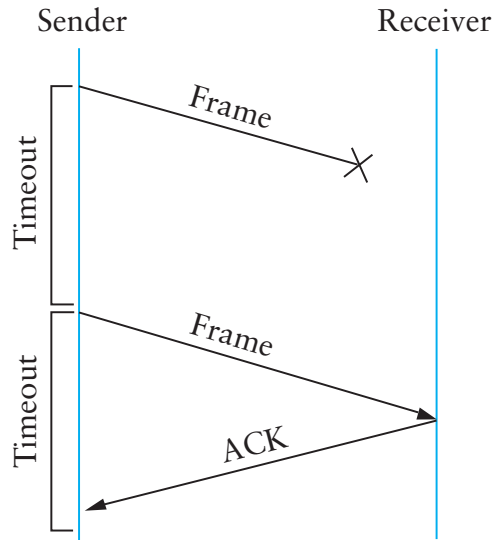




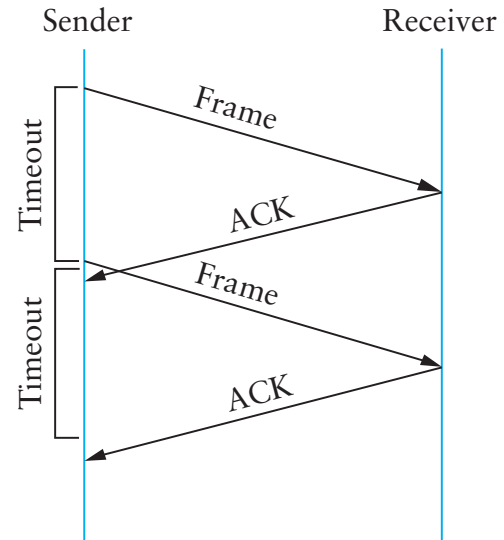
(a)



(c)



(b)



(d)

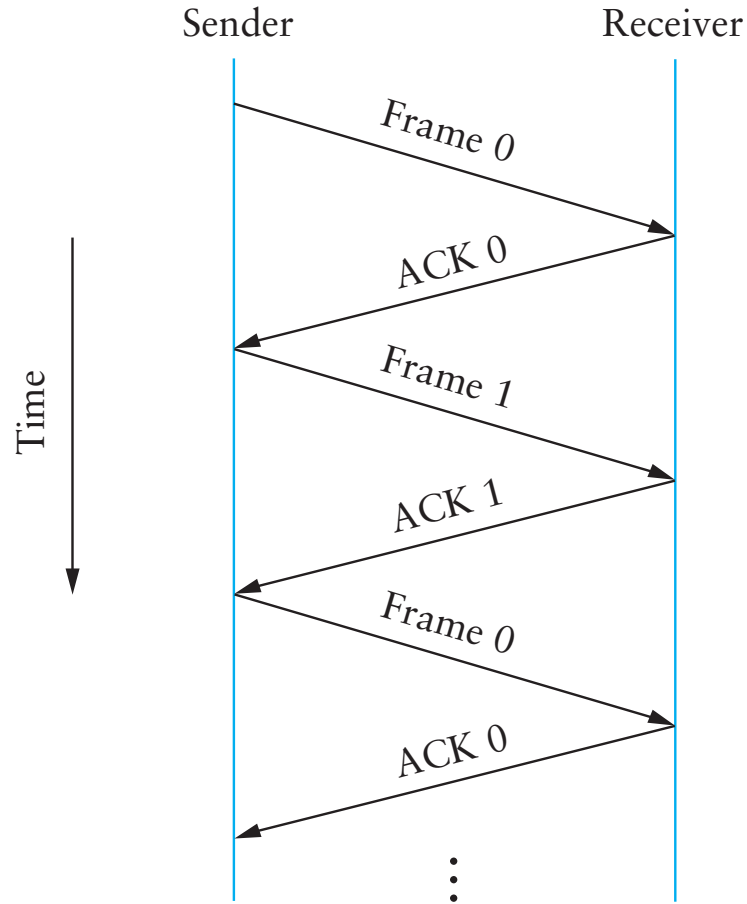


Stop and Wait Problems

- **Duplicate data**
- **Duplicate acks**
- **Slow (channel idle most of the time!)**
- **May be difficult to set the timeout value**



Duplicate data: adding sequence numbers



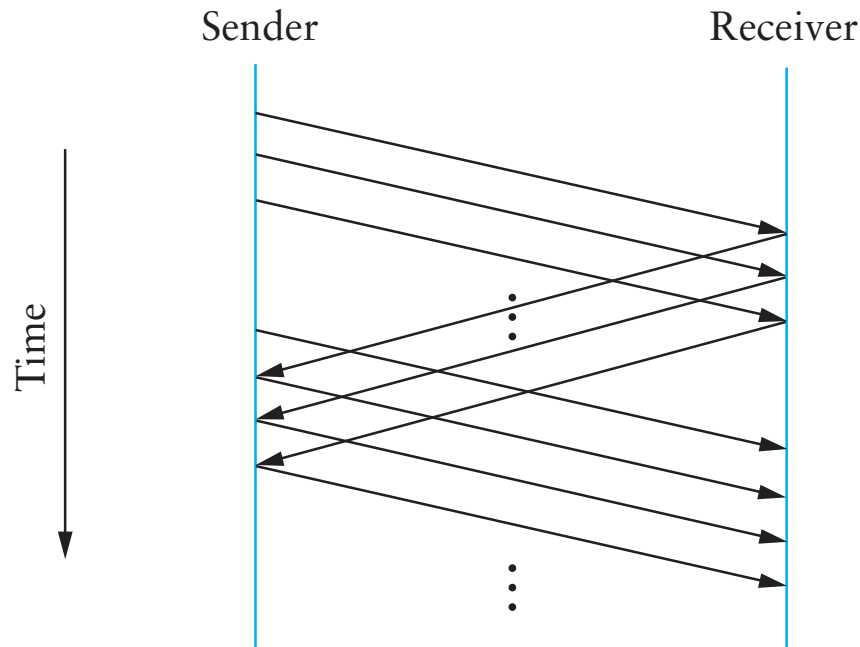
At Most Once Semantics

- **How to avoid duplicates?**
 - Uniquely identify each packet
 - Have receiver and sender remember
- **Stop and Wait: add 1 bit to the header**
 - Why is it enough?

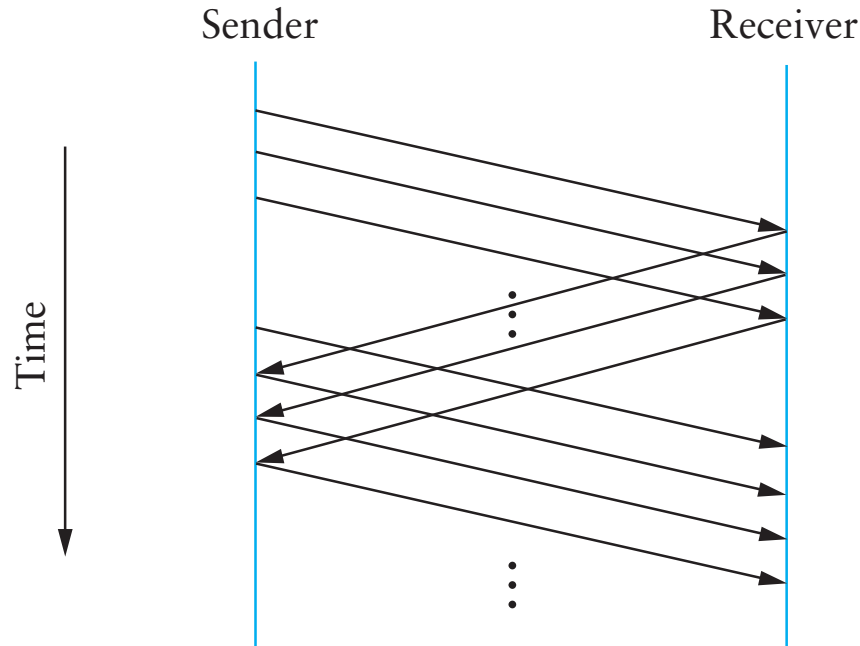


Going faster: sliding window protocol

- **Still have the problem of keeping pipe full**
 - Generalize approach with > 1 -bit counter
 - Allow multiple outstanding (unACKed) frames
 - Upper bound on unACKed frames, called *window*



How big should the window be?



- **How many bytes can we transmit in one RTT?**
 - $BW \text{ B/s} \times RTT \text{ s} \Rightarrow$ “Bandwidth-Delay Product”



Maximizing Throughput

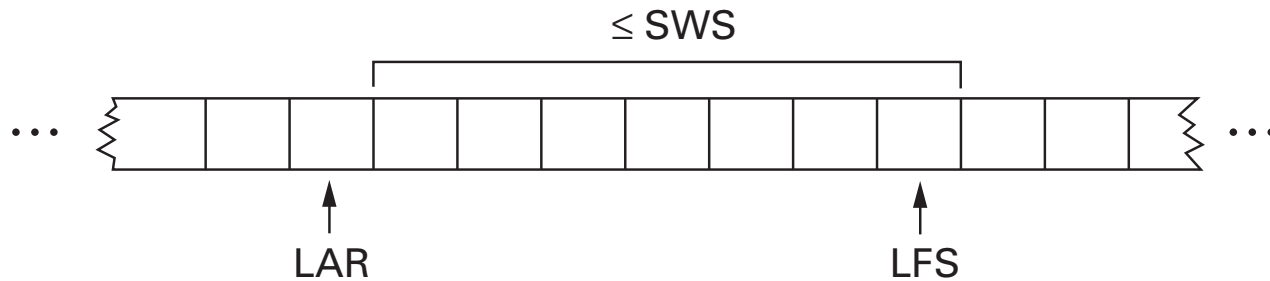


- **Can view network as a pipe**
 - For full utilization want bytes in flight \geq bandwidth \times delay
 - But don't want to overload the network (future lectures)
- **What if protocol doesn't involve bulk transfer?**
 - Get throughput through concurrency – service multiple clients simultaneously



Sliding Window Sender

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

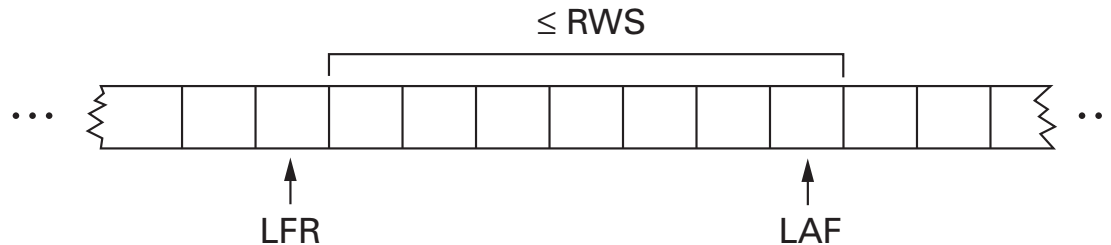


- **Maintain invariant: $LFS - LAR \leq SWS$**
- **Advance LAR when ACK arrives**
- **Buffer up to SWS frames**



Sliding Window Receiver

- **Maintain three state variables:**
 - receive window size (RWS)
 - largest acceptable frame (LAF)
 - last frame received (LFR)



- **Maintain invariant: $LAF - LFR \leq RWS$**
- **Frame SeqNum arrives:**
 - if $LFR < SeqNum \leq LAF$, accept
 - if $SeqNum \leq LFR$ or $SeqNum > LAF$, discard
- **Send *cumulative* ACKs**



Tuning Send Window

- **How big should SWS be?**
 - “Fill the pipe”
- **How big should RWS be?**
 - $1 \leq RWS \leq SWS$
- **How many distinct sequence numbers needed?**



Example

- **SWS = RWS = 5. Are 6 seq #s enough?**
- **Sender sends 0,1,2,3,4**
- **All acks are lost**
- **Sender sends 0,1,2,3,4 again**
- **...**
- **What are the possible views of the sender and receiver?**



Tuning Send Window

- **How big should SWS be?**
 - “Fill the pipe”
- **How big should RWS be?**
 - $1 \leq RWS \leq SWS$
- **How many distinct sequence numbers needed?**
 - SWS can't be more than half of the space of valid seq#s.



Summary

- **Want exactly once**
 - At least once: acks + timeouts + retransmissions
 - At most once: sequence numbers
- **Want efficiency**
 - Sliding window





Error Detection

- **Idea: have some codes be *invalid***
 - Must add bits to catch errors in packet
- **Sometimes can also *correct* errors**
 - If enough redundancy
 - Might have to retransmit
- **Used in multiple layers**
- **Three examples today:**
 - Parity
 - Internet Checksum
 - CRC



Simplest Schemes

- **Repeat frame n times**
 - Can we detect errors?
 - Can we correct errors?
 - Voting
 - Problem: high redundancy : n
- **Example: send each bit 3 times**
 - Valid codes: 000 111
 - Invalid codes : 001 010 011 100 101 110
 - Corrections : 0 0 1 0 1 1



Parity

- **Add a parity bit to the end of a word**
- **Example with 2 bits:**
 - Valid: 000 011 011 110
 - Invalid: 001 010 010 111
 - Can we correct?
- **Can detect odd number of bit errors**
 - No correction

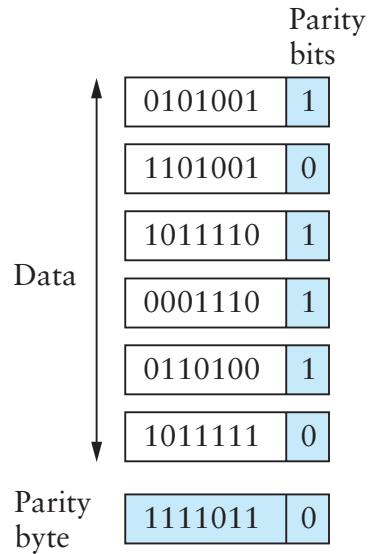


In general

- **Hamming distance: number of bits that are different**
 - E.g.: HD (00001010, 01000110) = 3
- **If min HD between valid codewords is d :**
 - Can detect $d-1$ bit error
 - Can correct $\lfloor (d-1)/2 \rfloor$ bit errors
- **What is d for parity and 3-voting?**



2-D Parity



- **Add 1 parity bit for each 7 bits**
- **Add 1 parity bit for each bit position across the frame)**
 - Can correct single-bit errors
 - Can detect 2- and 3-bit errors, most 4-bit errors
- **Find a 4-bit error that can't be corrected**



IP Checksum

- **Fixed-length code**
 - n-bit code should capture all but 2^{-n} fraction of errors
 - Why?
 - Trick is to make sure that includes all *common* errors
- **IP Checksum is an example**
 - 1's complement of 1's complement sum of every 2 bytes

```
uint16 cksum(uint16 *buf, int count) {
    uint32 sum = 0;
    while (count-- > 0)
        if ((sum += *buf++) & 0xffff0000) // carry
            sum = (sum & 0xffff) + 1;
    return ~(sum & 0xffff);
}
```



How good is it?

- **16 bits not very long: misses how many errors?**
 - 1 in 2^{16} , or 1 in 64K errors
- **Checksum does catch all 1-bit errors**
- **But not all 2-bit errors**
 - E.g., increment word ending in 0, decrement one ending in 1
- **Checksum also optional in UDP**
 - All 0s means no checksums calculated
 - If checksum word gets wiped to 0 as part of error, bad news



From rfc791 (IP)

“This is a simple to compute checksum and experimental evidence indicates it is adequate, but it is provisional and may be replaced by a CRC procedure, depending on further experience.”



CRC – Error Detection with Polynomials

- **Goal: maximize protection, minimize bits**
- **Consider message to be a polynomial in $\mathbb{Z}_2[x]$**
 - Each bit is one coefficient
 - E.g., message 10101001 $\rightarrow m(x) = x^7 + x^5 + x^3 + 1$
- **Can reduce one polynomial modulo another**
 - Let $n(x) = m(x)x^3$. Let $C(x) = x^3 + x^2 + 1$.
 - $n(x)$ “**mod**” $C(x)$: $r(x)$
 - Find $q(x)$ and $r(x)$ s.t. $n(x) = q(x)C(x) + r(x)$ and degree of $r(x) <$ degree of $C(x)$
 - Analogous to taking $11 \bmod 5 = 1$



Polynomial Division Example

- Just long division, but addition/subtraction is XOR

$$\begin{array}{r} \text{Generator} \rightarrow 1101 \overline{) 10011010000} \leftarrow \text{Message} \\ \underline{1101} \\ 1001 \\ \underline{1101} \\ 1000 \\ \underline{1101} \\ 1011 \\ \underline{1101} \\ 1100 \\ \underline{1101} \\ 1000 \\ \underline{1101} \\ 101 \leftarrow \text{Remainder} \end{array}$$



CRC

- **Select a divisor polynomial $C(x)$, degree k**
 - $C(x)$ should be *irreducible* – not expressible as a product of two lower-degree polynomials in $Z_2[x]$
- **Add k bits to message**
 - Let $n(x) = m(x)x^k$ (add k 0's to m)
 - Compute $r(x) = n(x) \bmod C(x)$
 - Compute $n'(x) = n(x) - r(x)$ (will be divisible by $C(x)$)
(subtraction is XOR, just set k lowest bits to $r(x)$!)
- **Checking CRC is easy**
 - Reduce message by $C(x)$, make sure remainder is 0



Why is this good?

- **Suppose you send $m(x)$, recipient gets $m'(x)$**
 - $E(x) = m'(x) - m(x)$ (all the incorrect bits)
 - If CRC passes, $C(x)$ divides $m'(x)$
 - Therefore, $C(x)$ must divide $E(x)$
- **Choose $C(x)$ that doesn't divide any common errors!**
 - All single-bit errors caught if x^k, x^0 coefficients in $C(x)$ are 1
 - All 2-bit errors caught if at least 3 terms in $C(x)$
 - Any odd number of errors if last two terms $(x + 1)$
 - Any error burst less than length k caught



Common CRC Polynomials

- **Polynomials not trivial to find**
 - Some studies used (almost) exhaustive search
- **CRC-8: $x^8 + x^2 + x^1 + 1$**
- **CRC-16: $x^{16} + x^{15} + x^2 + 1$**
- **CRC-32: $x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x^1 + 1$**
- **CRC easily computable in hardware**



An alternative for reliability

- **Erasur coding**
 - Assume you can detect errors
 - Code is designed to tolerate entire missing frames
 - Collisions, noise, drops because of bit errors
 - Forward error correction
- **Examples: Reed-Solomon codes, LT Codes, Raptor Codes**
- **Property:**
 - From K source frames, produce $B > K$ encoded frames
 - Receiver can reconstruct source with *any* K' frames, with K' *slightly* larger than K
 - Some codes can make B as large as needed, on the fly



LT Codes

- **Luby Transform Codes**
 - Michael Luby, circa 1998
- **Encoder: repeat B times**
 1. Pick a degree d
 2. Randomly select d source blocks. Encoded block $t_n =$
XOR of selected blocks



LT Decoder

- Find an encoded block t_n with $d=1$
- Set $s_n = t_n$
- For all other blocks t_n , that include s_n ,
set $t_n' = t_n \text{ XOR } s_n$
- Delete s_n from all encoding lists
- Finish if
 1. You decode all source blocks, or
 2. You run out of blocks of degree 1



Next class

- **Link Layer II**
 - Ethernet: dominant link layer technology
 - Framing, MAC, Addressing
 - Switching

