CSCI-1680
Link Layer I

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Based partly on lecture notes by David Mazières, Phil Levis, John Jannotti

- **Last time**
  - Physical layer: encoding, modulation
- **Today**
  - Link layer framing
  - Getting frames across: reliability, performance

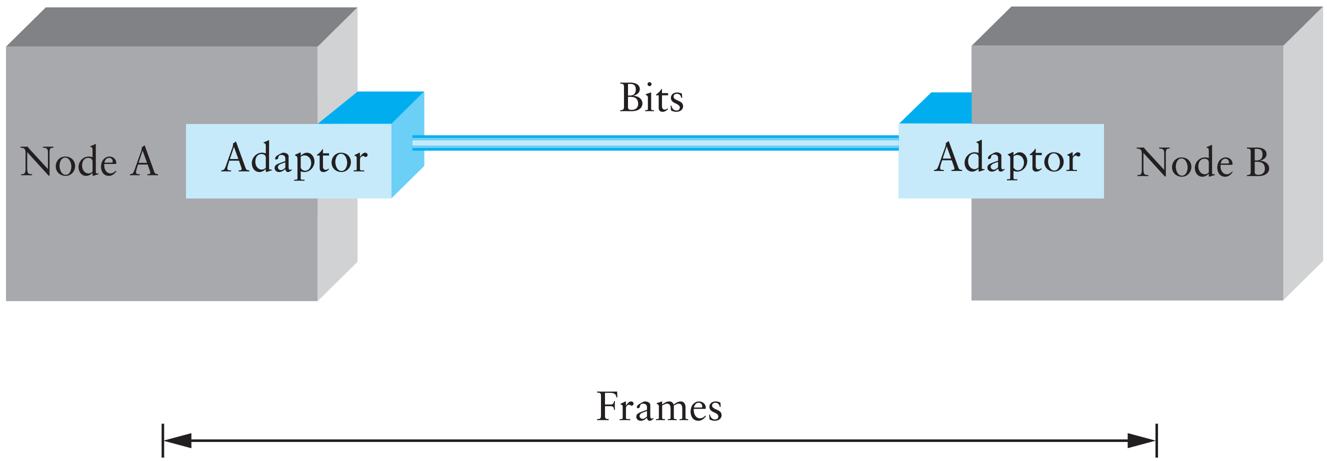
Layers, Services, Protocols

Application	Service: user-facing application. Application-defined messages
Transport	Service: multiplexing applications Reliable byte stream to other node (TCP), Unreliable datagram (UDP)
Network	Service: move packets to any other node in the network IP: Unreliable, best-effort service model
Link	Service: move frames to other node across link. May add reliability, medium access control
Physical	Service: move bits to other node across link

Link Layer
Framing

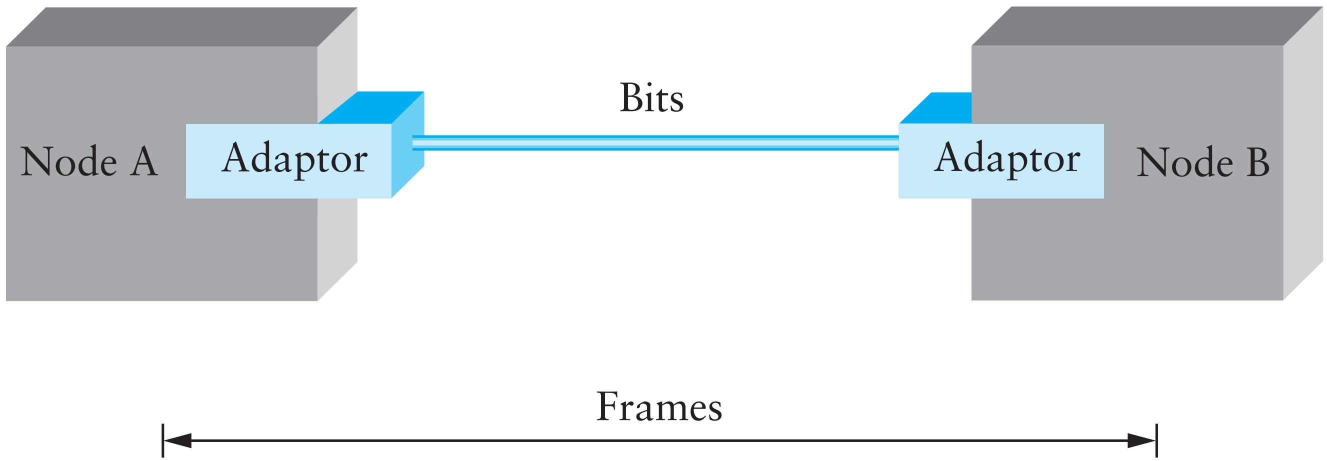
Framing

- Given a stream of bits, how can we represent boundaries?
- Break sequence of bits into a frame
- Typically done by network adaptor



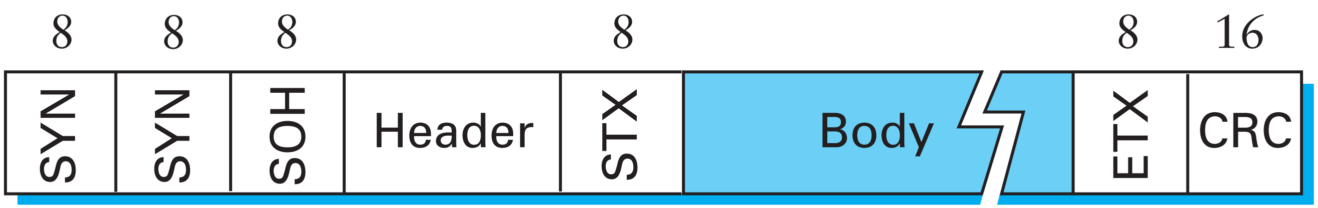
Representing Boundaries

- Sentinels
- Length counts
- Clock-based



Sentinel-based Framing

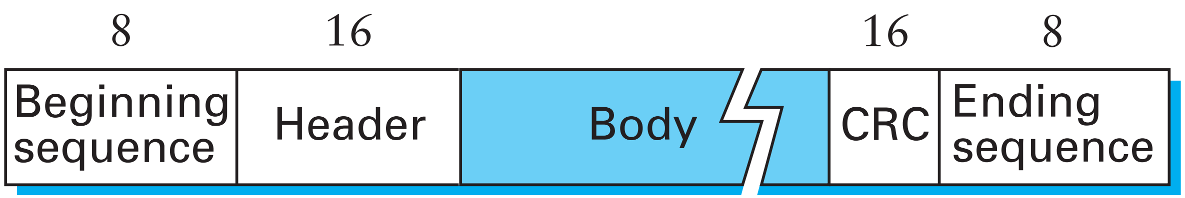
- **Byte-oriented protocols (*e.g.* BISYNC, PPP)**
  - Place special bytes (SOH, ETX,…) in the beginning, end of messages



- **What if ETX appears in the body?**
  - Escape ETX byte by prefixing DEL byte
  - Escape DEL byte by prefixing DEL byte
  - Technique known as *character stuffing*

Bit-Oriented Protocols

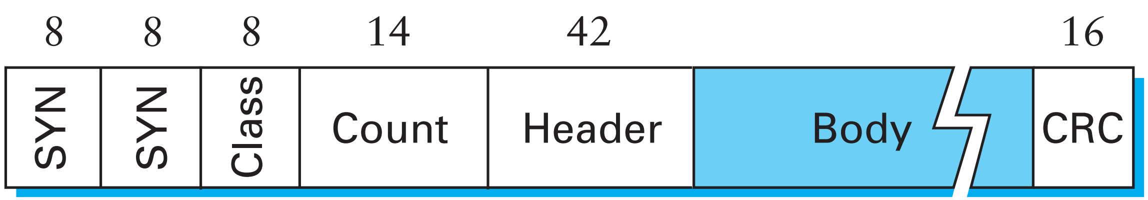
- **View message as a stream of bits, not bytes**
- **Can use sentinel approach as well (*e.g.*, HDLC)**



  – HDLC begin/end sequence 01111110
- **Use *bit stuffing* to escape 01111110**
  – Always append 0 after five consecutive 1s in data
  – After five 1s, receiver uses next two bits to decide if stuffed, end of frame, or error.

Length-based Framing

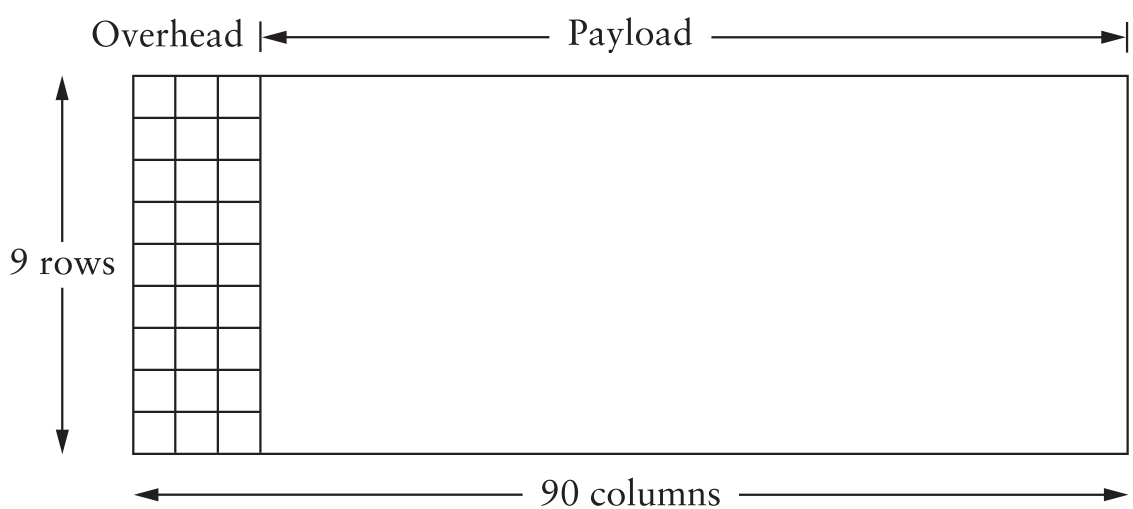
- **Drawback of sentinel techniques**
  - Length of frame depends on data
- **Alternative: put length in header (*e.g.*, DDCMP)**



- **Danger: Framing Errors**
  - What if high bit of counter gets corrupted?
  - Adds 8K to length of frame, may lose many frames
  - CRC checksum helps detect error

Clock-based Framing

- *E.g.*, SONET (Synchronous Optical Network)
  - Each frame is 125μs long
  - Look for header every 125μs
  - Encode with NRZ, but first XOR payload with 127-bit string to ensure lots of transitions



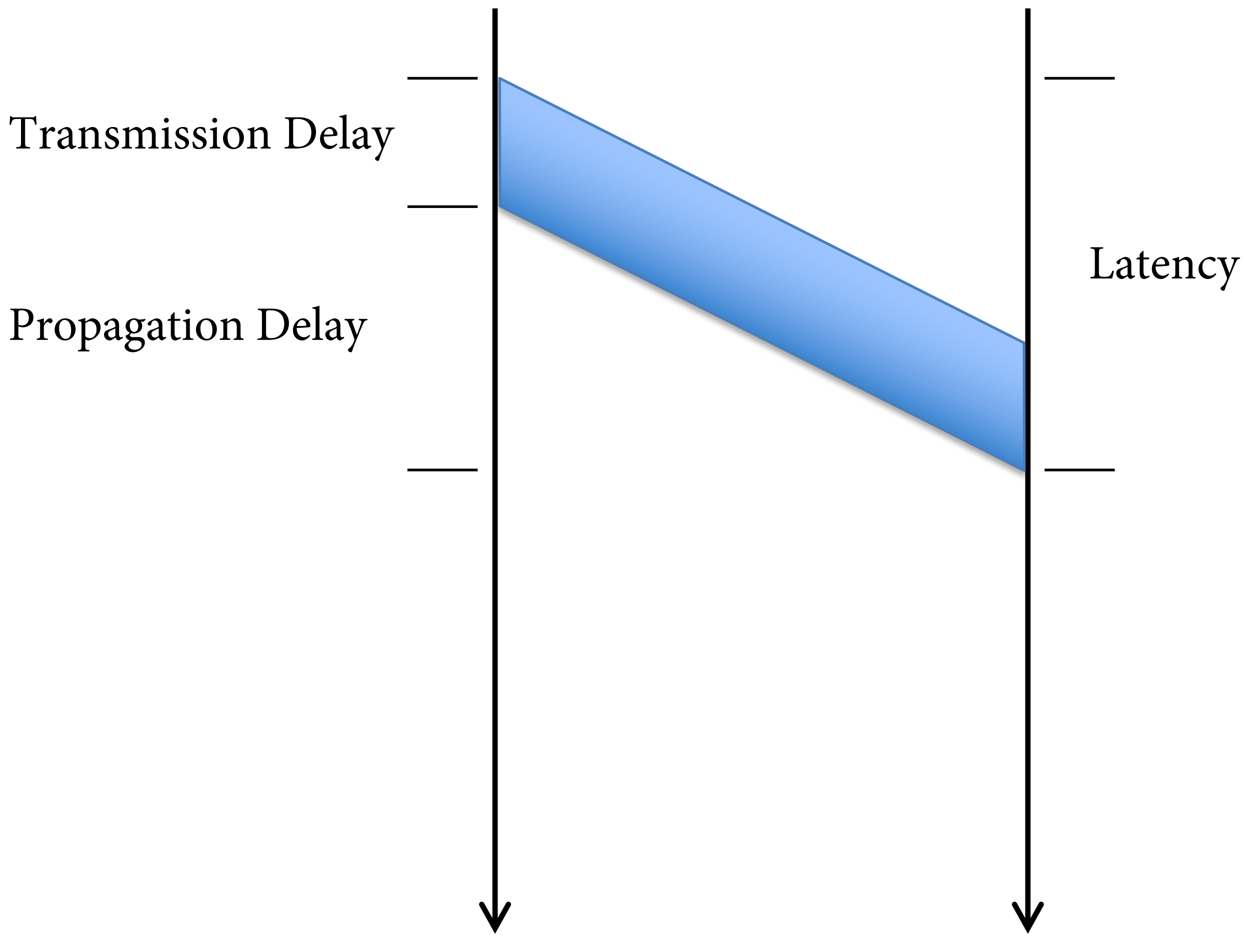
Error Detection

- **Basic idea: use a checksum**
  - Compute small checksum value, like a hash of packet
- **Good checksum algorithms**
  - Want several properties, *e.g.*, detect any single-bit error
  - Details later

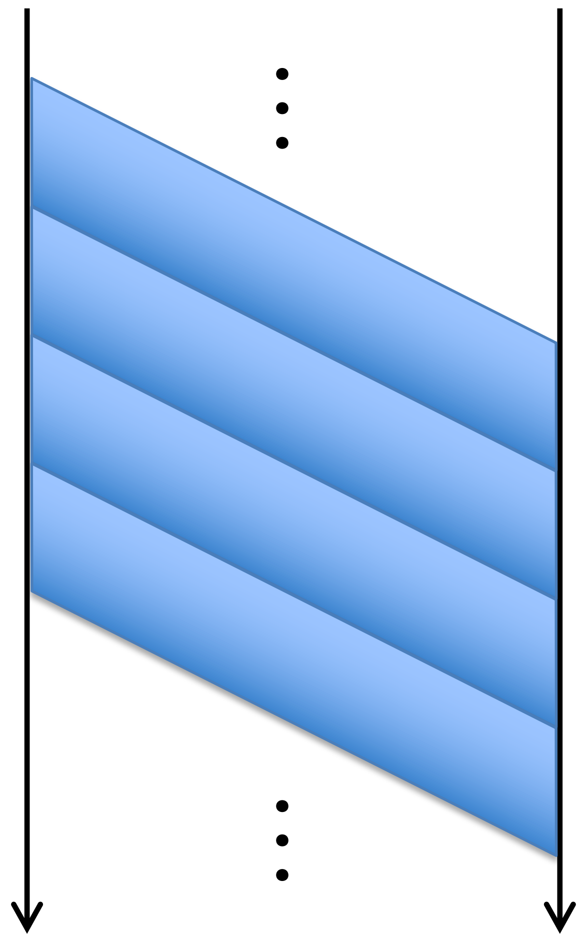
Link Layer

Getting Frames Across
Reliability and Performance

Sending Frames Across



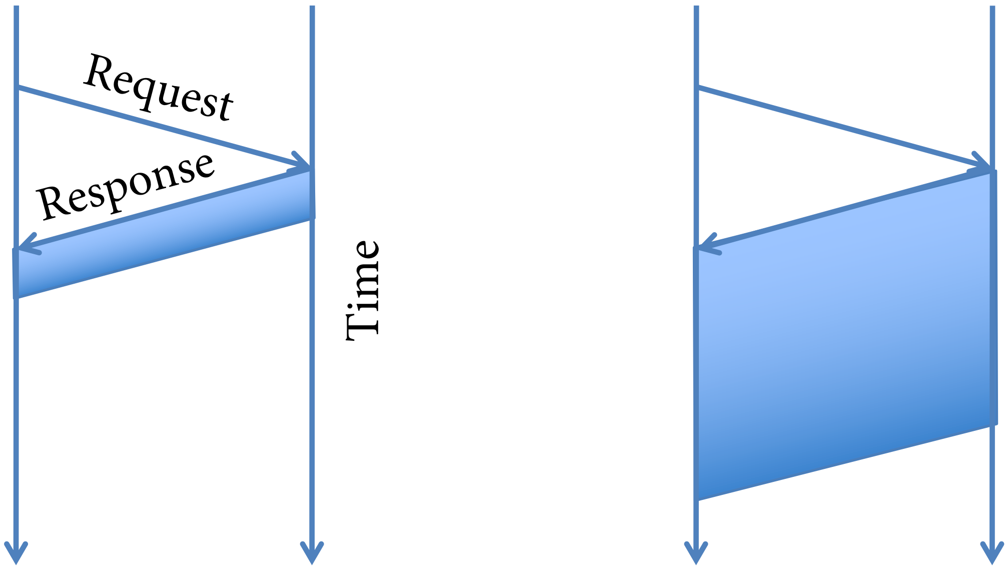
Sending Frames Across



Throughput: bits / s

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

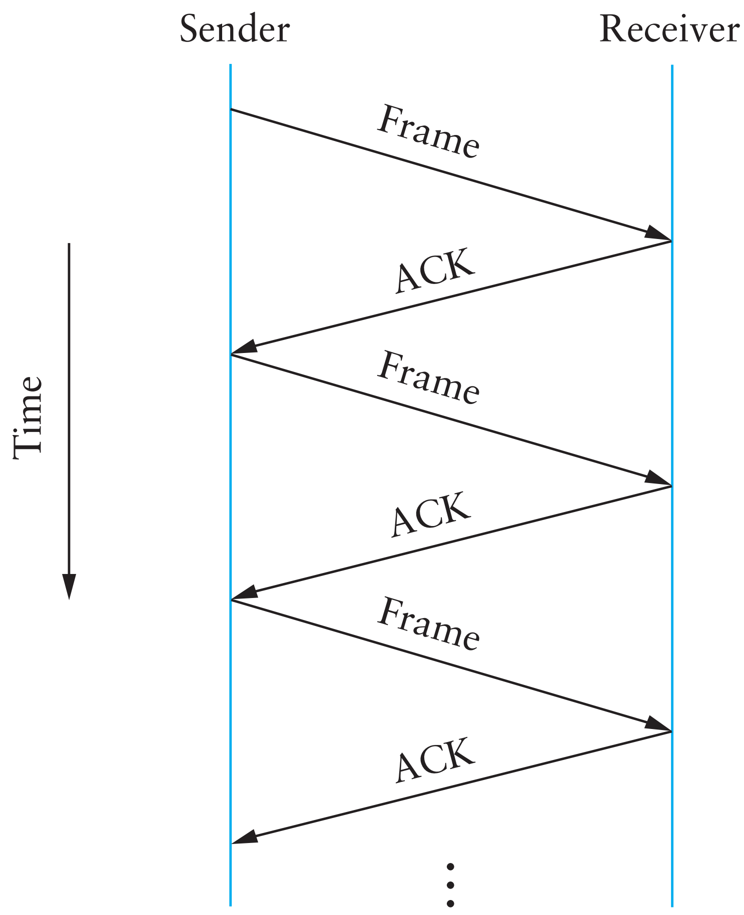
- **Processing**
  - Per message, small, limits throughput
  - *e.g.* $\frac{100Mb}{s} \times \frac{pkt}{1500B} \times \frac{B}{8b} \approx 8{,}333 pkt/s$ or 120μs/pkt
- **Queue**
  - Highly variable, offered load vs outgoing b/w
- **Transmission**
  - Size/Bandwidth
- **Propagation**
  - Distance/Speed of Light

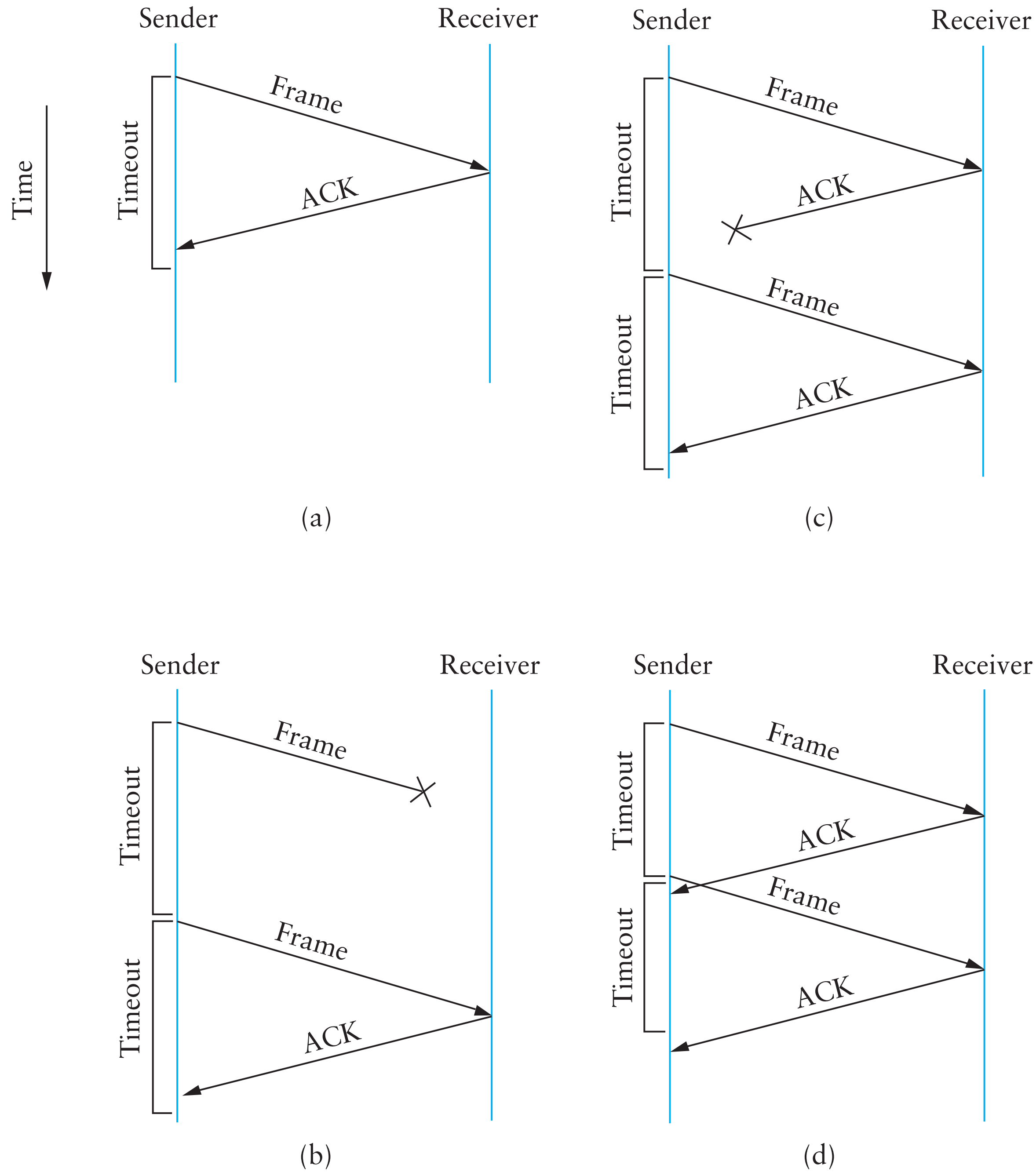
Reliable Delivery

- **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

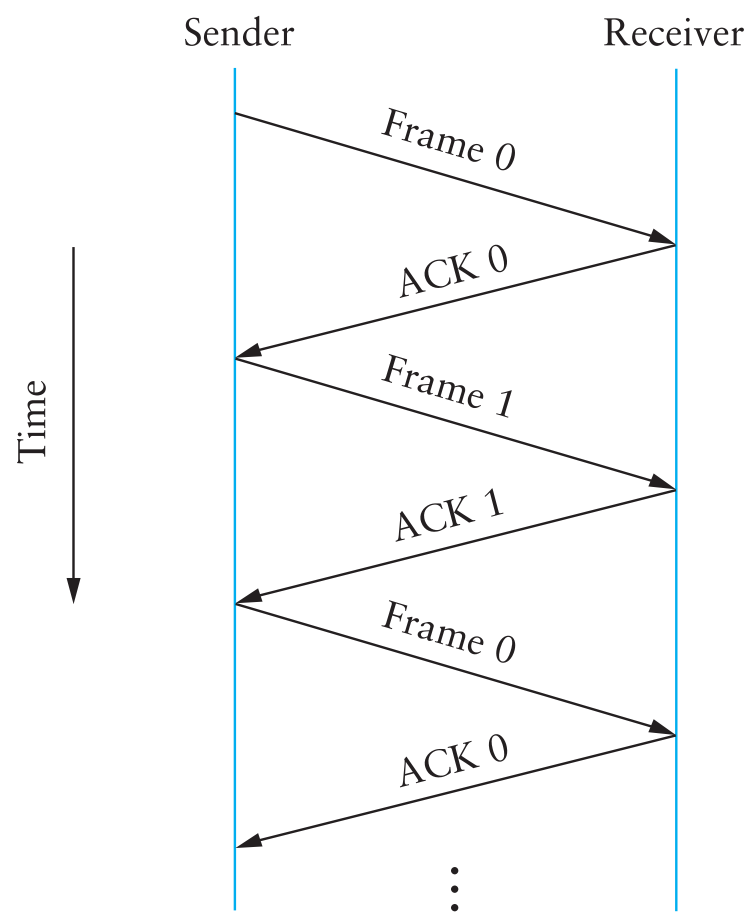

Sender
Receiver
Frame
ACK
Frame
ACK
Frame
ACK
Time


Sender
Receiver
Time
Timeout
Frame
ACK
(a)
Sender
Receiver
Timeout
Frame
ACK
Timeout
Frame
ACK
(c)
Sender
Receiver
Timeout
Frame
Timeout
Frame
ACK
(b)
Sender
Receiver
Timeout
Frame
ACK
Timeout
Frame
ACK
(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

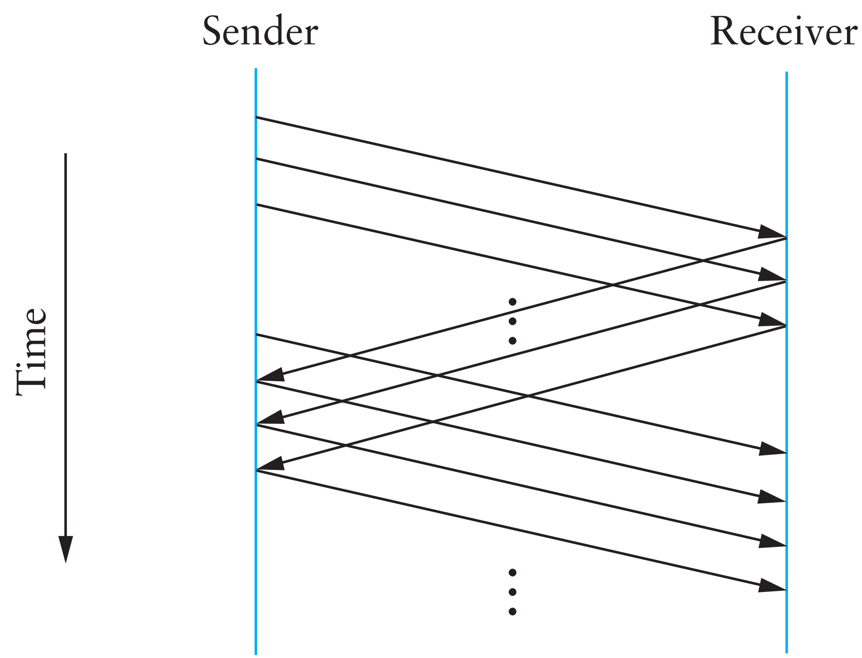


At Most Once Semantics

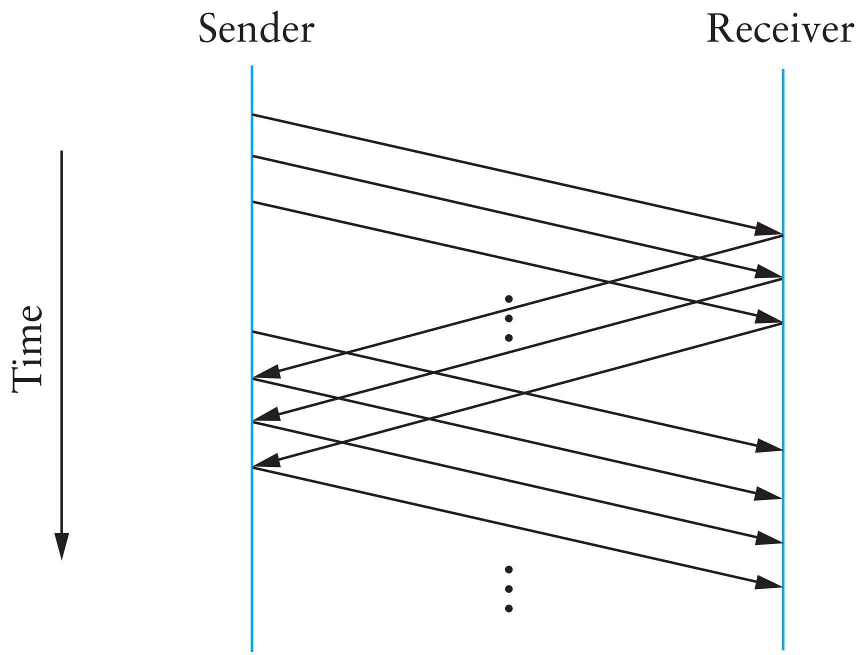
- **How to avoid duplicates?**
  - Uniquely identify each packet
  - Have receiver and sender remember
- **Stop and Wait: add 1 bit to the header**
  - Why is it enough?

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?



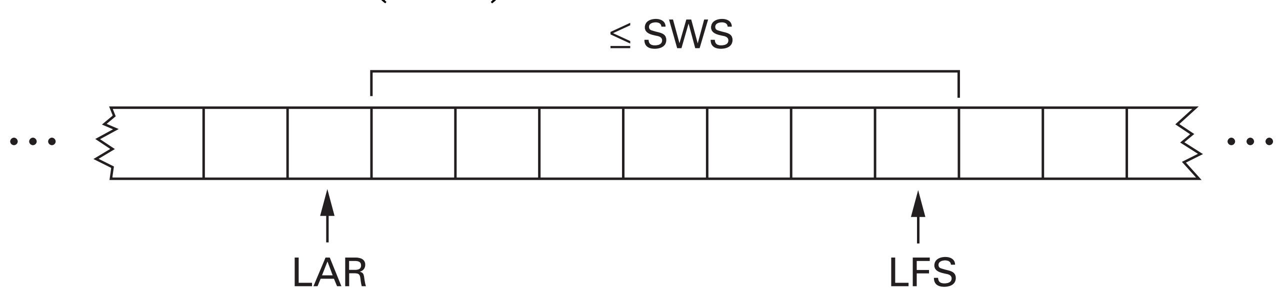
- **How many bytes can we transmit in one RTT?**
  - BW B/s x RTT s => "Bandwidth-Delay Product"

Maximizing Throughput

- **Can view network as a pipe**
  - For full utilization want bytes in flight ≥ bandwidth × 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 ≤ 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 ≤ RWS**
- **Frame SeqNum arrives:**
  - if LFR < SeqNum ≤ LAF, accept
  - if SeqNum ≤ 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 and Correction

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

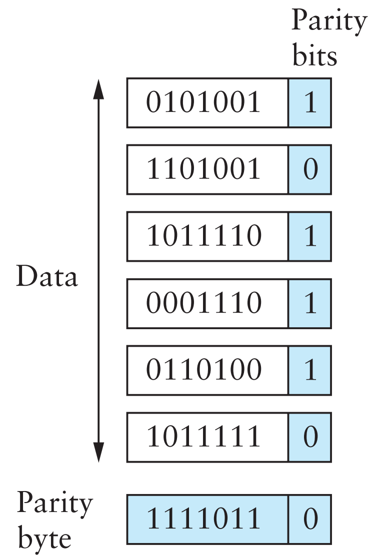
Parity

- **Add a parity bit to the end of a word**
- **Example with 2 bits:**
  - Valid: 000 011 101 110
  - 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 $\lfloor (d\text{-}1)/2 \rfloor$ 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**

We did not cover these...

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--)
        if ((sum += *buf++) & 0xffff0000) // carry
            sum = (sum & 0xffff) + 1;
    return ~(sum & 0xffff);
}
```

- **Checking**
  - Do the sum again, including the checksum. If correct, the sum should be all 1's (This is super fast to check)

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 $Z_2[x]$**
  - Each bit is one coefficient
  - E.g., message 10101001 -> $m(x) = x^7 + x^5 + x^3 + 1$
- **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 **mod** 5 = 1

Polynomial Division Example

- **Just long division, but addition/subtraction is XOR**

```
                 11111001
Generator → 1101)10011010000 ← Message
                 1101
                  1001
                  1101
                   1000
                   1101
                    1011
                    1101
                     1100
                     1101
                        1000
                        1101
                         101 ← Remainder
```

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

- **Erasure 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 or 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 $t_{n'}$=$t_{n'}$ XOR s_n
- **Delete s_n from all encoding lists**
- **Finish if**
  1. You decode all source blocks, or
  2. You run out out blocks of degree 1

Next class

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