Reliable Byte-Stream (TCP)

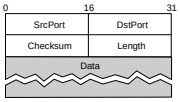
Outline
- Connection Establishment/Termination
- Sliding Window Revisited
- Flow Control
- Adaptive Timeout

End-to-End Protocols

- Underlying best-effort network
  - drop messages
  - re-orders messages
  - delivers duplicate copies of a given message
  - limits messages to some finite size
  - delivers messages after an arbitrarily long delay
- Common end-to-end services
  - guarantee message delivery
  - deliver messages in the same order they are sent
  - deliver at most one copy of each message
  - support arbitrarily large messages
  - support synchronization
  - allow the receiver to flow control the sender
  - support multiple application processes on each host

Simple Demultiplexor (UDP)

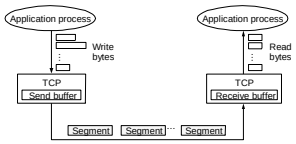
- Unreliable and unordered datagram service
- Adds multiplexing
- No flow control
- Endpoints identified by ports
  - servers have *well-known* ports
  - see **`/etc/services`** on Unix
- Header format



- Optional checksum
  - psuedo header + UDP header + data

TCP Overview

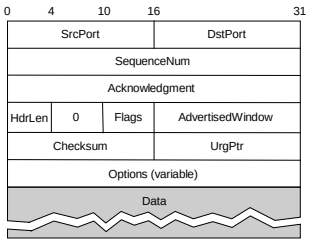
- Connection-oriented
- Byte-stream
  - app writes bytes
  - TCP sends *segments*
  - app reads bytes
- Full duplex
- Flow control: keep sender from overrunning receiver
- Congestion control: keep sender from overrunning network



Data Link Versus Transport

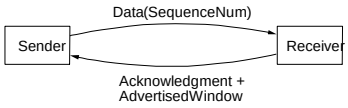
- Potentially connects many different hosts
  - need explicit connection establishment and termination
- Potentially different RTT
  - need adaptive timeout mechanism
- Potentially long delay in network
  - need to be prepared for arrival of very old packets
- Potentially different capacity at destination
  - need to accommodate different node capacity
- Potentially different network capacity
  - need to be prepared for network congestion

Segment Format



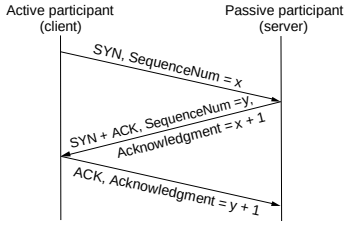
Segment Format (cont)

- Each connection identified with 4-tuple:
  - **`(SrcPort, SrcIPAddr, DsrPort, DstIPAddr)`**
- Sliding window + flow control
  - **`acknowledgment, SequenceNum, AdvertisedWinow`**

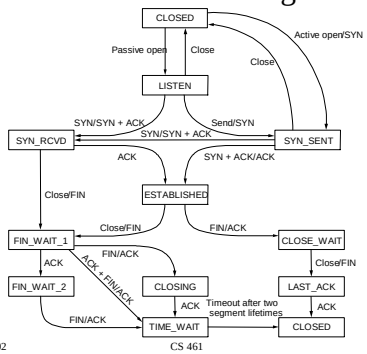


- Flags
  - **`SYN, FIN, RESET, PUSH, URG, ACK`**
- Checksum
  - pseudo header + TCP header + data

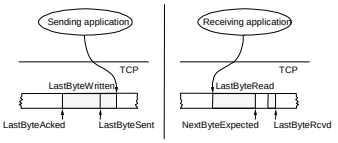
Connection Establishment and Termination



State Transition Diagram



Sliding Window Revisited



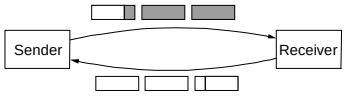
- Sending side
  - **`LastByteAcked`** < = **`LastByteSent`**
  - **`LastByteSent`** < = **`LastByteWritten`**
  - buffer bytes between **`LastByteAcked`** and **`LastByteWritten`**
- Receiving side
  - **`LastByteRead`** < **`NextByteExpected`**
  - **`NextByteExpected`** < = **`LastByteRcvd +1`**
  - buffer bytes between **`NextByteRead`** and **`LastByteRcvd`**

Flow Control

- Send buffer size: **`MaxSendBuffer`**
- Receive buffer size: **`MaxRcvBuffer`**
- Receiving side
  - **`LastByteRcvd`** - **`LastByteRead`** < = **`MaxRcvBuffer`**
  - **`AdvertisedWindow`** = **`MaxRcvBuffer`** - (**`NextByteExpected`** - **`NextByteRead`**)
- Sending side
  - **`LastByteSent`** - **`LastByteAcked`** < = **`AdvertisedWindow`**
  - **`EffectiveWindow`** = **`AdvertisedWindow`** - (**`LastByteSent`** - **`LastByteAcked`**)
  - **`LastByteWritten`** - **`LastByteAcked`** < = **`MaxSendBuffer`**
  - block sender if (**`LastByteWritten`** - **`LastByteAcked`**) + *y* > **`MaxSenderBuffer`**
- Always send ACK in response to arriving data segment
- Persist when **`AdvertisedWindow = 0`**

Silly Window Syndrome

- How aggressively does sender exploit open window?



- Receiver-side solutions
  - after advertising zero window, wait for space equal to a maximum segment size (MSS)
  - delayed acknowledgements

Nagle's Algorithm

- How long does sender delay sending data?
  - too long: hurts interactive applications
  - too short: poor network utilization
  - strategies: timer-based vs self-clocking
- When application generates additional data
  - if fills a max segment (and window open): send it
  - else
    - if there is unack'ed data in transit: buffer it until ACK arrives
    - else: send it

Protection Against Wrap Around

- 32-bit **`SequenceNum`**

Bandwidth	Time Until Wrap Around
T1 (1.5 Mbps)	6.4 hours
Ethernet (10 Mbps)	57 minutes
T3 (45 Mbps)	13 minutes
FDDI (100 Mbps)	6 minutes
STS-3 (155 Mbps)	4 minutes
STS-12 (622 Mbps)	55 seconds
STS-24 (1.2 Gbps)	28 seconds

Keeping the Pipe Full

- 16-bit **`AdvertisedWindow`**

Bandwidth	Delay x Bandwidth Product
T1 (1.5 Mbps)	18KB
Ethernet (10 Mbps)	122KB
T3 (45 Mbps)	549KB
FDDI (100 Mbps)	1.2MB
STS-3 (155 Mbps)	1.8MB
STS-12 (622 Mbps)	7.4MB
STS-24 (1.2 Gbps)	14.8MB

assuming 100ms RTT

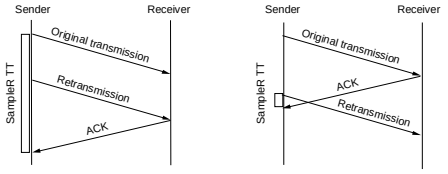
TCP Extensions

- Implemented as header options
- Store timestamp in outgoing segments
- Extend sequence space with 32-bit timestamp (PAWS)
- Shift (scale) advertised window

Adaptive Retransmission (Original Algorithm)

- Measure **`SampleRTT`** for each segment / ACK pair
- Compute weighted average of RTT
  - **`EstRTT`** = α x **`EstRTT`** + β x **`SampleRTT`**
  - where $\alpha + \beta = 1$
  - α between 0.8 and 0.9
  - β between 0.1 and 0.2
- Set timeout based on **`EstRTT`**
  - **`TimeOut`** = **`2`** x **`EstRTT`**

Karn/Partridge Algorithm



- Do not sample RTT when retransmitting
- Double timeout after each retransmission

Jacobson/ Karels Algorithm

- New Calculations for average RTT
- **Diff** = **SampleRTT** - **EstRTT**
- **EstRTT = EstRTT + (δ** x **Diff)**
- **Dev = Dev + δ(|Diff| - Dev)**
  - where δ is a factor between 0 and 1
- Consider variance when setting timeout value
- **TimeOut** = μ x **EstRTT** + ϕ x **Dev**
  - where $\mu = 1$ and $\phi = 4$
- Notes
  - algorithm only as good as granularity of clock (500ms on Unix)
  - accurate timeout mechanism important to congestion control (later)