CHAPTER 5
End-to-End protocols

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Fall 2001
End-to-End (Transport) Protocols

- Underlying best-effort network
  - drops 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 apply flow control to the sender
  - support multiple application processes on each host

Simple Demultiplexer (UDP)

- Unreliable and unordered datagram service
- Adds multiplexing - multiple connections between hosts
- No flow control
- Endpoints identified by ports (16 bits - \(2^{16} = 64K\) possible per host)
  - servers have well-known ports
  - client and server use these to agree on other port for communication
  - see /etc/services on Unix
- Checksum (Optional IPv4, Mandatory IPv6) - same as IP algorithm
  - pseudo header + udp header + udp data
  - pseudo header is IP protocol number, source and destination IP addresses, UDP length field

Header format

<table>
<thead>
<tr>
<th>Src Port</th>
<th>Dest Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Check Sum</td>
<td>Length</td>
</tr>
</tbody>
</table>
Reliable Byte-Stream (TCP)

Overview

- Connection-oriented
- Byte-stream
  - sending process writes some number of bytes
  - TCP breaks into segments and sends via IP
  - receiving process reads some number of bytes

- Full duplex
- Flow control: keep sender from overrunning receiver
- Congestion control: keep sender from overrunning network

End-to-End Issues

Based on sliding window protocol used at data link level, but the situation is very different.

1. Potentially connects many different hosts
   - need explicit connection establishment and termination
2. Potentially different RTT
   - need adaptive timeout mechanism
3. Potentially long delay in network
   - need to be prepared for arrival of very old packets
   - is limit, discarded after TTL
   - MSL (maximum segment lifetime) - recommended 120 sec
4. Potentially different capacity at destination
   - need to accommodate different amounts of buffering
5. Potentially different network capacity
   - need to be prepared for network congestion
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Reliable Byte-Stream (TCP)

Segment Format

<table>
<thead>
<tr>
<th>Src Port</th>
<th>Dest Port</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SequenceNum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acknowledgement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HdrLen 0 Flags 0</th>
<th>Advertised Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CheckSum</th>
<th>UrgPtr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>options (variable)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

- Each connection identified with 4-tuple:
  - (SrcPort, SrcIPAddr, DstPort, DstIPAddr)
- Sliding window + flow control
  - Acknowledgment, SequenceNum, AdvertisedWindow

Flags

- SYN: TCP connection establishing
- FIN: TCP connection terminating
- RESET: Receiver is confused - abort connection
- PUSH: Sender invokes push operation
- URG: segment contains urgent data
- ACK: Acknowledgment

Checksum

- pseudo header + tcp header + data

When does TCP send segment?

1. After MSS (Maximum Segment Size) bytes are buffered
   - usually largest size that IP will not fragment
   - MSS = MTU - sizeof(TCP + IP headers)
2. if sender flushes buffer with push operation
   - Telnet does after each character
3. when timer expires
**Connection Establishment and Termination**

**Three-Way Handshake**

<table>
<thead>
<tr>
<th>Active Participant</th>
<th>Passive Participant</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYN, SequenceNum = x</td>
<td>SYN + ACK, SequenceNum = y</td>
</tr>
<tr>
<td>Acknowledgement = x + 1</td>
<td>Acknowledgement = y + 1</td>
</tr>
</tbody>
</table>

- Each byte has a sequence number
- ACKs are cumulative
- Sending side
  - LastByteAcked ≤ LastByteSent
  - LastByteSent ≤ LastByteWritten
  - bytes between LastByteAcked and LastByteWritten must be buffered
- Receiving side
  - LastByteRead < NextByteExpected, Why?
  - NextByteExpected ≤ LastByteRcvd + 1, Why?
Flow Control

- Receiver advertises a window size to prevent buffer overflow
- Sender buffer size: MaxSendBuffer
- Receive buffer size: MaxRcvBuffer
- Receiving side
  - LastByteRcvd - LastByteRead \leq MaxRcvBuffer
  - AdvertisedWindow = MaxRcvBuffer - (LastByteRcvd - LastByteRead)
- Sending side
  - LastByteSent - LastByteAcked \leq AdvertisedWindow
  - EffectiveWindow = AdvertisedWindow - (LastByteSent - LastByteAcked)
  - LastByteWritten - LastByteAcked \leq MaxSendBuffer
  - TCP blocks sender from sending $y$ bytes if $(LastByteWritten - LastByteAcked) + y > MaxSendBuffer$
- Always send ACK in response to an arriving data segment, but not otherwise
- Sender persists in sending 1 byte when AdvertisedWindow=0
- Eventually ACK will arrive with new AdvertisedWindow

Keeping the Pipe Full

- Wrap Around: 32-bit SequenceNum - want no wrap in 120 sec

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Time Until Wrap Around</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 (1.5Mbps)</td>
<td>6.4 hours</td>
</tr>
<tr>
<td>32/ (1.544/8)</td>
<td>6.18 hrs</td>
</tr>
<tr>
<td>Ethernet (10Mbps)</td>
<td>57 minutes</td>
</tr>
<tr>
<td>T3 (45Mbps)</td>
<td>13 minutes</td>
</tr>
<tr>
<td>FDDI (100Mbps)</td>
<td>6 minutes</td>
</tr>
<tr>
<td>STS-3 (155Mbps)</td>
<td>4 minutes</td>
</tr>
<tr>
<td>STS-12 (622Mbps)</td>
<td>55 seconds</td>
</tr>
<tr>
<td>STS-24 (1.2Gbps)</td>
<td>28 seconds</td>
</tr>
</tbody>
</table>

- Bytes in Transit: 16-bit AdvertisedWindow allows 64KB of data in pipe

<table>
<thead>
<tr>
<th>Bandwidth</th>
<th>Delay \times Bandwidth Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 (1.5Mbps)</td>
<td>18KB</td>
</tr>
<tr>
<td>Ethernet (10Mbps)</td>
<td>122KB</td>
</tr>
<tr>
<td>T3 (45Mbps)</td>
<td>549KB</td>
</tr>
<tr>
<td>FDDI (100Mbps)</td>
<td>1.2MB</td>
</tr>
<tr>
<td>STS-3 (155Mbps)</td>
<td>1.8MB</td>
</tr>
<tr>
<td>STS-12 (622Mbps)</td>
<td>7.4MB</td>
</tr>
<tr>
<td>STS-24 (1.2Gbps)</td>
<td>14.8MB</td>
</tr>
</tbody>
</table>
Adaptive Retransmission

Original Algorithm

- Measure SampleRTT for each segment/ACK pair
- Compute weighted average of RTT
  - \( \text{EstimatedRTT} = \alpha \times \text{EstimatedRTT} + \beta \times \text{SampleRTT} \)
  - where \( \alpha + \beta = 1 \)
  - \( \alpha \) between 0.8 and 0.9
  - \( \beta \) between 0.1 and 0.2
- Set timeout based on EstimatedRTT
  - \( \text{TimeOut} = 2 \times \text{EstimatedRTT} \)

A flaw

- Does ACK really acknowledges a transmission?
- No, it acknowledges receipt of a segment
- How many retransmissions had taken place before ACK arrived?

Wrong samples

(a) Sample RTT too long
- in (a) sample should be for the second attempt

(b) Sample RTT too short
- in (b) sample should be for the first attempt

Karn/Partridge Algorithm

- Do not sample RTT when retransmitting
- Double timeout after each retransmission
  - Similar to backoff algorithm
Jacobson/Karels Algorithm

- Karn/Partridge algorithm was introduced when the Internet was not suffering the current congestion
- Consider variance when setting timeout value
- Jacobson/Karels came up with a new calculation for average RTT
  \[
  \text{Difference} = \text{SampleRTT} - \text{EstimatedRTT}
  \]
  \[
  \text{EstimatedRTT} = \text{EstimatedRTT} + (\delta \times \text{Difference})
  \]
  \[
  \text{Deviation} = \text{Deviation} + \delta \left( |\text{Difference}| - \text{Deviation} \right)
  \]
  where \( \delta \) is a fraction between 0 and 1
- TimeOut = \( \mu \times \text{EstimatedRTT} + \phi \times \text{Deviation} \)
  where \( \mu = 1 \) and \( \phi = 4 \)

Remote Procedure Call

- Common pattern of communication used by application programs
- Also called message transaction
Peterson divides RPC protocol into three basic functions:

- **BLAST**: fragments and assembles large messages.
- **CHAN**: synchronizes request and reply messages.
- **SELECT**: dispatches request messages to the correct process.

**Bulk Transfer (BLAST)**

Unlike AAL and IP in that it tries to recover from lost fragments; persistent, but does not guarantee delivery. Strategy is to use selective retransmission (or partial acknowledgments).
BLAST Header Format

| ProtoNum | MID | Length | NumFrags | Type | FragMask |

- MID must protect against wrap around
- Type = DATA or SRR
- NumFrags indicates number of fragments in message
- FragMask distinguishes among fragments:
  - if Type=DATA, identifies this fragment
  - if Type=SRR, identifies missing fragments

Request/Reply (CHAN)

Guarantees message delivery, and synchronizes client with server; i.e., blocks client until reply received. Supports \textit{at-most-once} semantics.

Simple case:

Implicit Acknowledgments:
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Remote Procedure Call

Dispatcher (SELECT)
Dispatches request messages to the appropriate procedure; fully synchronous counterpart to UDP.

Address Space for Procedures
- Flat: unique id for each possible procedure
- Hierarchical: program + procedure within program

Putting it All Together
Simple RPC Stack