Transport Layer III

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Chapter 3: Roadmap

3.1 Transport-layer services
3.2 Multiplexing and demultiplexing
3.3 Connectionless transport: UDP
3.4 Principles of reliable data transfer (cont)
3.5 Connection-oriented transport: TCP
   - Segment structure
   - Reliable data transfer
   - Flow control
   - Connection management
3.6 Principles of congestion control
3.7 TCP congestion control
**Pipelined Protocols**

- **Pipelining:** sender allows multiple, “in-flight”, yet-to-be-acknowledged pkts
  - Range of sequence numbers must be increased
  - Buffering at sender and/or receiver

- Two generic forms of pipelined protocols: **Go-Back-N** and **Selective Repeat**
Pipelining: Increased Utilization

- First packet bit transmitted, $t = 0$
- Last bit transmitted, $t = L / R$
- Last packet bit arrives, send ACK
- Last bit of 2$^{nd}$ packet arrives, send ACK
- Last bit of 3$^{rd}$ packet arrives, send ACK

Increases utilization by a factor of 3!

\[ U_{\text{sender}} = \frac{3 \times L / R}{RTT + L / R} = \frac{0.024}{30.008} = 0.0008 \]
Go-Back-N (GBN)

Sender:

- **Window** of up to $N$ consecutive unack’ed pkts allowed
- A field in header that holds $k$ unique seq numbers

- ACK(n): ACKs all consecutive pkts up to & including seq # $n$ (cumulative ACK)
  - Means packets 1...n have been delivered to application
- Timer for the oldest unacknowledged pkt (send_base):
  - Upon timeout: retransmit all pkts in current window (yellow in the figure); reset the timer
GBN: Sender Extended FSM

\[
\text{rdt\_send(data)} \\
\text{if (nextseqnum < base+N) \{} \\
\text{sndpkt[nextseqnum] = make_pkt(nextseqnum, data, chksum)} \\
\text{udt\_send (sndpkt[nextseqnum])} \\
\text{if (base == nextseqnum) start\_timer} \\
\text{nextseqnum++} \\
\text{\}} \\
\text{else refuse\_data(data)} \\
\\]

\[
\begin{align*}
\text{timeout} & \quad \text{start\_timer} \\
\text{udt\_send(sndpkt[base])} \\
\text{udt\_send(sndpkt[base+1])} \\
& \quad \ldots \\
\text{udt\_send(sndpkt[nextseqnum-1])}
\end{align*}
\]

**Diagram**

- Wait

\[
\begin{align*}
\Lambda & \quad \text{base=1} \\
\text{nextseqnum=1} & \quad \text{timeout} \quad \text{start\_timer} \\
\text{rdt\_rcv(rcvpkt) \&\& corrupt(rcvpkt)} & \quad \Lambda \\
\Lambda & \quad \text{rdt\_rcv(rcvpkt) \&\& NOT corrupt(rcvpkt)} \\
\text{new\_base = getacknum(rcvpkt)+1} & \quad \text{if (new\_base > base) \{} \\
\text{base = new\_base;} & \quad \text{if (base == nextseqnum) \{} \\
\text{stop\_timer} & \quad \text{// last ACK in window} \\
\text{else start\_timer \} }
\end{align*}
\]
GBN: Receiver Extended FSM

- **ACK-only**: always send ACK for correctly-received pkt with highest *in-order* seq #
  - Duplicate ACKs during loss
  - Need only remember `expectedseqnum`

- **Out-of-order pkt**:
  - Discard \( \rightarrow \) *no receiver buffering!*
  - Re-ACK pkt with highest in-order seq #
GBN in Action

Sender (N=4)

1
2
3
4
5
6

Receiver

ACK1, deliver
ACK2, deliver
ACK2, discard
ACK2, discard
ACK2, discard
ACK2, discard
ACK3, deliver
ACK4, deliver
ACK5, deliver
ACK6, deliver

ignore
ignore
ignore

timeout
Selective Repeat

- Receiver *individually* acknowledges all correctly received pkts
  - Buffers pkts, as needed, for eventual in-order delivery to upper layer
- Sender only resends pkts for which ACK was not received
  - Separate timer for each unACKed pkt
- Sender window
  - $N$ consecutive packets in [snd_base, snd_base+N-1]
Selective Repeat: Sender, Receiver Windows

Sender (N=7)

- snd_base
- nextseqnum

Receiver (N=7)

- rcv_base

- sent & acked
- sent & not acked
- not sent & available
- not available
- received and delivered
- received and buffered
- expected but not received
- available slot
Selective Repeat

**sender**

Data from above:
- If next available seq # in window, send pkt

Timeout(n):
- Resend pkt n, restart timer n

ACK(n) in [snd_base, snd_base+N-1]:
- Mark pkt n as received
- If n == snd_base, advance snd_base to the next unACKed seq #

**receiver**

Receive pkt n in [rcv_base, rcv_base+N-1]
- Send ACK(n)
- Out-of-order (n>rcv_base): buffer
- In-order (n == rcv_base): deliver, advance rcv_base to next not-yet-received pkt, deliver all buffered, in-order pkts

Pkt n in [rcv_base-N, rcv_base-1]
- ACK(n)

Otherwise:
- Ignore
Selective Repeat in Action (N=4)

0 1 2 3 4 5
0 1 2 3 4 5
0 1 2 3 4 5
0 1 2 3 4 5
0 1 2 3 4 5

timeout on pkt 2

ACK0
ACK1
ACK3
ACK4
ACK5
ACK2

0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9
Selective Repeat: Dilemma

Q: How many distinct seq #s are needed for window size N in selective repeat?

Example:
- Seq #’s: 0, 1, 2, 3
- Window size = 3
- Receiver sees no difference in two scenarios!
- Incorrectly passes duplicate data as new in (a)