COMP 431
Internet Services & Protocols

The Transport Layer
Pipelined Transport Protocols

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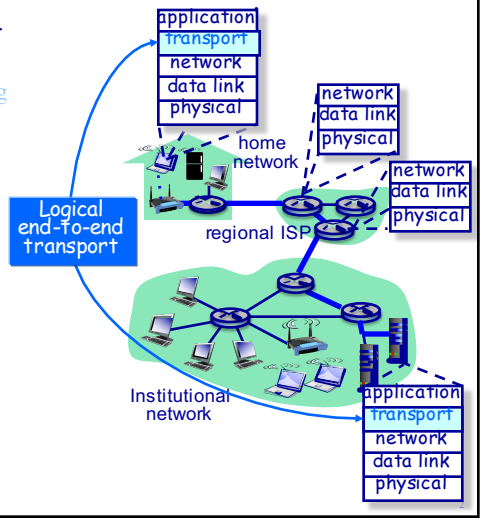
Transport Layer Protocols & Services
Outline

- Fundamental transport layer services
  - » Multiplexing/Demultiplexing
  - » Error detection
  - » Reliable data delivery
  - » Pipelining
  - » Flow control
  - » Congestion control
- Service implementation in Internet transport protocols
  - » UDP
  - » TCP



Transport Protocol Performance

Performance of RDT3.0

- Can an end-system make efficient use of a network under RDT 3.0?
- Consider a 1 Gbps link with 15 *ms* end-to-end propagation delay
- How busy is the network under RDT 3.0?

$$utilization = \frac{time\ network\ busy}{observation\ interval} = \frac{time\ to\ transmit\ a\ packet}{packet\ generation\ time}$$

- How long does it take to transmit a 1,000 byte packet?

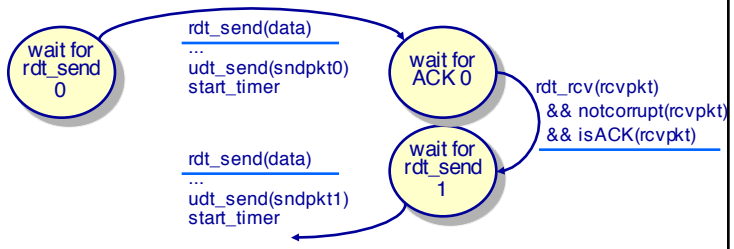
$$transmission\ time = \frac{1\ kB\ packet \times 8\ b/byte}{10^9\ bps} = 8\ \mu s$$

- How fast can an end-system generate packets?

15miliseconds + 8microseconds for packet 0

Transport Protocol Performance

Performance of RDT3.0



- How fast can an end-system generate packets?
  - » Packet transmission time = 8 *μs*
  - » Propagation delay to receiver = 15 *ms*
  - » ACK generation/transmission time ≈ 8 *μs*
  - » Propagation time for ACK to return to sender = 15 *ms*
- Best case: 1 packet every 30.016 *ms*

Transport Protocol Performance

Performance of RDT3.0

- How busy is the network under RDT 3.0?

$$utilization = \frac{time\ network\ busy}{observation\ interval} = \frac{time\ to\ transmit\ a\ packet}{packet\ generation\ time}$$

$$= \frac{8\ \mu s}{30.016\ ms} = 0.027\%$$

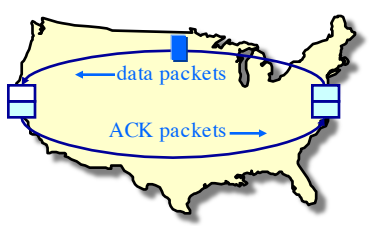
- Is this good?
  - » 1,000 byte packet every 30 *ms* results in (maximum) throughput of 266 *kbps* over a 1 Gbps link!
    (266,000 *bps* over a 1,000,000,000 *bps* link)

Network protocols limit the use of physical resources!

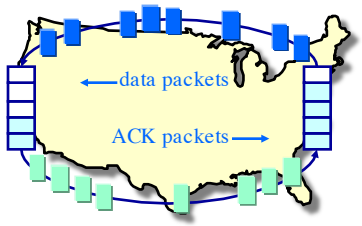
Improving Transport Protocol Performance

Pipelining data transmissions

- Performance can be improved by allowing the sender to have multiple unacknowledged packets "in flight"



Stop-and-Wait protocol



Pipelined protocol

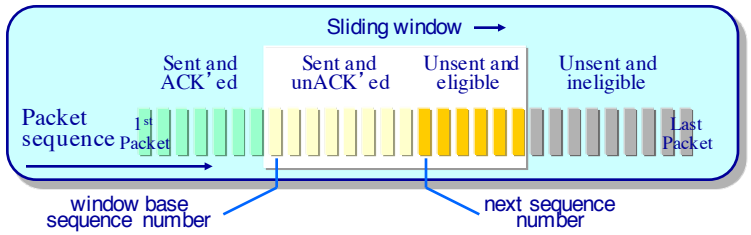
- Issues?
  - » The range of sequence numbers must be increased
  - » More packets must be buffered at sender and receiver

receiver needs to have buffer space to account for things arriving out of order

sender needs buffer space because it cant remove a file until it is confirmed to have been received byt he receiver

Pipelined Protocols

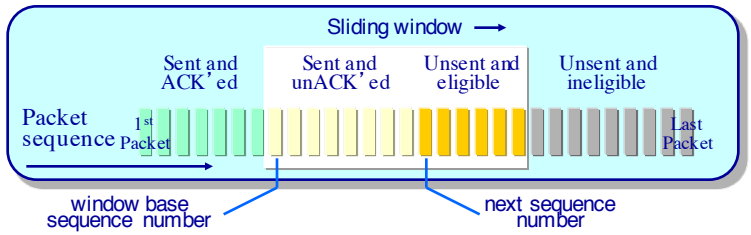
"Go-Back-*n*" protocols



- Packet header contains a k-bit sequence number
- A "window" of up to $N \leq 2^k$ consecutive, unacknowledged packets allowed to be in-flight
  - » Up to N packets may be buffered at the sender
  - » Window advances as ACKs are received
- Receiver generates "cumulative ACKs"
  - » ACKs contain the sequence number of the last in-order packet received

Pipelined Protocols

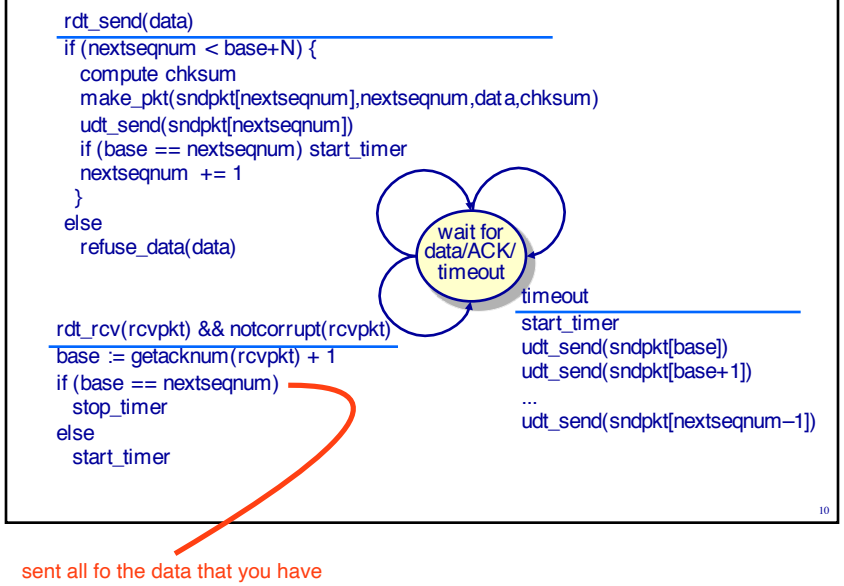
"Go-Back-*n*" protocols



- Receiver protocol
  - » Use cumulative ACKs — ACK packet n only if all packets numbered less than n have been received
  - » If losses occur, sender may receive duplicate ACKs
- Sender protocol
  - » A timer is set for each (or just the oldest) in-flight packet
  - » On timeout for packet n, retransmit packet n and **all** higher number packets in the current window

Go-Back-*n* Protocol

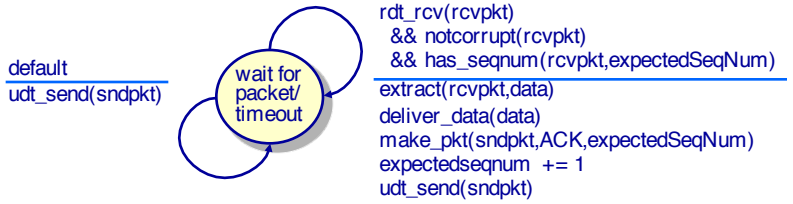
Sender extended FSM



sent all fo the data that you have

Go-Back-*n* Protocol

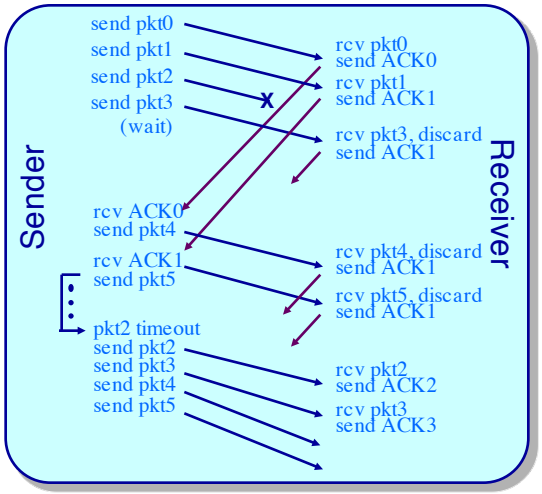
Receiver extended FSM



- In-order packets processed, out-of-order packets discarded
  - » Sender will eventually timeout and retransmit out-of-order packets
  - » Thus the receiver need not buffer any packets
- Always send ACK for correctly-received packet with highest *in-order* sequence number
  - » May generate duplicate ACKs
  - » But minimal state — need only remember *expectedseqnum*

Go-Back-*n* Protocol

Execution example



- Assume a window size of 4 packets
- Receiver ignores out-of-order packets
- Sender retransmits only on timeout
  - » (Duplicate ACKs now have no effect)

Transport Protocol Performance

Performance of Go-Back-*n* protocols

- Can an end-system make more efficient use of a network under a Go-Back-*n* protocol?
- Consider again transmitting 1,000 byte packets on a 1 Gbps link with 15 *ms* end-to-end propagation delay

$$utilization = \frac{time\ to\ transmit\ a\ packet}{packet\ generation\ time}$$

$$transmission\ time = \frac{1\ kB\ packet \times 8\ b/byte}{10^9\ bps} = 8\ \mu s$$

- How fast can an end-system transmit packets?
  - » Depends on the window size!

Transport Protocol Performance

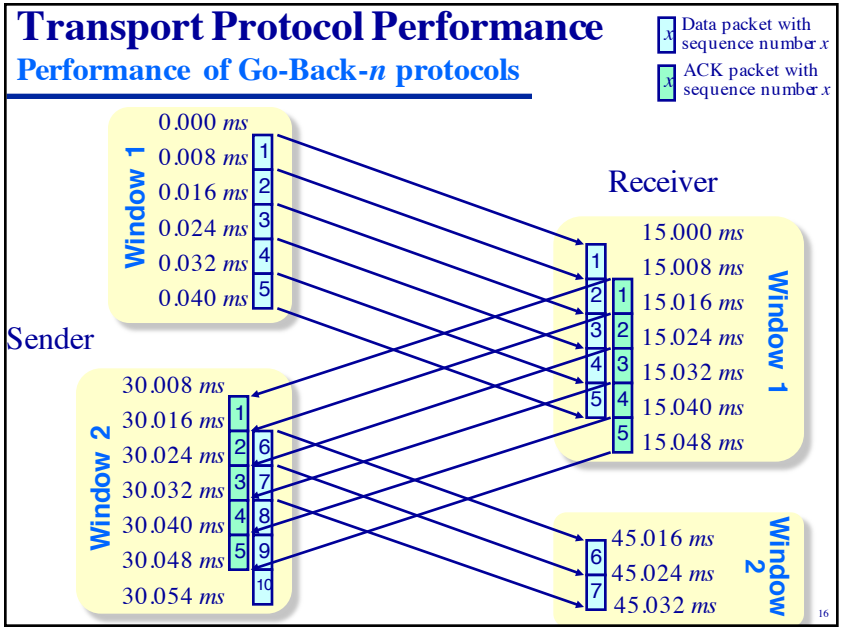
Performance of Go-Back-*n* protocols

```
rdt_send(data)
if (nextseqnum < base+N) {
  compute chksum
  make_pkt(sndpkt[nextseqnum],nextseqnum,data,chksum)
  udt_send(sndpkt[nextseqnum])
  if (base == nextseqnum) start_timer
  nextseqnum += 1
 }
```

- How fast can an end-system transmit packets?
  - » *N* packets can be sent before the sender must wait for an ACK
- *N* packets sent every 30.016 *ms*
  - » Packet generation/transmission time = 8 μs
  - » Round-trip-time to receiver = 30 *ms*
  - » ACK generation/transmission time ≈ 8 μs

Transport Protocol Performance

Performance of Go-Back-*n* protocols



Transport Protocol Performance

Performance of Go-Back-*n* protocols

- Performance with a window size of $N = 64$ packets:

$$utilization = \frac{time\ to\ transmit\ N\ packets}{time\ to\ receipt\ of\ first\ ACK} = \frac{512\ \mu s}{30.016\ ms} = 1.7\%$$

RTT

A 64x improvement!

- Is this good?
  - » 64 1,000 byte packets every 30 *ms* results in (maximum) throughput of 17 *Mbps* over a 1 Gbps link!

RTT * capacity / pktsize

Pipelined Protocols

"Selective Repeat" protocols

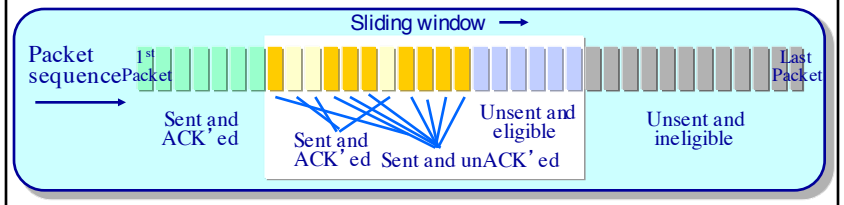
- Receiver *individually* acknowledges all correctly received packets
  - » Buffers packets as needed for eventual in-order delivery to upper layer
- Sender only resends packets for which an ACK has not been received
  - » Sender maintains a timer for each unACK'ed packet
- Sender window is the same as before
  - » *N* consecutive sequence numbers
    (Limits the sequence numbers of sent, unACK'ed packets)

Bandwidth delay product = maxi number of bits thats can be on the network at a time

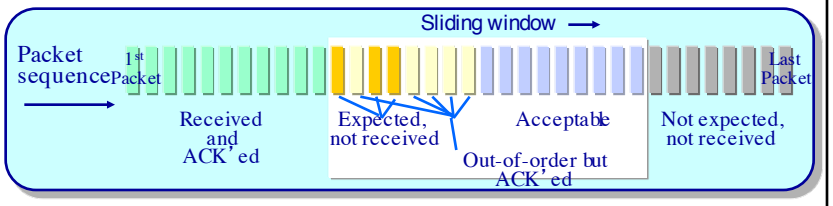
Selective Repeat Protocols

Sender and receiver windows

- Sender's view of sequence number space

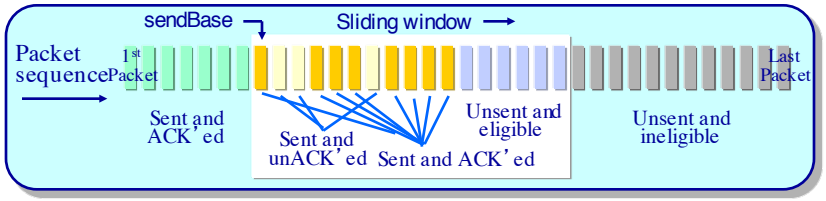


- Receiver's view of sequence number space



Selective Repeat Protocols

Sender state machine



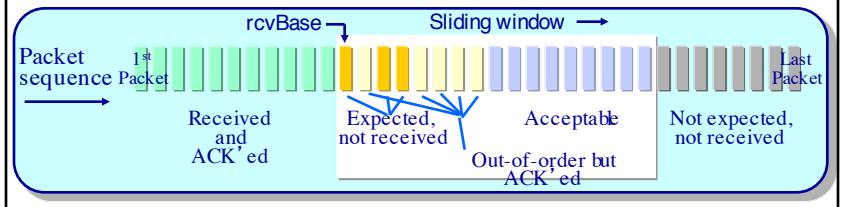
- Call from above:
  - » If next available sequence number is within window, send the packet and start a timer for it
- Timeout for packet *n*:
  - » Resend packet *n*, restart timer for packet *n*
- ACK received for packet with sequence number *n*:
  - » If *n* in [*sendBase*, *sendBase*+*N*–1] then mark packet *n* as received
  - » If *n* == *sendBase*, advance *sendBase* to next highest unACKed sequence number and move the window forward by that amount

The senders window can be to the right of the receivers but not to the left

up to go back will be on the midterm

Selective Repeat Protocols

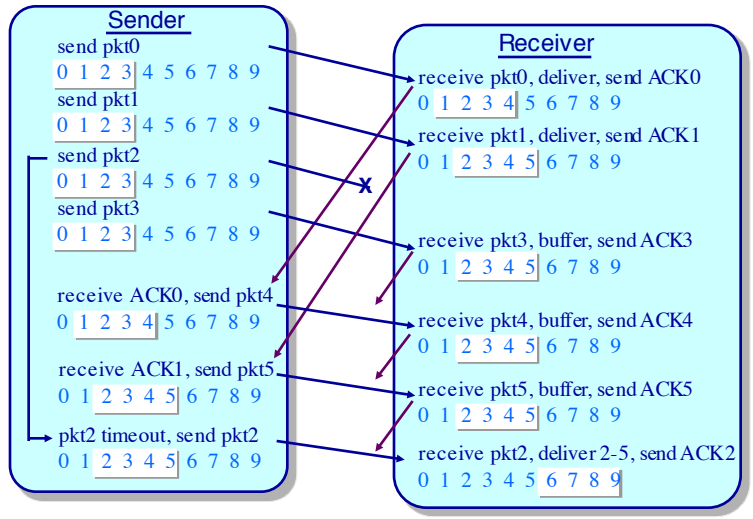
Receiver state machine



- Packet *n* in [*rcvbase*, *rcvbase*+*N*–1] correctly received:
  - » Send an ACK for packet *n*
  - » If packet *n* is out-of-order then buffer
  - » If *n* == *rcvBase*, deliver packet *n*, and all other buffered consecutive in-order packets, to application, and advance the window by the number of delivered packets
- Packet *n* in [*rcvbase*–*N*, *rcvbase*–1] received:
  - » Send an ACK for packet *n*
- Otherwise discard packet (without ACK'ing)

Selective Repeat Protocols

Execution example



Selective Repeat Protocols

Window state ambiguity

- How many sequence numbers do we need?
  - » As many as the largest number of packets that can be in flight?
- If the sequence number space is close to the window size then the receiver can get confused