COMP 431
Internet Services & Protocols

The Transport Layer
Pipelined Transport Protocols

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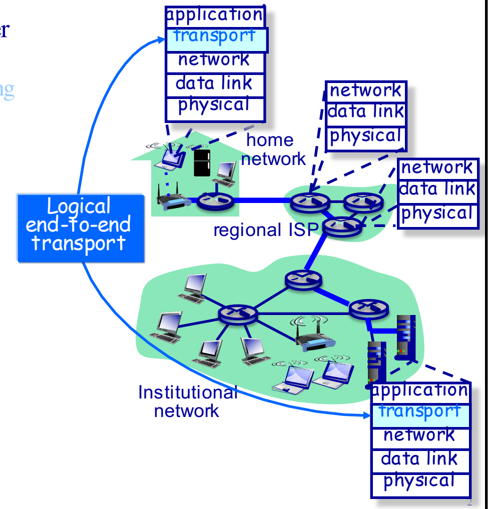
Transport Layer Protocols & Services
Outline

- 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?

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

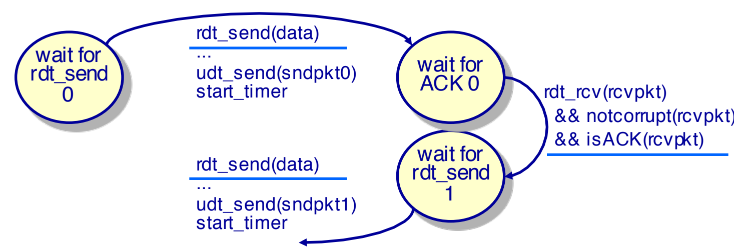
- How long does it take to transmit a 1,000 byte packet?

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

- How fast can an end-system generate packets?

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?

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

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

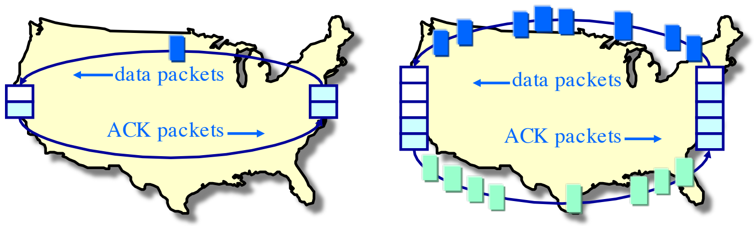
- Is this good?
  - » 1,000 byte packet every 30 *ms* results in (maximum) throughput of 266 *kbps* over a 1 Gbps link!
    (266,000 *bps* over a 1,000,000,000 *bps* link)

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"



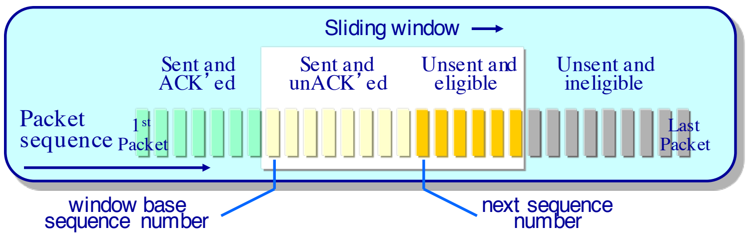
Stop-and-Wait protocol

Pipelined protocol

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

Pipelined Protocols

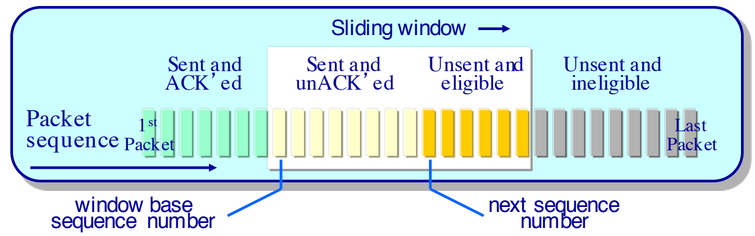
"Go-Back-*n*" protocols



- 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

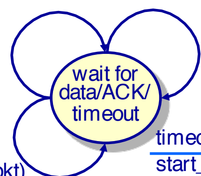


- Receiver protocol
  - » Use cumulative ACKs — ACK packet n only if all packets numbered less than n have been received
  - » If losses occur, sender may receive duplicate ACKs
- Sender protocol
  - » A timer is set for each (or just the oldest) in-flight packet
  - » On timeout for packet n, retransmit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

Go-Back-*n* Protocol

Sender extended FSM

```
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
 }
else
   refuse_data(data)
```



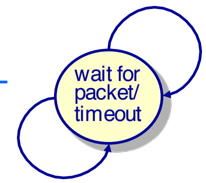

```
rdt_rcv(rcvpkt) && notcorrupt(rcvpkt)
_____________________________________
base := getacknum(rcvpkt) + 1
if (base == nextseqnum)
  stop_timer
else
  start_timer
```

```
timeout
_____________________________________
start_timer
udt_send(sndpkt[base])
udt_send(sndpkt[base+1])
...
udt_send(sndpkt[nextseqnum–1])
```


Go-Back-*n* Protocol

Receiver extended FSM

```
default
_____________________________________
udt_send(sndpkt)
```

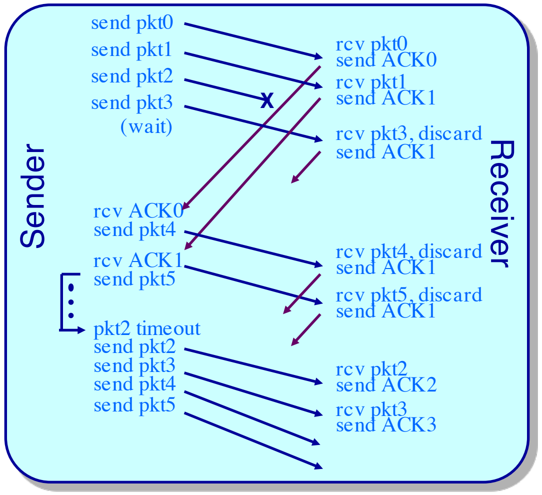



```
rdt_rcv(rcvpkt)
 && notcorrupt(rcvpkt)
 && has_seqnum(rcvpkt,expectedSeqNum)
_____________________________________
extract(rcvpkt,data)
deliver_data(data)
make_pkt(sndpkt,ACK,expectedSeqNum)
expectedseqnum += 1
udt_send(sndpkt)
```

- 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

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

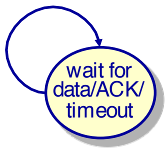
$$transmission\ time = \frac{1\ kB\ packet \times 8\ b/byte}{10^9\ bps} = 8\ \mu s$$

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

Transport Protocol Performance

Performance of Go-Back-*n* protocols

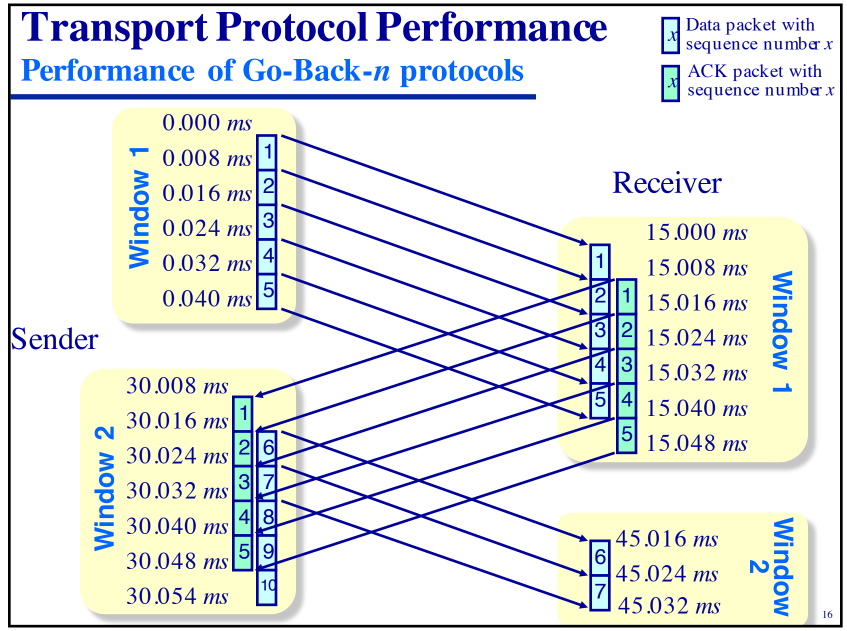
```
rdt_send(data)
if (nextseqnum < base+N) {
  compute chksum
  make_pkt(sndpkt[nextseqnum],nextseqnum,data,chksum)
  udt_send(sndpkt[nextseqnum])
  if (base == nextseqnum) start_timer
  nextseqnum += 1
}
```



- 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:

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

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!

Pipelined Protocols

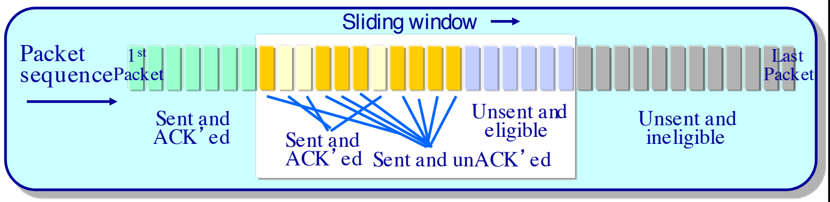
"Selective Repeat" protocols

- 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)

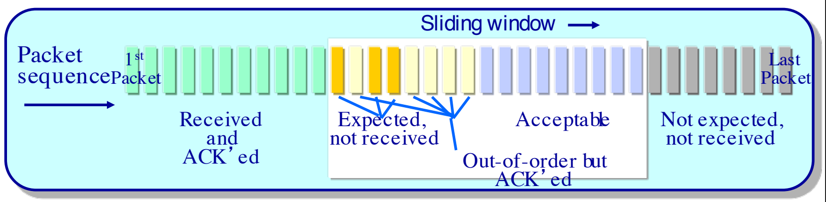
Selective Repeat Protocols

Sender and receiver windows

- Sender's view of sequence number space

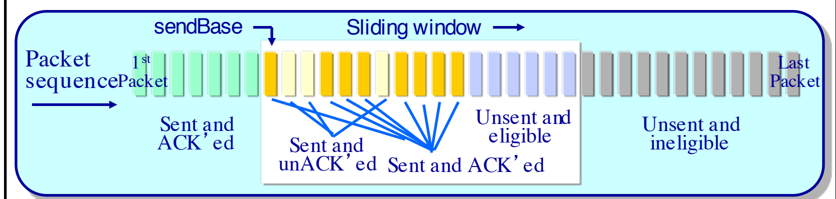


- Receiver's view of sequence number space



Selective Repeat Protocols

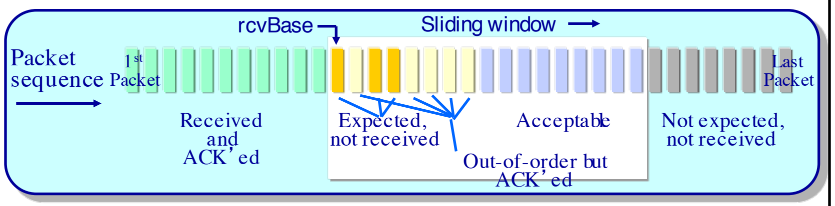
Sender state machine



- 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

Selective Repeat Protocols

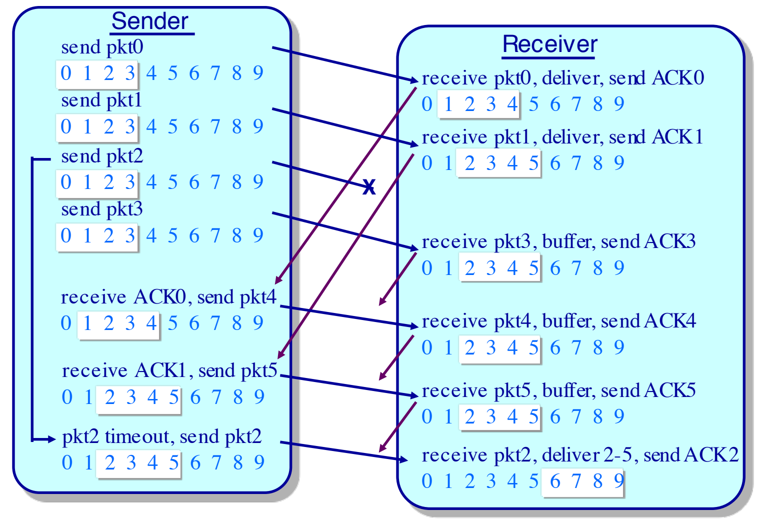
Receiver state machine



- 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