Network Transport Layer: Reliable Data Transfer; TCP

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https://qiaoxiang.me/courses/cnns-xmuf22/index.shtml

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This deck of slides are heavily based on CPSC 433/533 at Yale University, by courtesy of Dr. Y. Richard Yang.

Outline

- Admin and recap
- Reliable data transfer

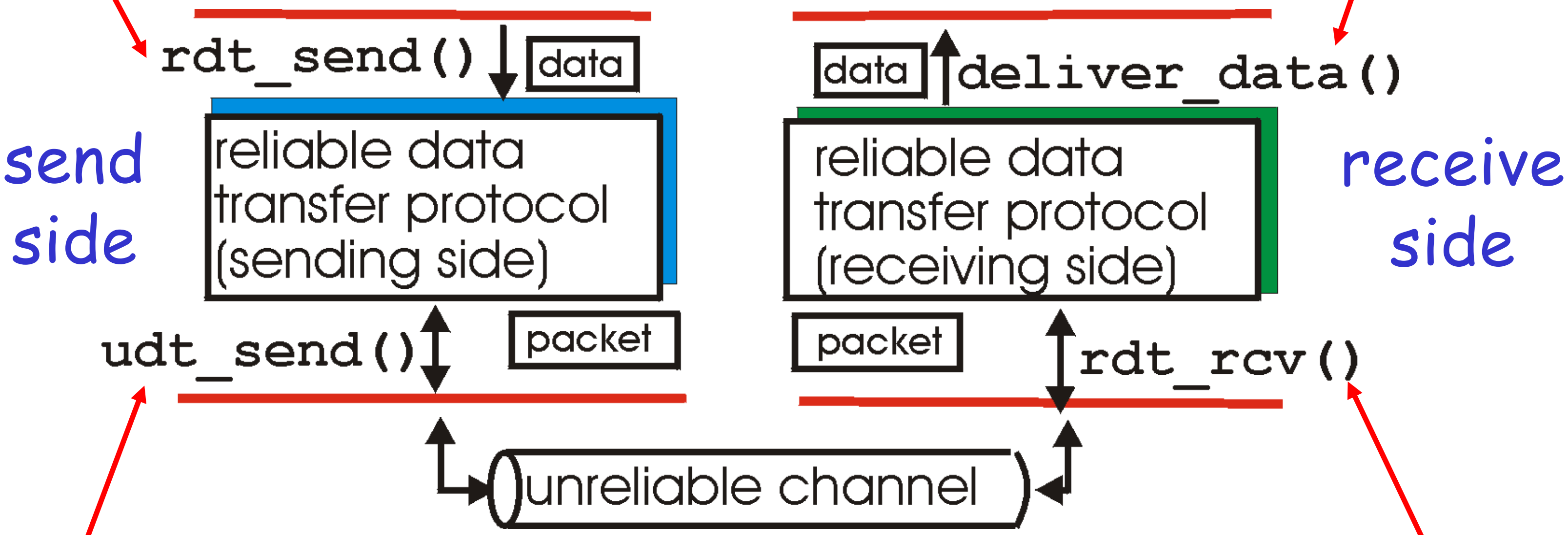
Admin

- Guest lecture on Oct. 27 class (morning)
  - Guest lecturer: Ennan Zhai (Alibaba)
  - Lecture title: Intent-Based Network in Alibaba

Recap: Reliable Data Transfer Context

rdt_send(): called from above, (e.g., by app.)

deliver_data(): called by **rdt** to deliver data to upper



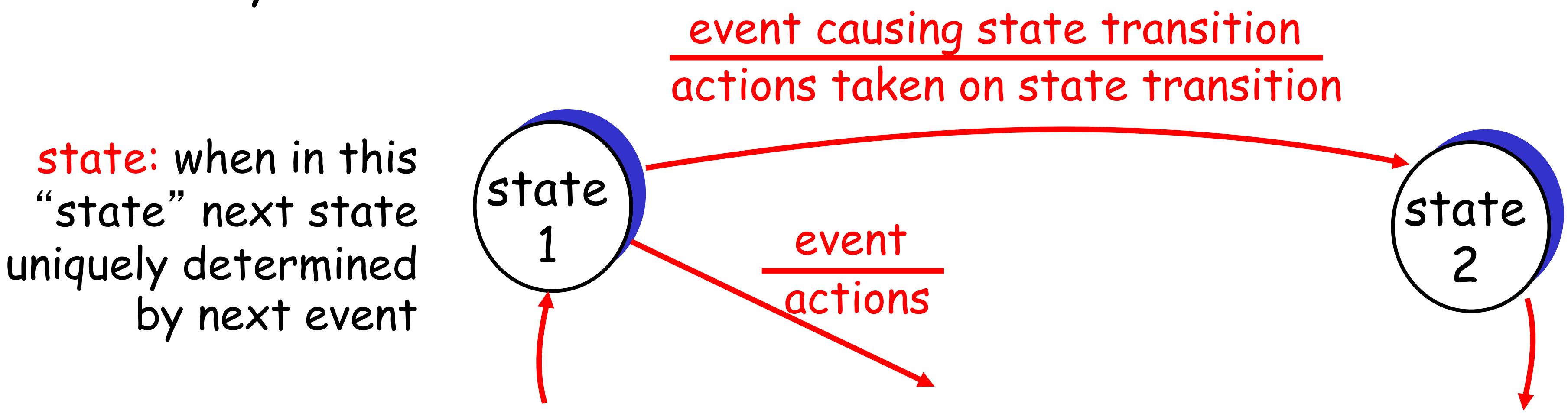
udt_send(): called by rdt, to transfer packet over unreliable channel to receiver

rdt_rcv(): called from below; when packet arrives on rcv-side of channel

Reliable Data Transfer: Getting Started

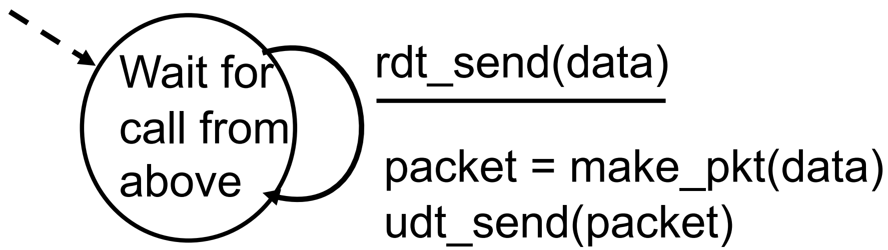
We'll:

- incrementally develop sender, receiver sides of reliable data transfer protocol (rdt)
- consider only unidirectional data transfer
  - but control info will flow on both directions !
- use finite state machines (FSM) to specify sender, receiver

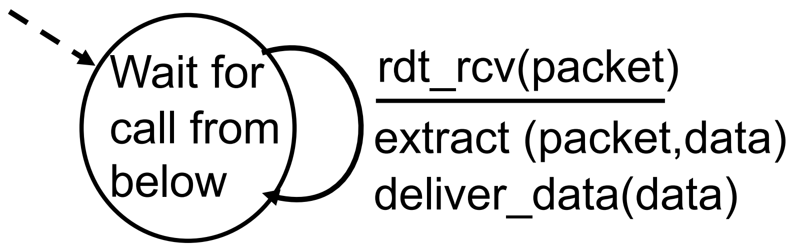


Rdt1.0: reliable transfer over a reliable channel

- separate FSMs for sender, receiver:
  - sender sends data into underlying channel
  - receiver reads data from underlying channel



sender

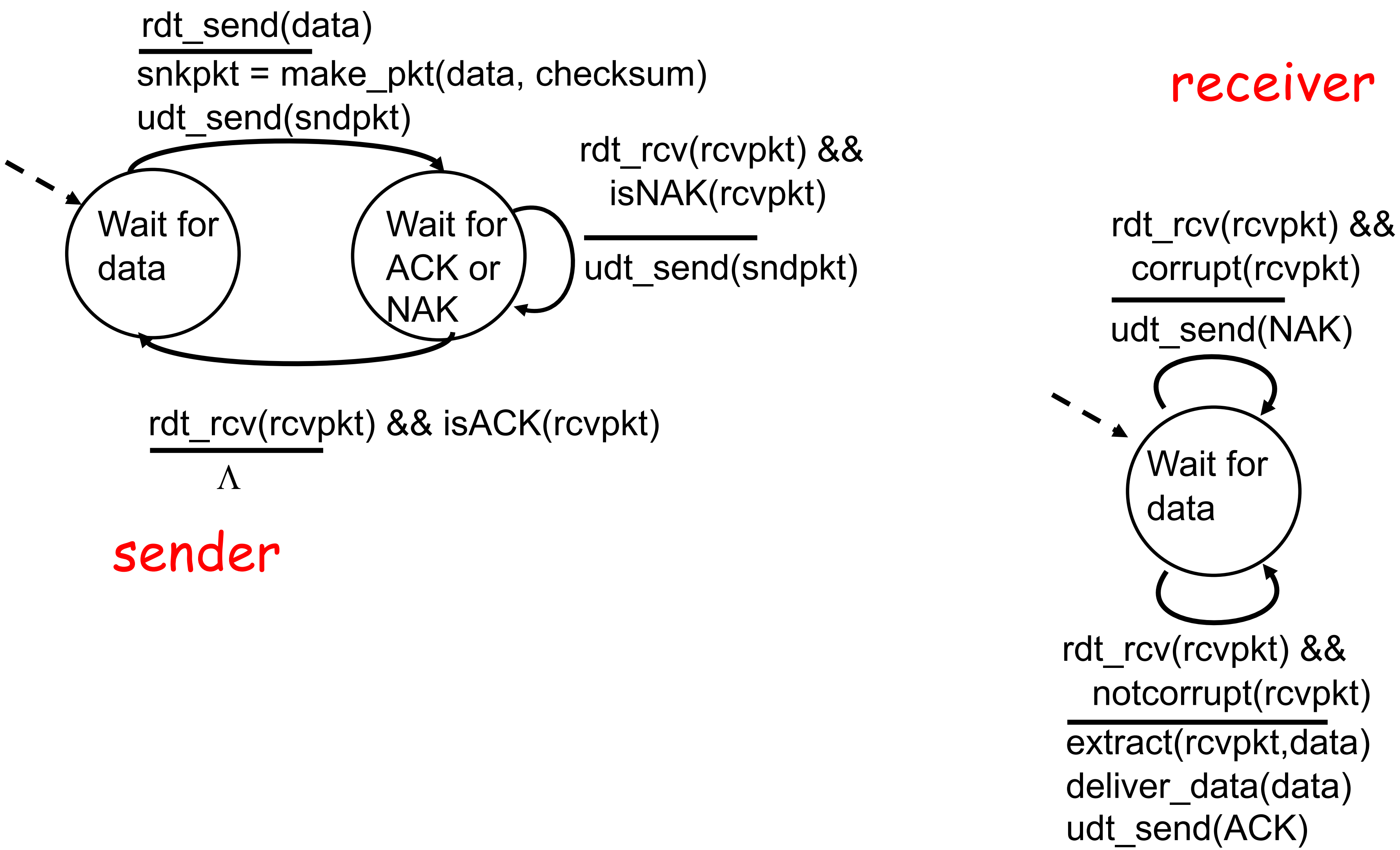


receiver

Exercise: Prove correctness of Rdt1.0.

Correctness: for every single packet, one and only one copy is received by receiver correctly (no error) and in-order

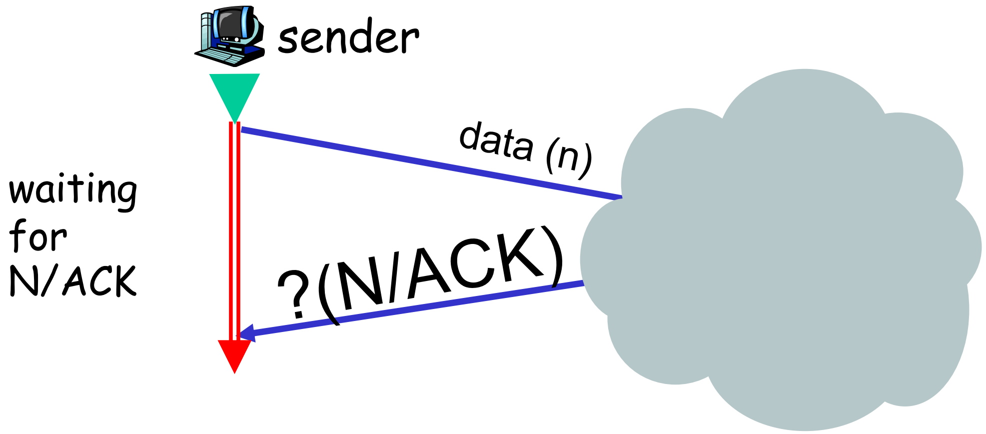
Recap: rdt2.0: Reliability allowing only Data Msg Corruption



rdt2.0 is Incomplete!

What happens if ACK/NAK corrupted?

- Although sender receives feedback, but doesn't know what happened at receiver!



rdt2.1b: Summary

Sender:

- seq # added to pkt
- must check if received ACK/NAK corrupted

Receiver:

- must check if received packet is duplicate
  - by checking if the packet has the expected pkt seq #

rdt2.1c: Summary

Sender:

- state must "remember" whether "current" pkt has 0 or 1 seq. #

Receiver:

- must check if received packet is duplicate
  - state indicates whether 0 or 1 is expected pkt seq #

rdt2.2: a NAK-free protocol

- Same functionality as rdt2.1c, using ACKs only
- Instead of NAK, receiver sends ACK for last pkt received OK
  - receiver must *explicitly* include seq # of pkt being ACKed
- Duplicate ACK at sender results in same action as NAK: *retransmit current pkt*

rdt3.0: Channels with Errors *and* Loss

New assumption: underlying channel can also lose packets (data or ACKs)

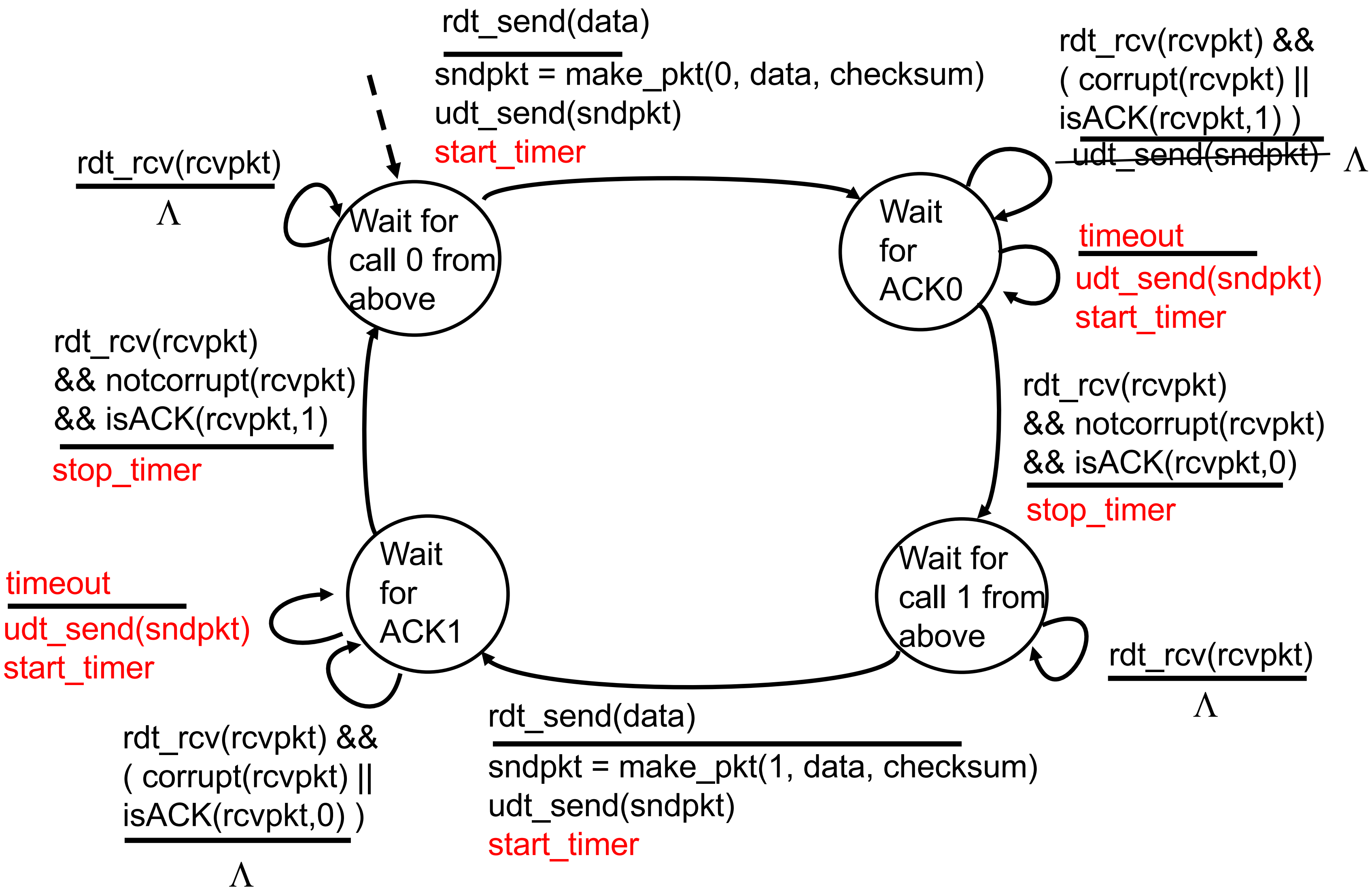
- checksum, seq. #, ACKs, retransmissions will be of help, but not enough

Q: Does rdt2.2 work under losses?

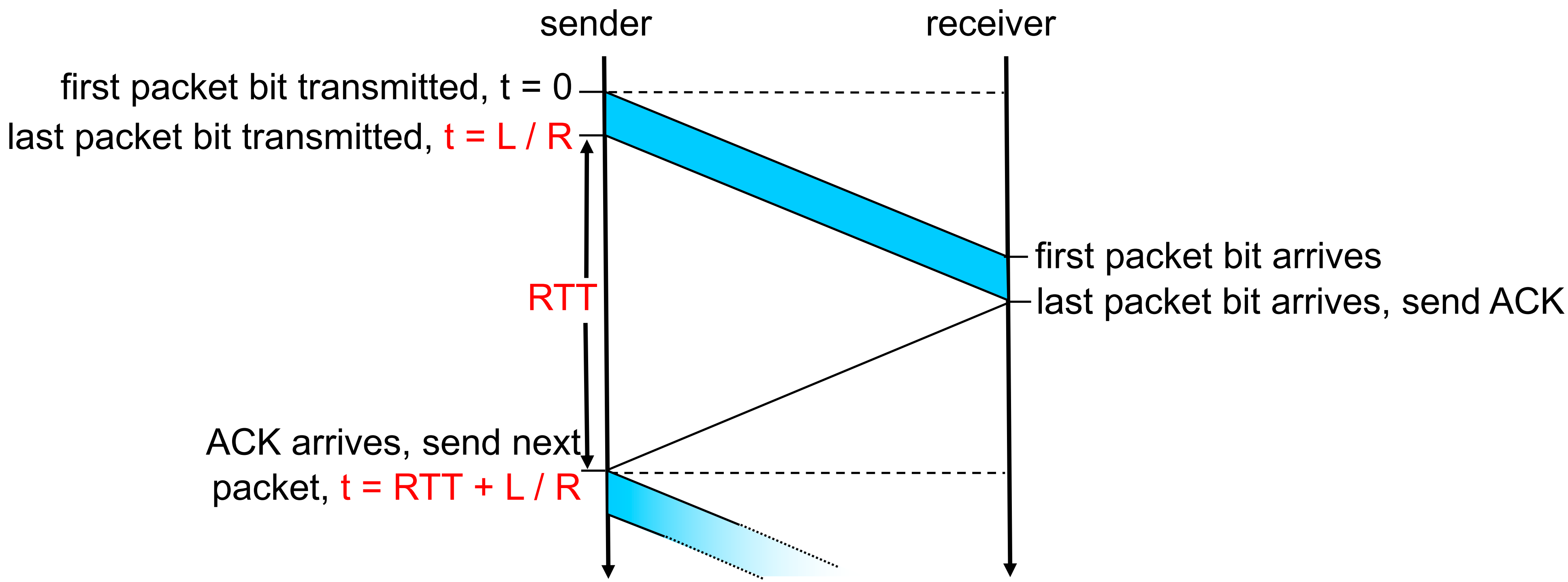
Approach: sender waits "reasonable" amount of time for ACK

- requires countdown timer
- retransmits if no ACK received in this time
- if pkt (or ACK) just delayed (not lost):
  - retransmission will be duplicate, but use of seq. #'s already handles this
  - receiver must specify seq # of pkt being ACKed

rdt3.0 Sender



rdt3.0: Stop-and-Wait Performance



What is U_{sender}: utilization – fraction of time link busy sending?

Assume: 1 Gbps link, 15 ms e-e prop. delay, 1KB packet

Performance of rdt3.0

- rdt3.0 works, but performance stinks
- Example: 1 Gbps link, 15 ms e-e prop. delay, 1KB packet:

$$T_{transmit} = \frac{L \text{ (packet length in bits)}}{R \text{ (transmission rate, bps)}} = \frac{8\text{kb/pkt}}{10^{**}9 \text{ b/sec}} = 8 \text{ microsec}$$

$$U_{sender} = \frac{L / R}{RTT + L / R} = \frac{.008}{30.008} = 0.00027$$

- 1KB pkt every 30 msec -> 33kB/sec throughput over 1 Gbps link
- network protocol limits use of physical resources !

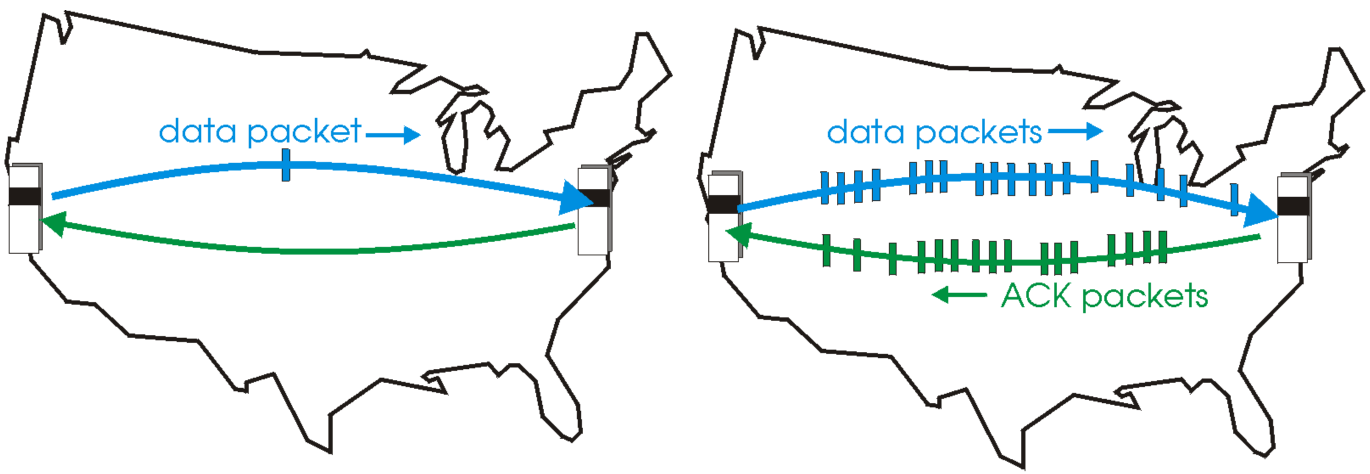
A Summary of Questions

- How to improve the performance of rdt3.0?
- What if there are reordering and duplication?
- How to determine the "right" timeout value?

Sliding Window Protocols: Pipelining

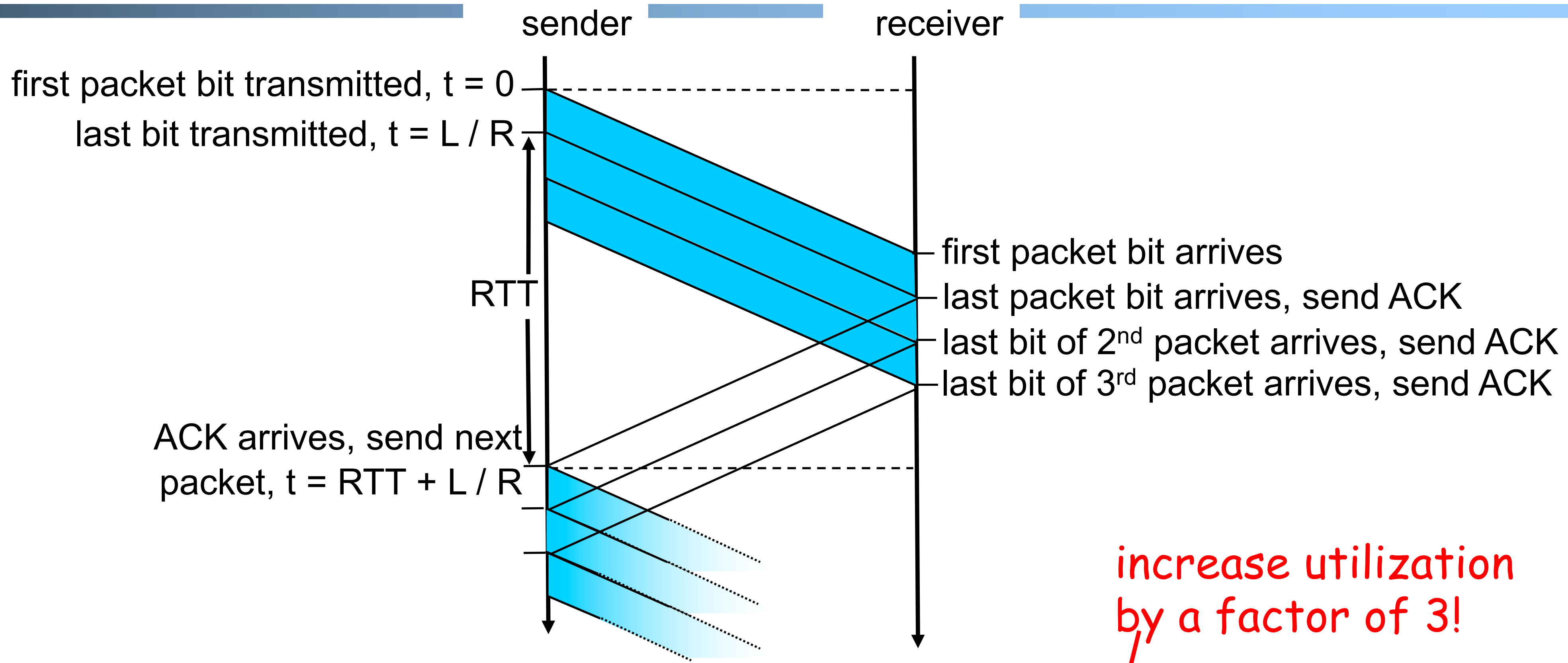
Pipelining: sender allows multiple, "in-flight", yet-to-be-acknowledged pkts

- range of sequence numbers must be increased
- buffering at sender and/or receiver



(a) a stop-and-wait protocol in operation (b) a pipelined protocol in operation

Pipelining: Increased Utilization



increase utilization
by a factor of 3!

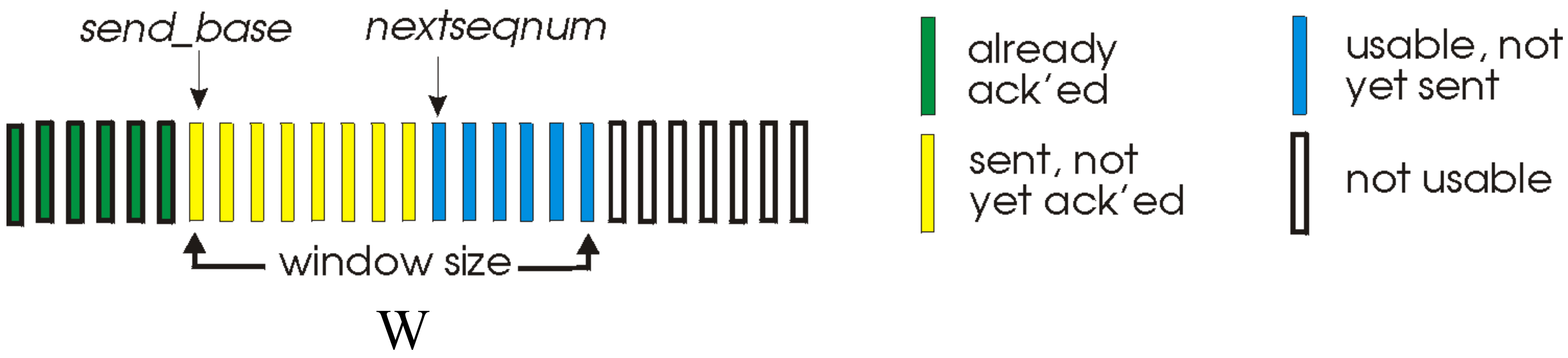
$$U_{sender} = \frac{3 * L / R}{RTT + L / R} = \frac{.024}{30.008} = 0.0008$$

Question: a rule-of-thumb window size?

Realizing Sliding Window: Go-Back-n

Sender:

- k-bit seq # in pkt header
- "window" of up to W, consecutive unack'ed pkts allowed



- ACK(n): ACKs all pkts up to, including seq # n - "cumulative ACK"
  - note: ACK(n) could mean two things: I have received upto and include n, or I am waiting for n
- timer for the packet at base
- *timeout(n):* retransmit pkt n and all higher seq # pkts in window

GBN: Sender FSM

rdt_send(data)

```
if (nextseqnum < base+W) {
    sndpkt[nextseqnum] = make_pkt(nextseqnum,data,chksum)
    udt_send(sndpkt[nextseqnum])
    if (base == nextseqnum) start_timer
    nextseqnum++
 } else
    block sender
```

Λ

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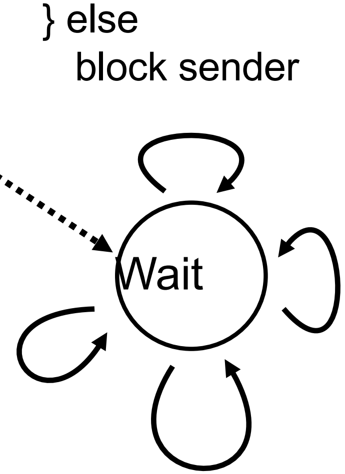
base=1
nextseqnum=1



timeout

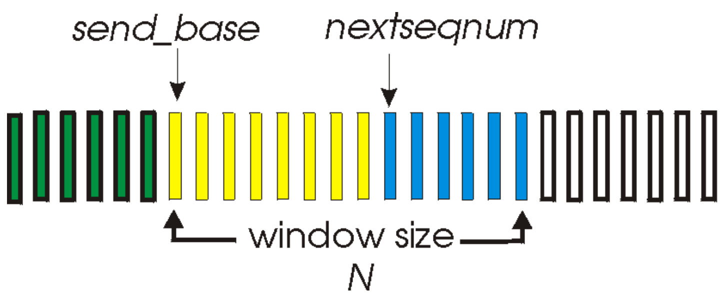
```
start_timer
udt_send(sndpkt[base])
udt_send(sndpkt[base+1])
…
udt_send(sndpkt[nextseqnum-1])
```

rdt_rcv(rcvpkt)
  && corrupt(rcvpkt)

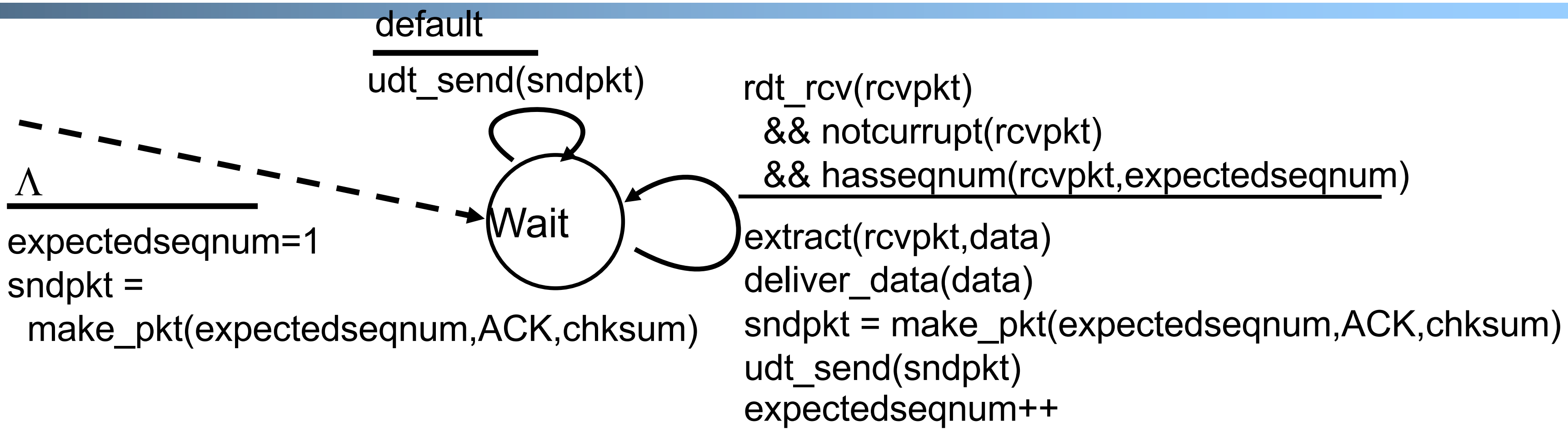
---

rdt_rcv(rcvpkt) &&
  notcorrupt(rcvpkt)

```
if (new packets ACKed) {
   advance base;
   if (more packets waiting)
       send more packets
}
if (base == nextseqnum)
  stop_timer
else
  start_timer for the packet at new base
```



GBN: Receiver FSM

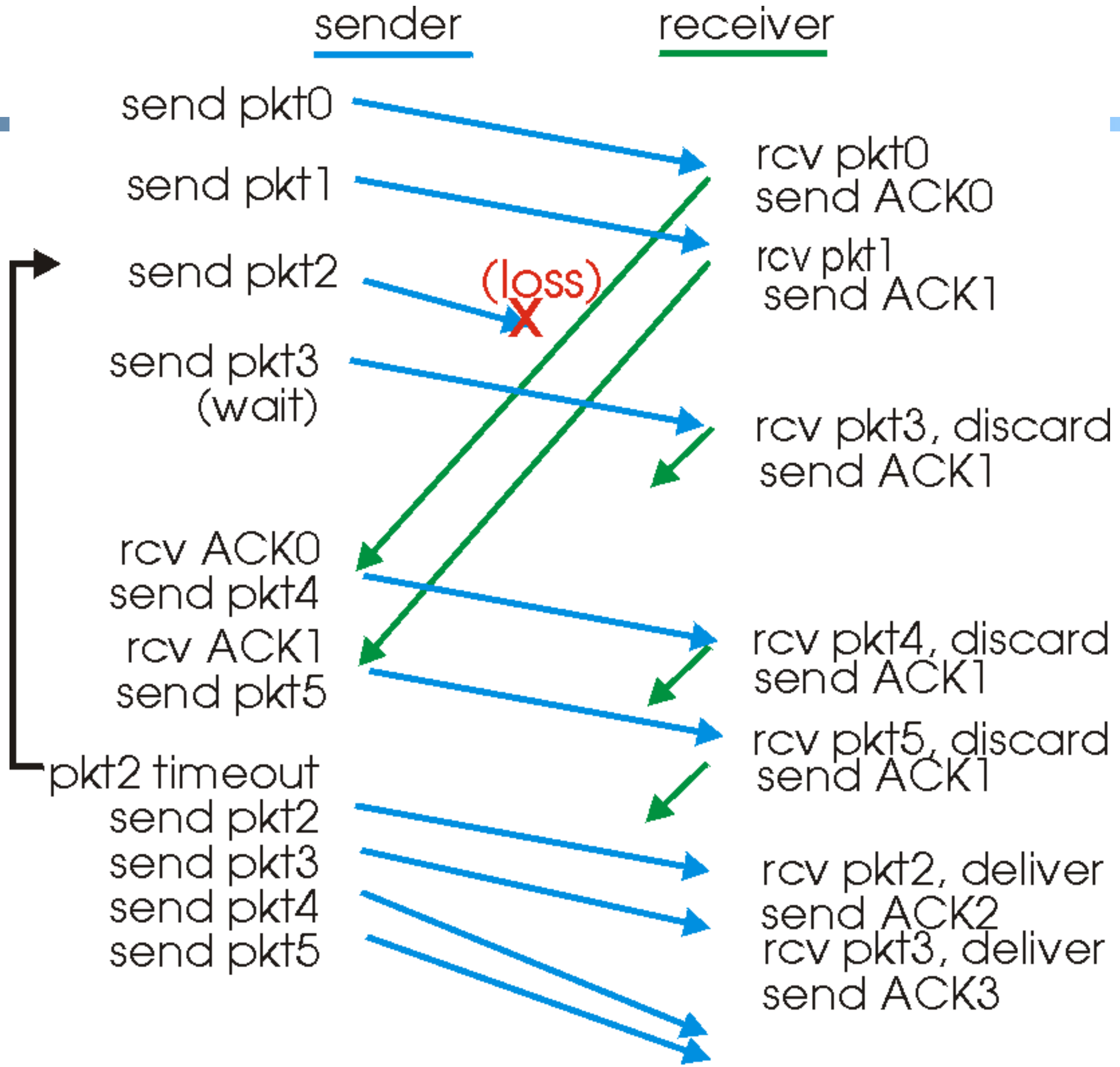


Only state: **`expectedseqnum`**

- out-of-order pkt:
  - discard (don't buffer) -> no receiver buffering!
  - re-ACK pkt with highest in-order seq #
  - may generate duplicate ACKs

GBN in Action

window size = 4



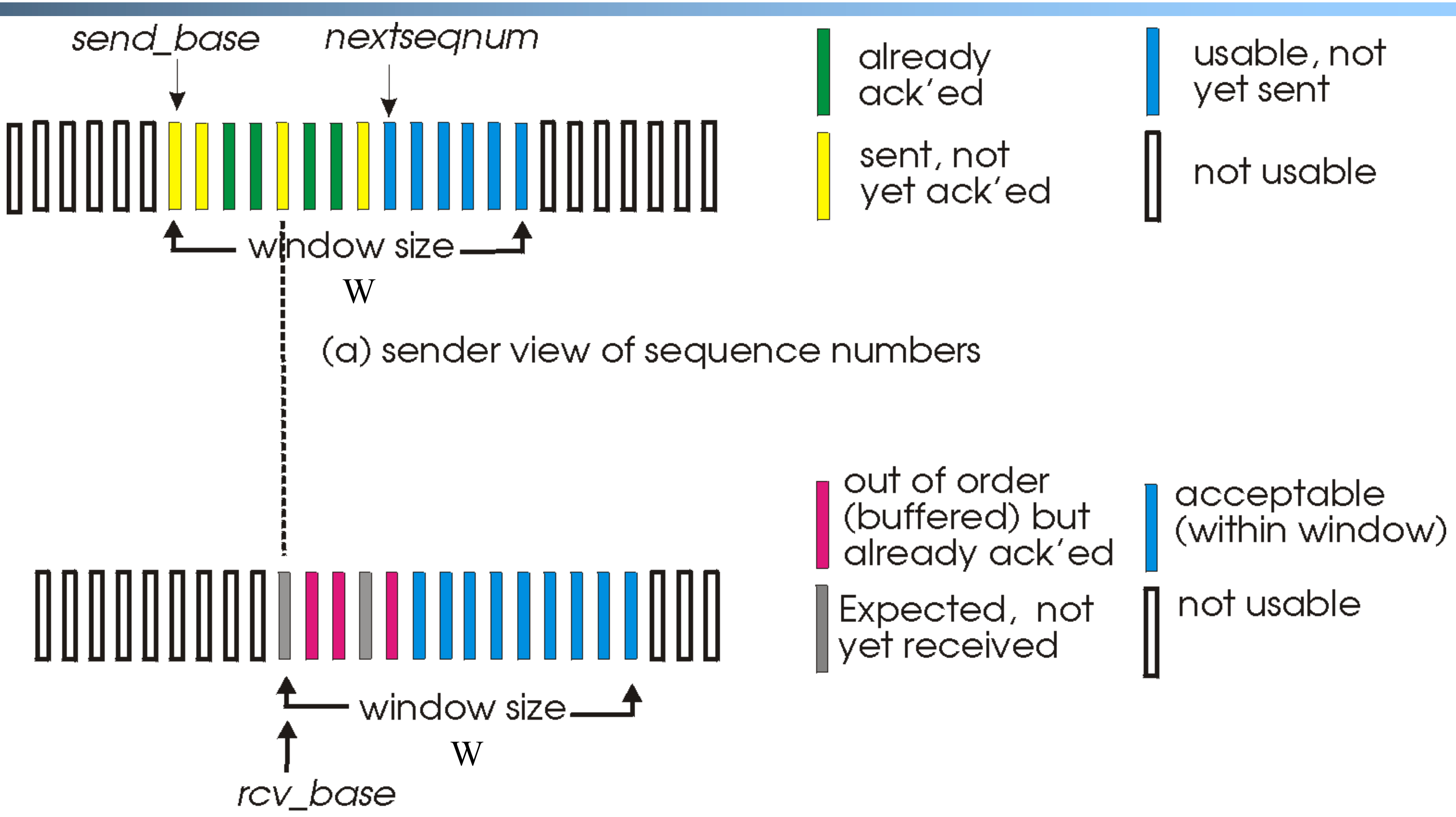
Analysis: Efficiency of Go-Back-n

- Assume window size W
- Assume each packet is lost with probability p
- On average, how many packets do we send for each data packet received?

Selective Repeat

- Sender window
  - Window size W: W consecutive unACKed seq #'s
- Receiver *individually* acknowledges correctly received pkts
  - buffers out-of-order pkts, for eventual in-order delivery to upper layer
  - ACK(n) means received packet with seq# n only
  - buffer size at receiver: window size
- Sender only resends pkts for which ACK not received
  - sender timer for each unACKed pkt

Selective Repeat: Sender, Receiver Windows



(a) sender view of sequence numbers

(b) receiver view of sequence numbers

Selective Repeat

sender

data from above :

- unACKed packets is less than window size W, send; otherwise block app.

timeout(n):

- resend pkt n, restart timer

ACK(n) in [sendbase,sendbase+W-1]:

- mark pkt n as received
- update sendbase to the first packet unACKed

receiver

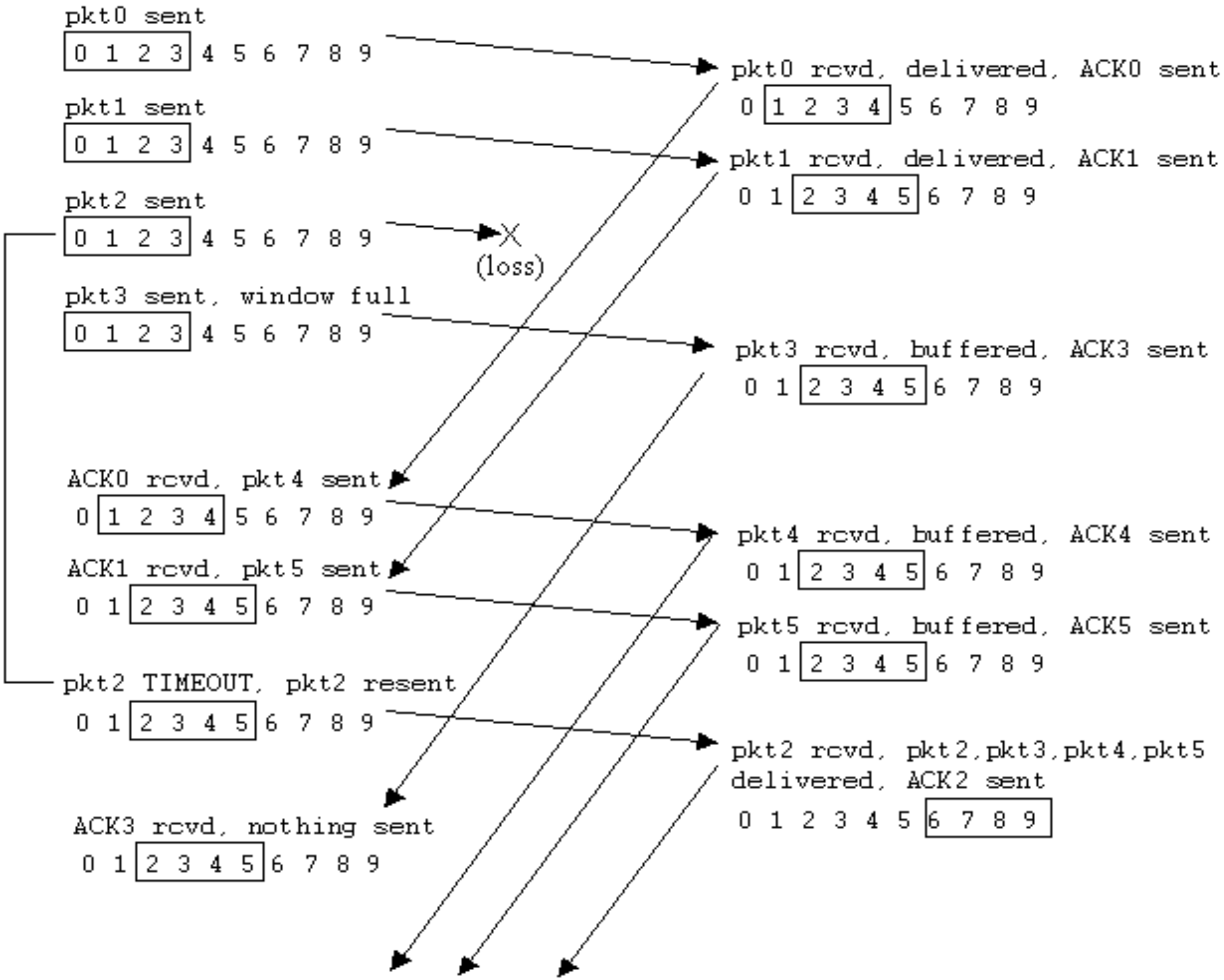
pkt n in [rcvbase, rcvbase+W-1]

- send ACK(n)
- if (out-of-order)
  mark and buffer pkt n
  else /*in-order*/
  deliver any in-order packets

otherwise:

- ignore

Selective Repeat in Action



Discussion: Efficiency of Selective Repeat

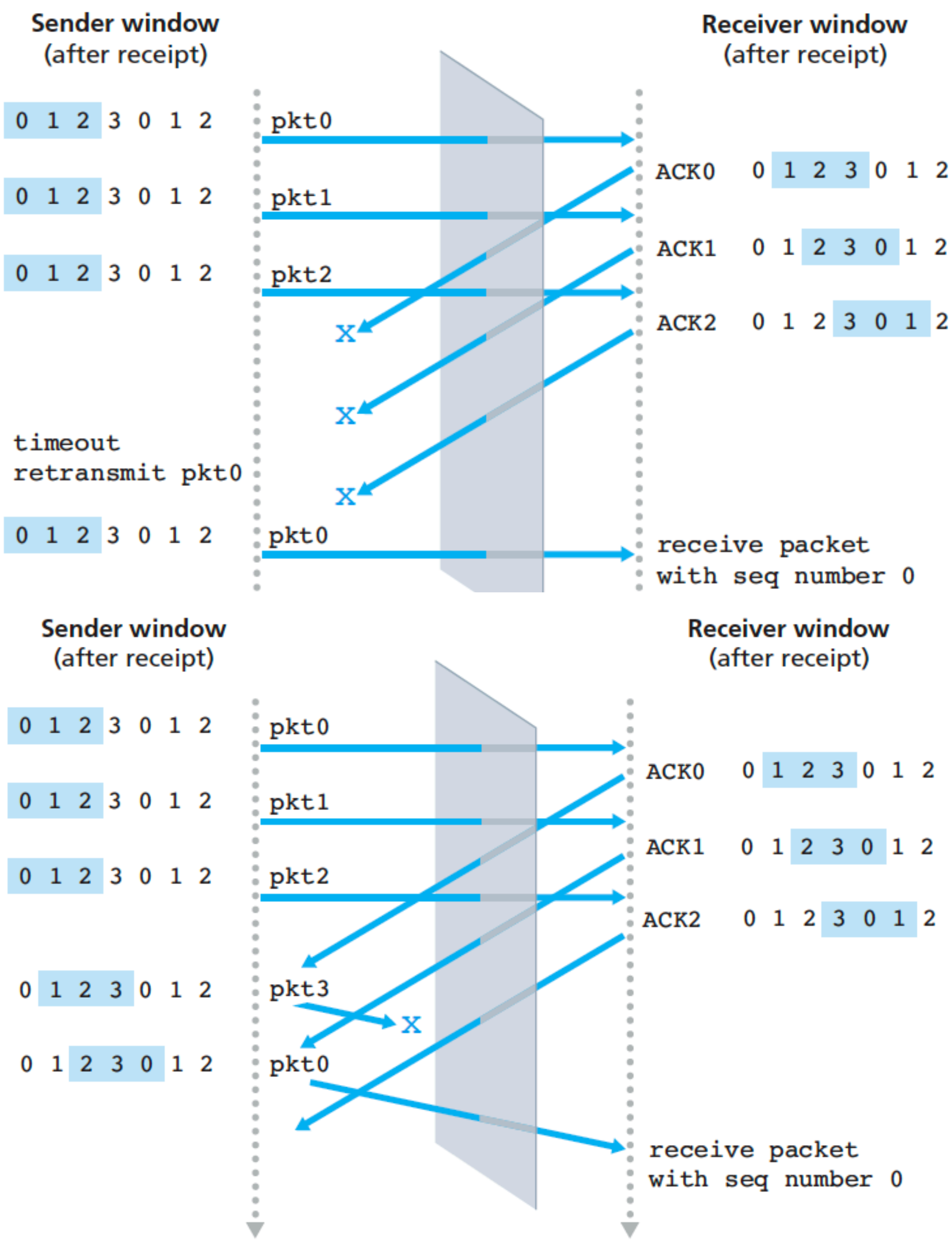
- Assume window size W
- Assume each packet is lost with probability p
- On average, how many packets do we send for each data packet received?

Selective Repeat: Seq# Ambiguity

Example:

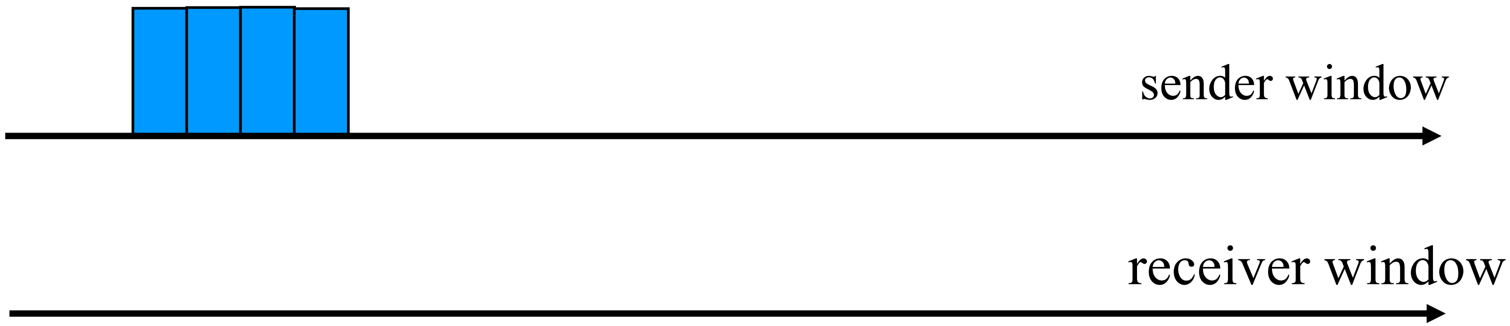
- seq #'s: 0, 1, 2, 3
- window size=3

- Error: incorrectly passes duplicate data as new.

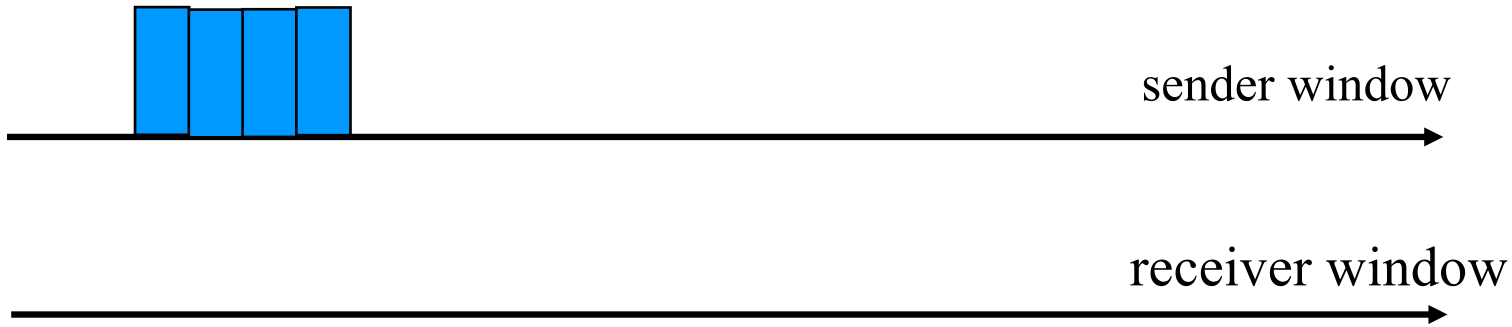


State Invariant: Window Location

- Go-back-n (GBN)



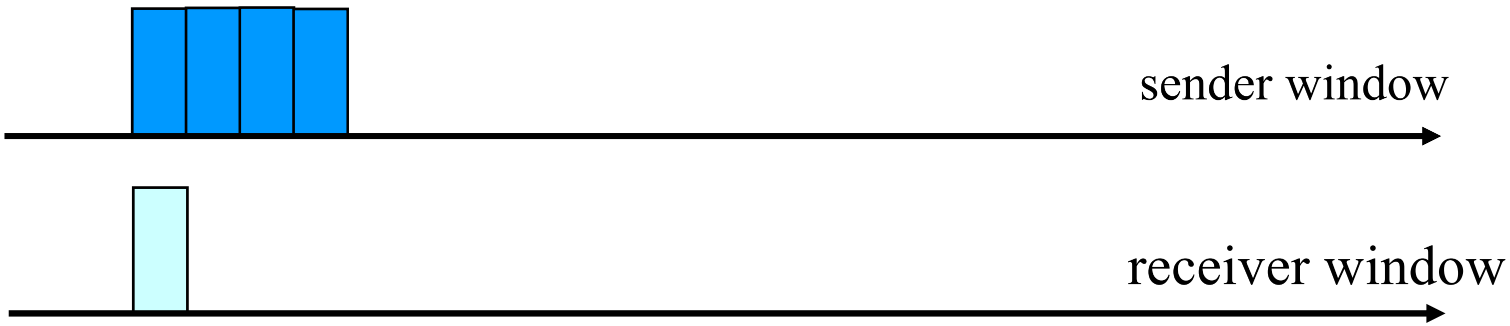
- Selective repeat (SR)



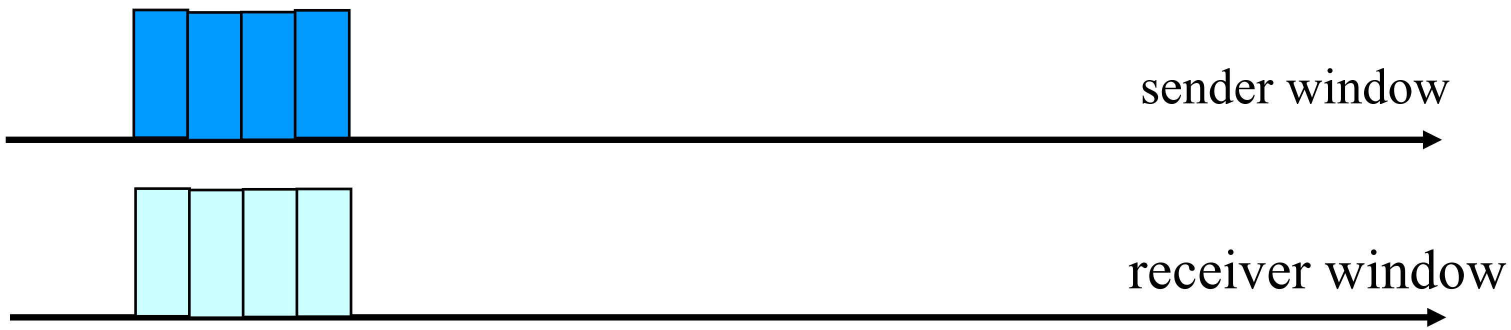
Window Location

Q: what relationship between seq # size and window size?

- Go-back-n (GBN)



- Selective repeat (SR)



Selective Repeat

sender

data from above :

- unACKed packets is less than window size W, send; otherwise block app.

timeout(n):

- resend pkt n, restart timer

ACK(n) in [sendbase,sendbase+W-1]:

- mark pkt n as received
- update sendbase to the first packet unACKed

receiver

pkt n in [rcvbase, rcvbase+W-1]

- send ACK(n)
- if (out-of-order)
    mark and buffer pkt n
  else /*in-order*/
    deliver any in-order packets

pkt n in [rcvbase-W, rcvbase-1]

- send ACK(n)

otherwise:

- ignore

Sliding Window Protocols: Go-back-n and Selective Repeat

	Go-back-n	Selective Repeat
data bandwidth: sender to receiver (avg. number of times a pkt is transmitted)	Less efficient $\frac{1-p+pw}{1-p}$	More efficient $\frac{1}{1-p}$
ACK bandwidth (receiver to sender)	More efficient	Less efficient
Relationship between M (the number of seq#) and W (window size)	M > W	M ≥ 2W
Buffer size at receiver	1	W
Complexity	Simpler	More complex

p: the loss rate of a packet; M: number of seq# (e.g., 3 bit M = 8); W: window size