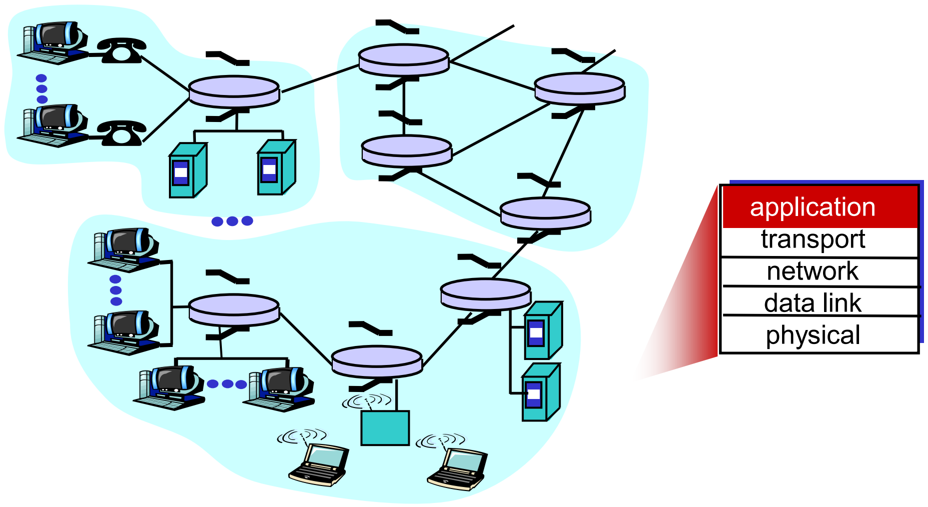
CS 4390
Computer Networks



Transport Layer – Pipelined Protocols

Performance of rdt3.0

- rdt3.0 is correct, but performance stinks
- e.g.: 1 Gbps link, 15 ms prop. delay, 8000 bit packet:

$$D_{trans} = \frac{L}{R} = \frac{8000 \text{ bits}}{10^9 \text{ bits/sec}} = 8 \text{ microsecs}$$

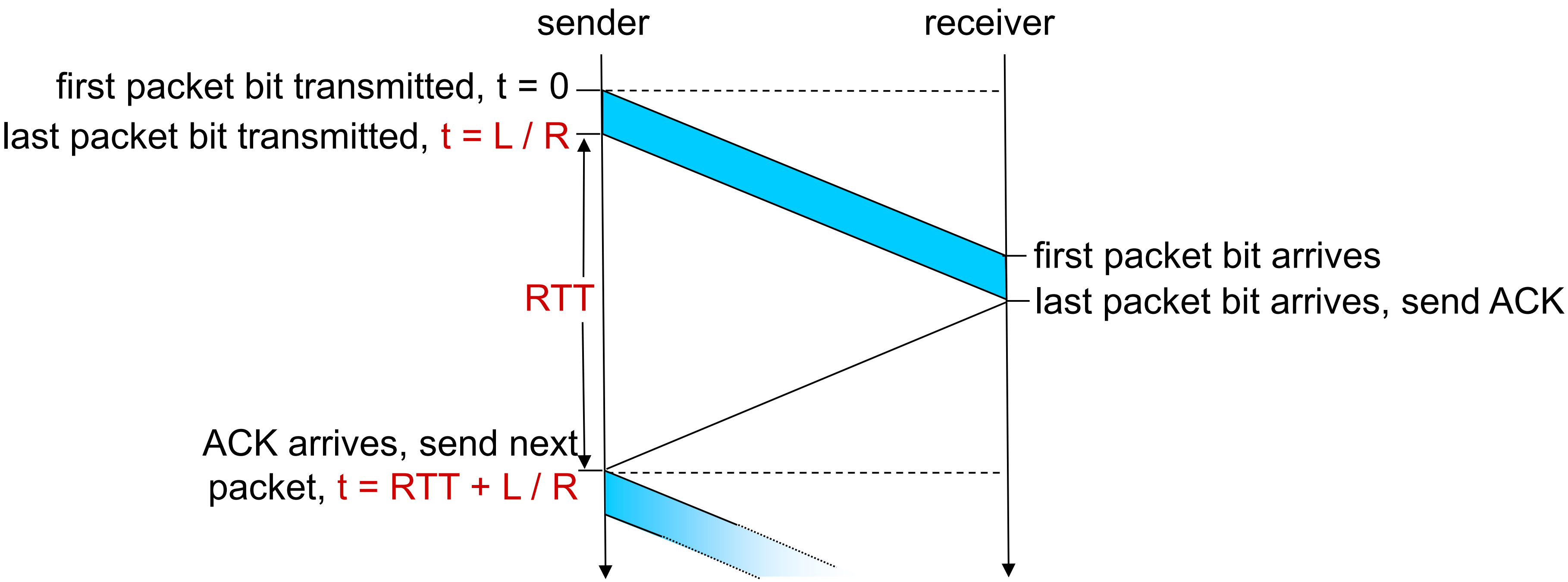
- U_{sender}: *utilization* – fraction of time sender busy sending

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

- *if RTT=30 msec, 1KB pkt every 30 msec: 33kB/sec throughput over 1 Gbps link!!!*

- Network protocol limits use of physical resources!
- Need to identify the cause and fix it: *why utilization is so low*?

Stop-and-wait Operation of rdt3.0



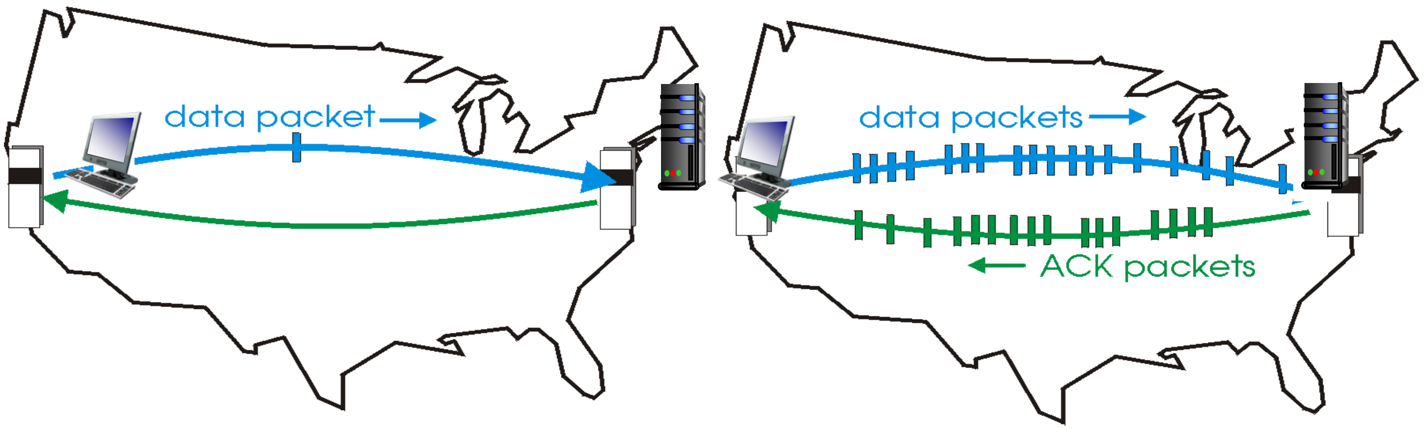
$$U_{sender} = \frac{L / R}{RTT + L / R} = \frac{.008}{30.008} = 0.00027$$

How to improve channel utilization?

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



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

- No more 'stop-and-wait'!
- Generic form of '*sliding window*' protocols

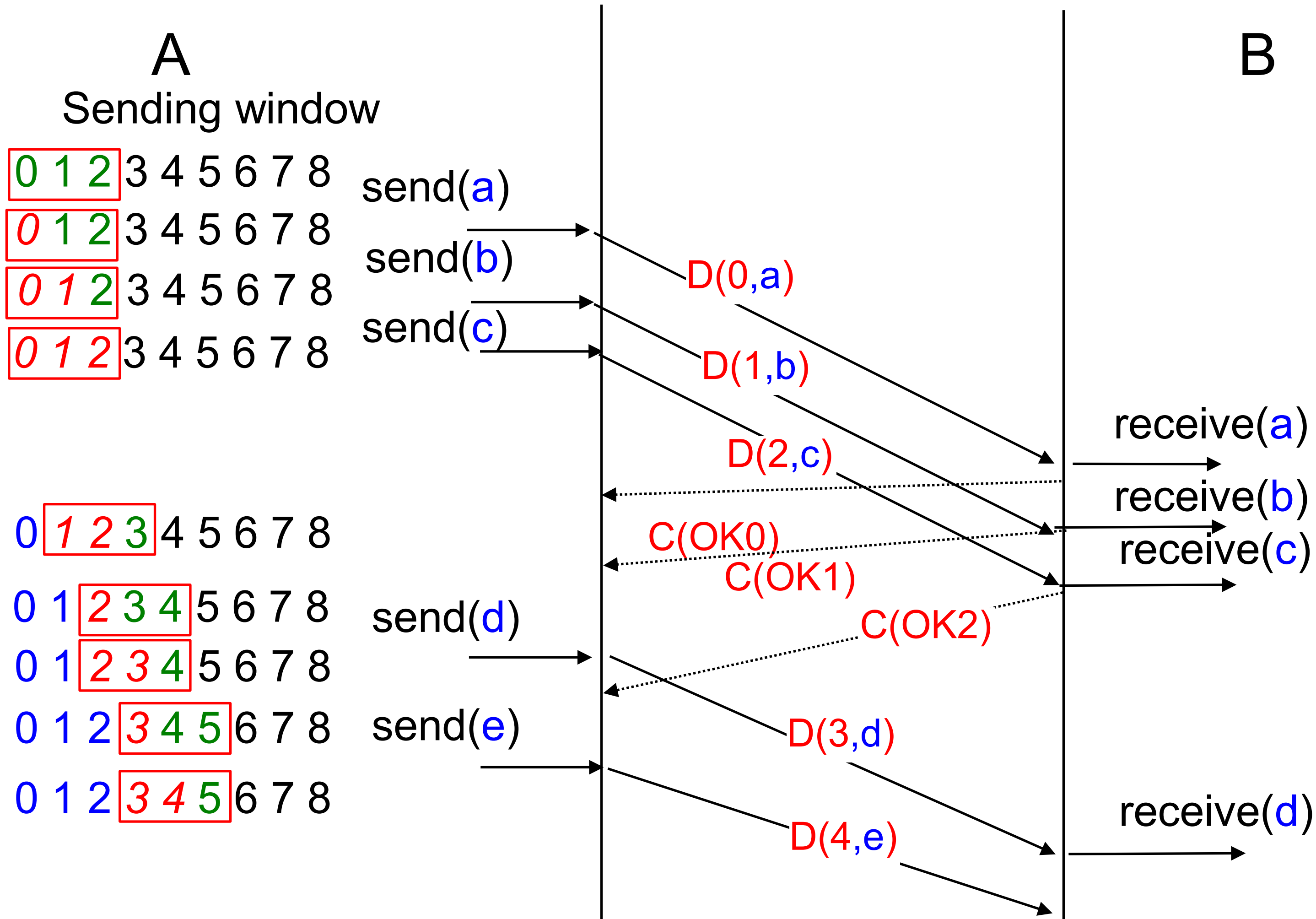
Sliding Window Protocol

- To avoid ‘stop-and-wait’ behavior
  - Sender keeps a list of all the segments that it is allowed to send: *sending_window*
  - Receiver also maintains a receiving window with the list of acceptable sequence numbers: *receiving_window*
  - During data transfer the windows appear to be sliding across segment sequential numbers
- Sender and receiver must use compatible windows (e.g. negotiated during connection establishment phase)

adapted from slides by Prof. O. Bonaventure

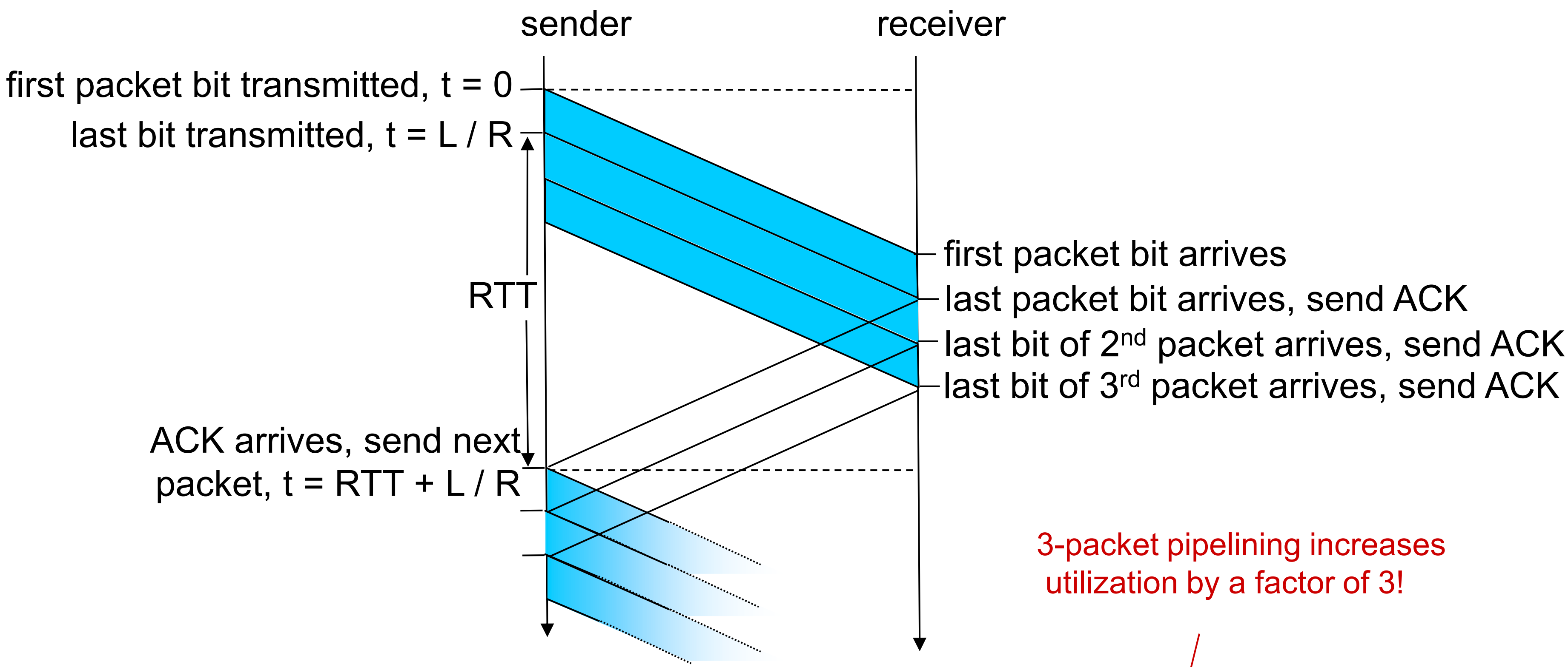
Sliding Windows Example

- Sending and receiving window size : 3 segments



credit: Prof. O. Bonaventure

Pipelining: Increased Utilization



3-packet pipelining increases utilization by a factor of 3!

$$U_{sender} = \frac{3L / R}{RTT + L / R} = \frac{.0024}{30.008} = 0.00081$$

rdt with Pipelined Protocol

- *Problem:* how to provide reliable data transfer with a pipelined protocol?
- Basic solutions:
  1. *Go-Back-N*
     - simple implementation (particularly on receiving side)
     - throughput will be limited when losses occur
  2. *Selective Repeat*
     - more difficult from an implementation viewpoint
     - throughput can remain high when limited losses occur

Pipelined Protocols: Overview

Go-back-N:

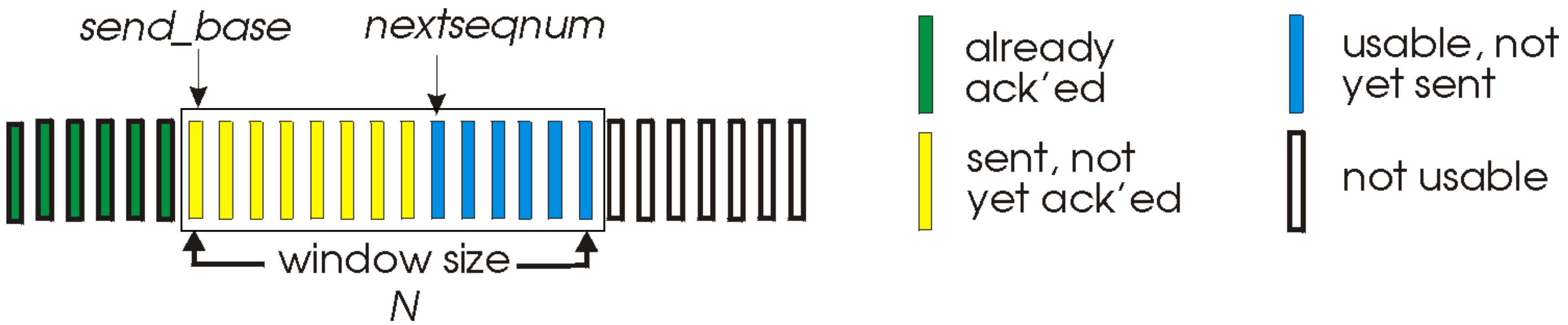
- sender can have up to N unack'ed packets in pipeline
- receiver only sends *cumulative ack*
  - doesn't ack packet if there's a gap
- sender has timer for oldest unack'ed packet
  - when timer expires, retransmit *all* unack'ed packets

Selective Repeat:

- sender can have up to N unack' ed packets in pipeline
- rcvr sends *individual ack* for each packet
- sender maintains timer for each unack'ed packet
  - when timer expires, retransmit only that unack'ed packet

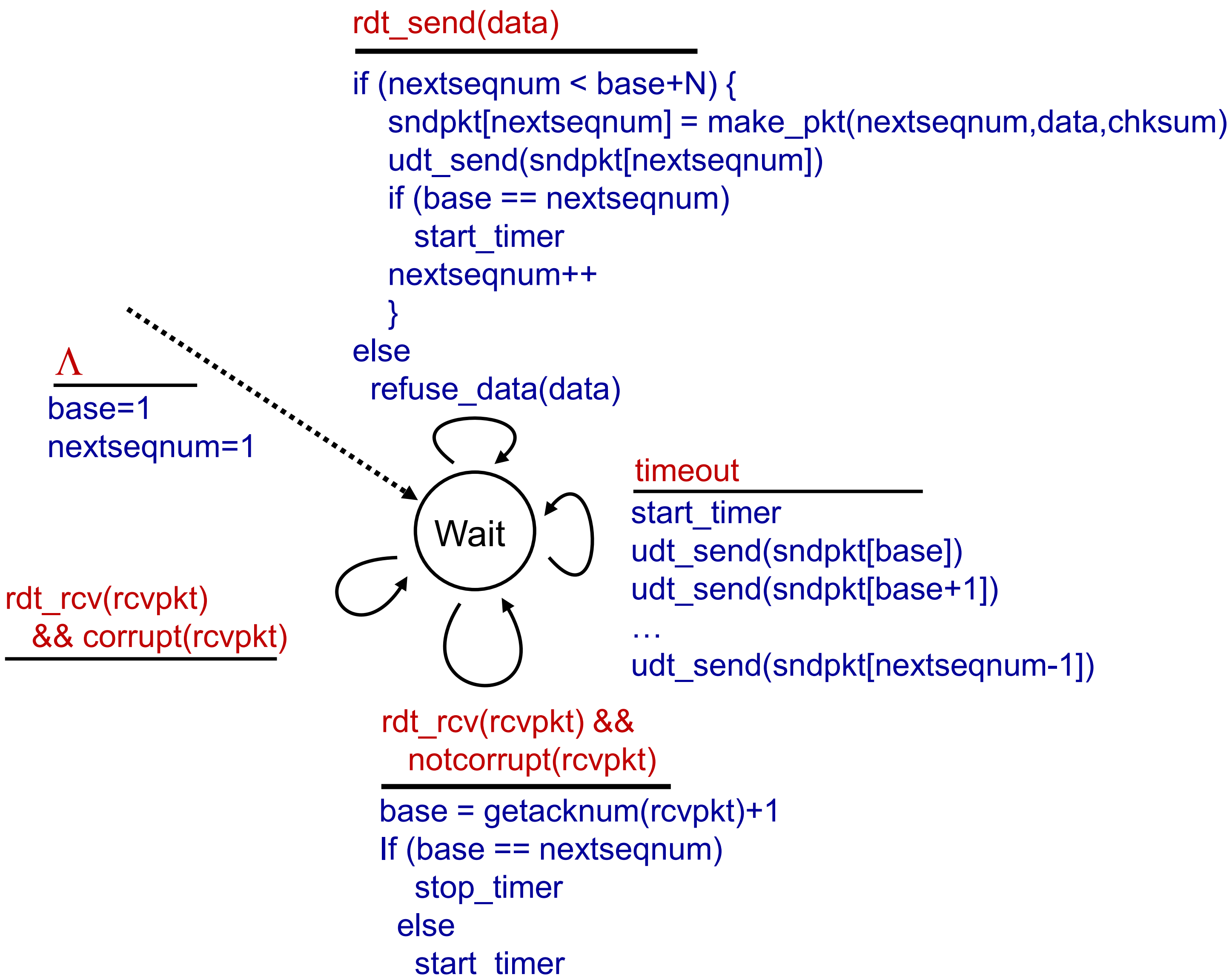
Go-Back-N: Sender

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

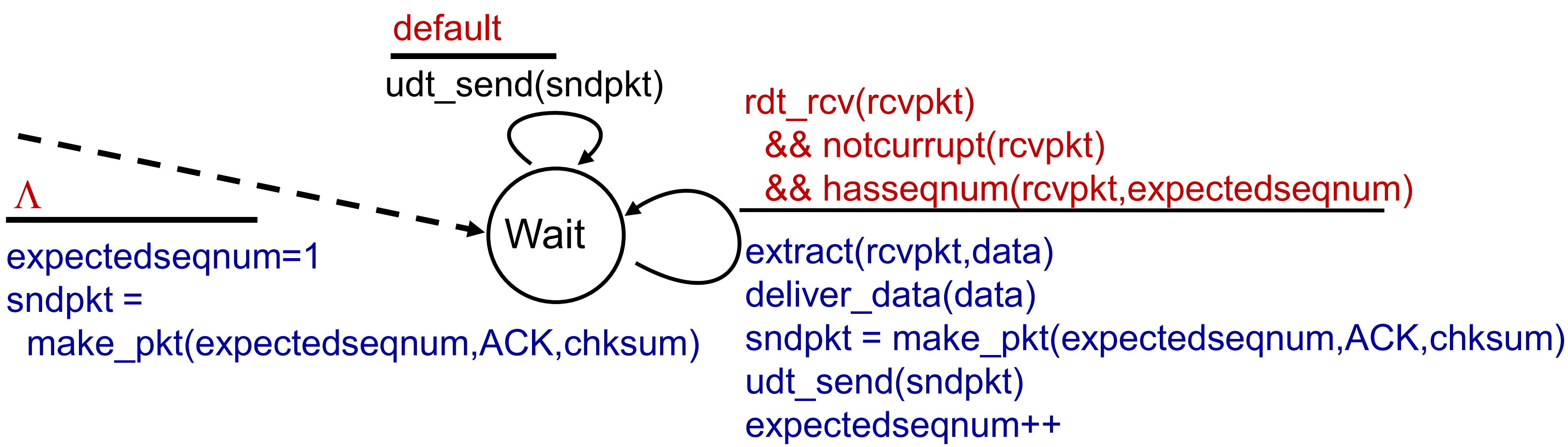


- ACK(n): ACKs all pkts up to, including seq # n - *"cumulative ACK"*
  - may receive duplicate ACKs (see receiver)
- timer for oldest in-flight pkt
- *timeout(n):* retransmit packet n and all higher seq # pkts in window

GBN: Extended FSM for Sender



GBN: Extended FSM for Receiver

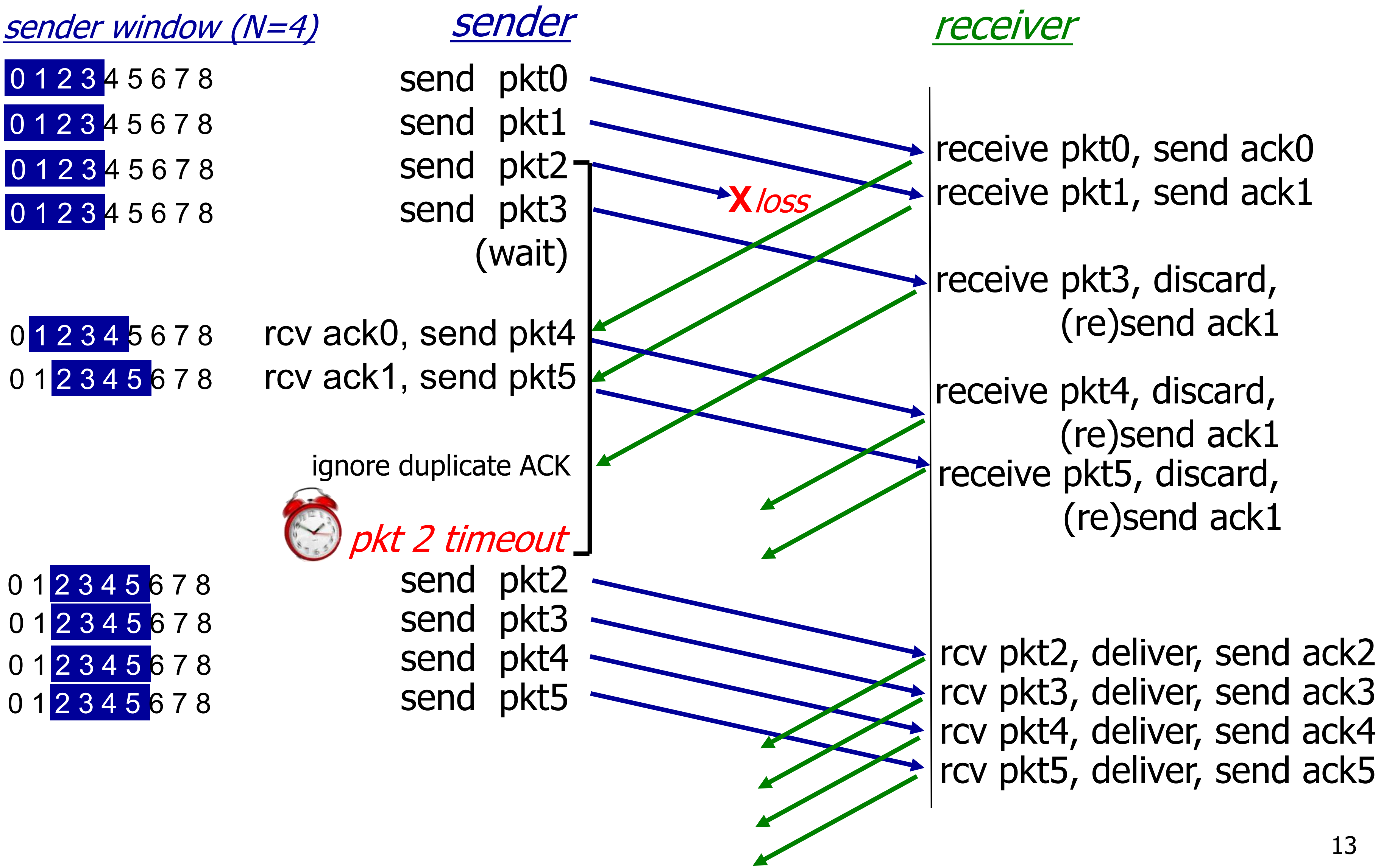


ACK-only: always send ACK for correctly-received pkt with highest *in-order* seq #

- may generate duplicate ACKs
- need only remember **`expectedseqnum`**

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

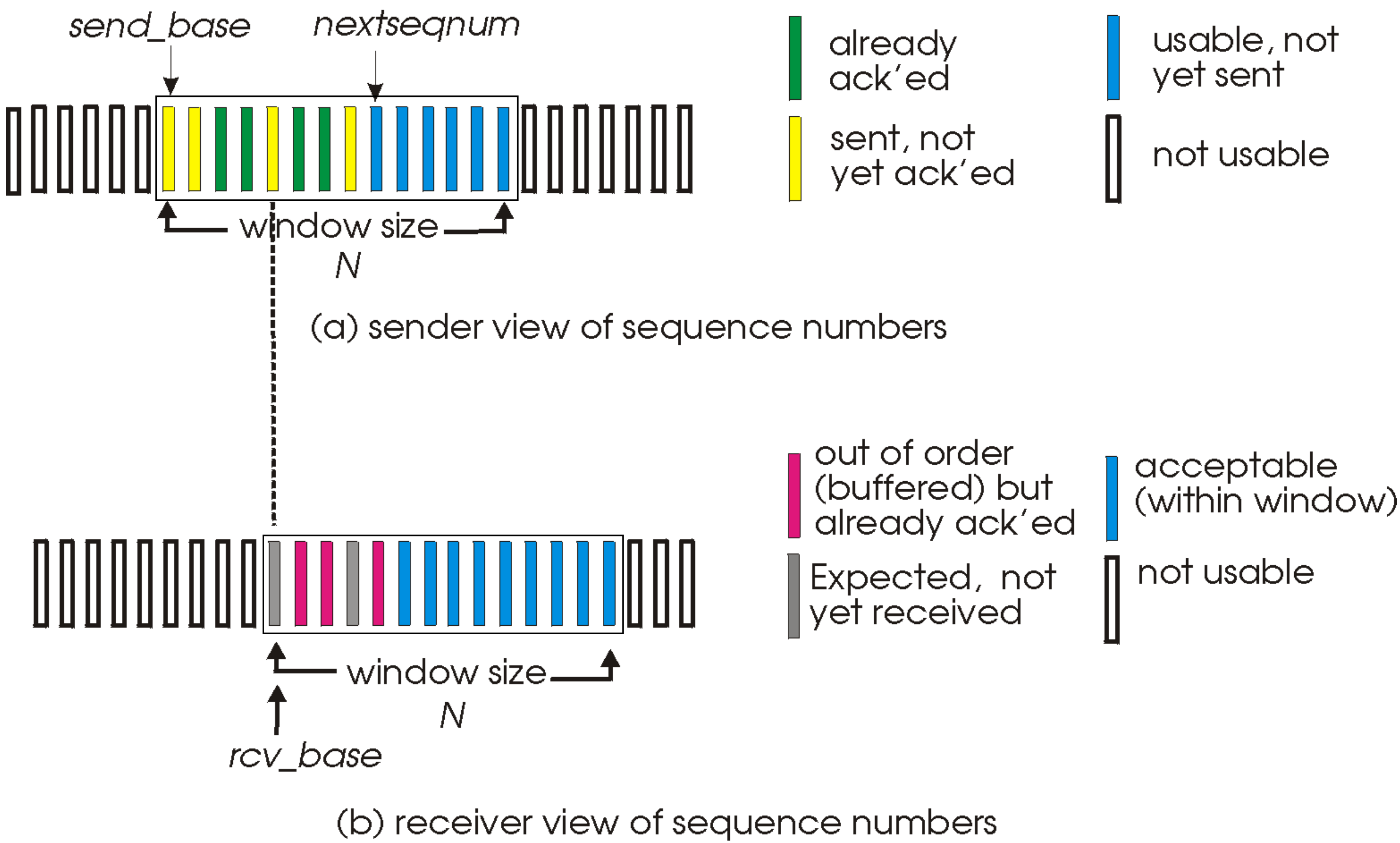
GBN in Action



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 not received
  – sender timer for each unACK'ed pkt
- sender window
  – *N* consecutive seq #'s
  – limits seq #s of sent, unACK'ed pkts

Selective Repeat: sender, receiver Windows



Selective Repeat

sender

data from above:

- if next available seq # in window, send pkt

timeout(n):

- resend pkt n, restart timer

ACK(n) in [sendbase,sendbase+N]:

- mark pkt n as received
- if n smallest unACKed pkt, advance window base to next unACKed seq #

receiver

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

- send ACK(n)
- out-of-order: buffer
- in-order: deliver (also deliver buffered, in-order pkts), advance window to next not-yet-received pkt

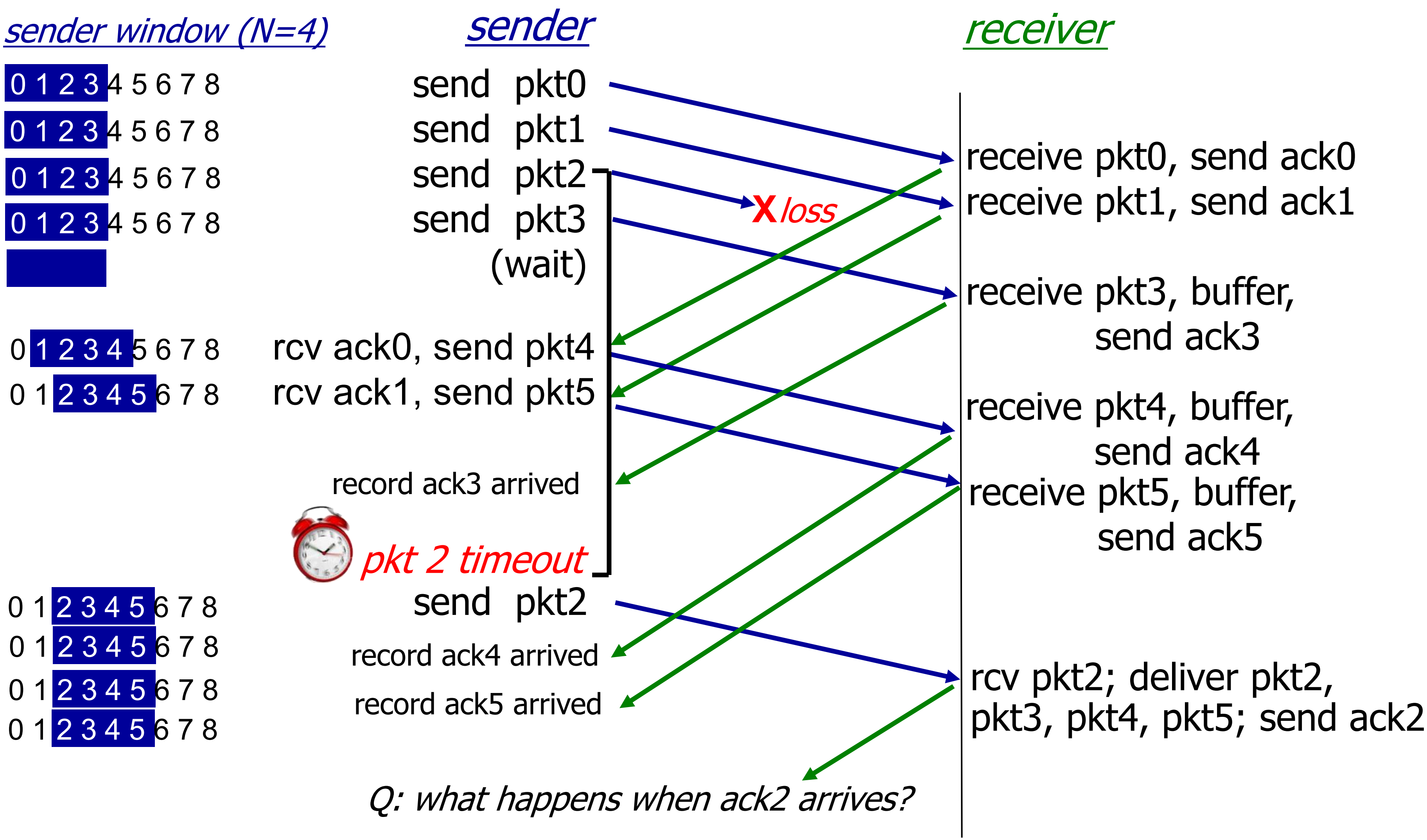
pkt n in [rcvbase-N,rcvbase-1]

- ACK(n)

otherwise:

- ignore

Selective Repeat in Action



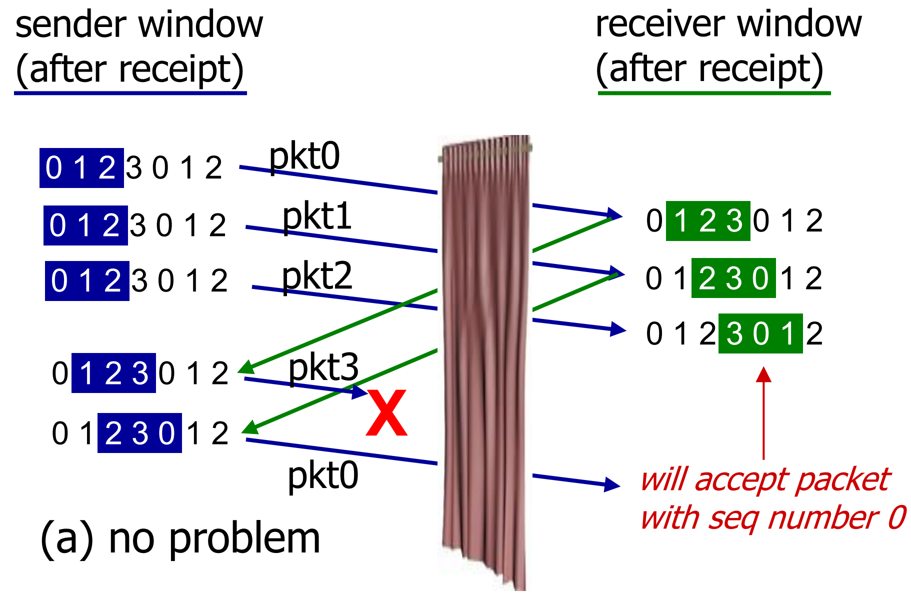
Selective Repeat: Dilemma

example:

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

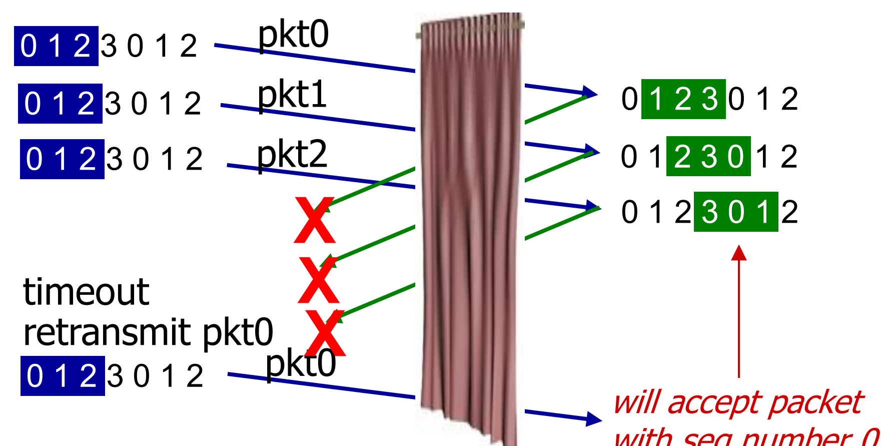
- receiver sees no difference in two scenarios!
- duplicate data accepted as new in (b)

Q: what relationship between seq # size and window size to avoid problem in (b)?



(a) no problem

receiver can't see sender side.
receiver behavior identical in both cases!
something is (very) wrong!



(b) oops!