EECS 122: Introduction to Communication Networks

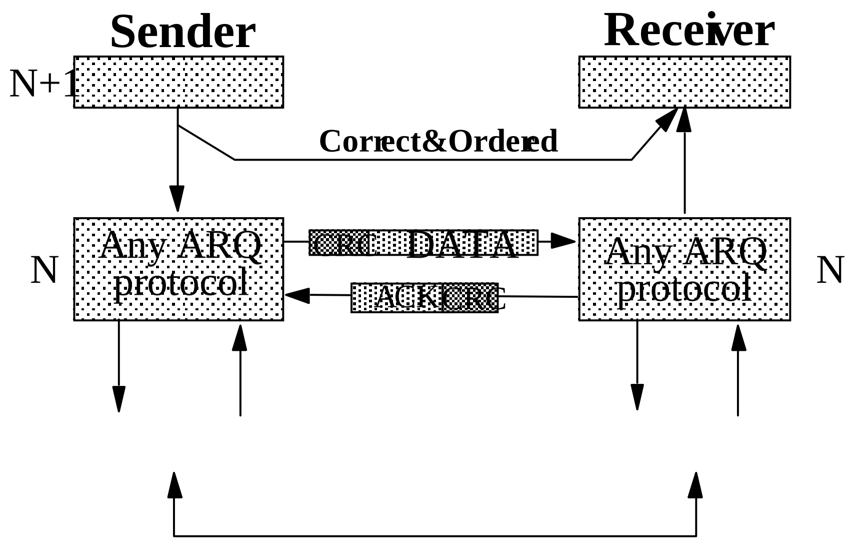
Unit 11: ARQ

ARQ - Overview

- Literature
- Automatic Repeat Request
- Send-And-Wait/ABP
- Continues ARQ: Selective Repeat, Go-Back-N

ARQ (1)

- ARQ - Automatic Repeat Request
- The concept of ARQ is the retransmission of erroneous frames by using a feedback oriented approach.
- Why do we need acknowledgments?
- An ideal channel does not exist,
- We have to deal with various kinds of errors (duplicates, misordered packets, lost packets, corrupted packets)



ARQ (2)

- Possible only for connection oriented transmission.
  - Exception: Acknowledged Datagrams
- Sender and receiver create- each- their individual **local context** expressing their **local view.**
- Neither the transmitter nor the receiver has a complete information on the state of the transmission.
  - => (Control-)Information exchange is needed!
- **Sequence numbers** are used to detect lost, disordered or duplicated packets and to relate **ACKs** to data packets.
- **Timers** are also needed to avoid deadlocks.
- Acknowledgments and timers are used to provide the transmitter with information on the state of the receiver.
- Sequence numbers of PDUs are used to provide the receiver with information about the state of the transmission.

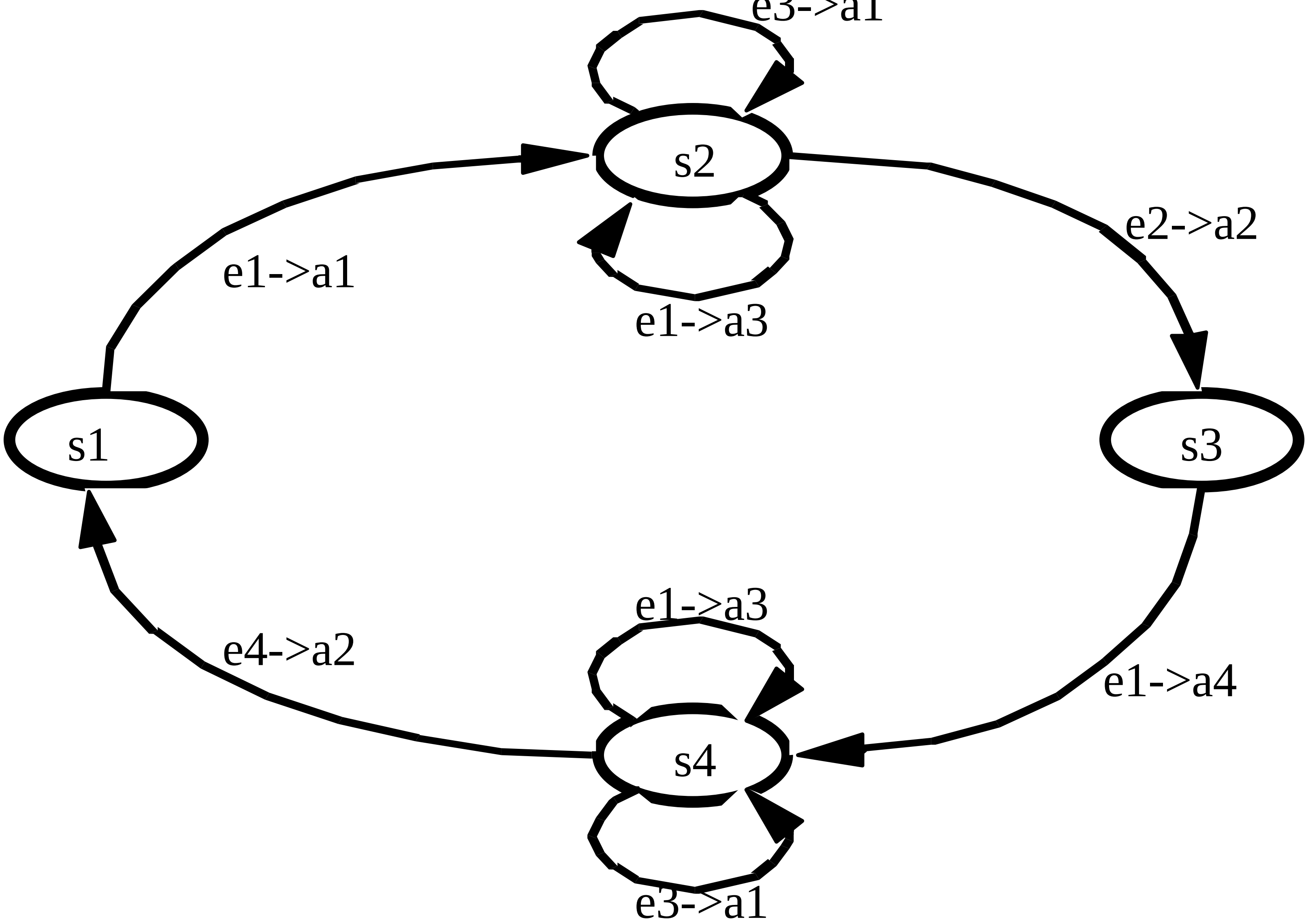
Send-and-Wait

- We know it already, remedies for the problems..
- Infinite loop possible, in case of broken connectivity
  - ⇨ Remedy: A counter for limiting the number of transmission repetitions
- Packets are duplicated if acknowledgement lost...
  - Remedy: An additional one-bit identifier used
- This is called alternating bit protocol (ABP)
- Performance problem
  - Bit rate is limited: one packet per round trip delay...

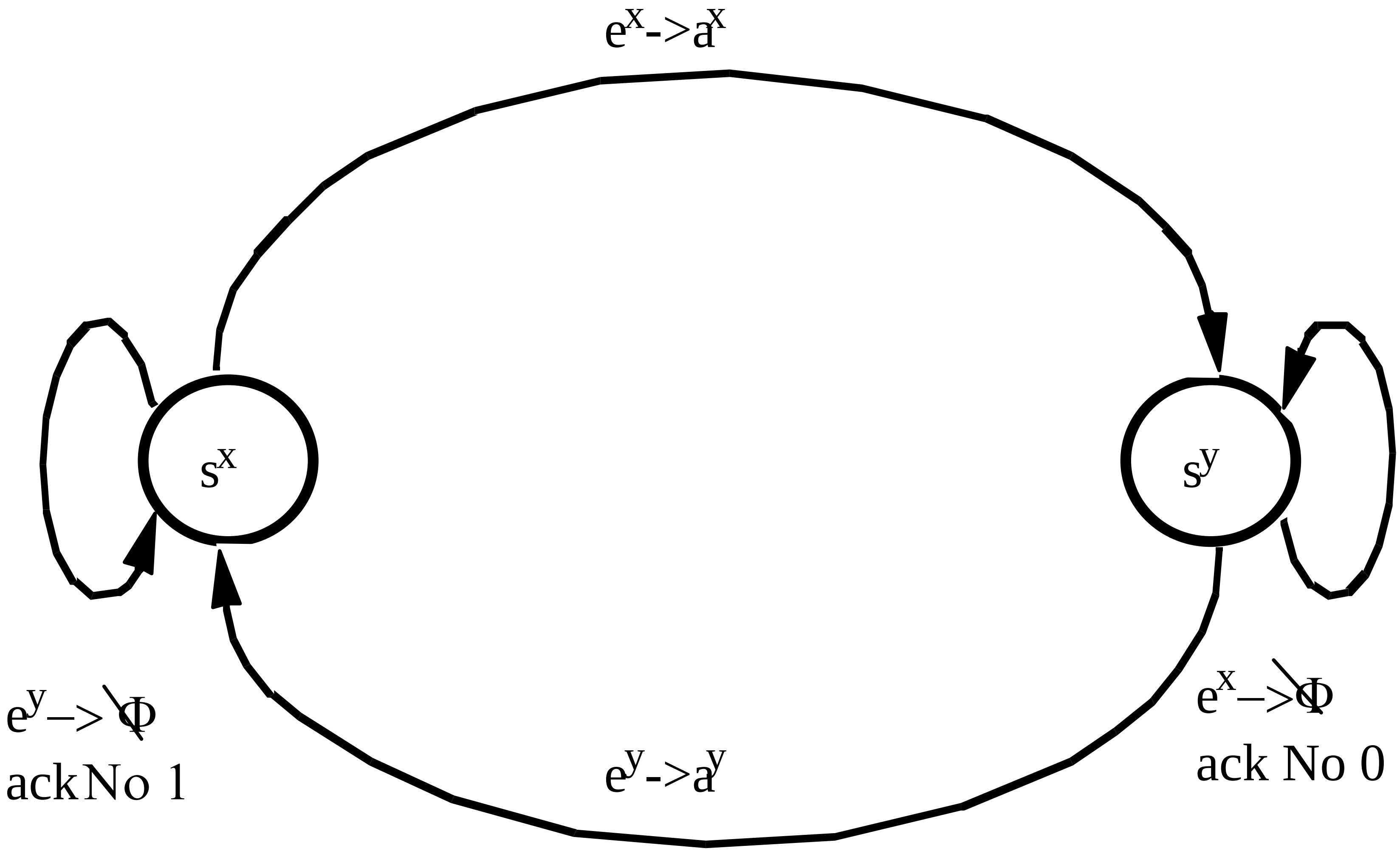
Alternating Bit - Sender (1)

- States
  - s^1 - free, sequence number 0 (Initial state)
  - s^2 - waiting for acknowledgement of the packet
  - s^3 - free, sequence number 1
  - s^4 - waiting for the acknowledgement of the packet
- Events
  - e^1 - Transmit message (Request)
  - e^2 - Packet No. 0 acknowledged
  - e^3 - Timer expired
  - e^4 - Packet No. 1 acknowledged
- Actions
  - a^1 - Send packet No. 0, set timer
  - a^2 - Issue Positive Confirmation, timer disabled
  - a^3 - Issue Negative Confirmation (busy)
  - a^4 - Send packet No. 1, set timer

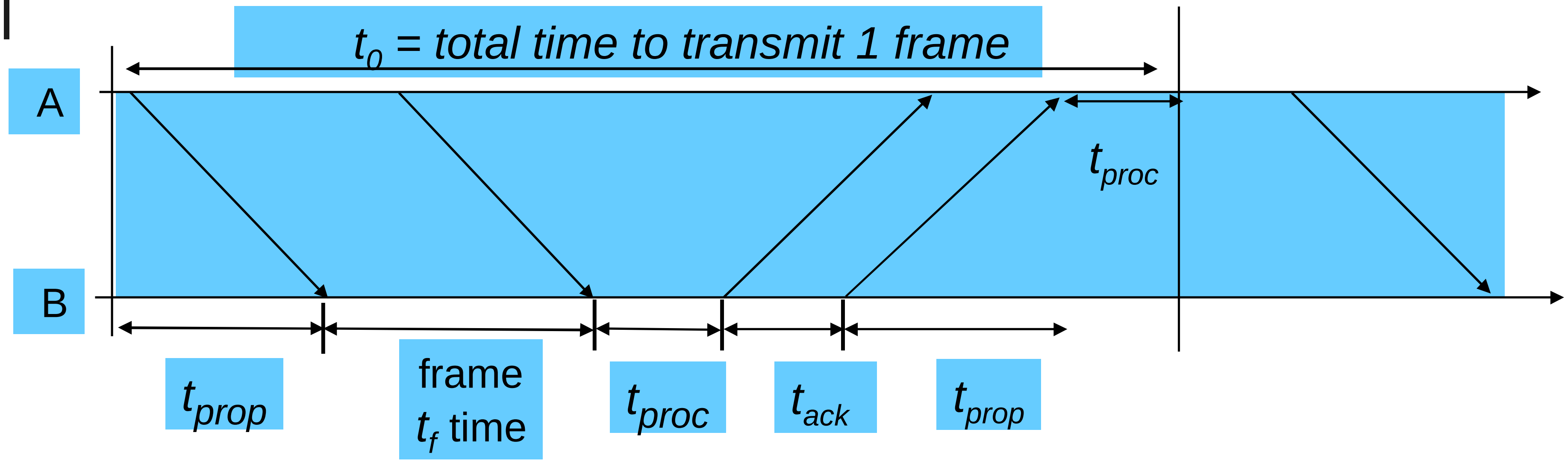
Alternating Bit - Sender (2)



Receiver



Send-and-Wait (S&W) Performance



$$t_0 = 2t_{prop} + 2t_{proc} + t_f + t_{ack}$$

$$= 2t_{prop} + 2t_{proc} + \frac{n_f}{R} + \frac{n_a}{R}$$

bits/info frame

bits/ACK frame

channel transmission rate

Note: S&W and ABP (Alternating Bit) have the same performance

S&W Efficiency on Error-free channel

Effective transmission rate:

bits for header & CRC

$$R_{eff}^{0} = \frac{\text{number of information bits delivered to destination}}{\text{total time required to deliver the information bits}} = \frac{n_f - n_o}{t_0},$$

Transmission efficiency:

Effect of frame overhead

$$\eta_0 = \frac{R_{eff}}{R} = \frac{\frac{n_f - n_o}{t_0}}{R} = \frac{1 - \frac{n_o}{n_f}}{1 + \frac{n_a}{n_f} + \frac{2(t_{prop} + t_{proc})R}{n_f}}.$$

Effect of ACK frame

Effect of ***Delay-Bandwidth Product***

Example: Impact of Delay-Bandwidth Product

n_f =1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Signal propagation delay = 2/3 speed of light ➔ delay is 5 μs/ km

BDP = Bandwidth- delay produkt; η = efficiency

Delay RTT / Bit rate	1 ms (200 km)	10 ms (2000 km)	100 ms (20000 km)	1 sec (200000 km)
1 Mbps	BDT=10^3 η=88%	10^4 49%	10^5 9%	10^6 1%
1 Gbps	10^6 1%	10^7 0.1%	10^8 0.01%	10^9 0.001%

Delay xBW* and *Efficiency as functions **of the system parameters**

Send-and-Wait does not work well for very high speeds or long propagation delays

Efficiency of ABP in the Case of Errors

- There is always a packet ready for transmission
- Packets are lost with the probability Π.
- Successful transmission is acknowledged after a constant time b.
- The time S needed for a successful transmission is
  - b with probability $(1-\Pi)$
  - $2b$ with probability $(1-\Pi)\,\Pi$
  - $3b$ with probability $(1-\Pi)\,\Pi^2$
  - $(i+1)b$ with probability $(1-\Pi)\,\Pi^i$
- hence:

$$E(S) = \sum_{i=0}^{\infty}(i+1)b(1-\Pi)\Pi^i \quad \rightarrow \quad E(S) = b + b(1-\Pi)\sum_{i=0}^{\infty} i\Pi^i$$

$$E(S) = b + \frac{b\Pi}{1-\Pi} = \frac{b}{1-\Pi}$$

Packet Rate = 1/ E(S)

Efficiency of ABP in the Case of Errors (2)

Let us consider the maximal possible link throughput

$$\Lambda = \frac{1}{b}(1-\Pi) \ldots \frac{packets}{s}$$

x - link speed in bits/s

M- number of information bits in a packet

Δ- time needed for signal round trip (packet + ack)

C - number of overhead bits in a packet

$$b = \frac{M}{x} + \Delta$$

$$\Lambda = \frac{1-\Pi}{\frac{M}{x}+\Delta} \ldots \frac{packets}{s}$$

Net Data Throughput NDT

$$NDT = \frac{M-C}{\frac{M}{x}+\Delta}(1-\Pi) \ldots \frac{bits}{s}$$

For an independent bit error model with bit error rate(BER) denoted E

$$1-\Pi = (1-E)^M$$

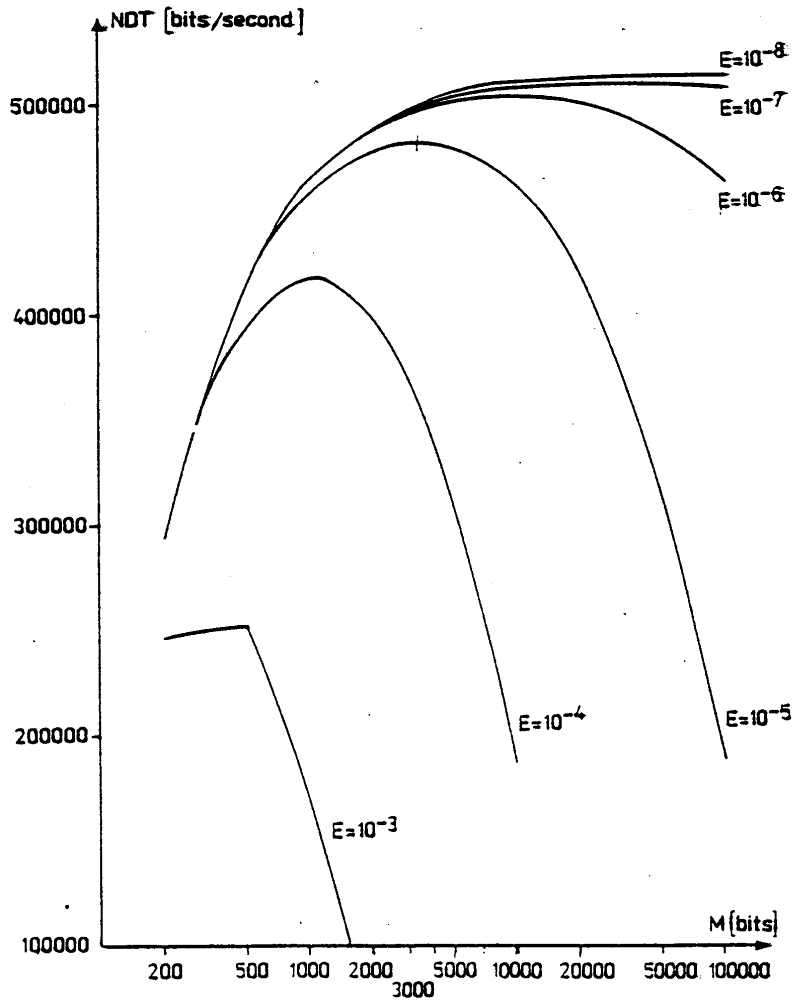
Example for

C=56 bits, x=0.5 Mbits/s, Δ=90 µs

Efficiency of ABP in the Case of Errors (3)

Table A1. Net data through-put NDT and optimal packet length M^*

E	M^* bits	NDT (M^*) bits per second
10^{-8}	101039	510931
10^{-7}	31954	508707
10^{-6}	10108	501558
10^{-5}	3200	480281
10^{-4}	1016	418078
10^{-3}	328	268136



The influence of packet length M on the net data throughput NDT for different values of rate E

Example: Impact of the Bit Error Rate

$$\eta = \eta_o (1 - P_f)$$

P_f - **packet error rate**

$$1 - P_f = (1 - p)^{n_f} \approx e^{-n_f p} \text{ for large } n_f \text{ and small } p$$

n_f =1250 bytes = 10000 bits, $n_a = n_o$=25 bytes = 200 bits

Find efficiency for random bit errors with p=0, 10^{-6}, 10^{-5}, 10^{-4}

$1 - P_f$ / **Efficiency**	0	10^{-6}	10^{-5}	10^{-4}
With:1 Mbps & 1 ms	1 88%	0.99 86.6%	0.905 79.2%	0.368 32.2%

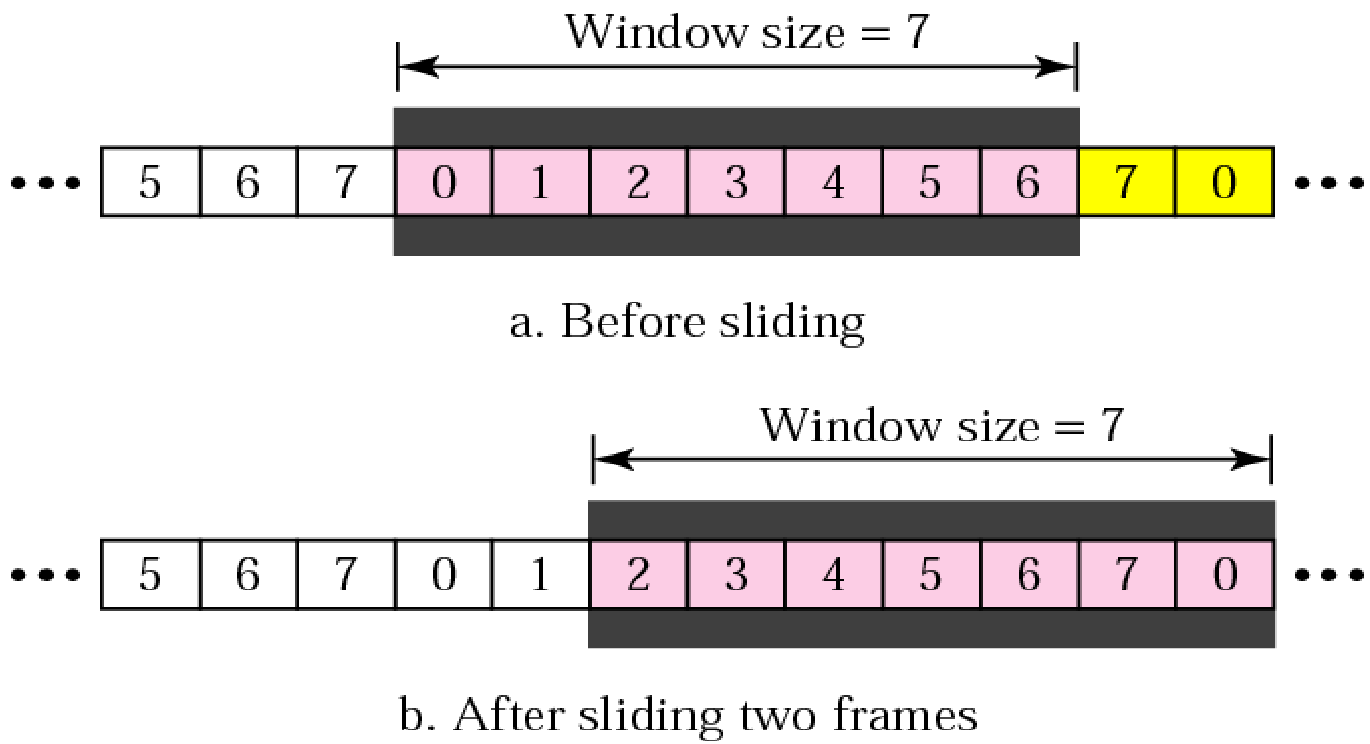
➔ *Bit errors impact performance as* $n_f p$ *approach 1*

Continues ARQ

- In the following we will discuss ARQ protocols that allow continuous transmission of PDUs
  - Selective Repeat
  - Go-Back-N
- Continuous transmission means that the sender is allowed to send continuously without waiting for every packet to be acknowledged.
- Since the memory capacity of a computer is finite, the maximum number of unacknowledged packets must be finite (window size)

The concept of WINDOW

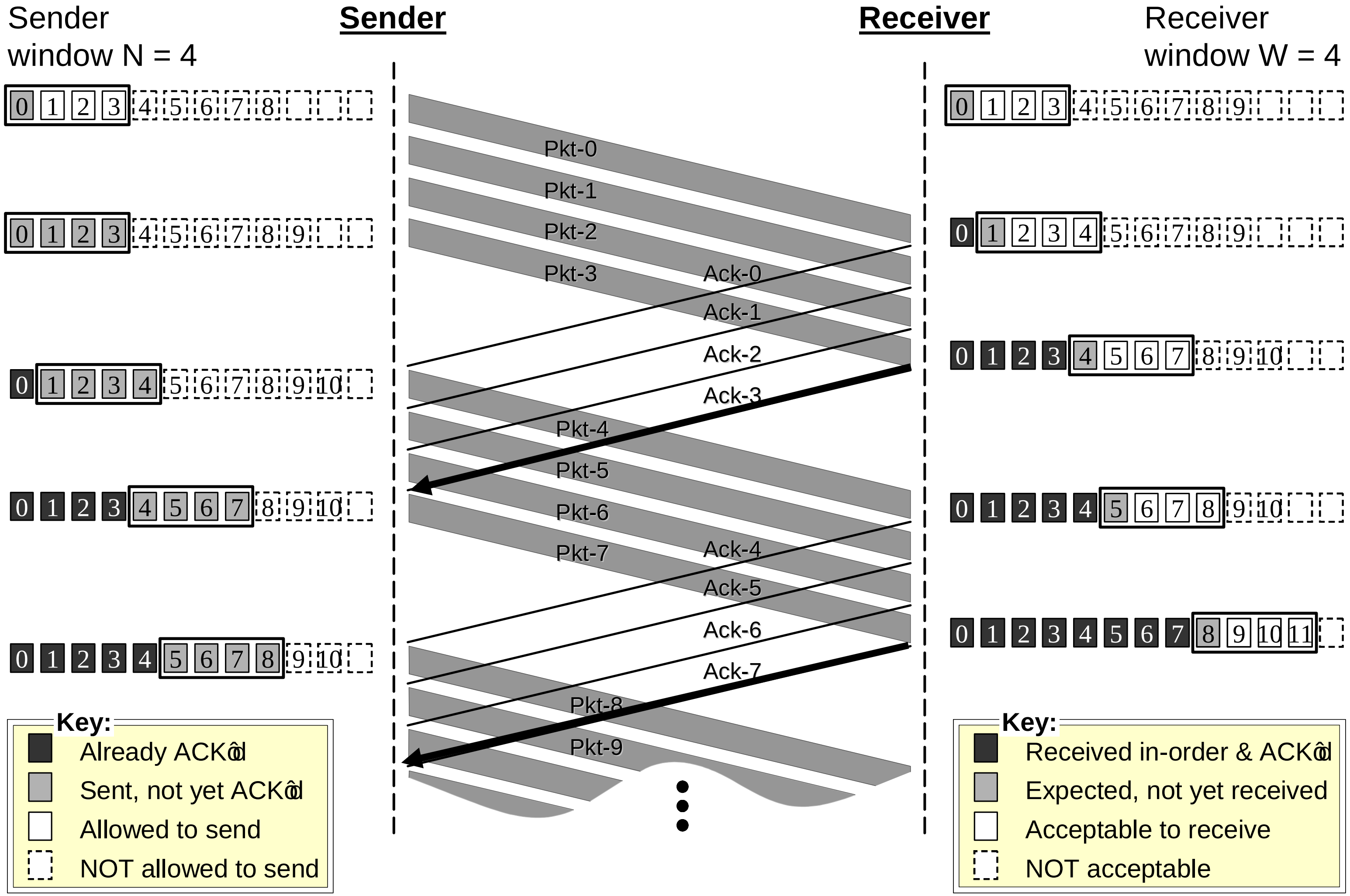
Packets are distinguished by **Sequence Numbers** belonging to a finite set!



The window defines the **scope** of Seq. Numb. Which might be transmitted **before the smallest** of them will be confirmed by the reciever (*not anyone!*)

Sliding Window ARQ

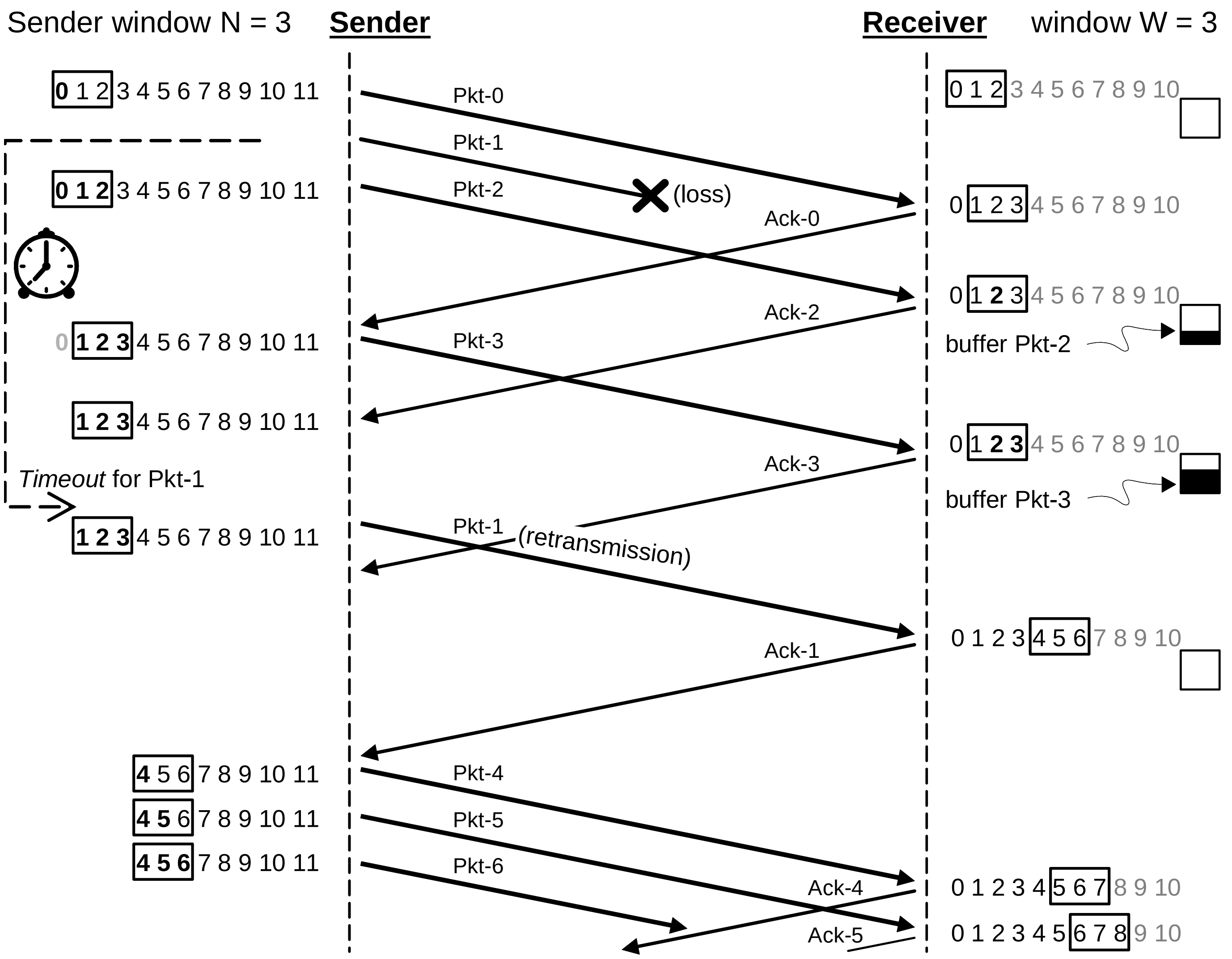
Comment: Frequently CUMULATIVE ACKs are used: the highest # confirmed



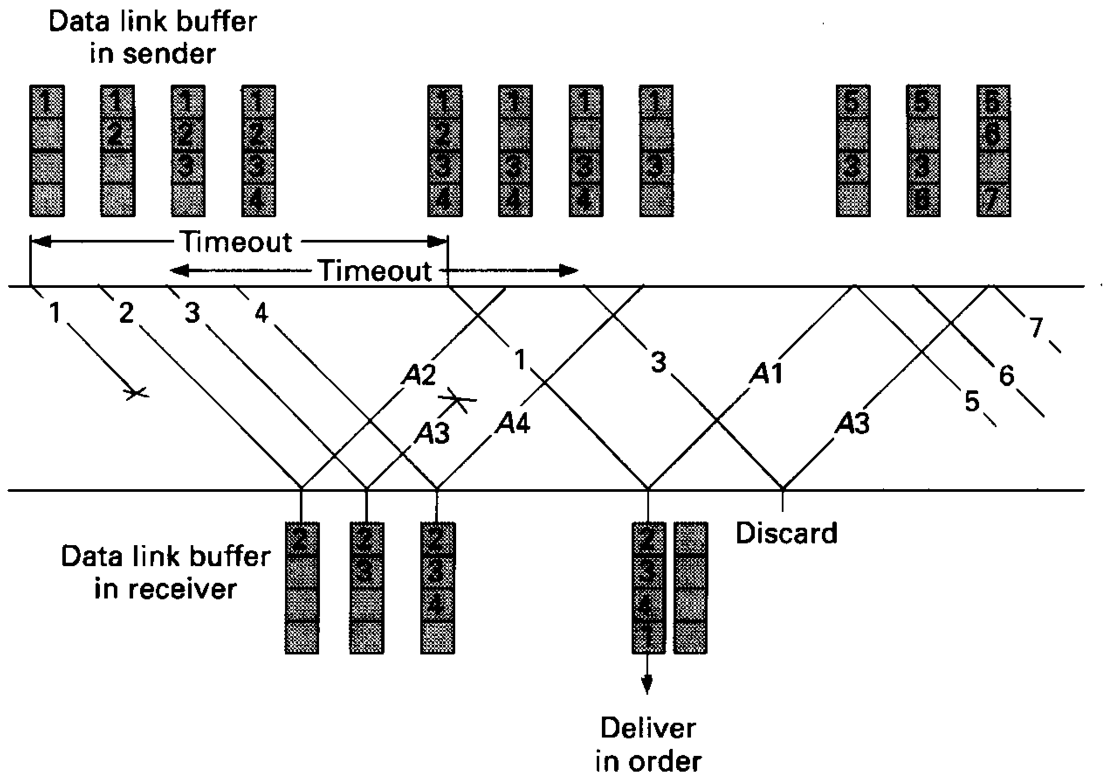
Selective Repeat - principle

- An ARQ protocol that only retransmits erroneous packets belongs to the class of Selective Repeat protocols.
- In the following a special case of a Selective Repeat protocol will be considered as an example:
  - Pure positive acknowledgments. This means that the sending side detects errors by using timeouts.
  - Each acknowledgment acknowledges exactly one packet.
  - Control packets are used as ACKs
  - An individual timer is used per PDU.
  - Window size w and infinite numbering space

Selective Repeat ARQ (SR)



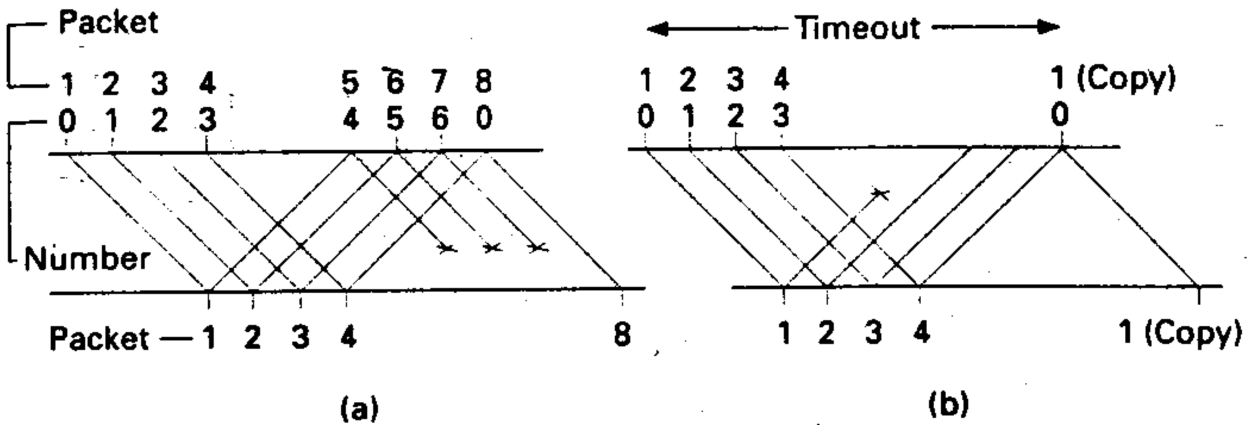
Selective Repeat – additional explanation



- Sequence of events in selective repeat protocol.
  - The sender transmits packets 1, 2, 3, and 4. Packet 1 is corrupted. The receiver sends ACK2, ACK3, and ACK 4, and ACK 3 is corrupted. The sender retransmits packet 1 and packet 3 after a timeout and the sender receives ACK1 and ACK3. The sender then transmits packets 5, 6, and 7. The figure indicates the contents of the buffers.

Selective Repeat Numbering (1)

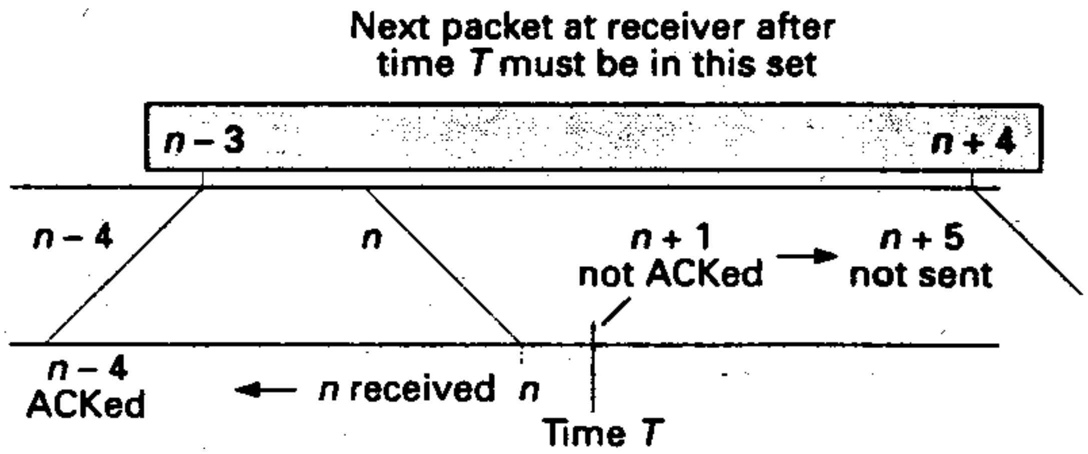
- Since sequence numbers within PDUs are not infinite one has to know the necessary number range R. Let us consider an example with *w=4* and *R = [0,..,6]*



- In case (a) the first four packets are successfully transmitted and acknowledged but the next three PDUs are lost while the eighth packet (numbered with 0) is transmitted successfully.
- In case (b) the first four packets are successfully transmitted but this time the ACK for the first packet is lost. Due to the lack of the first ACK the sender has to retransmit the first PDU (numbered 0).
- The receiver gets in both cases a PDU with the identifier 0. It can not distinguish whether it is the eighth PDU or a duplicate of the first PDU.

Selective Repeat Numbering (2)

- Determining the necessary number range for window size *w*.



- Let n be the last packet received by the receiver.
- As the sender has sent packet *n*, all packets up to (including) *n-w* must already have been acknowledged.
- The receiver may acknowledge the packet *n*. This allows the sender to transmit packets with sequence numbers *[n+1,...,n+w]*.
- Thus upon arrival of packet n the receiver can only receive packets in the range *[n-w+1,..,n,..,n+w]* and the sender can only receive ACKs within the same range.
- Conclusion: $R >= 2w$ is needed

Selective Repeat Efficiency

- OBVIOUSLY DEPENDENT ON THE WINDOW SIZE
- Ideally, one would like to keep the „flow of packets“ continuous…
- What window size would assure this?

  (Round trip delay / Packet insertion rate) +1

- WE WILL DISCUSS LATER REASONS why this might NOT be a good idea !!!!
- Keywords
  - Cumulative acknowledgements
  - Flow control, congestion cotrol..

Efficiency of Selective Repeat with full window size!

- Assume P_f frame loss probability, then time to deliver any single frame is: $t_f / (1-P_f)$

$$\eta_{SR} = \frac{\dfrac{n_f - n_o}{t_f/(1-P_f)}}{R} = (1 - \frac{n_o}{n_f})(1-P_f)$$

In error free case Selective Repeat achieves ideal efficiency

(for the forward link, the load on back-ward channel is ignored!)

Selective Repeat Summary (1)

- Packets can be sent continuously as long as there are no more than w packets unacknowledged.
- The packets are numbered consecutively in a cyclic way: $R=[0,..,2w-1]$
- The sender retransmits a copy of a packet that has not been acknowledged before a timeout.
- The receiver acknowledges the reception of a correct packet with an ACK that has the same number as the packet.
- The receiver stores the packets it receives out of order and it delivers them in order.
- SRP is more efficient than ABP because the sender does not have to wait for a packet to be acknowledged before sending the next one.

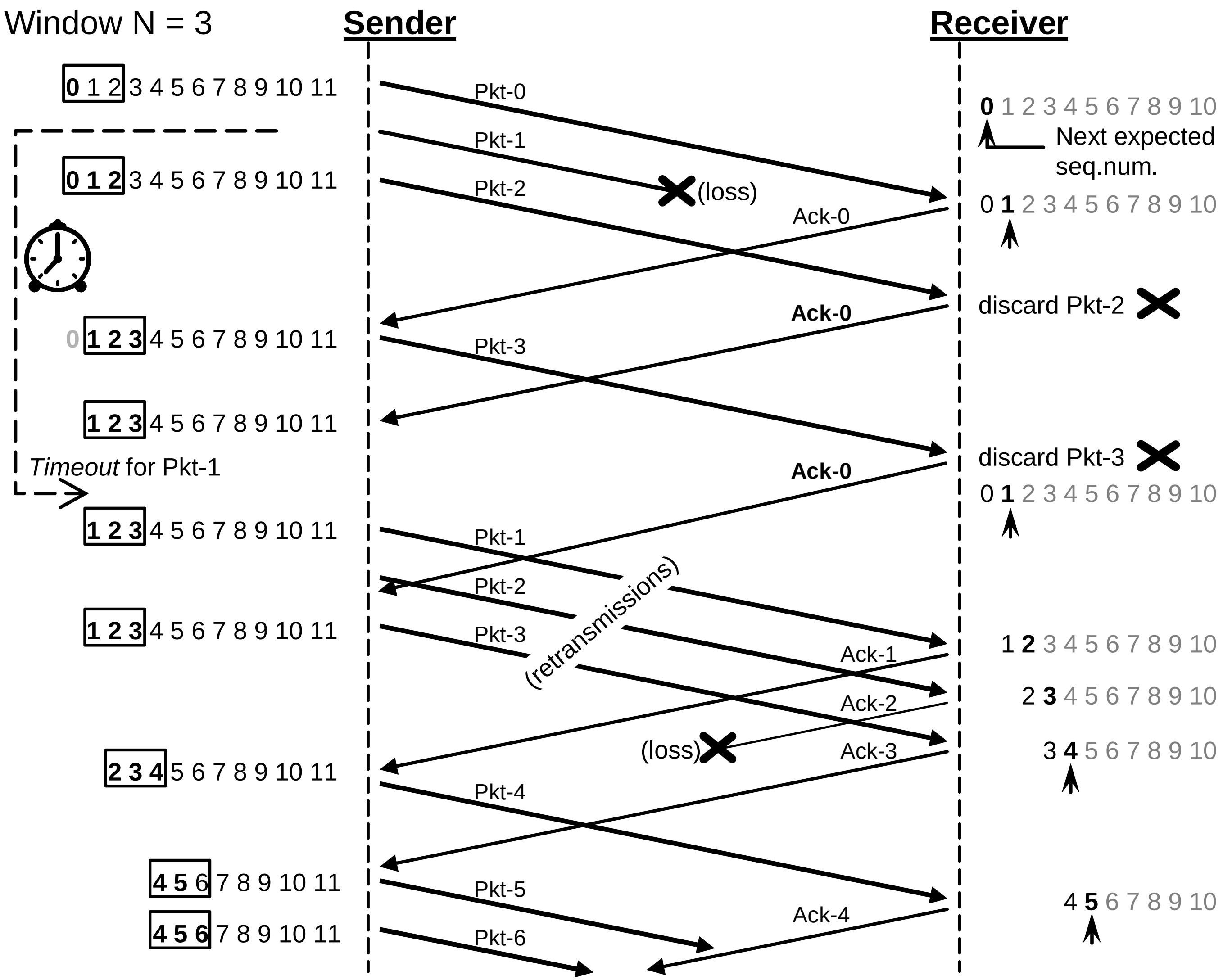
Selective Repeat Summary – a problem

- Selective Repeat requires buffering at the receiver in order to work correctly.
- What is the desired window size? Well – assuring that there are no transmission stops…will discuss it later in detail.

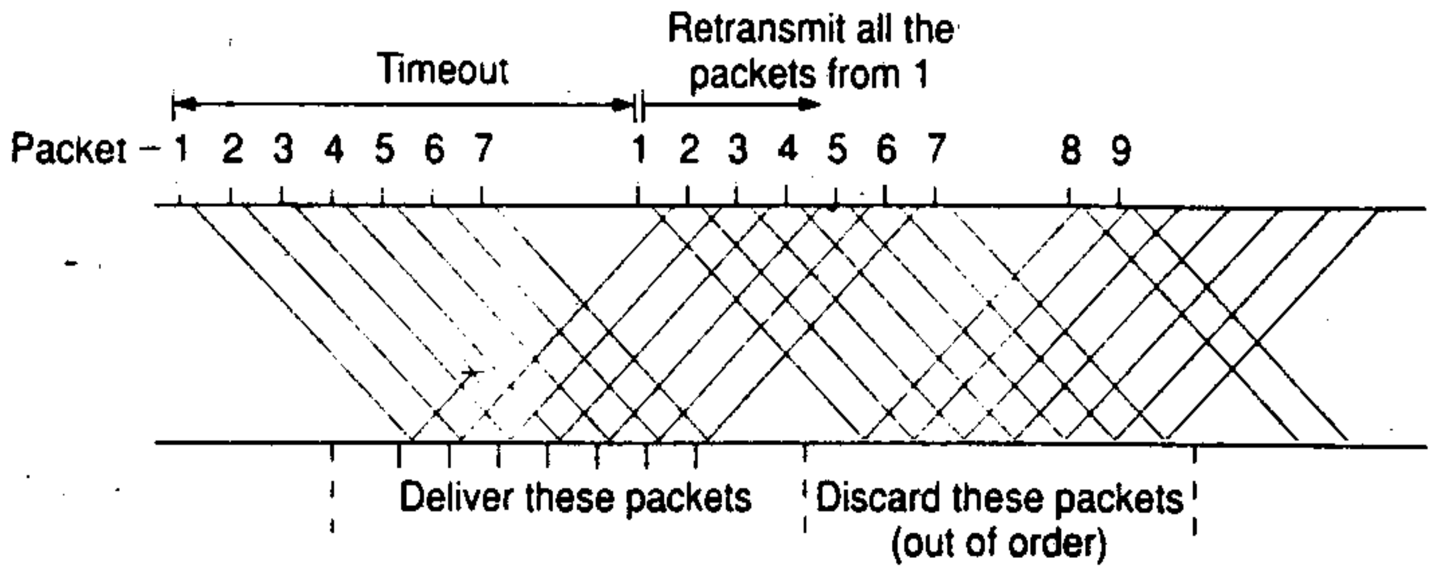
Go-Back-N Principle

- GBN works like SRP in absence of errors.
- But if the sender detects an error (e.g. due to a timeout) it retransmits the incorrect packet and all subsequent packets.
- GBN protocols allows the sender to have multiple unacknowledged packets without the receiver having to store out of sequence packets.
- The configuration considered here has the following properties:
  - Pure positive acknowledgments
  - An ACK acknowledges the corresponding data packet plus all previous data packets
  - Control packets are used
  - Individual timer per PDU (Sender only)

Go-back-N ARQ


Window N = 3
Sender
Receiver
0 1 2 3 4 5 6 7 8 9 10 11
Pkt-0
Pkt-1
Pkt-2
(loss)
0 1 2 3 4 5 6 7 8 9 10
Next expected seq.num.
Ack-0
discard Pkt-2
Pkt-3
0 1 2 3 4 5 6 7 8 9 10 11
Timeout for Pkt-1
discard Pkt-3
(retransmissions)
Ack-1
Ack-2
Ack-3
Pkt-4
Pkt-5
Pkt-6
Ack-4
1 2 3 4 5 6 7 8 9 10
2 3 4 5 6 7 8 9 10
3 4 5 6 7 8 9 10
4 5 6 7 8 9 10
2 3 4 5 6 7 8 9 10 11
4 5 6 7 8 9 10 11

Go-Back-N – compare with explanation of SR



Sequences of events with the GO BACK N protocol.

Go-Back-N Summary

- The packets are numbered consecutively in a cyclic way: ***R=[0,…,w]   (Compare with SR!)***
- The receiver acknowledges a correct packet with an ACK that has the same number as the packet.
- The receiver discards packets received out of order.
- The sender can have up to w unacknowledged packets.
- When the sender does not receive the acknowledgment of a packet before a timeout, it retransmits copies of the packet and all the subsequent packets
- The efficiency of GBN lies between ABP and SRP. No buffering is required at the receiver.

Example: Impact Bit Error Rate on GBN

n_f=1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Compare S&W with GBN efficiency for random bit errors with p = 0, 10^{-6}, 10^{-5}, 10^{-4} and R = 1 Mbps & 100 ms

1 Mbps x 100 ms = 100000 bits = 10 frames Ÿ Use W_s = 11

Efficiency \ BER	BER=0	$=10^{-6}$	$=10^{-5}$	$=10^{-4}$
S&W	8.9%	8.8%	8.0%	3.3%
GBN	98%	88.2%	45.4%	4.9%

Å *Go-Back-N significant improvement over Stop-and-Wait for large delay-bandwidth product*

Å *Go-Back-N becomes inefficient as error rate increases*

Efficiency of Go-Back-N

- GBN is completely efficient, if W_s large enough to keep channel busy, and if channel is error-free
- Assume P_f frame loss probability, then time to deliver a frame is:
  - t_f if first frame transmission succeeds $(1 - P_f)$
  - $t_f + W_s t_f/(1-P_f)$ if the first transmission does not succeed P_f

$$t_{GBN} = t_f(1-P_f) + P_f\{t_f + \frac{W_s t_f}{1-P_f}\} = t_f + P_f \frac{W_s t_f}{1-P_f} \text{ and}$$

$$\eta_{GBN} = \frac{\frac{n_f - n_o}{t_{GBN}}}{R} = \frac{1-\frac{n_o}{n_f}}{1+(W_s-1)P_f}(1-P_f)$$

Delay-bandwidth product determines W_s

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Å *Go-Back-N significant improvement over Stop-and-Wait for large delay-bandwidth product*

Å *Go-Back-N becomes inefficient as error rate increases*

ARQ – possible variants

- Transmission Strategies
  - Packets may be transmitted either individually or continuously.
- Strategies for issuing ACKs
  - Positive ACKs vs. negative ACKs
    - Pure positive ACKs are sufficient
    - Pure negative ACKs are insufficient
    - Mix is used for optimization
  - ACKs can acknowledge either a single packet or a set of packets (cumulative acknowledgment)
  - Control packet vs. piggybacked acknowledgment
- Retransmission strategies
  - Retransmit only the erroneous packet(s).
  - Retransmit the erroneous and all succeeding packets.
- Timers
  - Individual timer per PDU vs. a timer per connection
  - Also the receiver might use timers…

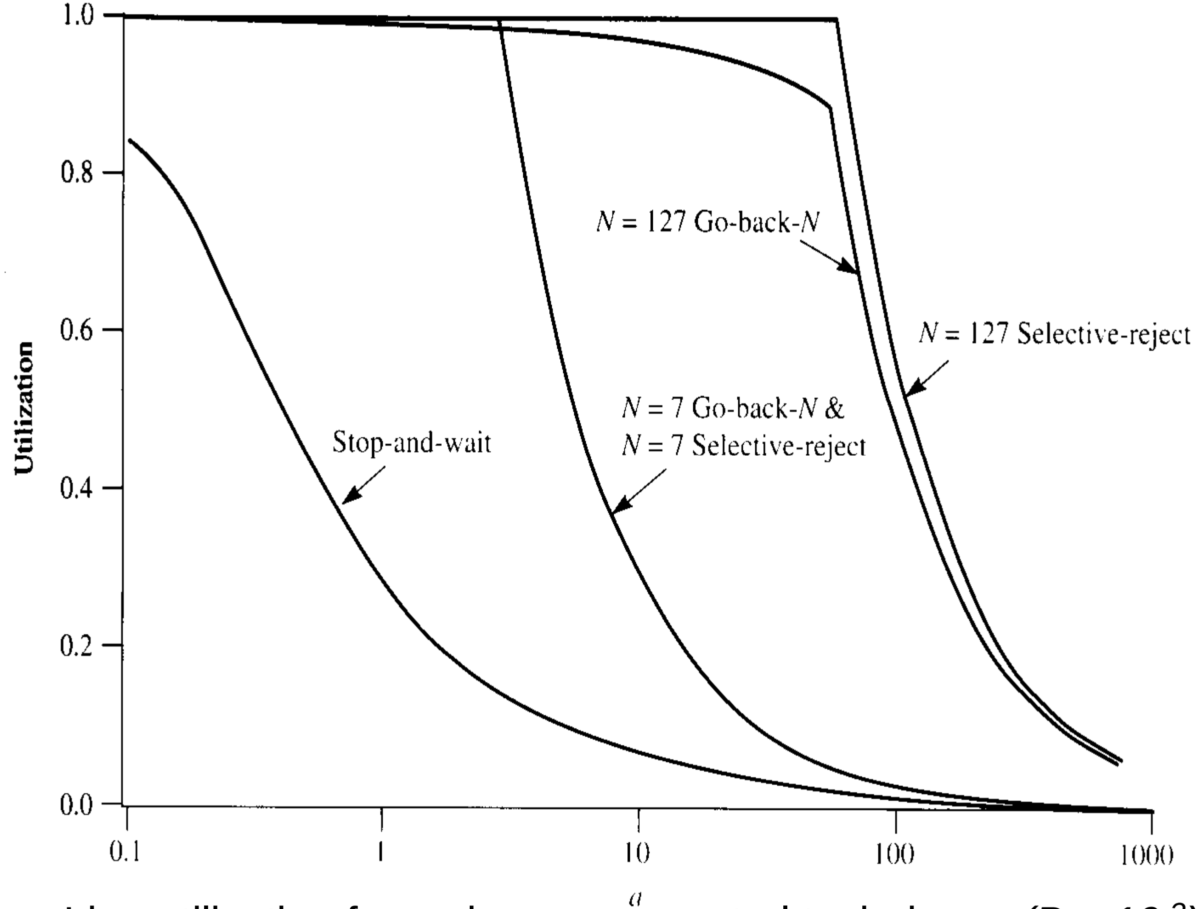
Impact of error bit Rate on the three options

n_f=1250 bytes = 10000 bits, n_a=n_o=25 bytes = 200 bits

Compare S&W, GBN & SR efficiency for random bit errors with p=0, 10^{-6}, 10^{-5}, 10^{-4} and R= 1 Mbps & 100 ms

Efficiency	0	10^{-6}	10^{-5}	10^{-4}
S&W	8.9%	8.8%	8.0%	3.3%
GBN	98%	88.2%	45.4%	4.9%
SR	98%	97%	89%	36%

Comparison of ARQ Protocols



Line utilization for various error-control techniques *(P = 10^-3)*

$$\alpha = \frac{Propagation\ Delay}{Transmission\ Time}$$

P : Probability that a single frame is in error.