521150A
Introduction to Internet

Lecture 4 – Data link layer, part II: Link Control

Erkki Harjula 2023

Schedule of the course

PART I: Basics of networking and Internet, data link layer

Mon 13.3. 10-12 L6/Zoom	Lecture 1: Introduction & motivation
Tue 14.3. 10-12 L6/Zoom	Lecture 2: Architecture & design principles
Wed 15.3. 10-12 L5/Zoom	Lecture 3: Data link layer – basics part I
Thu 16.3. 10-12 L4/Zoom	Exercise session 1A
Mon 20.3. 10-12 L6/Zoom	Lecture 4: Data link layer – basics part II
Tue 21.3. 10-12 L6/Zoom	Exercise session 1B
Tue 21.3. 14-18 AT122/Zoom	Lab exercise 1 – group 3
Wed 22.3. 10-12 L5/Zoom	Lecture 5: Data link layer – Wired networks
Wed 22.3. 14-18 AT122/Zoom	Lab exercise 1 – group 4
Thu 23.3. 14-18 AT122/Zoom	Lab exercise 1 – group 2
Fri 24.3. 12-16 AT122/Zoom	Lab exercise 1 – group 1
Mon 27.3. 14-16 L5/Zoom	Exercise session 1C
Tue 28.3. 10-12 L6/Zoom	Lecture 6: Data link layer – Wireless networks
Wed 29.3. 10-12 Moodle	Theory exam 1

PART II: Network and transport layers

Thu 30.3. 8-10 L5/Zoom	Lecture 7: Network layer part I
Mon 3.4. 14-16 L5/Zoom	Exercise session 2A
Tue 4.4. 10-12 L6/Zoom	Lecture 8: Network layer part II
Wed 5.4. 10-12 L5/Zoom	Lecture 9: Transport layer part I Course work intro
Tue 11.4. 10-12 L6/Zoom	Lecture 10: Transport layer part II
Tue 11.4. 14-18 AT122/Zoom	Lab exercise 2 – group 3
Wed 12.4. 10-12 Moodle	Theory exam 2
Wed 12.4. 14-18 AT122/Zoom	Lab exercise 2 – group 4
Thu 13.4. 8-10 L5/Zoom	Exercise session 2B
Thu 13.4. 14-18 AT122/Zoom	Lab exercise 2 – group 2
Fri 14.4. 12-16 AT122/Zoom	Lab exercise 2 – group 1

PART III: Application layer, network security and multimedia

Fri 14.4. 10-12 L5/Zoom	Lecture 11: Networking applications
Mon 17.4. 14-16 L5/Zoom	Lecture 12: Network security
Tue 18.4. 10-12 L6/Zoom	Exercise session 3A
Wed 19.4. 10-12 L5/Zoom	Lecture 13: Multimedia and QoS
Mon 24.4. 14-16 L5/Zoom	Exercise session 3B
Tue 25.4. 14-18 AT122/Zoom	Lab exercise 3 – group 3
Wed 26.4. 10-12 L5/Zoom	Lecture 14: Challenges&Future Internet trends
Wed 26.4. 14-18 AT122/Zoom	Lab exercise 3 – group 4
Thu 27.4. 14-18 AT122 /Zoom	Lab exercise 3 – group 2
Fri 28.4. 12-16 AT122 /Zoom	Lab exercise 3 – group 1
Wed 3.5. 10-12 Moodle	Theory exam 3
Thu 25.5. 16-19 L1	Final exam

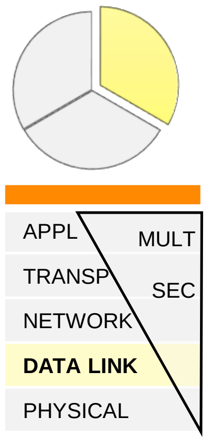
Course work (independent work)

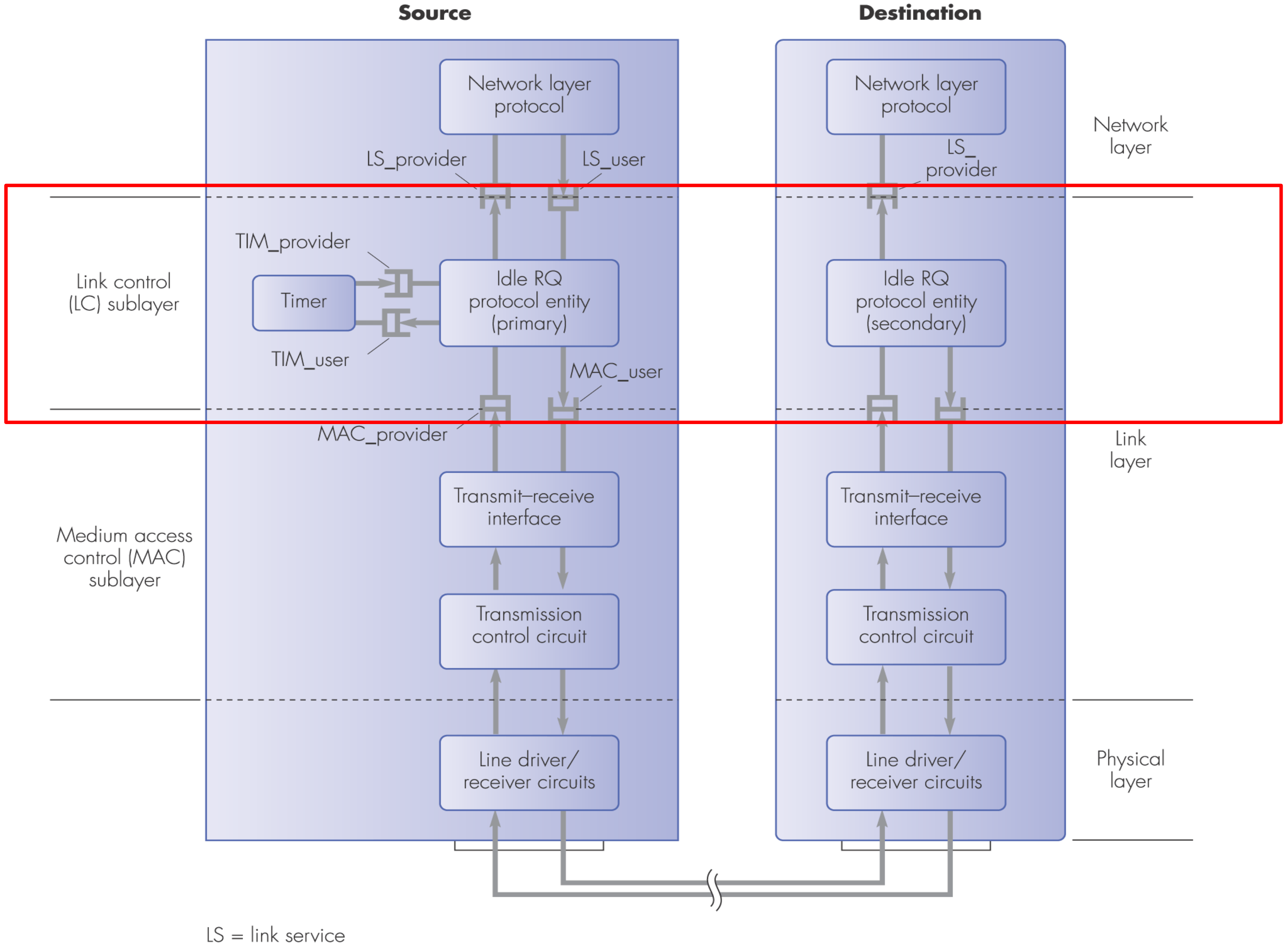
Main learning objectives of this lecture

1. **Know the main functions of Link Control**
2. **Understand the basic concept of flow control and know its basic types:**
   - Stop&wait
   - Pipelining
   - Sliding window
3. **Understand the concept of error control and know its basic types:**
   - Stop&wait ARQ
   - Go-Back-N ARQ
   - Selective repeat

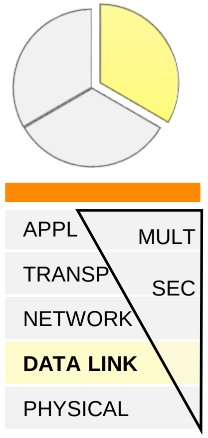
Basics of Link Control

Link Control (LC)



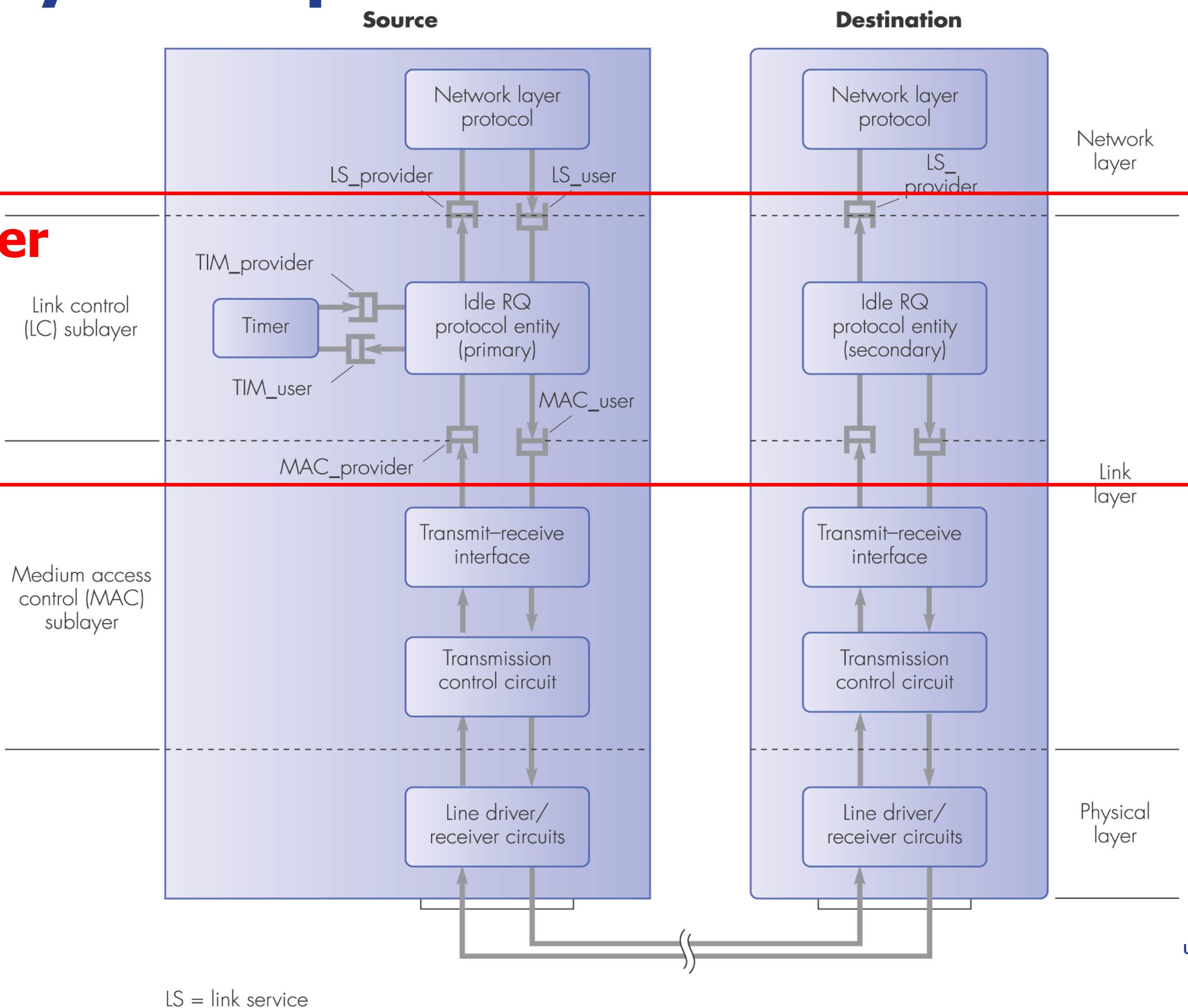


Data link layer architecture

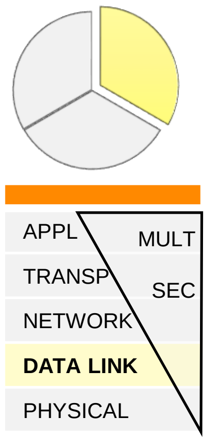


Typically data link layer comprises of two sublayers:

- **Link control (LC) sublayer**
  - Error control
  - Flow control
- **Medium access control (MAC) sublayer**
  - Framing
  - Transmission (medium access)



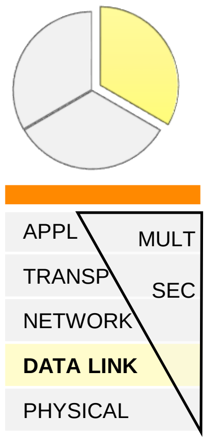
Data link control protocols



- **Requirements/objectives for effective data communication between two directly-connected transmitting-receiving stations**
  - **Frame synchronization**: data are sent in frames, the beginning and end of each frame must be recognizable;
  - **Flow control**: sending station must not send frames at a rate faster than the receiving station can absorb them;
  - **Error control**: bit errors introduced by the transmission system should be corrected, or at least the upper layer should be informed;
  - **Addressing**: in a shared link (such as LAN), the identity of the two stations involved in transmission must be specified;
  - **Control and data on same link**: not desirable to have a separate physical communication path for control information, receiver must be able to distinguish control information from the data being transmitted;
  - **Link management**: procedures for coordination and cooperation among stations for the initiation, maintenance and termination of sustained data exchange;

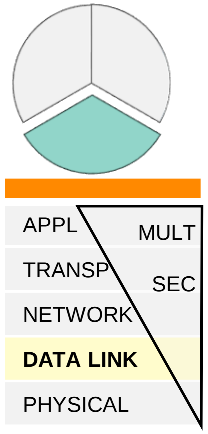
→ A data link control protocol is needed

Specification of a data link control protocol

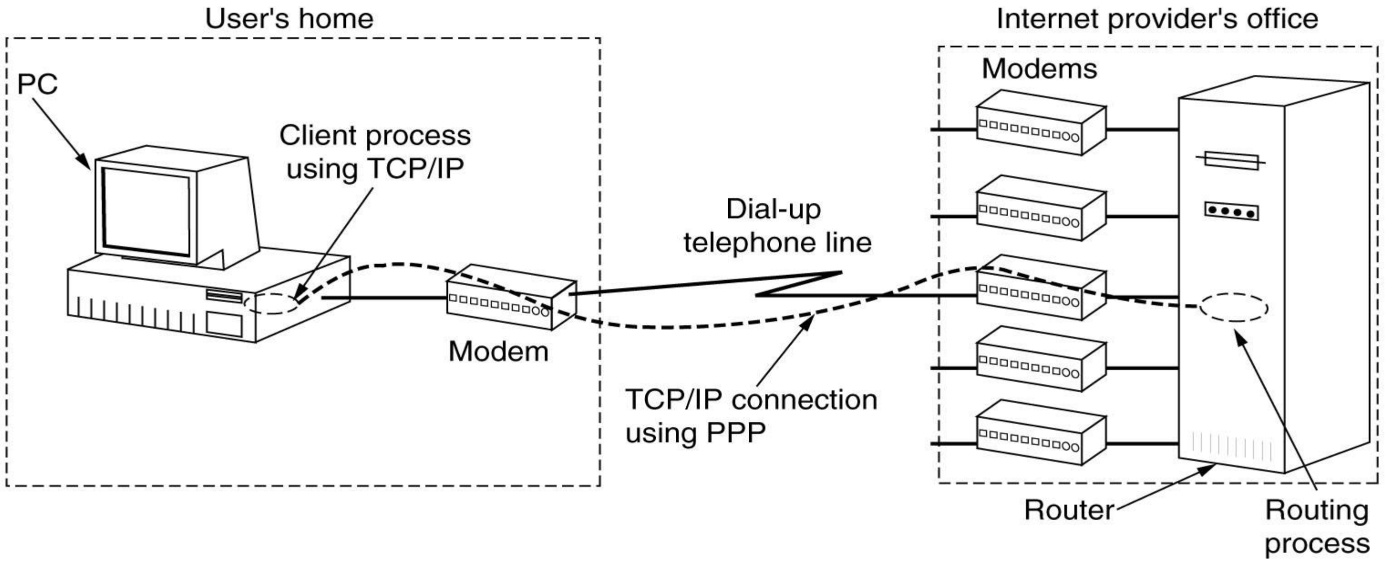


- **Building blocks**
  - Frames (data, acknowledgments)
  - Buffers
  - Timers
  - Sequence numbers (frame ID’s)
  - Flow control
  - Error control (incl. error detection)
- **Notation of following protocol examples**
  - P = primary (sender, source)
  - S = secondary (receiver, destination)
  - I(N) = information (data) with sequence number N
  - ACK = positive acknowledgment frame
  - NAK = negative acknowledgment frame

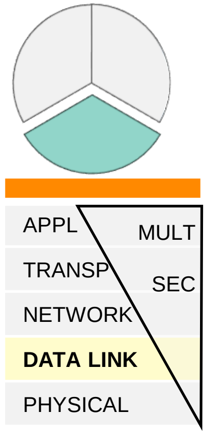
PPP: Point-to-point data link control



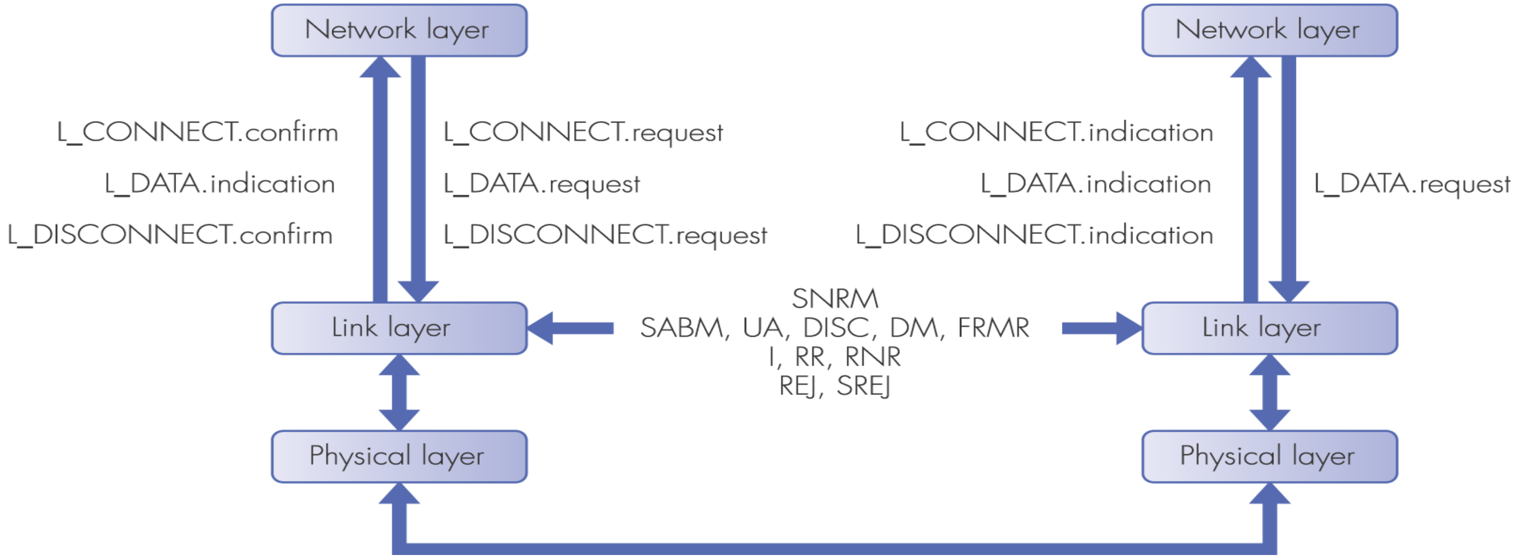
- **RFC 1661 etc.**
- **One sender, one receiver, one link**
- **Easier than shared broadcast link**
  - No medium access control
  - No need for explicit MAC addressing
  - E.g., dialup link, ISDN line



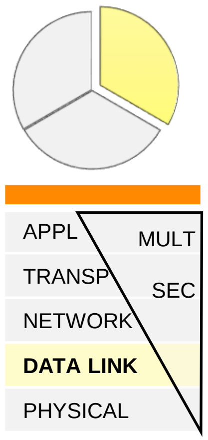
HDLC (High-level Data Link Control)



- **ISO 3009, ISO 4335**
- **Most important data link control protocol**
- **Bit-oriented**
- **Synchronous transmission**
  - All transmission in form of frames
- **Widely used for point-to-point and point-to-multipoint links**
- **Also basis for many other important data link protocols**

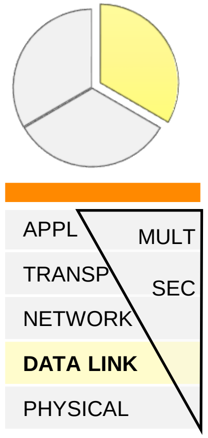


Link performance characterization (1)



- **Assumptions**
  - d: length of the physical link (m)
  - V: signal propagation speed in the link medium (m/s)
  - L: length of a frame (bits)
  - **Data rate (R, bps) (also called bit rate or bandwidth)**
  - Amount of data (bits) that can be transmitted per unit of time (s)
  - Note inverse relation between data rate and bit duration
- **Delays**
  - **Transmission delay T_x**: time taken to transmit a frame at the data rate of the link (L/R)
  - **Propagation delay T_p**: time for the signal to propagate (travel) from one of the link to the other end (medium specific) (d / V)
  - **One-way delay**: time from the transmission of the first bit of a frame to the arrival of the last bit of the frame at receiver
  - **Round-trip delay**: time from the transmission of the first bit of a frame to the arrival of the last bit of the acknowledgment sent by the receiver at sender

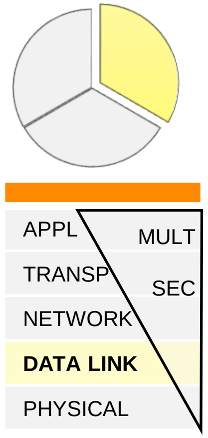
Link performance characterization (2)



- **Bit length of a link: B = R x (d / V)**
  - Number of bits fully occupying a link (i.e. *bandwidth* x *delay* product, bdp)
- **Let's define relationship $a = B / L = (d/V) / (L/R) = T_p / T_x$**
  - Number of frames in link of bit length B, when frame length is L
  - Ratio between propagation delay and transmission delay
- **Relationship between a and round-trip delay**
  - a<1 → round-trip delay determined primarily by transmission delay
  - a=1 → both delays have qual effect
  - a>1 → round-trip delay determined primarily by propagation delay
  - This relationship has great impact on link utilization, as we will soon see
- **Bandwidth-delay product (bdp)**
  - One-way: number of bits transmitted before first bit arrives at receiver
  - Round-trip: number of bits transmitted before sender receives acknowledgment

Flow control

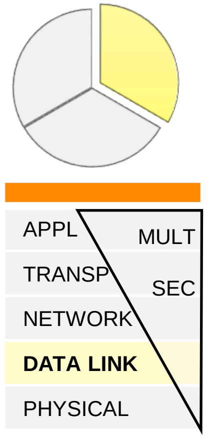
Flow control

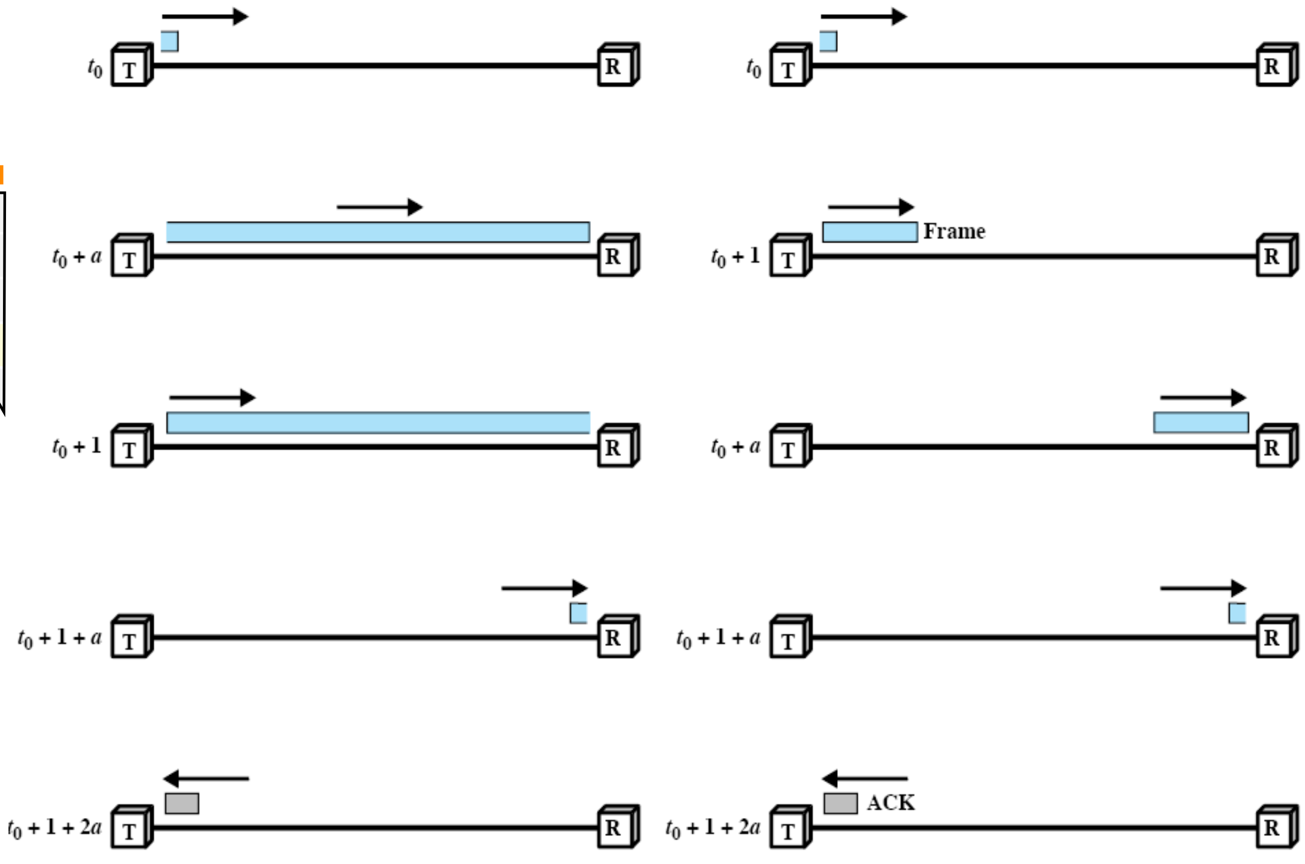


- **Regulate the flow of data in such manner that fast senders do not swamp slow receivers**
  - Receiver typically allocates data buffer of finite length for a connection

- **Two basic approaches**
  - **Feedback-based flow control**
    - Based on information provided by receiver to sender
    - Stop-and-wait flow control
    - Flow control with sliding windows
  - Rate-based flow control
    - Built in sender, not based on information provided by receiver
    - Not used in data link layer protocols

Stop-and-wait flow control



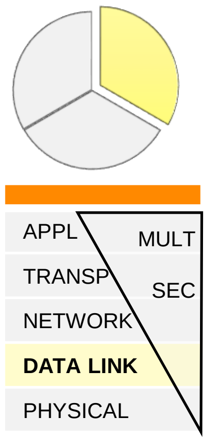


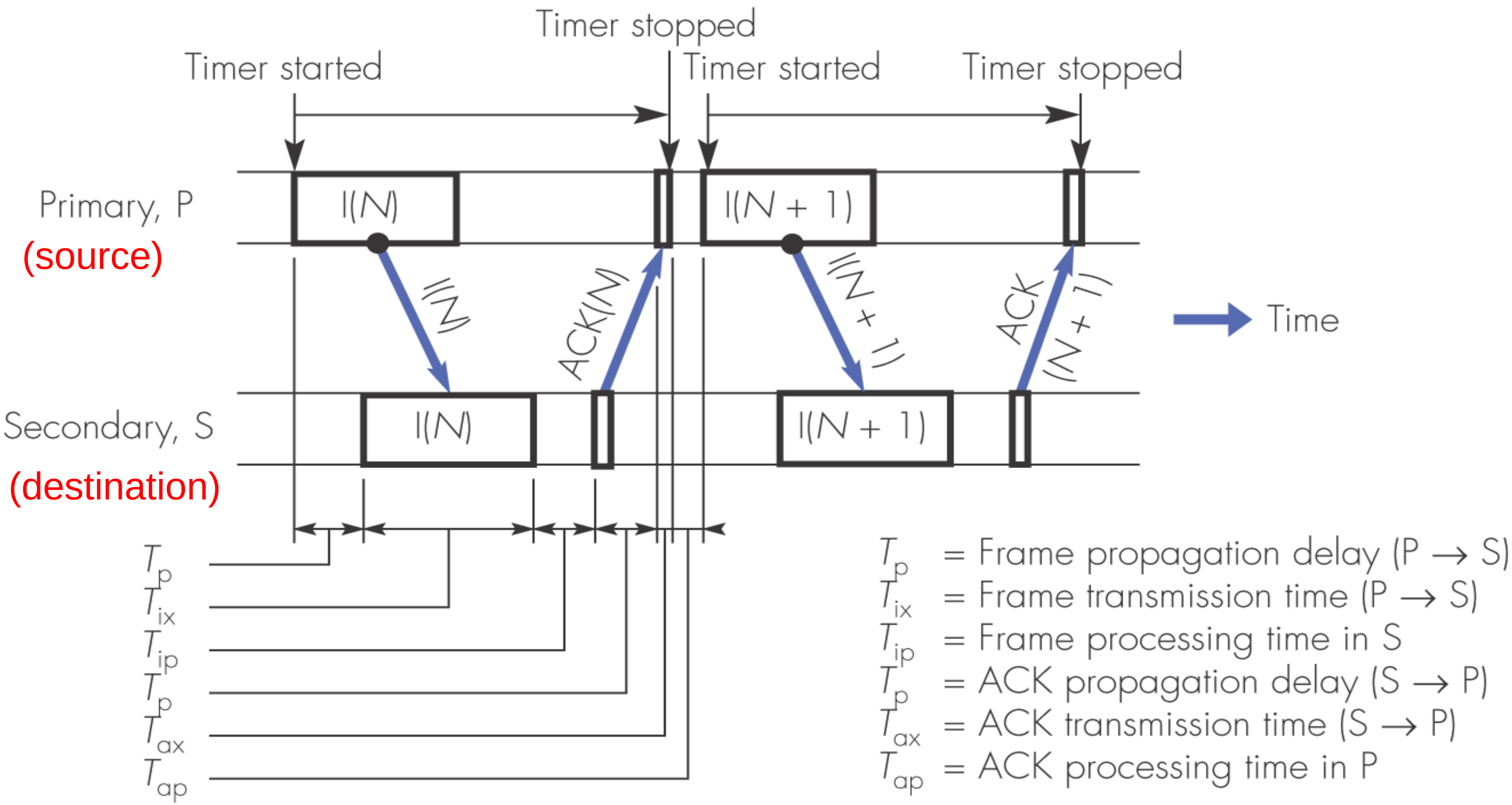
(a) $a < 1$ (b) $a > 1$

a<1: first bit of frame arrives at receiver before last bit has been transmitted

- Source transmits frame
- Destination receives frame and replies with acknowledgement (ACK)
- Source waits for ACK before sending next frame
- Destination can stop flow by not send ACK
- Only one frame in transit at any time

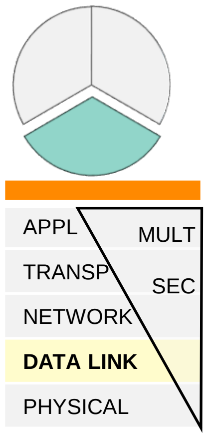
Stop-and-wait flow control (2)





Link utilization: $U=T_{ix}/T_t \sim T_{ix}/(T_{ix}+2T_p) = 1/(1+2T_p/T_{ix}) = \mathbf{1/(1+2a)}$**,** where $a = T_p/T_{ix}$

Stop-and-wait flow control: Example (1)



- **A series of 1000-bit frames is to be transmitted using stop-and-wait protocol.**
- **Determine the link utilization for the following types of data links assuming a transmission bit rate of:**

I. 1 kbps

II. 1 Mbps

III. 1 Gbps

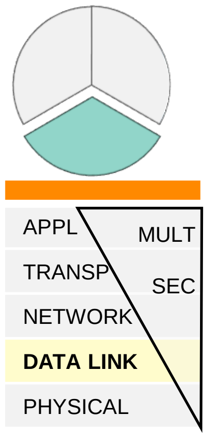
a) 1 km long twisted-pair cable. Signal propagation speed is 2×10^8 m/s.

b) 200 km long leased line. Signal propagation speed is 2×10^8 m/s.

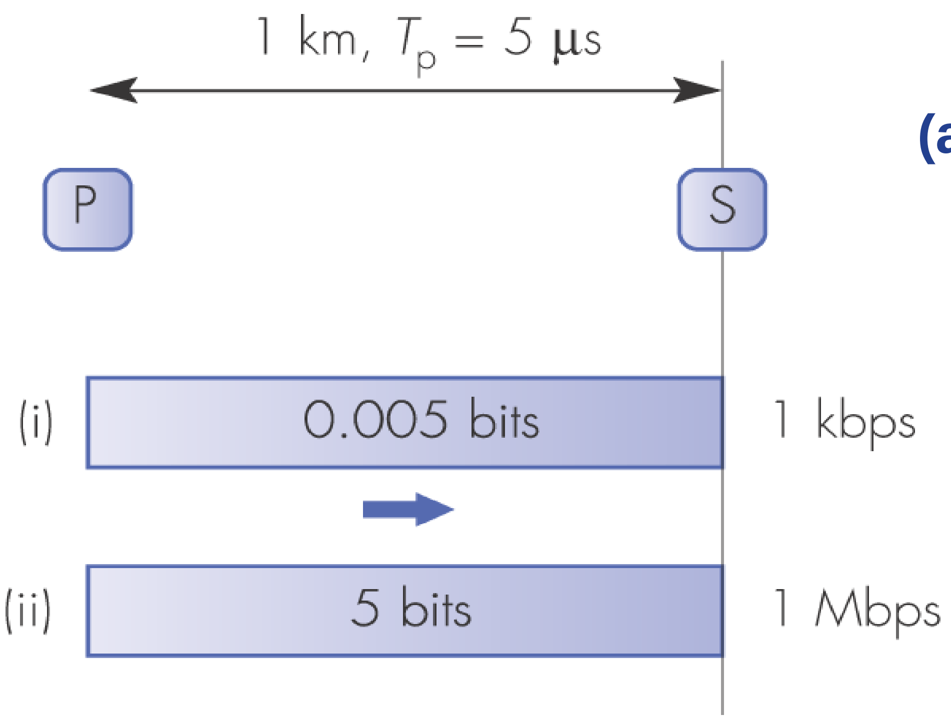
c) 50000 km long satellite link. Signal propagation speed is 3×10^8 m/s.

\- Bit error rate is negligible (can be ignored).

Stop-and-wait flow control: Example (2)



Twisted pair



Frame transmission time T_{ix} = Number of bits in frame / Bit rate

(i) 1 kbps: $T_{ix} = 1000$ b / 10^3 b/s = 1 s

(ii) 1 Mbps: $T_{ix} = 1000$ b / 10^6 b/s = 10^{-3} s = 1 ms

(iii) 1 Gbps: $T_{ix} = 1000$ b / 10^9 b/s = 10^{-6} s = 1 μs

(a) 1 km long twisted-pair cable. Signal propagation speed is $2\text{x}10^8$ m/s.

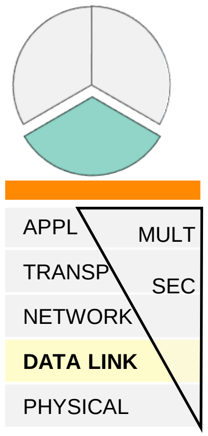
Frame propagation delay $T_p = 10^3$ m / $2\text{x}10^8$ m/s = $5\text{x}10^{-6}$ s

(i) $a = T_p/T_{ix}$ = $5\text{x}10^{-6}$ s / 1 s = $5\text{x}10^{-6} \rightarrow (1 + 2a) \approx 1$, U = 1

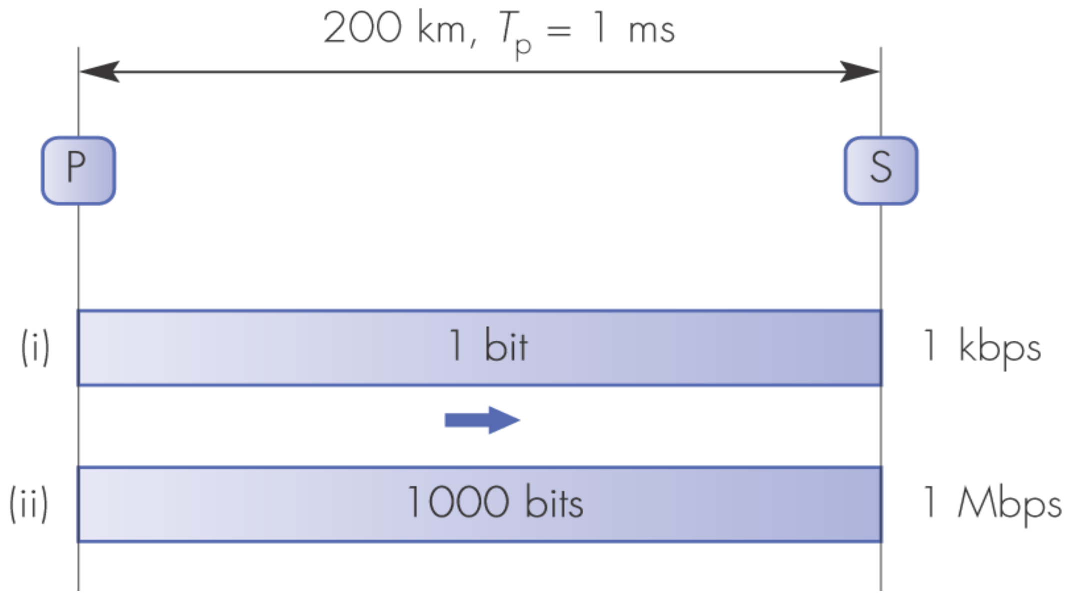
(ii) a = $5\text{x}10^{-6}$ s / 10^{-3} s = $5\text{x}10^{-3} \rightarrow (1 + 2a) \approx 1$, U = 1

(iii) a = $5\text{x}10^{-6}$ s / 10^{-6} s = 5 $\rightarrow$ (1 + 2a) = 11, U = 0.09

Stop-and-wait flow control: Example (3)



Leased line



Frame transmission time T_{ix} = Number of bits in frame / Bit rate

(i) 1 kbps: $T_{ix} = 1000\ b / 10^3\ b/s = 1\ s$

(ii) 1 Mbps: $T_{ix} = 1000\ b / 10^6\ b/s = 10^{-3}\ s = 1\ ms$

(iii) 1 Gbps: $T_{ix} = 1000\ b / 10^9\ b/s = 10^{-6}\ s = 1\ \mu s$

(b) 200 km long leased line. Signal propagation speed is $2x10^8$ m/s.

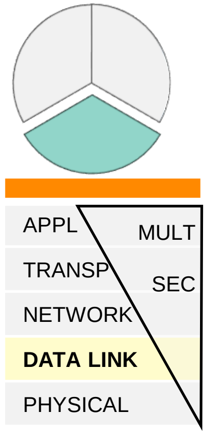
Frame propagation delay $T_p = 200x10^3\ m / 2x10^8\ m/s = 10^{-3}\ s$

(i) $a = T_p/T_{ix} = 10^{-3}\ s / 1\ s = 1x10^{-3} \rightarrow (1 + 2a) \approx 1$, U = 1

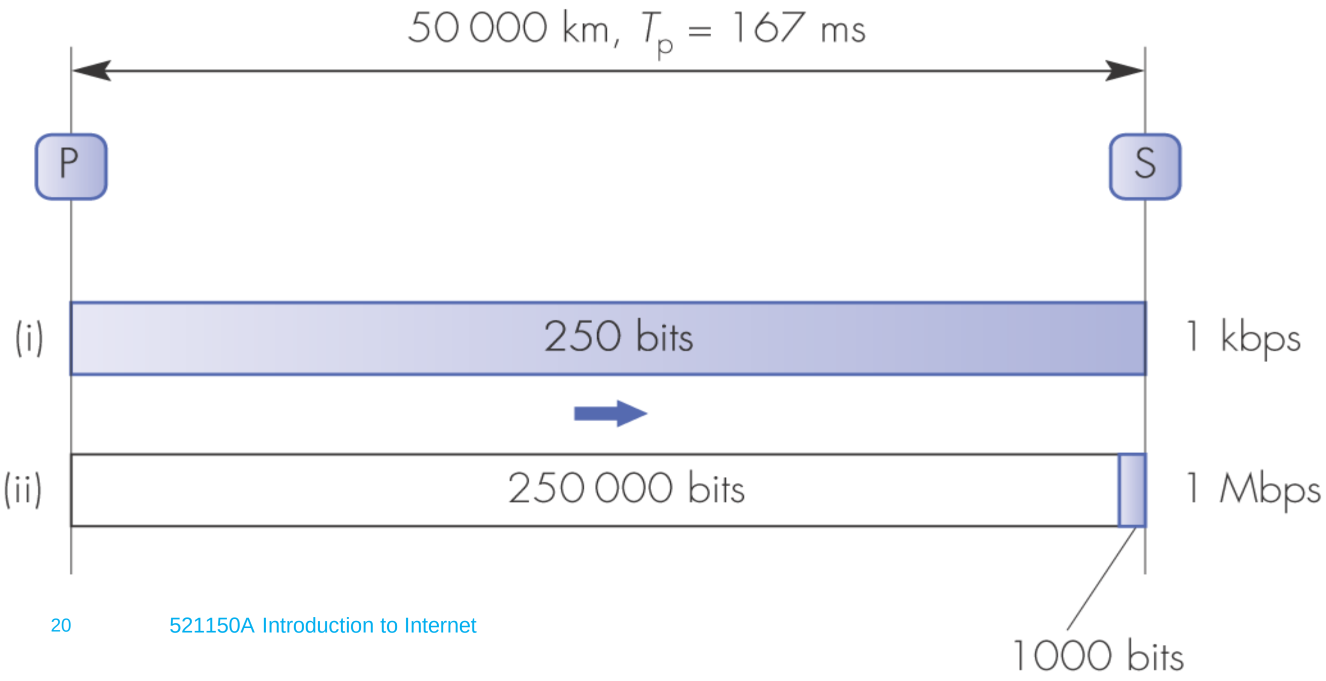
(ii) $a = 10^{-3}\ s / 10^{-3}\ s = 1 \rightarrow (1 + 2a) > 1$, U = 1/(1+2) = 0.33

(iii) $a = 10^{-3}\ s / 10^{-6}\ s = 1000 \rightarrow$ U = 0.0005

Stop-and-wait flow control: Example (4)



Satellite link



Frame transmission time T_{ix} = Number of bits in frame / Bit rate

(i) 1 kbps: T_{ix} = 1000 b / 10^3 b/s = 1 s

(ii) 1 Mbps: T_{ix} = 1000 b / 10^6 b/s = 10^{-3} s = 1 ms

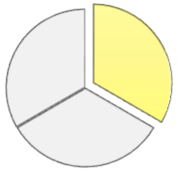
(c) A 50000 km long satellite link. Signal propagation speed is 3×10^8 m/s.

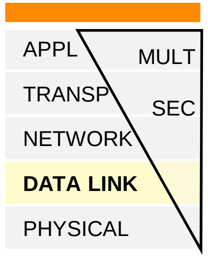
Frame propagation delay T_p = 50×10^6 m / 3×10^8 m/s = 0.167 s

(i) a = T_p/T_{ix} = 0.167 s / 1 s = 0.167 $\rightarrow$ (1 + 2a) > 1, U = 1/(1+0.334) = 0.75

(ii) a = 0.167 s / 10^{-3} s = 167 $\rightarrow$ (1 + 2a) > 1, U = 1/(1+334) = 0.003

Stop-and-wait flow control: Example (5)



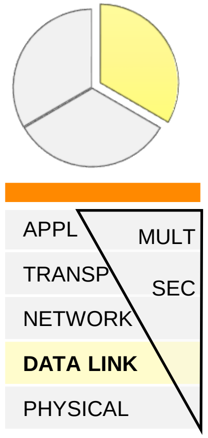


- **Observations**
  - Relatively short links
    - Link utilization is 100% for lower bit rates
  - Longer terrestial links
    - Link utilization is high for low bit rates
    - Link utilization falls off significantly as bit rate increases
  - Long satellite links
    - Link utilization is poor (due to high propagation delay)

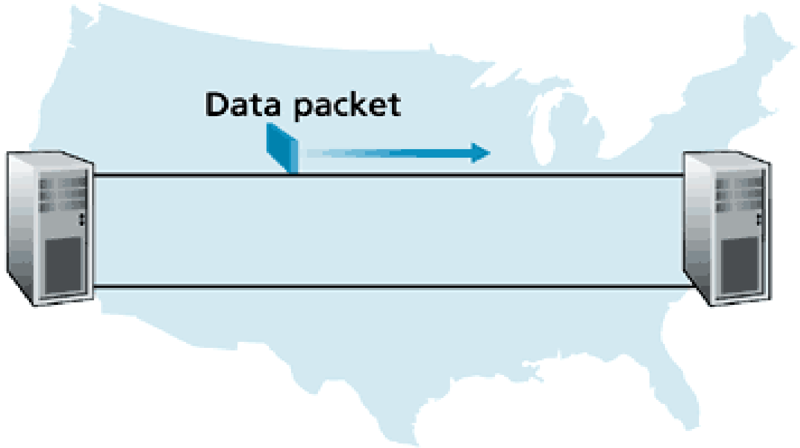
→**Stop-and-wait flow-control suitable for short and low bit rate links**

- E.g. links based on modems and analog PSTN

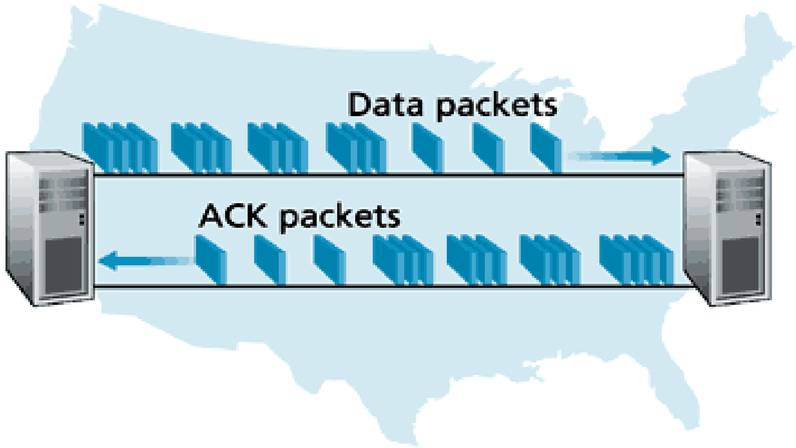
Pipelining (1)



– Primary (sender, source) is allowed to **send multiple packets without waiting for acknowledgements**



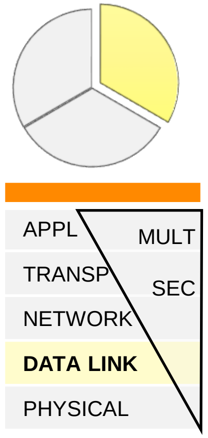
a. A stop-and-wait protocol in operation

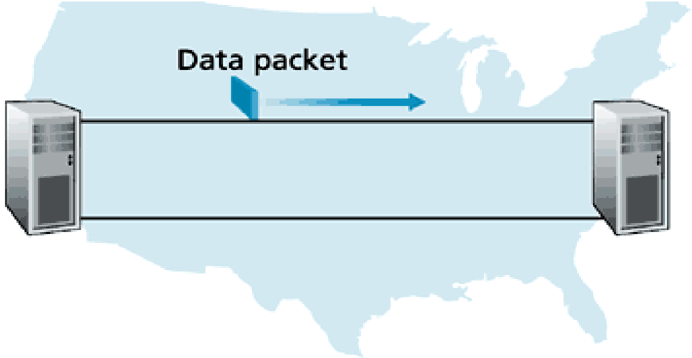


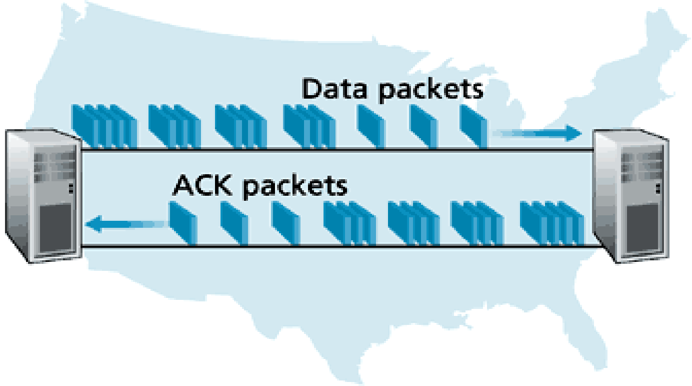
b. A pipelined protocol in operation

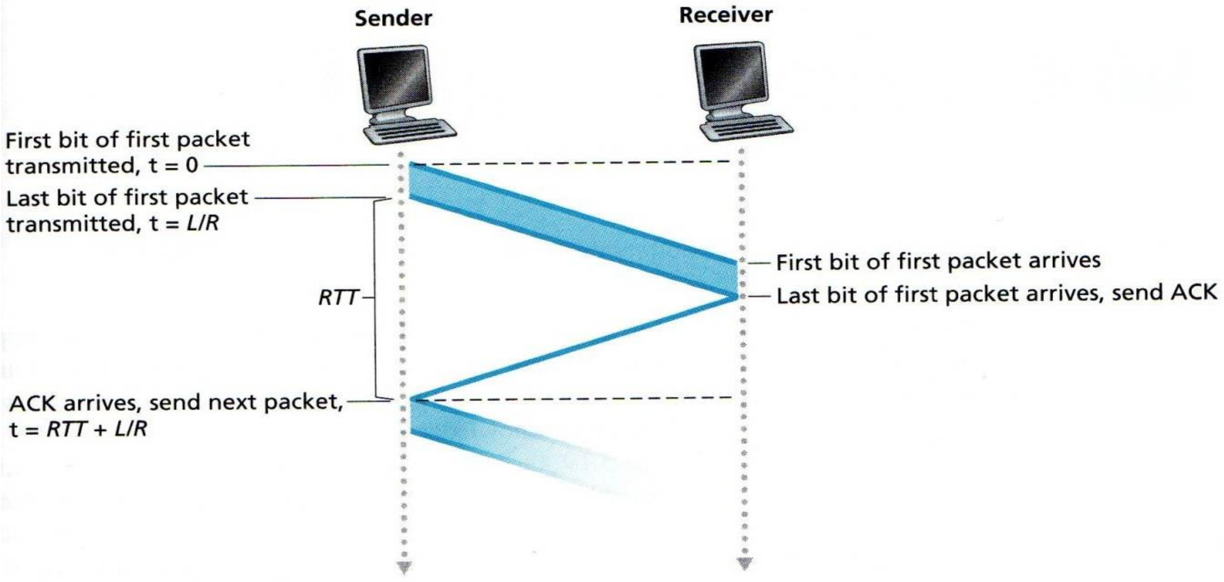
– Much **better utilization of link capacity**, with **increased buffer requirements** and **larger ranges of sequence numbers**
– Bi-directional, requires full-duplex link
– Requires flow control with sliding windows

Pipelining (2)

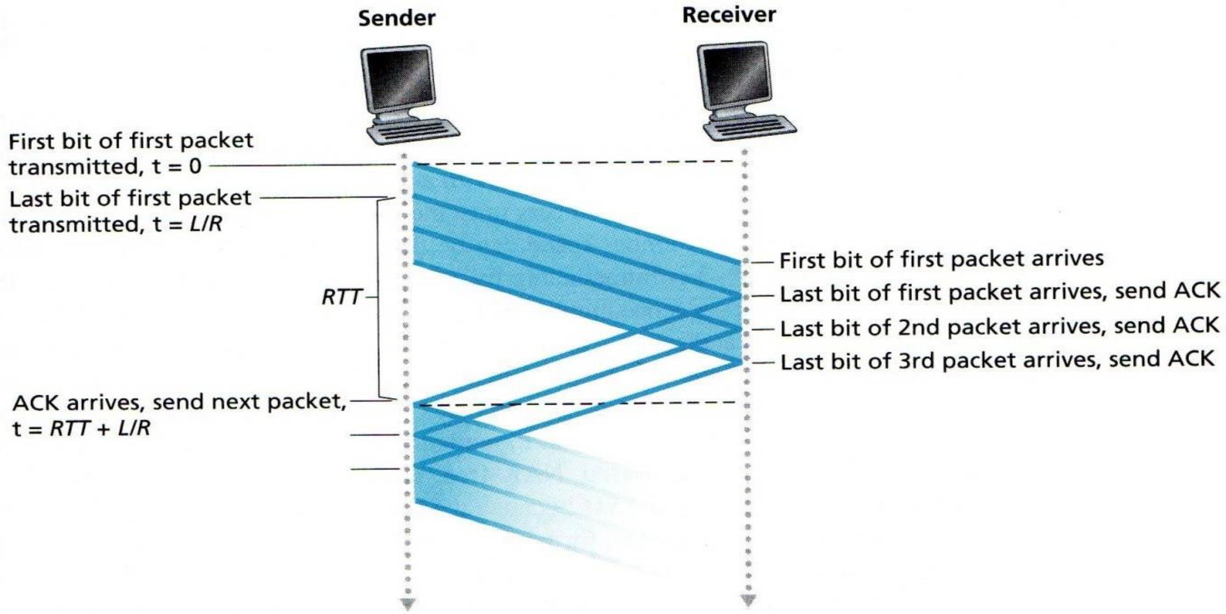






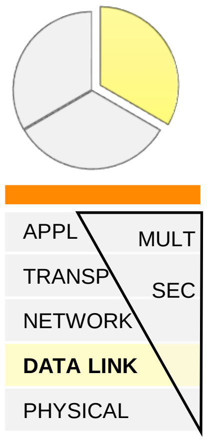


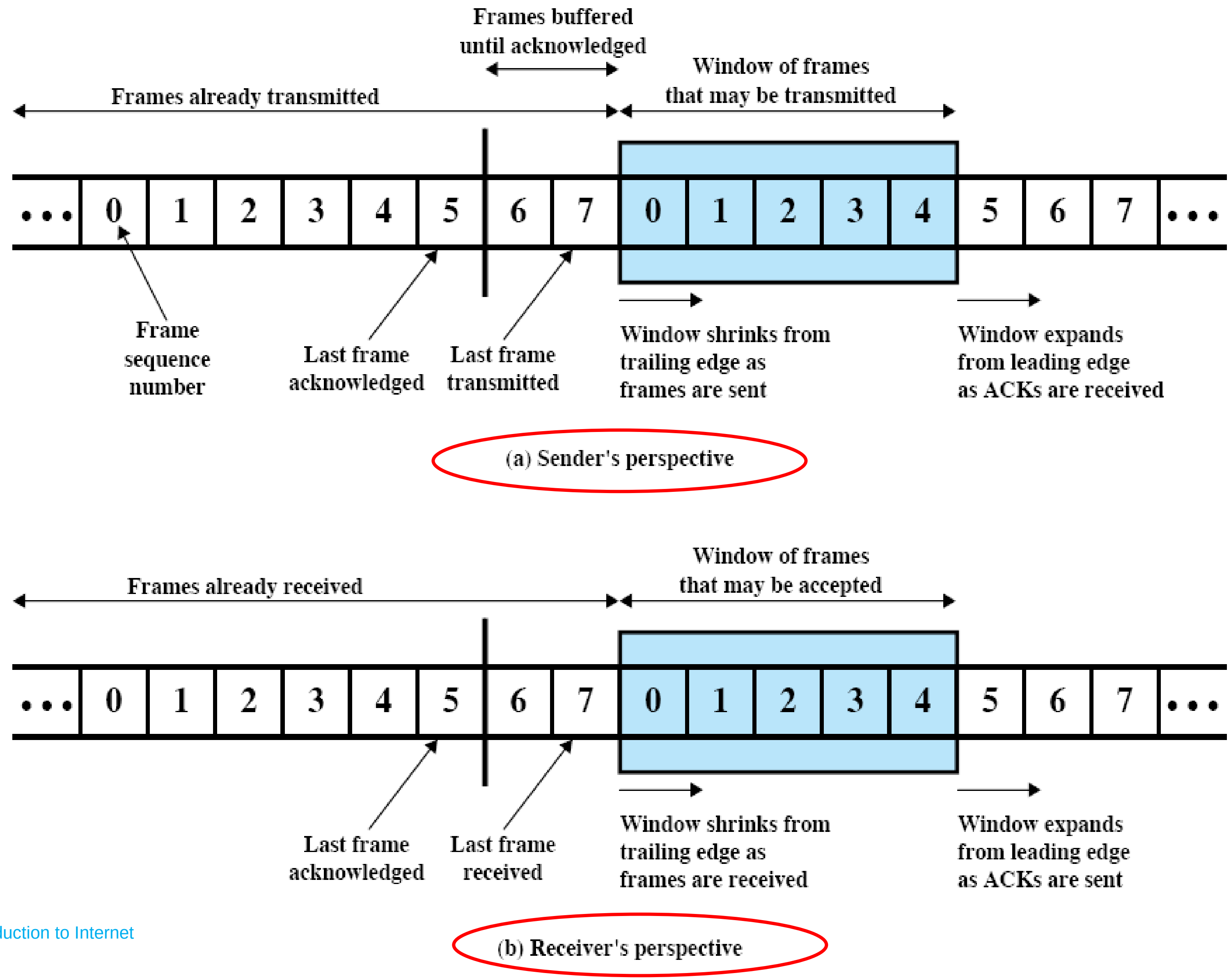
a. Stop-and-wait operation



b. Pipelined operation

–Flow control: Sliding windows (1)



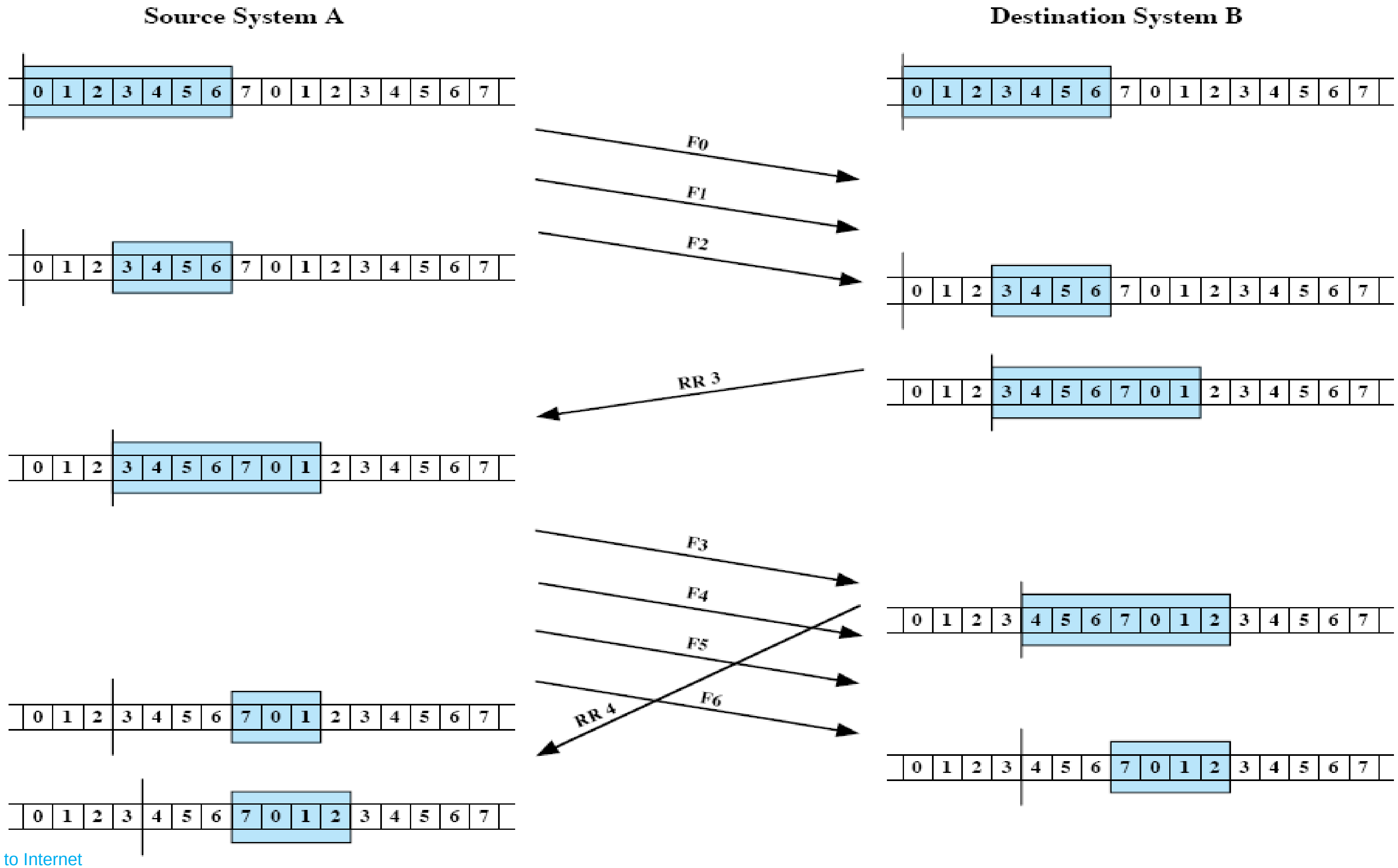


- Receiver has buffer W long
- Transmitter can send up to W frames without ACK
- Each frame is numbered
- ACK includes number of next frame expected

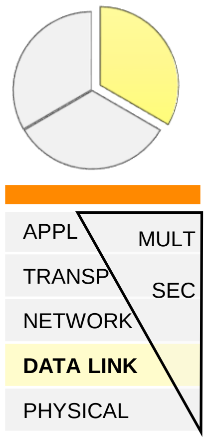
Flow control: Sliding windows (2)

APPL
MULT
TRANSP
SEC
NETWORK
DATA LINK
PHYSICAL

Example with sliding window of 7 frames



Flow control: Performance enhancements

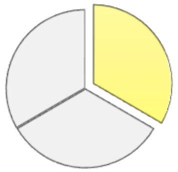


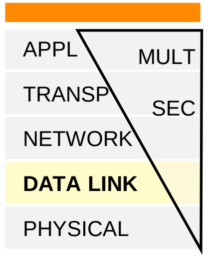
- **Receiver acknowledges multiple I frames with one ACK**

- **Piggybacking**
  - Acknowledgements are attached to I frames (ACK field), instead of being transmitted as separate ACK frames

Error control

Error control

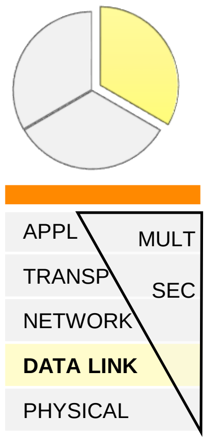




- **Two types of errors**
  - Lost frame
  - Damaged frame
- **Mechanisms used for error control**
  - Error detection
  - Positive acknowledgments
  - Retransmission after timeout (retransmission timer)
  - Negative acknowledgment and retransmission
- **Three types of ARQ (automatic repeat request)**
  - Stop-and-wait ARQ
  - Go-back-N ARQ
  - Selective repeat ARQ

} **Continuous RQ** (uses sliding window flow control)

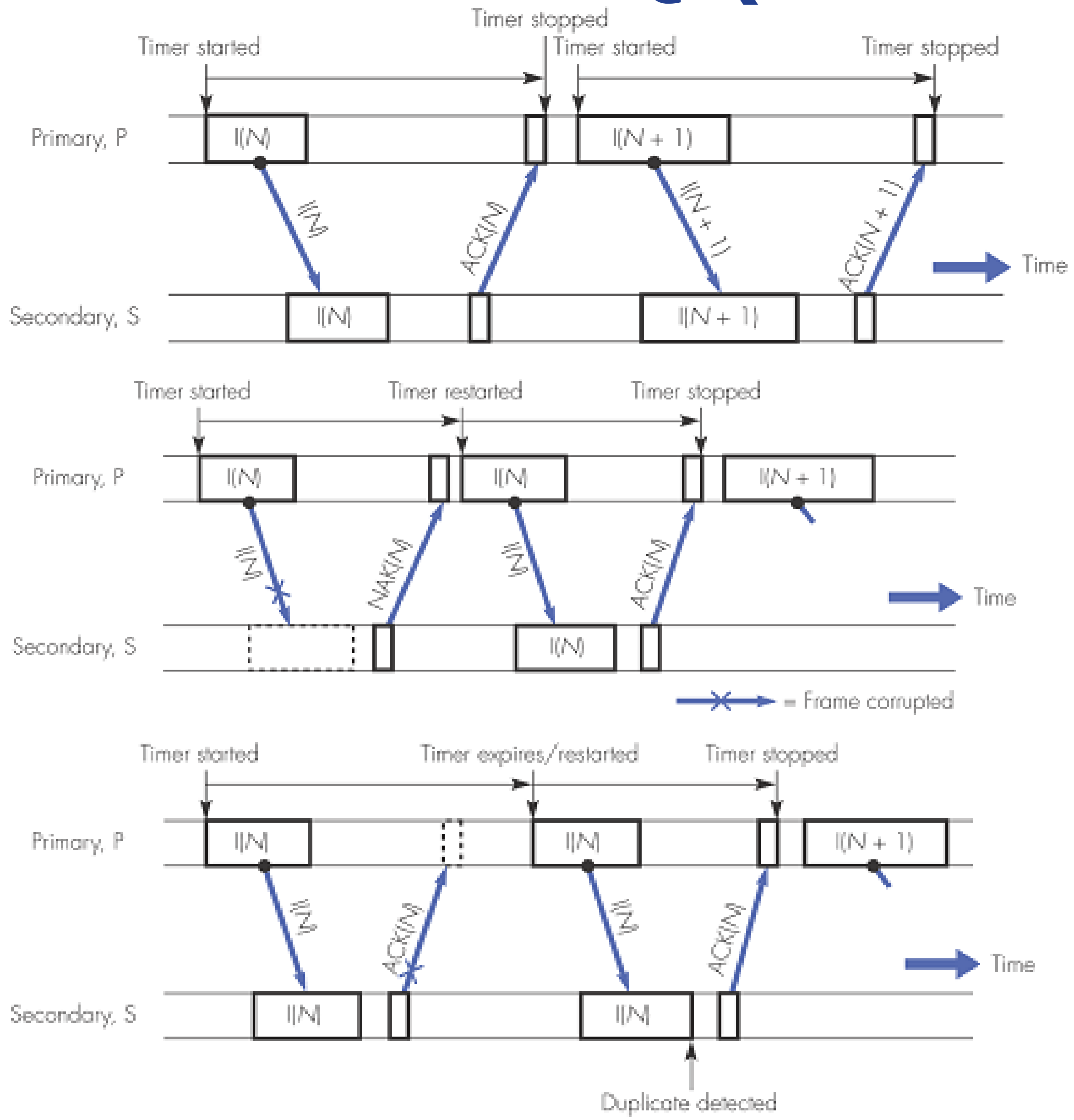
Stop-and-wait ARQ (aka idle RQ)



error free

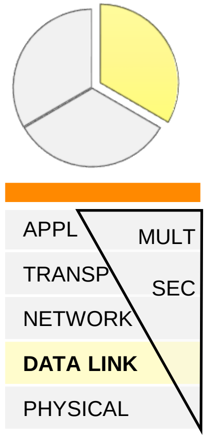
corrupted
I frame

corrupted
ACK frame



Building blocks

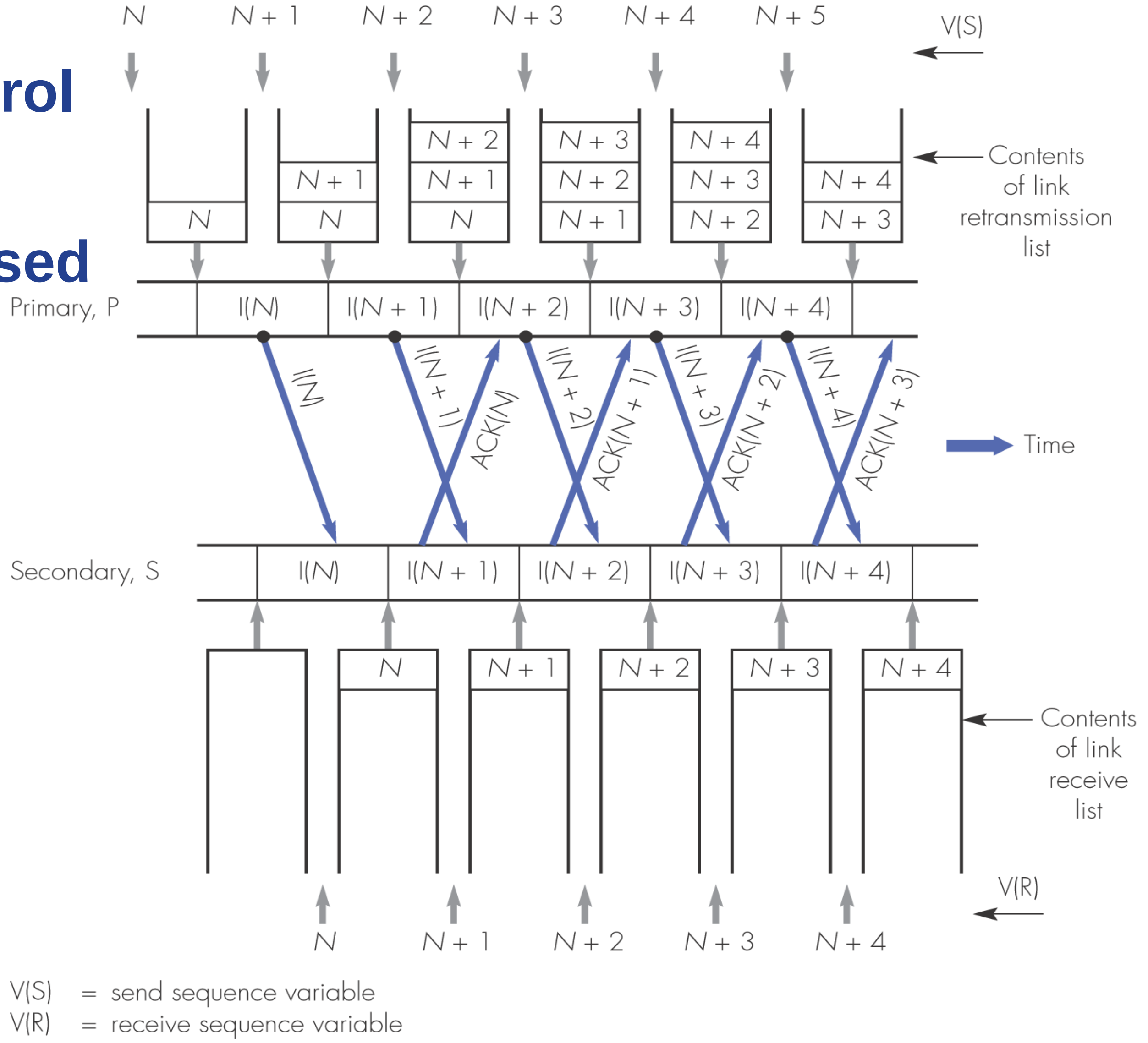
– Retransmission timer
– Error detection
– Receiver feedback (ACK, NAK)
– Retransmission



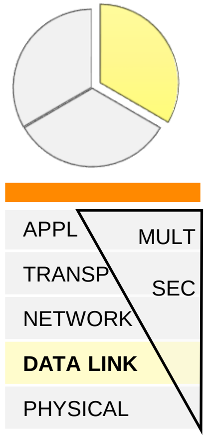
Continuous RQ

- **Incorporate flow control**
- **Link utilization much improved with increased buffer storage requirements**
- **Bidirectional**
  - Requires duplex link
- **Two basic types**
  - Go-back-N ARQ
  - Selective repeat ARQ

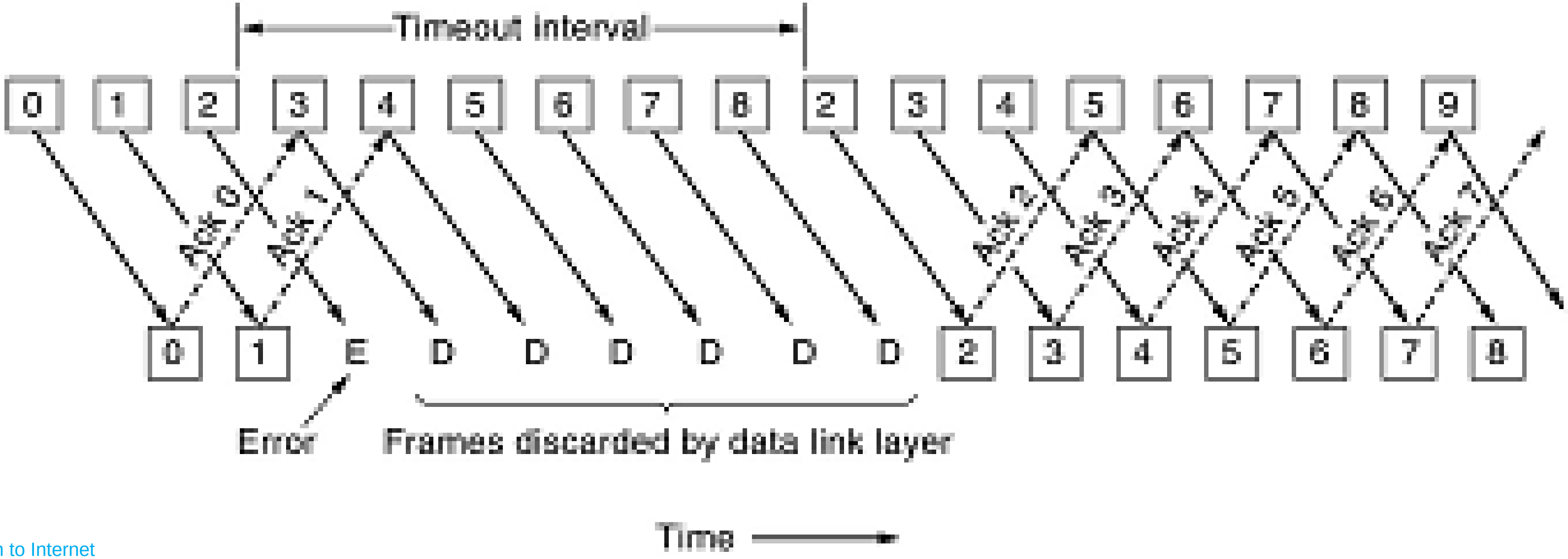
Continuous RQ frame sequence without transmission errors:



Go-back-N ARQ (1)

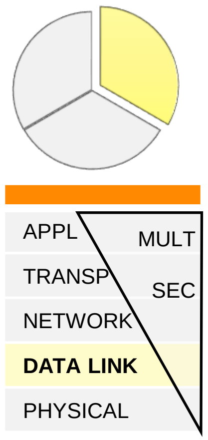


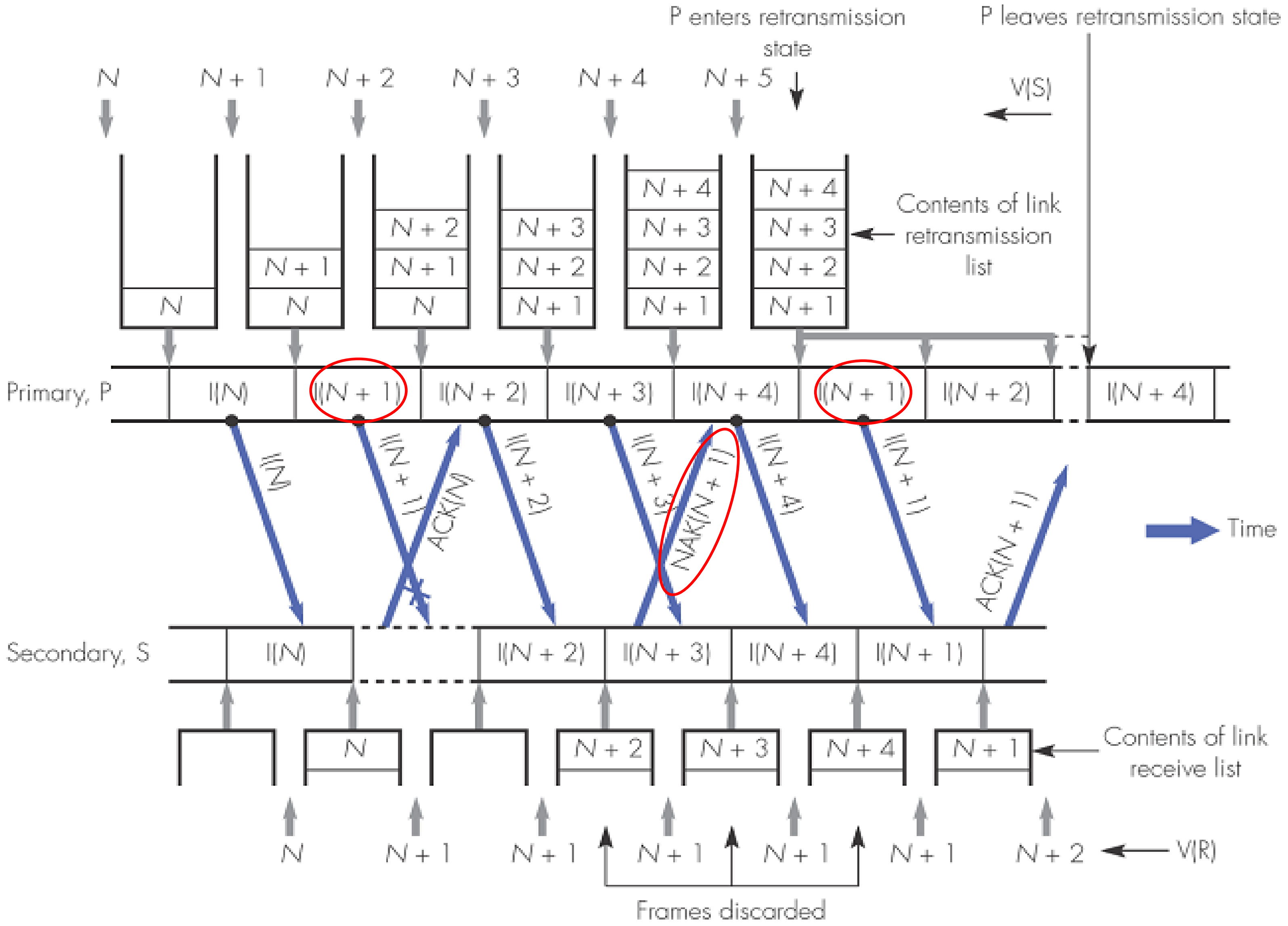
- **Receiver discards all frames after an erroneous frame**
- **Sender resends all discarded frames**
  - Sender has to buffer unacknowledged frames



Go-back-N ARQ (2)

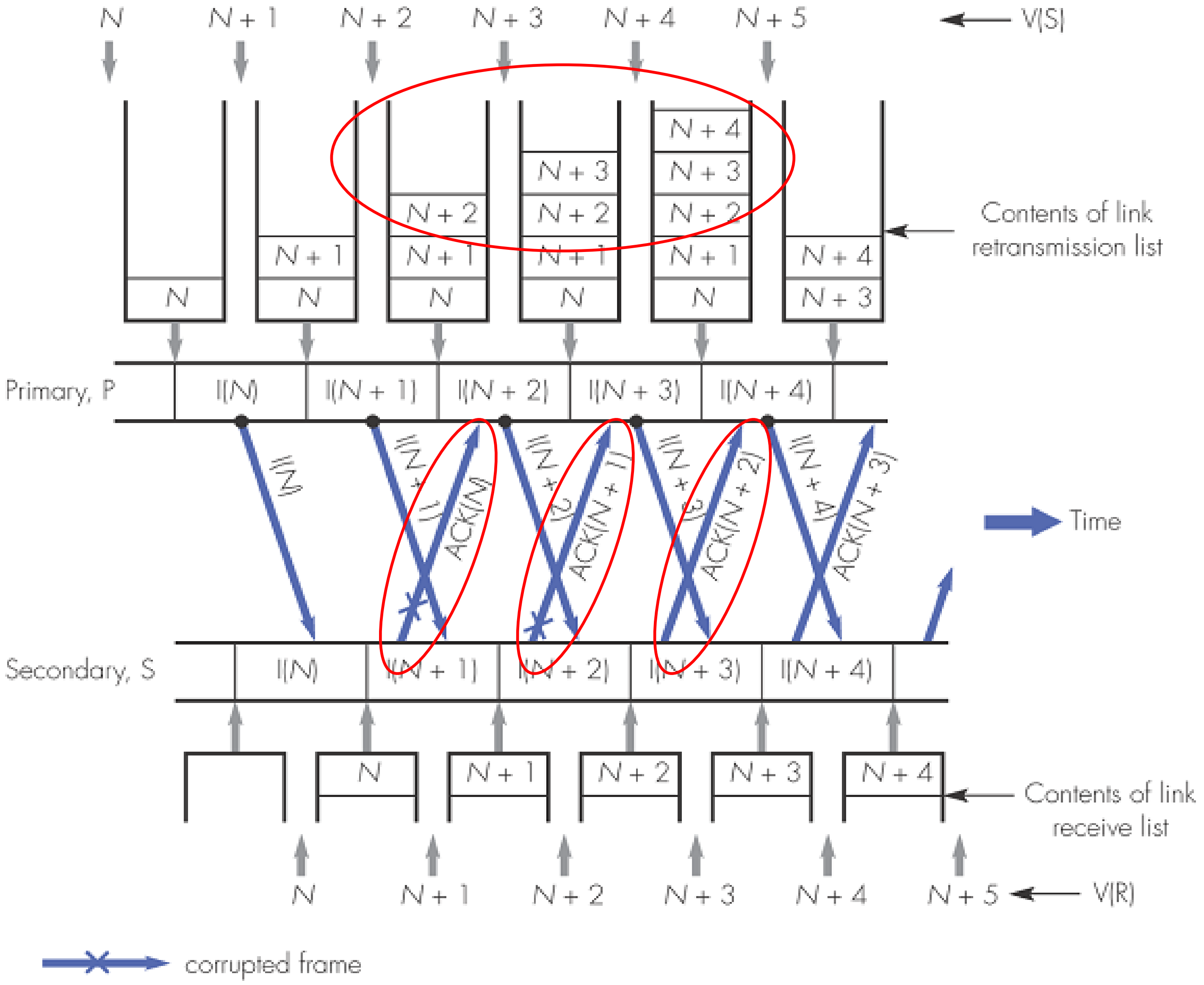
Corrupted I frame:

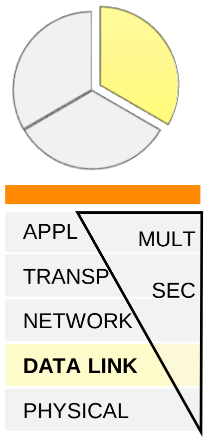




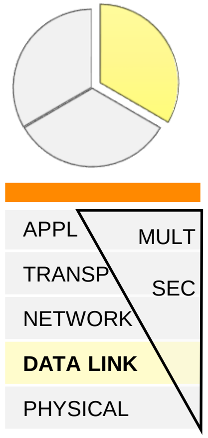
Go-back-N ARQ (3)

Corrupted ACK frame:



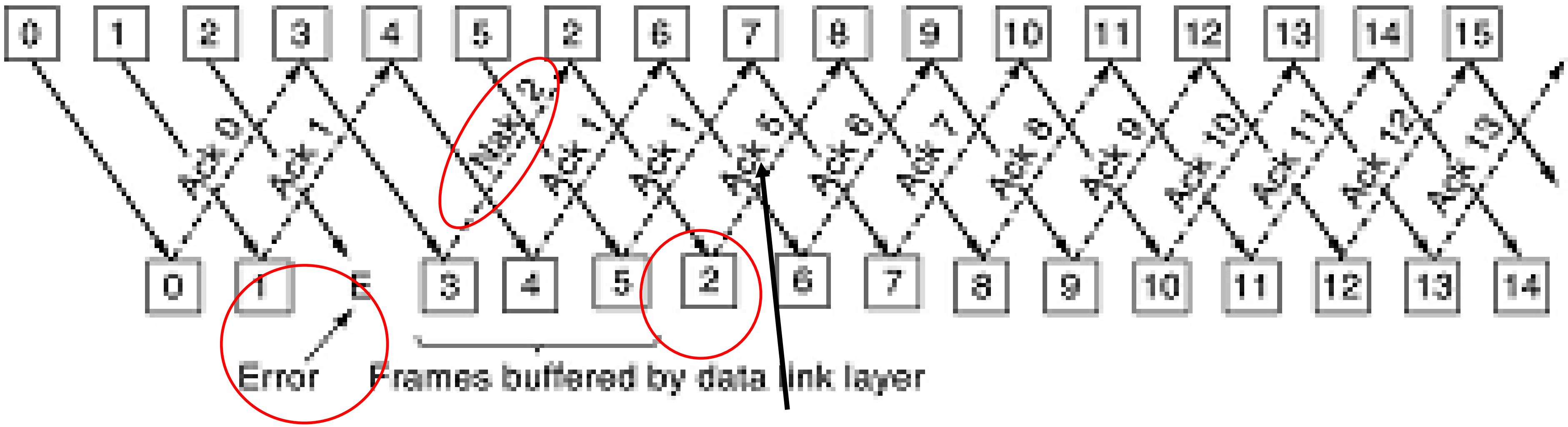


Selective repeat ARQ (1)



- **Receiver buffers frames received after an erroneous frame**

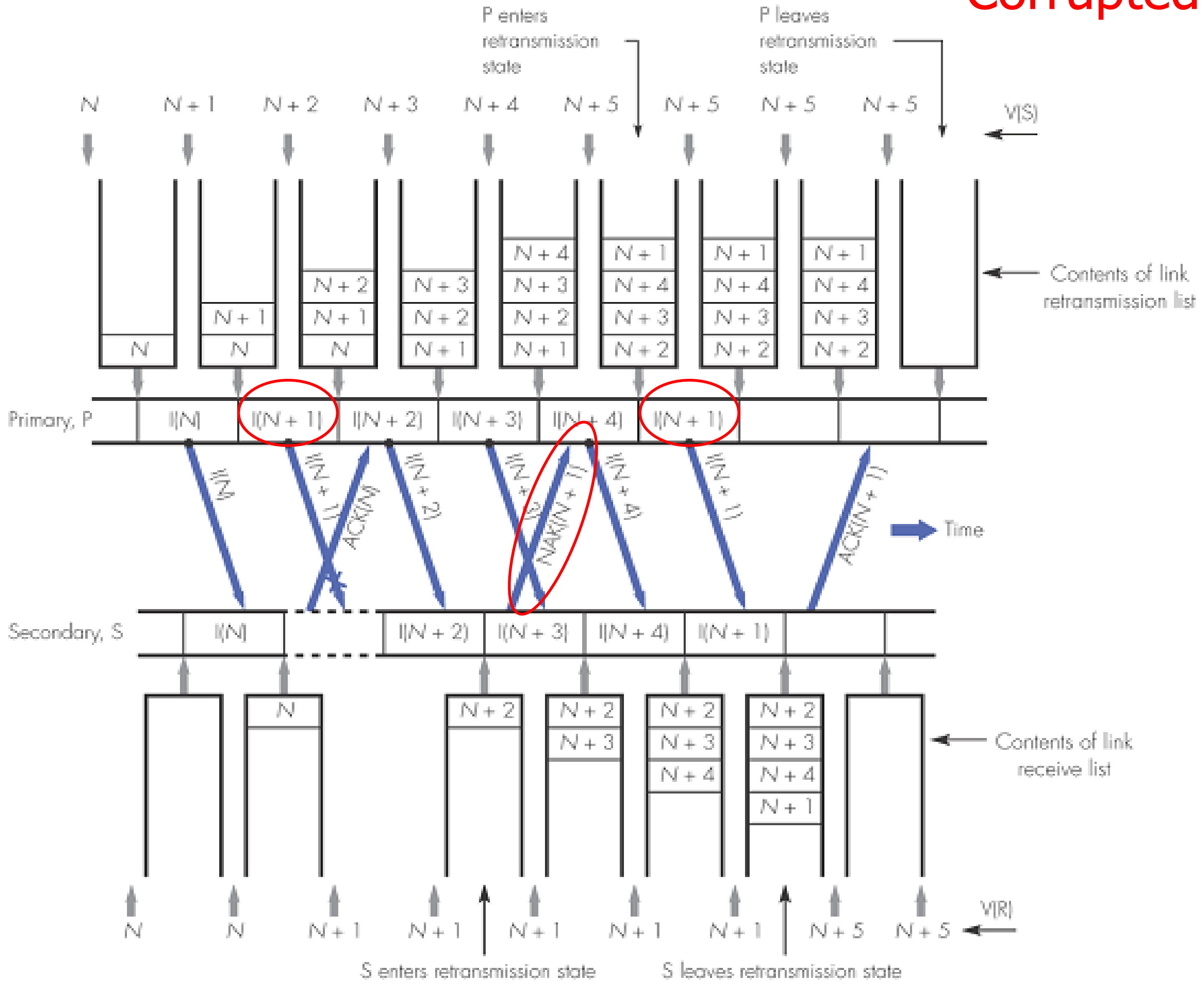
- **Sender retransmits only the erroneous frame**
  - Sender has to buffer unacknowledged frames



Selective repeat ARQ (2)

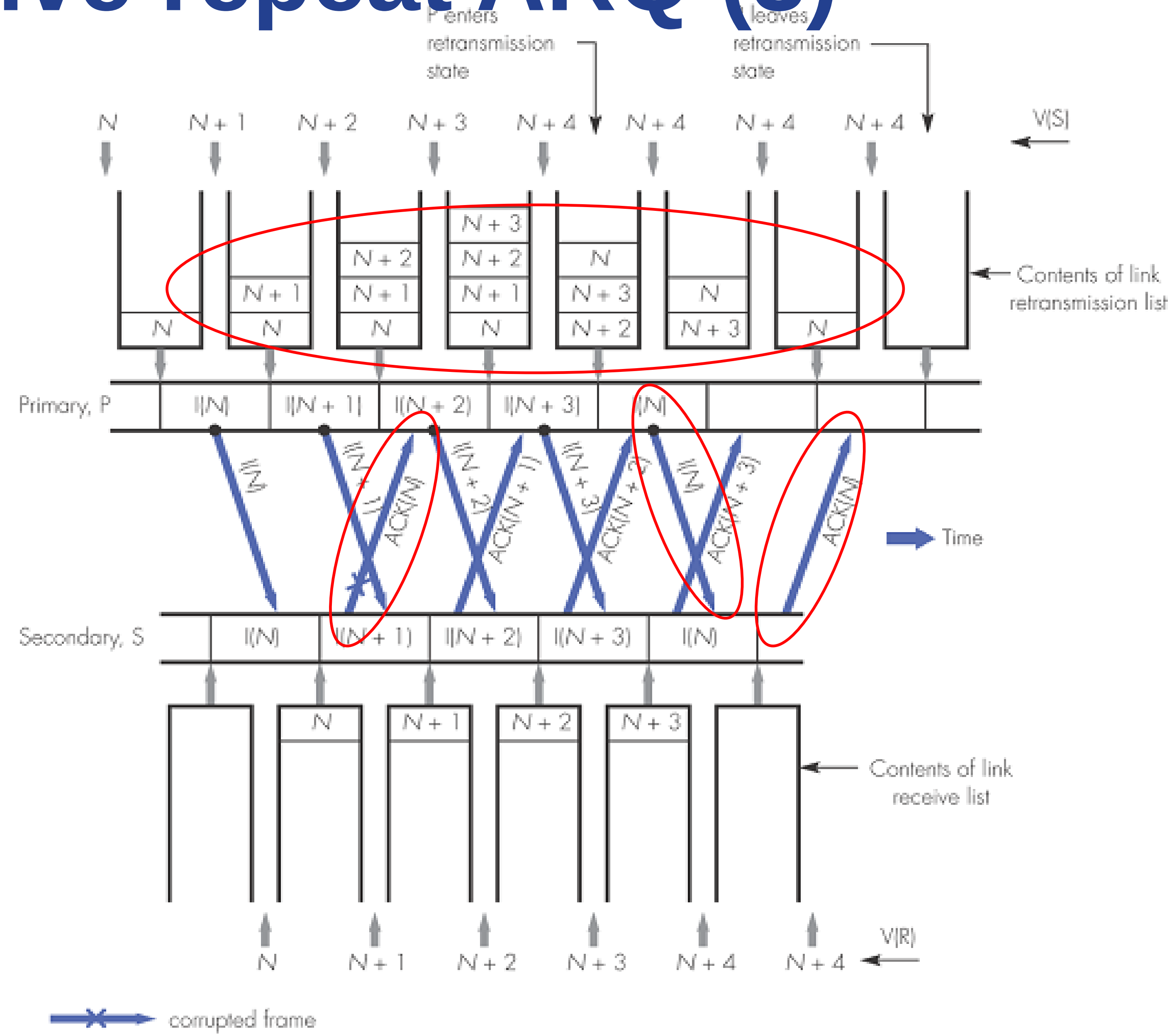
APPL
MULT
TRANSP
SEC
NETWORK
DATA LINK
PHYSICAL

Corrupted I frame:

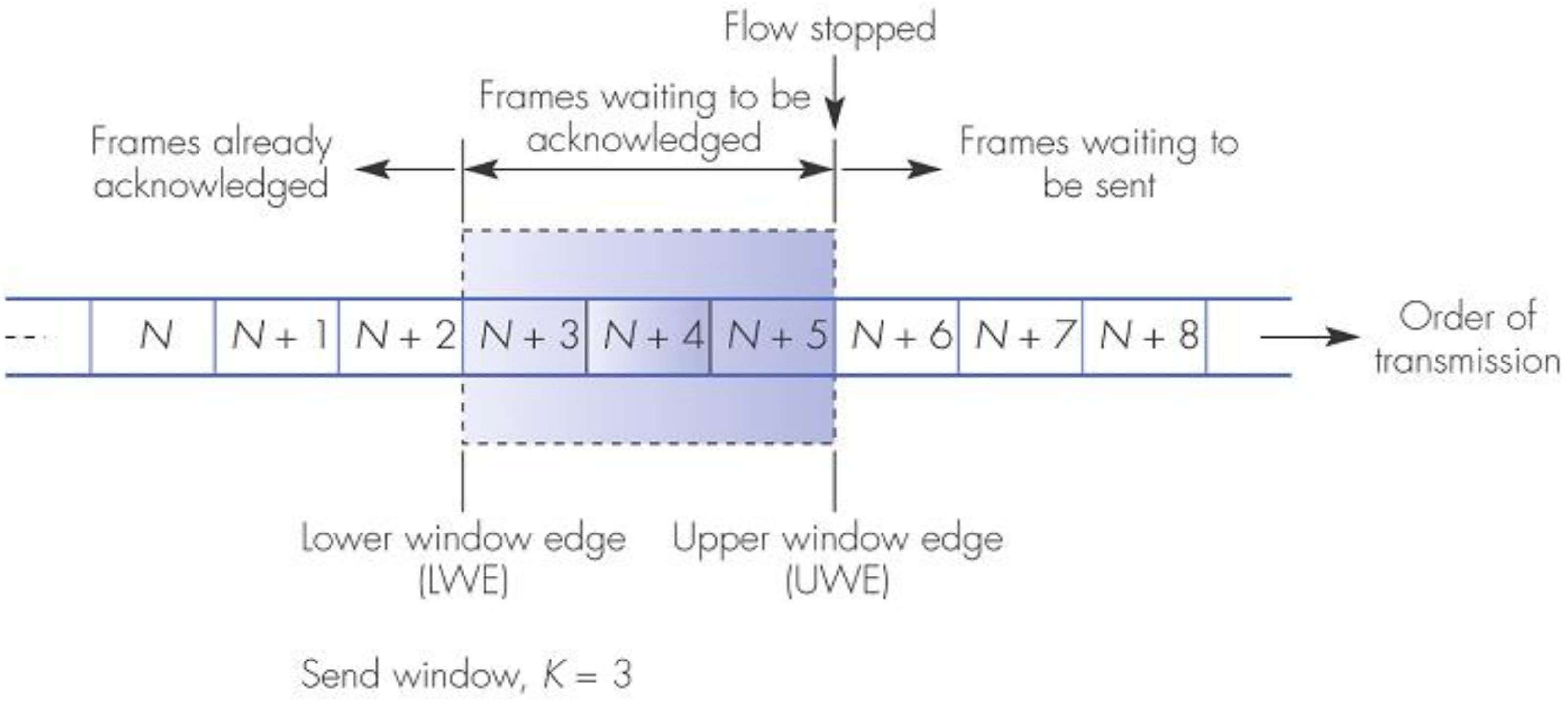


Selective repeat ARQ (3)

Corrupted ACK frame:

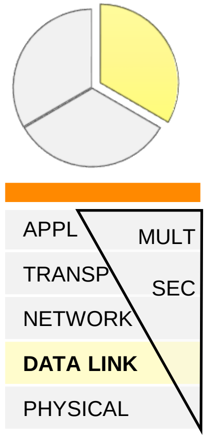


ARQ: Send/receive window sizes



Protocol	Send window	Receive window
Idle RQ	1	1
Selective repeat	K	K
Go-back-N	K	1

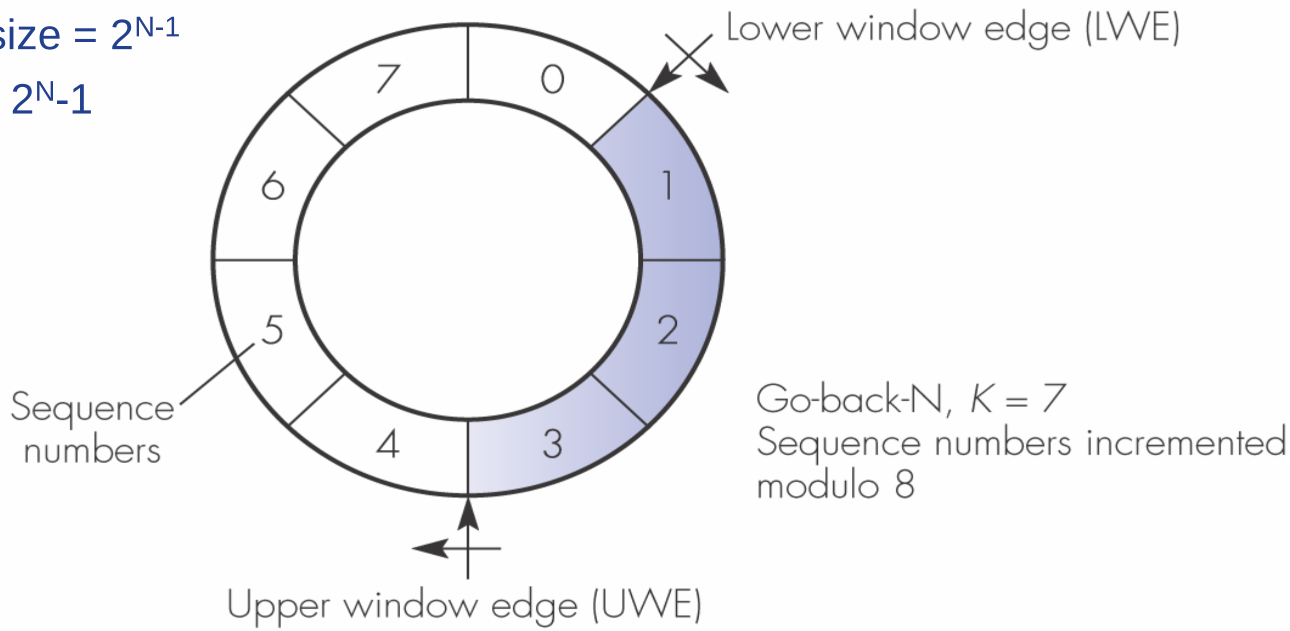
ARQ: Sequence numbers (frame ID’s)



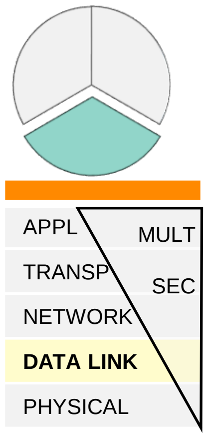
- **Number of sequence numbers required for *window size K***

Protocol	Maximum number of frame identifiers
Idle RQ	2
Selective repeat	$2K$
Go-back-N	$K + 1$

- **In practice, *N bits* reserved for sequence numbers**
  - Selective repeat: max window size = 2^{N-1}
  - Go-back-N: max window size = 2^N-1
  - Example:
    Go-back-N with
    window size K=7
    (need 8 sequence numbers,
    i.e. 3-bit field, $2^3=8$)



Performance: Error-free stop-and-wait flow control



Link utilization: $U = 1/(1+2a)$

$a = T_{prop} / T_{trans}$

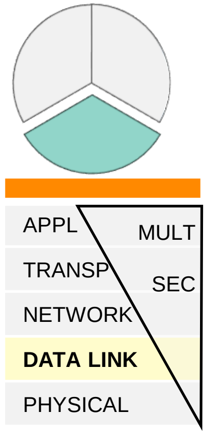
- a ~ Number of frames in link of bit length B, when frame length is L
- a ~ Ratio between propagation delay and transmission delay

$a = (d/V)/(L/R) = [Rd/V)] / L$

Rd/V = length of medium in bits (bit length)

L = length of frame in bits

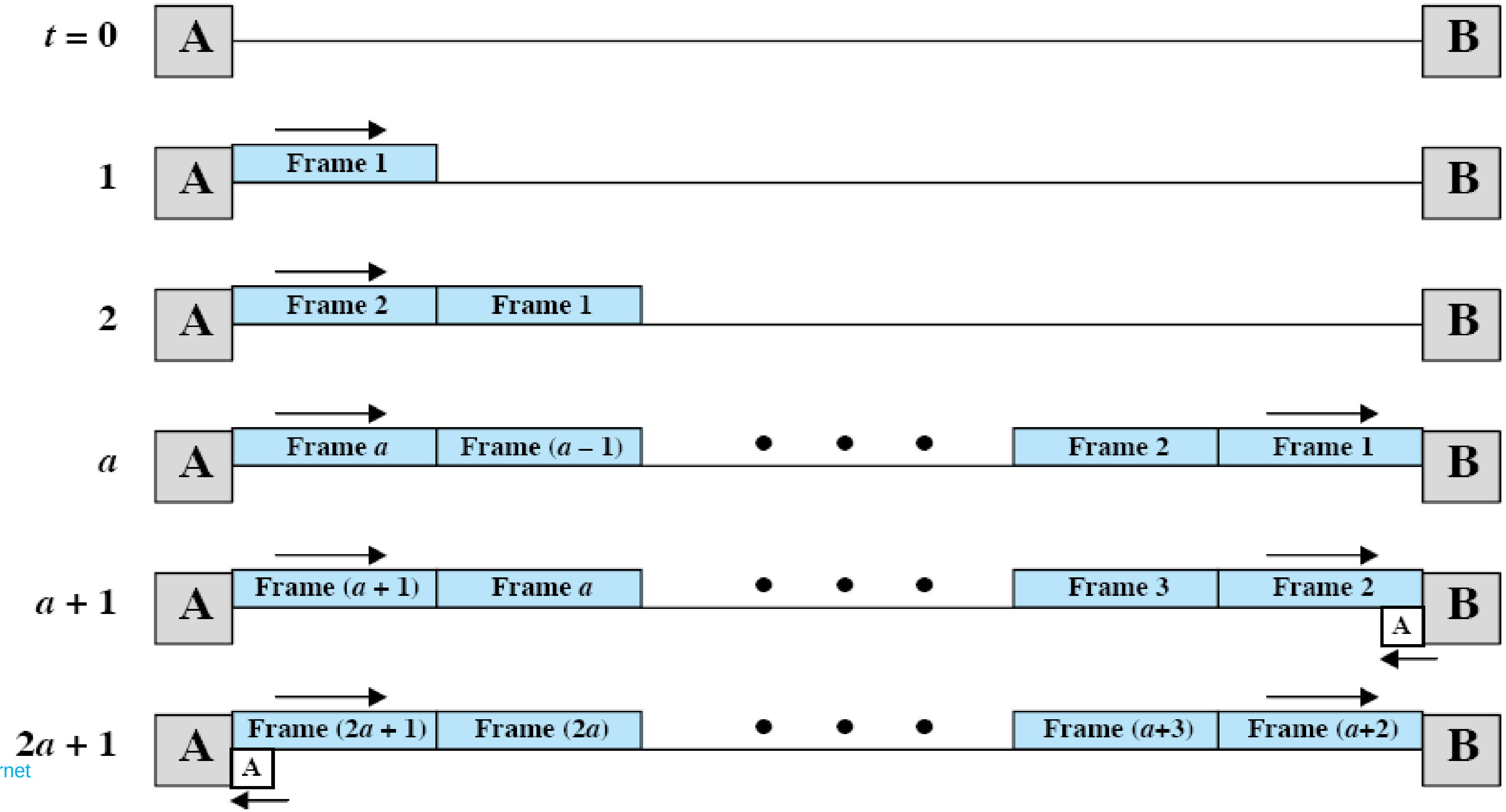
Performance: Error-free sliding window flow control (1)



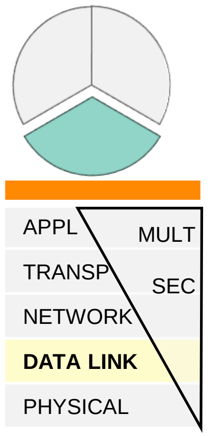
Case 1: W (window size) $\geq$ 2a+1

ACK reaches A at t = 2a+1

$\rightarrow$ A can transmit without pause $\rightarrow$ utilization = 1



Performance: Error-free sliding window flow control (2)

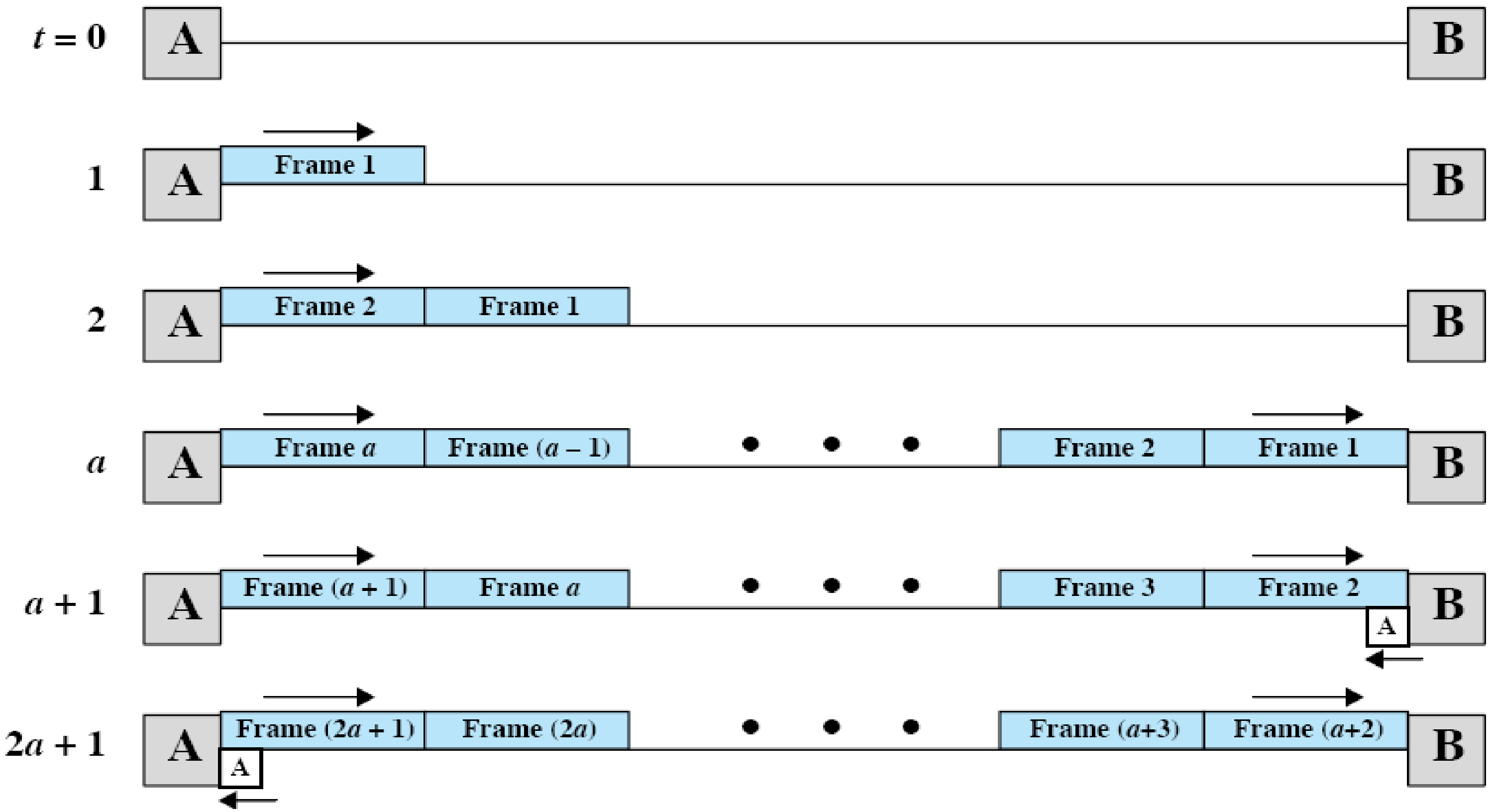


Case 2: W (window size) < 2a+1

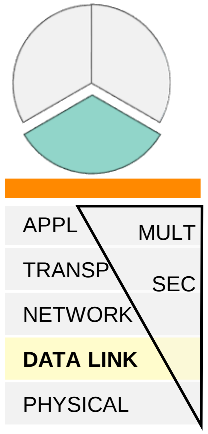
A exhausts its send window at t = W frames

→ A cannot send additional frames until t = 2a+1

→ utilization = W/(2a + 1)

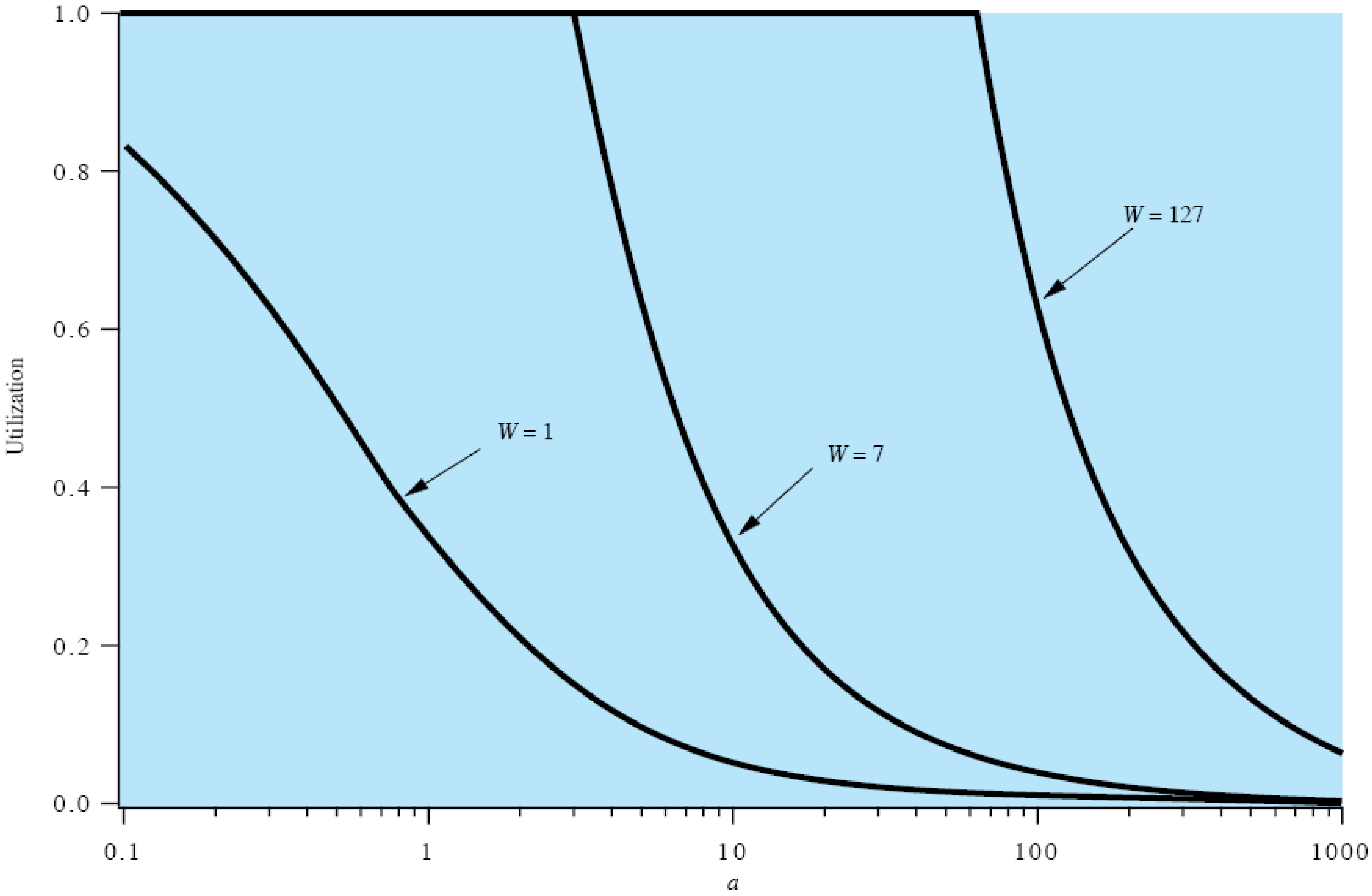


Performance: Error-free sliding window flow control (3)

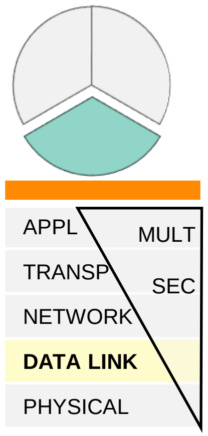


Utilization:

$$U = \begin{cases} 1 & W \geq 2a+1 \\ \dfrac{W}{2a+1} & W < 2a+1 \end{cases}$$



Performance: Stop-and-wait ARQ (1)



- **Utilization of error-free transmission:**

$$U = \frac{T_f}{T_t} \approx \frac{T_f}{T_f + 2T_p} = \frac{1}{1+2a}$$

where T_f = time for emitting single frame

T_t = total time of line being engaged in transmission of single frame

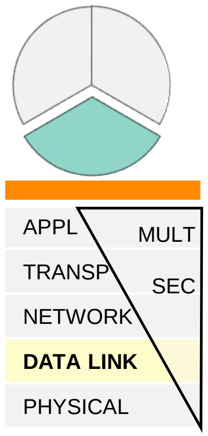
T_p = propagation time

- **If errors occur, then utilization**

$$U = \frac{T_f}{N_r T_t} = \frac{1}{N_r(1+2a)}$$

where N_r is the expected number of transmissions of a frame

Performance: Stop-and-wait ARQ (2)



- **N_r derived assuming**
  - A single data frame is in error with probability P
  - ACK and NAK are never in error

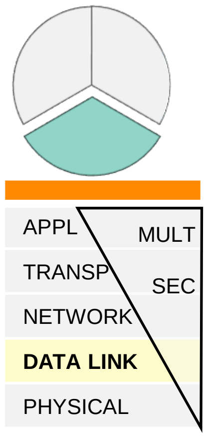
- **Propability it takes exactly k attempts to transmit a frame successfully is $P^{k-1}(1-P)$**
- **Then expected number of transmissions of a frame**

$$N_r = E[transmission] = \sum_{i=1}^{\infty}\left(i \times \Pr\left[i\ transmissions\right]\right) = \sum_{i=1}^{\infty}\left(iP^{i-1}\left(1-P\right)\right) = \frac{1}{1-P}$$

Derivation uses equality $\sum_{i=1}^{\infty}\left(iX^{i-1}\right) = \frac{1}{(1-X)^2}$ for $\left(-1 \prec X \prec 1\right)$

- **Hence utilization** $U = \begin{cases} \dfrac{1-P}{1+2a} \end{cases}$

Performance: Selective repeat ARQ



- Utilization without errors was

$$U = \begin{cases} 1 & W \geq 2a+1 \\ \dfrac{W}{2a+1} & W < 2a+1 \end{cases}$$

- Again utilization is divided by

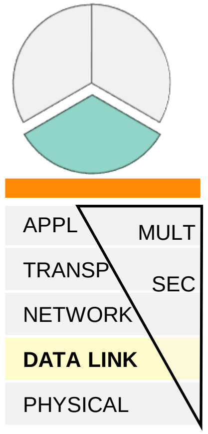
$$N_r = \frac{1}{1-P}$$

- Thus utilization for selective repeat ARQ

$$U = \begin{cases} 1-P & W \geq 2a+1 \\ \dfrac{W(1-P)}{2a+1} & W < 2a+1 \end{cases}$$

  - Note: W=1 $\rightarrow$ reduces to stop-and-wait ARQ utilization

Performance: Go-back-N ARQ (1)



- **Error in single frame generates requirement to retransmit K frames**

$$N_r = \mathrm{E}[\text{number of transmitted frames to successfully transmit one frame}] = \sum_{i=1}^{\infty} f(i) P^{i-1}(1-P)$$

where f(i) is the total number of frames transmitted if the original frame must be transmitted i times:

f(i) = 1 + (i-1)K = (1-K) + Ki

- **Substituting yields**

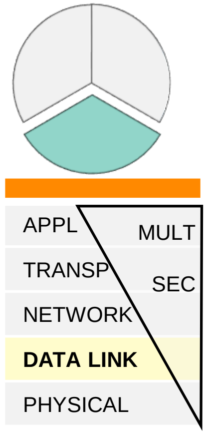
$$N_r = (1-K)\sum_{i=1}^{\infty} P^{i-1}(1-P) + K\sum_{i=1}^{\infty} iP^{i-1}(1-P)$$

$$= 1-K+\frac{K}{1-P} = \frac{1-P+KP}{1-P}$$

derivation uses equality

$$\sum_{i=1}^{\infty} X^{i-1} = \frac{1}{1-X} \quad \text{for } (-1 \prec X \prec 1)$$

Performance: Go-back-N ARQ (2)



- It can be approximated that

  K = (2a+1) for W ≥ (2a+1)

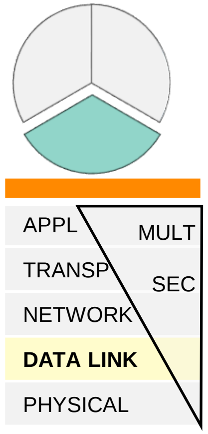
  K = W for W < (2a+1)

- Thus utilization for Go-back-N ARQ

$$U = \begin{cases} \dfrac{1-P}{1+2\mathrm{aP}} & W \geq 2a+1 \\ \dfrac{W(1-P)}{(2a+1)(1-P+WP)} & W < 2a+1 \end{cases}$$

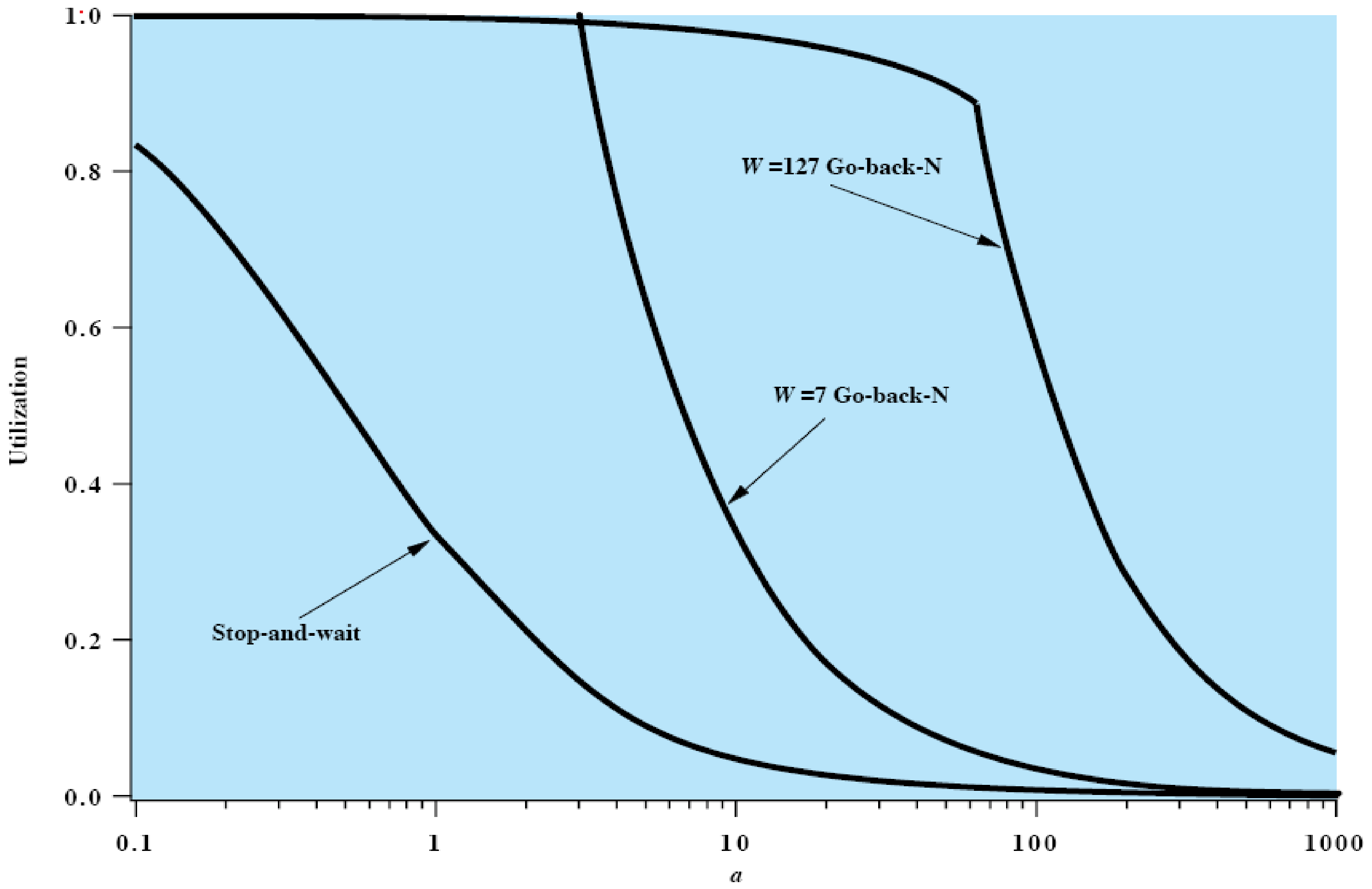
- Note: W=1 → reduces to stop-and-wait ARQ utilization

Performance: ARQ comparison



ARQ utilization as of a function of a ($P=10^{-3}$)

Selective repeat ARQ is effectively equal to Go-back-N ARQ



Key points to remember

1. **Main functions of Link Control**
2. **Flow control and its basic types:**
   - Stop&wait
   - Pipelining
   - Sliding window
3. **Error control and its basic types:**
   - Stop&wait ARQ
   - Go-Back-N ARQ
   - Selective repeat

Thank you!