Computer Networks - *Xarxes de Computadors*

Outline

- Course Syllabus
- Unit 1: Introduction
- Unit 2. IP Networks
- **Unit 3. TCP**
- Unit 4. LANs
- Unit 5. Network applications

Unit 3. TCP

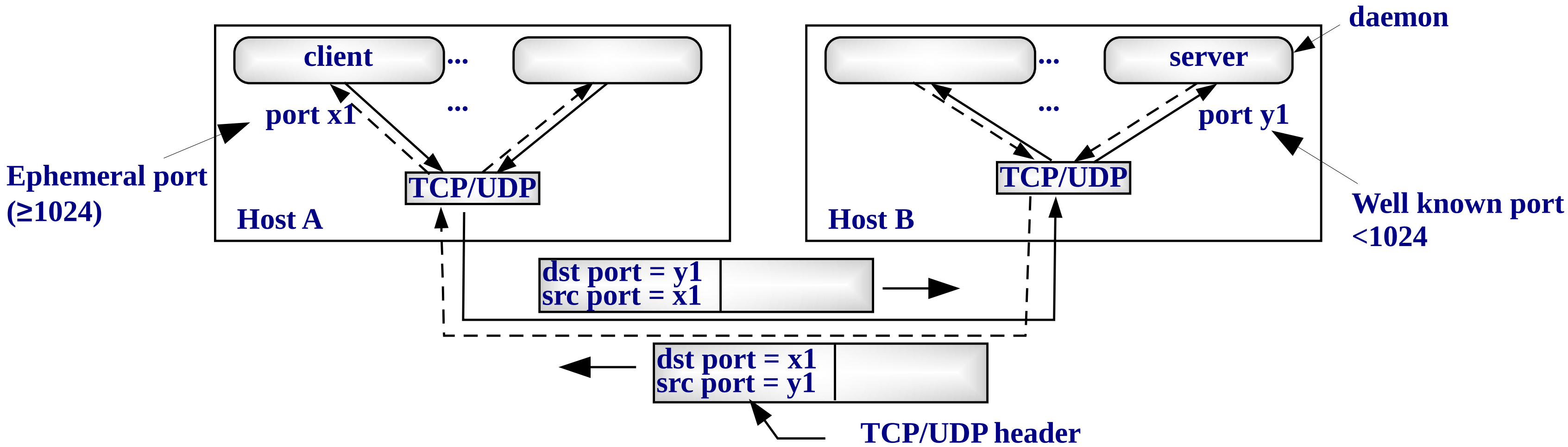
Outline

- **UDP Protocol**
- ARQ Protocols
- TCP Protocol

Unit 3. TCP

UPD Protocol – Introduction: The Internet Transport Layer

- Two protocols are used at the TCP/IP transport layer: User Datagram Protocol (UDP) and Transmission Control Protocol (TCP).
- UDP offers a *datagram service* (non reliable).
- TCP offers a reliable service.
- Transport layer offers a communication channel between applications.
- Transport layer access points (applications) are identified by a 16 bits port numbers.
- TCP/UDP use the client/server paradigm:



Unit 3. TCP

UPD Protocol – Description (RFC 768)

- Datagram service: same as IP.
  - Non reliable
  - No error recovery
  - No ack
  - Connectionless
  - No flow control
- UDP PDU is referred to as UDP datagram.
- UDP does not have a Tx buffer: each application write operation generates a UDP datagram.
- UDP is typically used:
  - Applications where short messages are exchanged: e.g. DHCP, DNS, RIP.
  - Real time applications: e.g. Voice over IP, videoconferencing, stream audio/video. These applications does not tolerate large delay variations (which would occur using an ARQ).

Unit 3. TCP

UPD Protocol – UDP Header

- Fixed size of 8 bytes.
- The checksum is computed using (i) the header, (ii) a pseudo-header, (iii) the payload.
- Drawback: because of the pseudo-header, the UDP checksum needs to be updated if PAT is used.

```
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          Source Port          |       Destination Port        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|            Length             |           Checksum            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

UDP datagram header

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Source Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Zero      |   Protocol    |          UDP length           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

UDP pseudo-header

Unit 3. TCP

Outline

- UDP Protocol
- **ARQ Protocols**
- TCP Protocol

Unit 3. TCP

ARQ protocols - Introduction

- Automatic Repeat reQuest (ARQ) protocols build a communication channel between endpoints, adding functionalities of the type:
  - Error detection
  - Error recovery
  - Flow control

Basic ARQ Protocols:

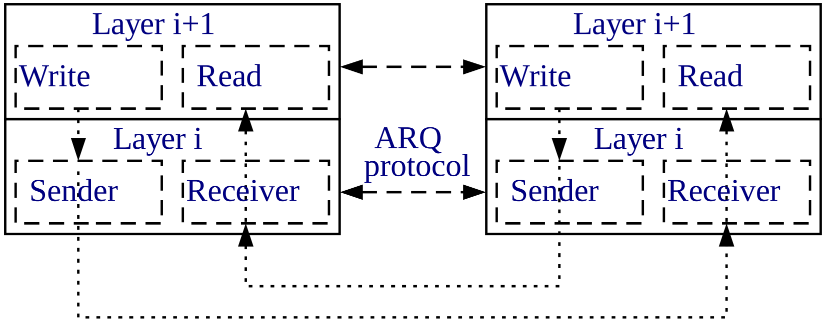
- Stop & Wait
- Go Back N
- Selective Retransmission

Unit 3. TCP

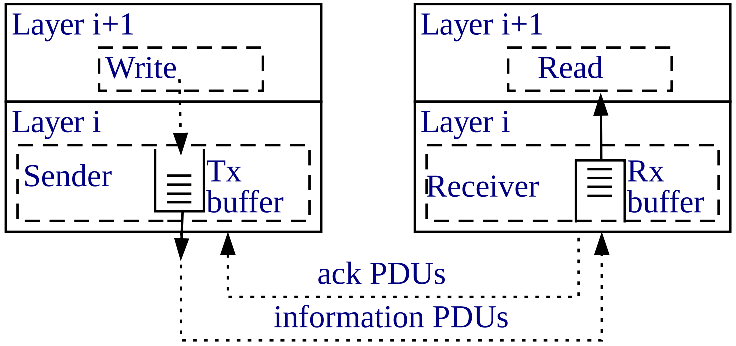
ARQ protocols - Introduction

ARQ Ingredients

- Connection oriented
- Tx/Rx buffers
- Acknowledgments (ack)
- Acks can be *piggybacked* in information PDUs sent in the opposite direction.
- Retransmission Timeout, RTO.
- Sequence Numbers



ARQ Protocol Architecture



ARQ Protocol Implementation (one way)

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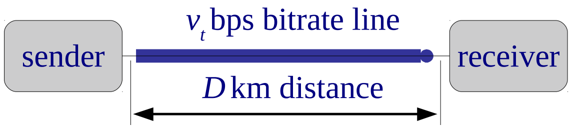
ARQ Protocols - Assumptions

- We shall focus on the the transmission in one direction.
- We shall assume a saturated source: There is always information ready to send.
- We shall assume full duplex links.
- Protocol over a line of D m distance and v_t bps bitrate.
- Propagation speed of v_p m/s, thus, propagation delay of D/v_p s.
- We shall refer to a generic layer, where the sender sends Information PDUs (I_k) and the receiver sends ack PDUs (A_k).
- Frames carrying I_k respectively A_k, are Tx using L_I and L_A bits, thus the Tx times are respectively: $t_t = L_I/v_t$ and $t_a = L_A/v_t$ s.



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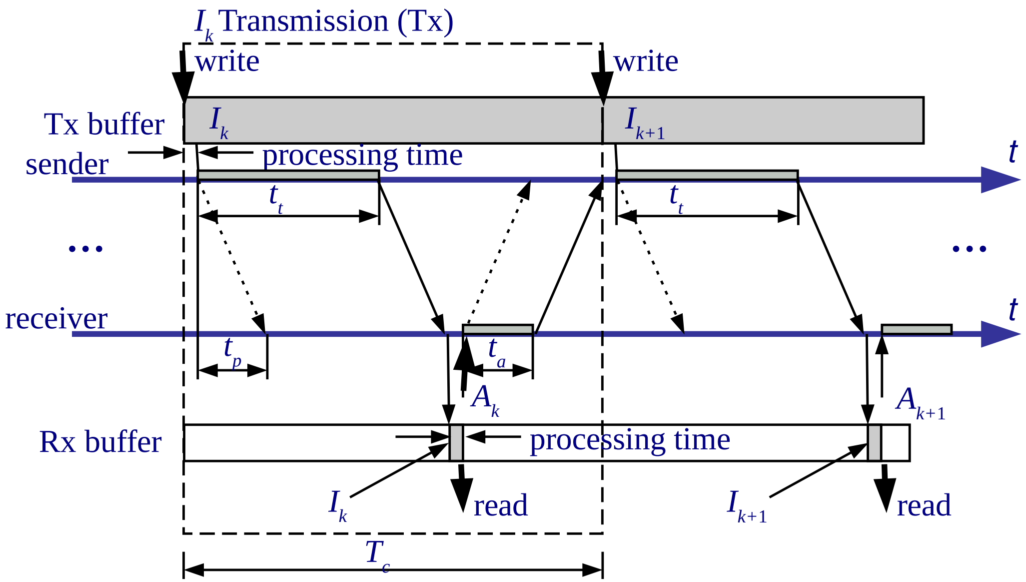
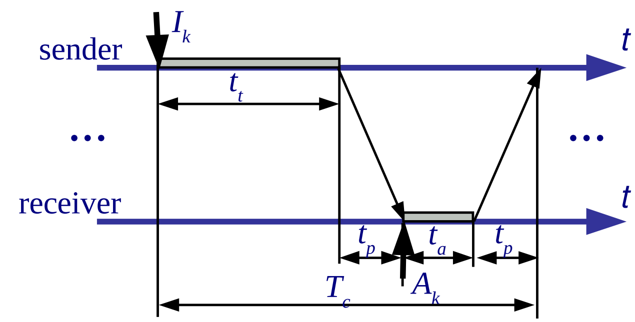
ARQ Protocols - Stop & Wait

1. When the sender is ready: (i) allows writing from upper layer, (ii) builds I_k, (iii) I_k goes down to data-link layer and Tx starts.
2. When I_k completely arrives to the receiver: (i) it is read by the upper layer, (ii) A_k is generated, A_k goes down to data-link layer and Tx starts.
3. When A_k completely arrives to the sender, goto 1.



Time diagram

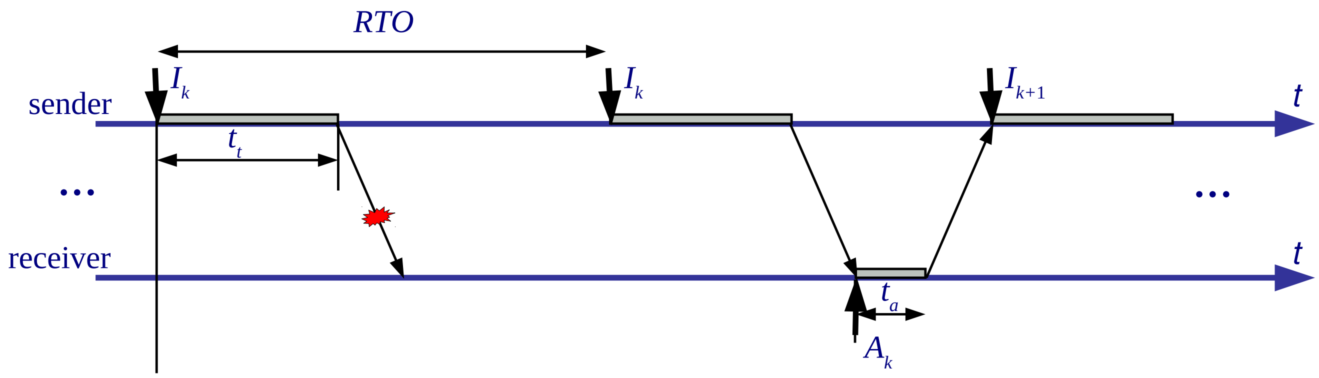


Simplified time diagram

Unit 3. TCP

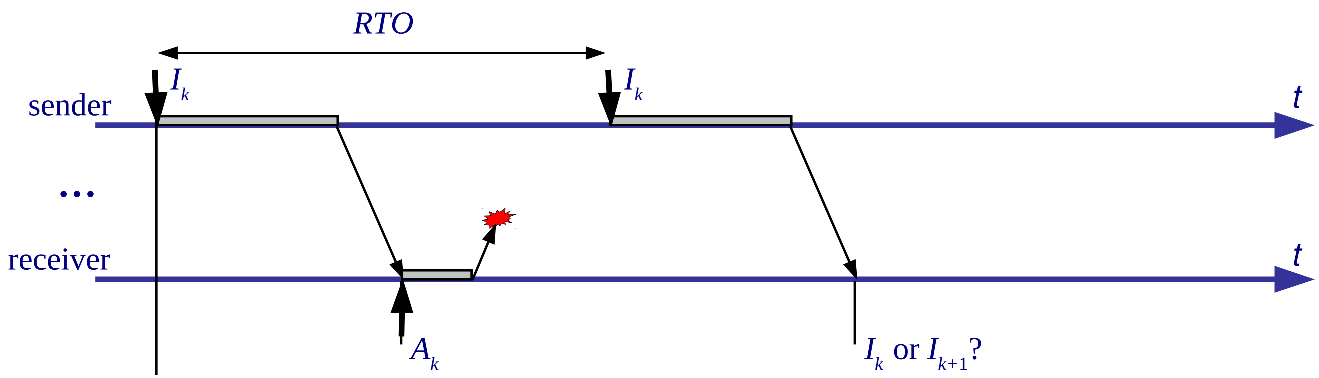
ARQ Protocols - Stop & Wait Retransmission

- Each time the sender Tx a PDU, a retransmission timeout (RTO) is started.
- If the information PDU do not arrives, or arrives with errors, no ack is sent.
- When RTO expires, the sender ReTx (retransmit) the PDU.

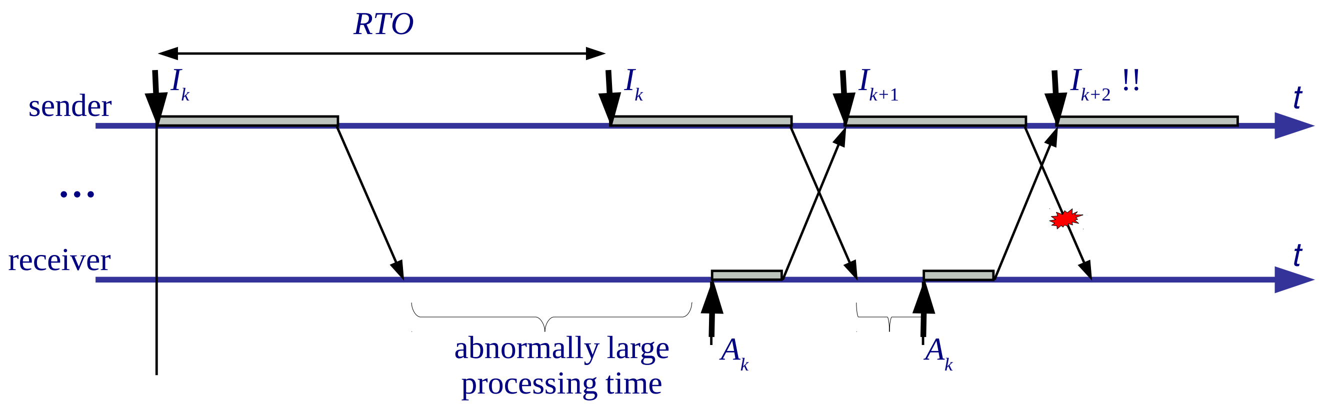


Unit 3. TCP

ARQ Protocols – Why sequence numbers are needed?



Need to number information PDUs

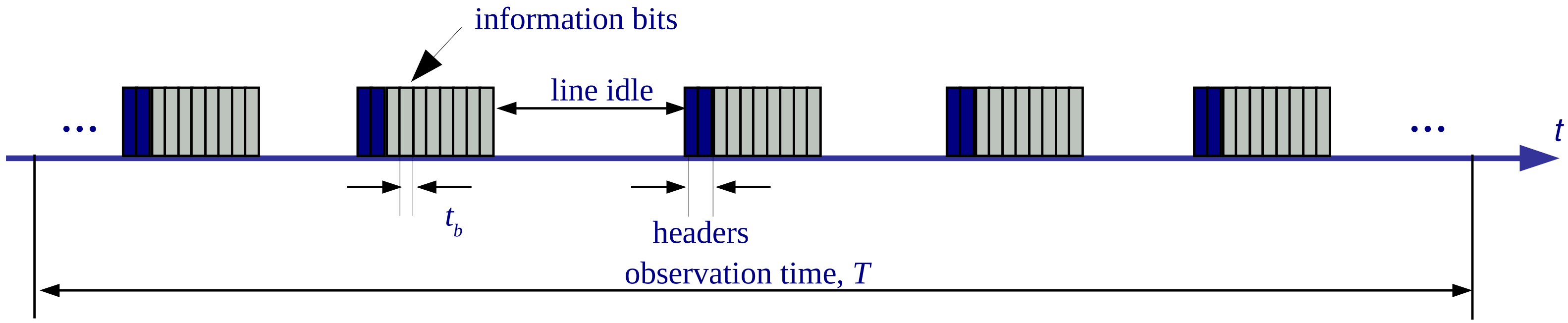


Need to number ack PDUs

Unit 3. TCP

ARQ Protocols – Notes on computing the efficiency (channel utilization)

- Line bitrate (*velocitat de transmissió de la línia*): $v_t = 1/t_b$, bps
- Throughput (*velocidad efectiva*) v_{ef} = number of inf. bits / obs. time, bps
- Efficiency or channel utilization $E = v_{ef} / v_t$ (times 100, in percentage)



$$E = \frac{v_{ef}}{v_t} = \frac{\#\text{info bits}/T}{1/t_b} = \begin{cases} \dfrac{\#\text{info bits} \times t_b}{T} = \dfrac{\text{time Tx information}}{T} \\[2ex] \dfrac{\#\text{info bits}}{T/t_b} = \dfrac{\#\text{info bits}}{\#\text{bits at line bitrate}} \end{cases}$$

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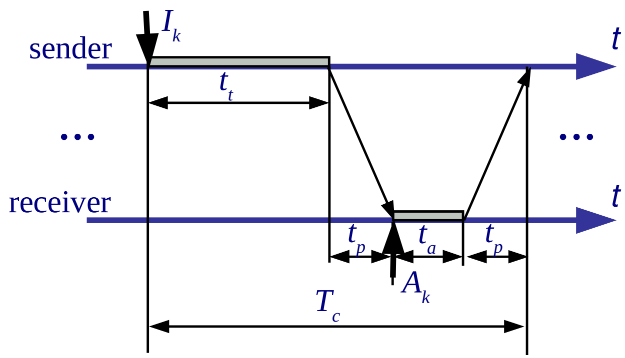
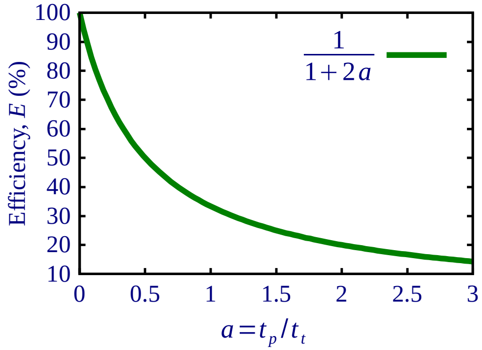
ARQ Protocols – Stop & Wait efficiency

- Assuming no errors (maximum efficiency), the Tx is periodic, with period T_c.
- $E_{protocol}$: We do not take into account headers.



$$E_{protocol} = \frac{t_t}{T_C} = \frac{t_t}{t_t + t_a + 2t_p} =$$

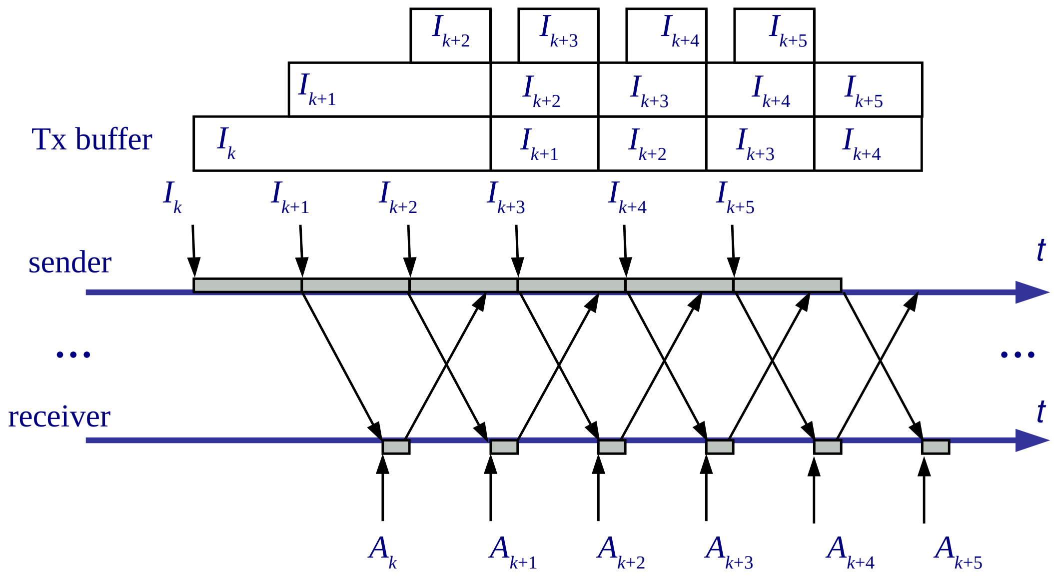
$$\frac{t_t}{t_t + 2t_p} \simeq \frac{1}{1+2a}, \text{ where } a = \frac{t_p}{t_t}$$



Unit 3. TCP

ARQ Protocols – Continuous Tx Protocols

- Goal: Allow high efficiency independently of propagation delay.
- Without errors: E = 100 %



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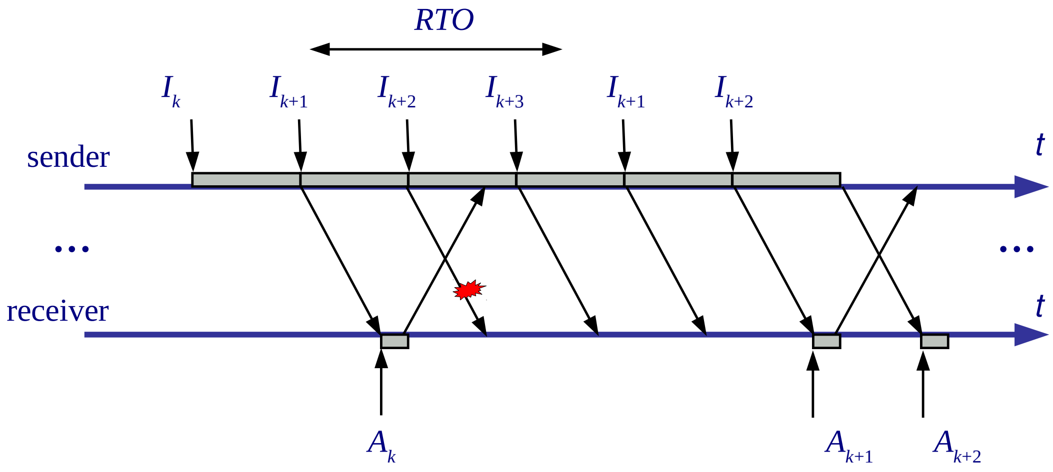
ARQ Protocols – Go Back N

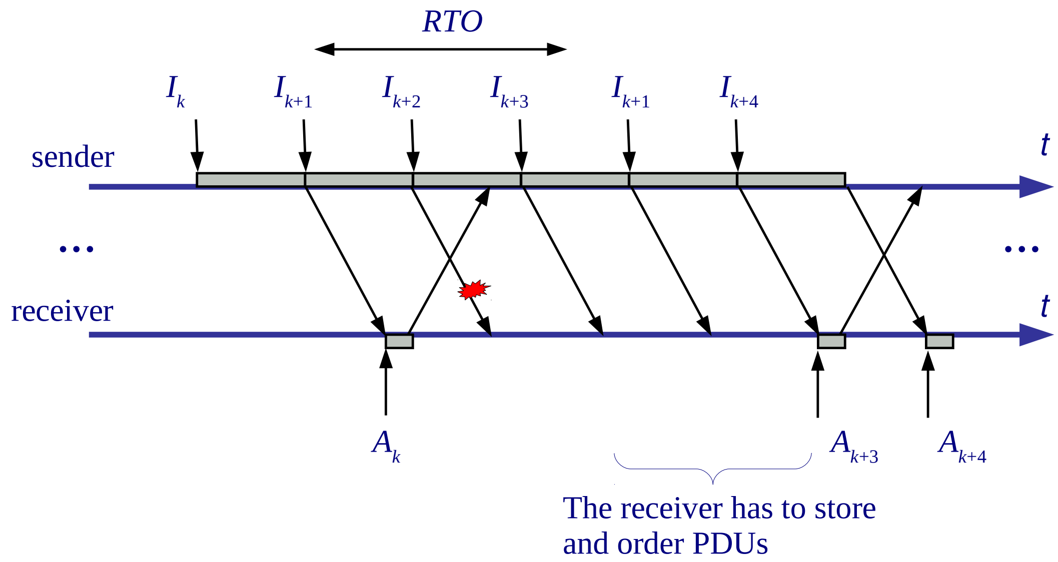
- Cumulative acks: A_k confirm I_i, $i \le k$
- If the sender receives an error or out of order PDU: Do not send acks, discards all PDU until the expected PDU arrives. Thus, the receiver does not store out of order PDUs.
- When a retransmission timeout RTO occurs, the sender *go back* and starts Tx from that PDU.



Unit 3. TCP

ARQ Protocols – Selective ReTx.

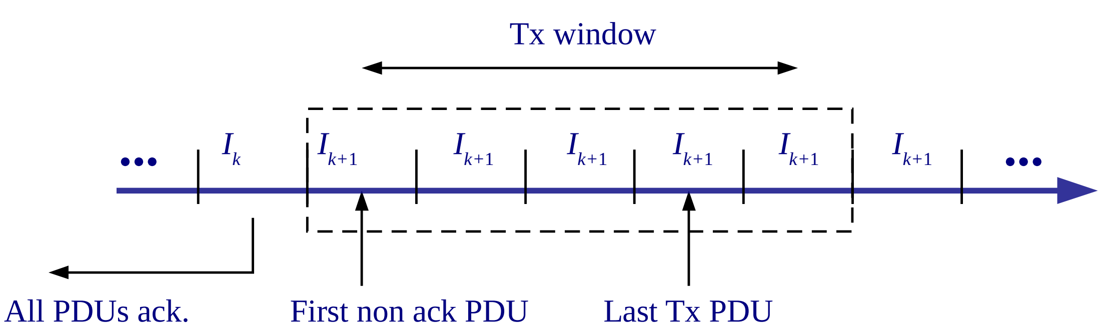
- The same as Go Back N, but:
  - The sender only ReTx a PDU when a RTO occurs.
  - The receiver stores out of order PDUs, and ack all stored PDUs when missing PDUs arrive.



Unit 3. TCP

ARQ Protocols – Flow Control and Window Protocols

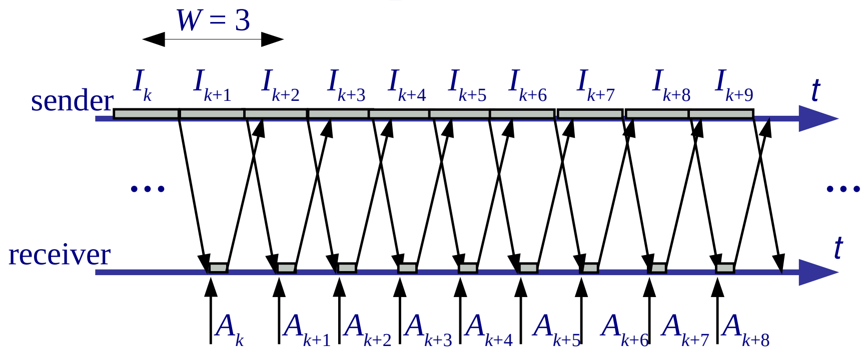
- ARQ are also used for flow control. Flow control consists on avoiding the sender to Tx at higher PDU rate than can be consumed by the receiver.
- With Stop & Wait, if the receiver is slower, acks are delayed and the sender reduces the throughput.
- With continuous Tx protocols: A *Tx window* is used. The window is the maximum number of non-ack PDUs that can be Tx. If the Tx window is exhausted, the sender stales.
- Stop & Wait is a window protocol with Tx window = 1 PDU.
- Furthermore, the Tx window allows dimensioning the Tx buffer, and the Rx buffer for Selective ReTx: No more the Tx window PDUs need to be stored.



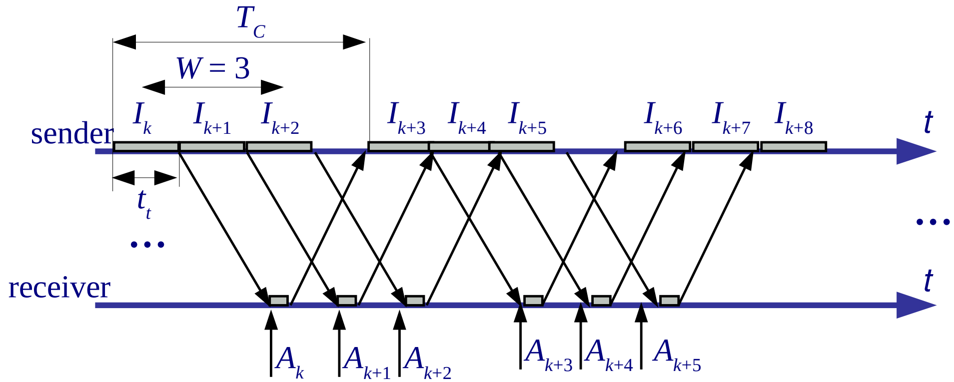
Unit 3. TCP

ARQ Protocols – Optimal Tx window

- Optimal window: Minimum window that allows the maximum throughput.
- Optimal window example:



- Non optimal window example:



- Clearly, for this example:

$$W_{opt} = \left\lceil \frac{T_C}{t_t} \right\rceil$$

Unit 3. TCP

Outline

- Introduction
- ARQ Protocols
- UDP Protocol
- **TCP Protocol**

Unit 3. TCP

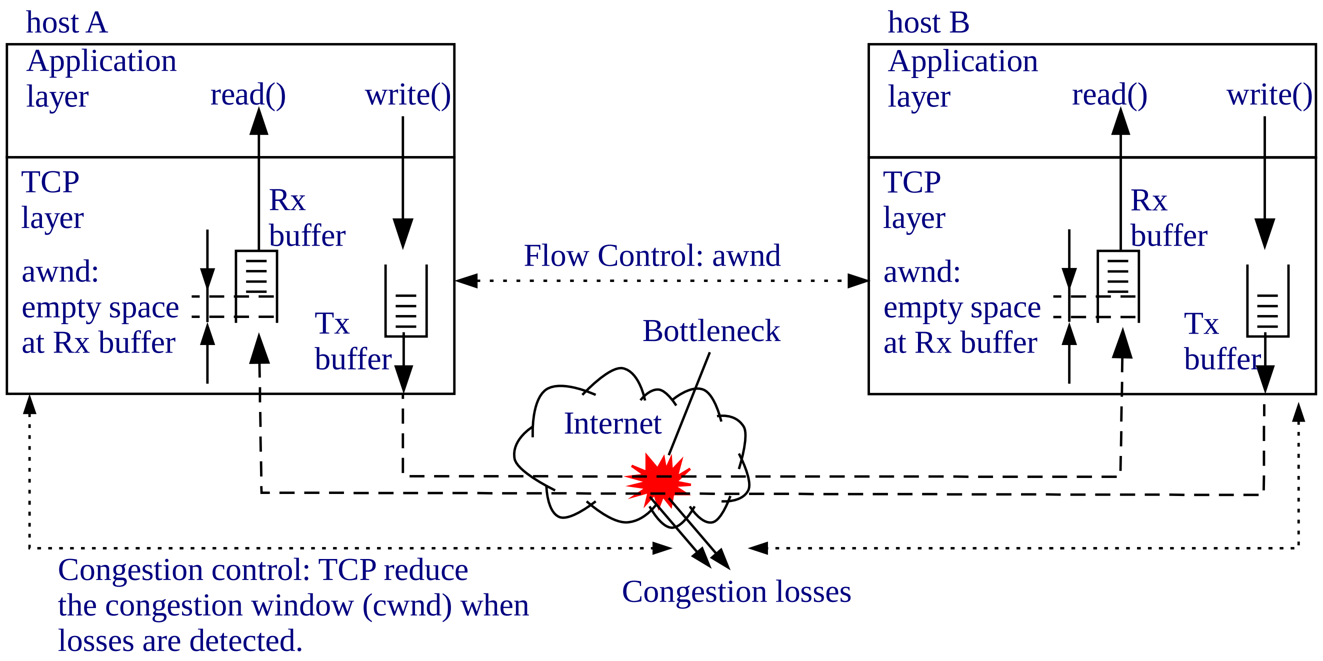
TCP Protocol – Description (RFC 793)

- Reliable service (ARQ).
  - Error recovery
  - Acknowledgments
  - Connection oriented
  - Flow control
- TCP PDU is referred to as TCP segment.
- Congestion control: Adapt the TCP throughput to network conditions.
- Segments of optimal size: Variable Maximum Segment Size (MSS).
- TCP is typically used:
  - Applications requiring reliability: Web, ftp, ssh, telnet, mail, ...

Unit 3. TCP

TCP Protocol – Basic operation

- ARQ window protocol, with variable window: **wnd = min(awnd, cwnd)**
- Each time a segment arrives, TCP send an ack (unless delayed ack is used) without waiting for the upper layer to read the data.
- The advertised window (**awnd**) is used for flow control.
- The congestion window (**cwnd**) is used for congestion control.



Unit 3. TCP

TCP Protocol – TCP Header

- Variable size: Fixed fields of 20 bytes + options (15x4 = 60 bytes max.).
- Like UDP, the checksum is computed using (i) the header, (ii) a pseudo-header, (iii) the payload, and needs to be updated if PAT is used.

```
                0                   1                   2                   3
                0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
               |          Source Port          |       Destination Port        |
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
               |                        Sequence Number                        |  TCP flags
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
  20 bytes     |                    Acknowledgment Number                      |
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
               | Header|         |U|A|P|R|S|F|                                 |
               | length| Reserved|R|C|S|S|Y|I|    Advertised window (awnd)     |
               |       |         |G|K|H|T|N|N|                                 |
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
               |           Checksum            |         Urgent Pointer        |
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 ? 40 bytes    |                    Options                    |    Padding    |
               +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

TCP segment header

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Source Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Zero      |   Protocol    |          TCP length           |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

TCP pseudo-header

Unit 3. TCP

TCP Protocol – TCP Flags

- URG (Urgent): The Urgent Pointer is used. It points to the first urgent byte. Rarely used. Example: ^C in a telnet session.
- ACK: The ack field is used. Always set except for the first segment sent by the client.
- PSH (Push): The sender indicates to “push” all buffered data to the receiving application. Most BSD derived TCPs set the PSH flag when the send buffer is emptied.
- RST (Reset): Abort the connection.
- SYN: Used in the connection setup (*three*-*way*-*handshaking*, *TWH*).
- FIN: Used in the connection termination.

Unit 3. TCP

TCP Protocol – TCP Flags

- tcpdump example:

```
TCP flags
  S: SYN
  P: PUSH
  .: No flag (except ack) is set
```

```
09:33:02.556785 IP 147.83.34.125.24374 > 147.83.194.21.80: S 3624662632:3624662632(0) win 5840
                <mss 1460,sackOK,timestamp 531419155 0,nop,wscale 7>
09:33:02.558054 IP 147.83.194.21.80 > 147.83.34.125.24374: S 2204366975:2204366975(0) ack
                3624662633 win 5792 <mss 1460,sackOK,timestamp 3872304344 531419155,nop,wscale 2>
09:33:02.558081 IP 147.83.34.125.24374 > 147.83.194.21.80: . ack 1 win 46 <nop,nop,timestamp
                531419156 3872304344>
09:33:02.558437 IP 147.83.34.125.24374 > 147.83.194.21.80: P 1:627(626) ack 1 win 46
                <nop,nop,timestamp 531419156 3872304344>
09:33:02.559146 IP 147.83.194.21.80 > 147.83.34.125.24374: . ack 627 win 1761 <nop,nop,timestamp
                3872304345 531419156>
09:33:02.559507 IP 147.83.194.21.80 > 147.83.34.125.24374: P 1:271(270) ack 627 win 1761
                <nop,nop,timestamp 3872304345 531419156>
09:33:02.559519 IP 147.83.34.125.24374 > 147.83.194.21.80: . ack 271 win 54 <nop,nop,timestamp
                531419156 3872304345>
09:33:02.560154 IP 147.83.194.21.80 > 147.83.34.125.24374: . 271:1719(1448) ack 627 win 1761
                <nop,nop,timestamp 3872304345 531419156>
09:33:02.560167 IP 147.83.34.125.24374 > 147.83.194.21.80: . ack 1719 win 77 <nop,nop,timestamp
                531419156 3872304345>
09:33:02.560256 IP 147.83.194.21.80 > 147.83.34.125.24374: . 1719:3167(1448) ack 627 win 1761
                <nop,nop,timestamp 3872304345 531419156>
09:33:02.560261 IP 147.83.34.125.24374 > 147.83.194.21.80: . ack 3167 win 100 <nop,nop,timestamp
                531419156 3872304345>
...
```

Unit 3. TCP

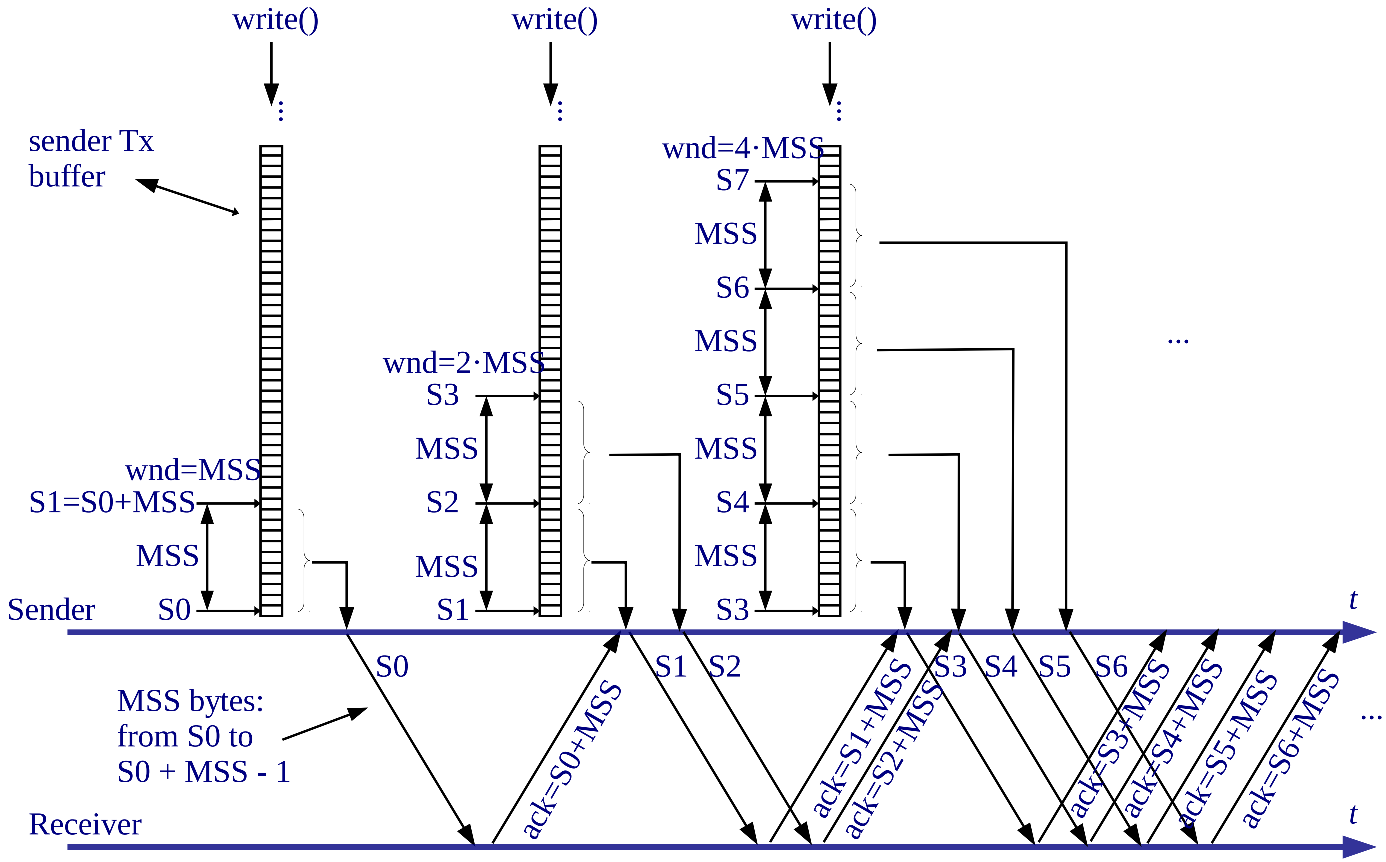
TCP Protocol – TCP Options

- Maximum Segment Size (MSS): Used in the TWH to initialize the MSS. In IPv4 it is set to MTU-40 (size of IPv4 and TCP headers without options).
- Window Scale factor: Used in the TWH. The awnd is multiplied by $2^{\text{Window Scale}}$ (i.e. the window scale indicates the number of bits to left-shift awnd). It allows using awnd larger than 2^{16} bytes.
- Timestamp: Used to compute the Round Trip Time (RTT). Is a 10 bytes option, with the timestamp clock of the TCP sender, and an echo of the timestamp of the TCP segment being ack.
- SACK: In case of errors, indicate blocks of consecutive correctly received segments for Selective ReTx.

Unit 3. TCP

TCP Protocol – TCP Sequence Numbers

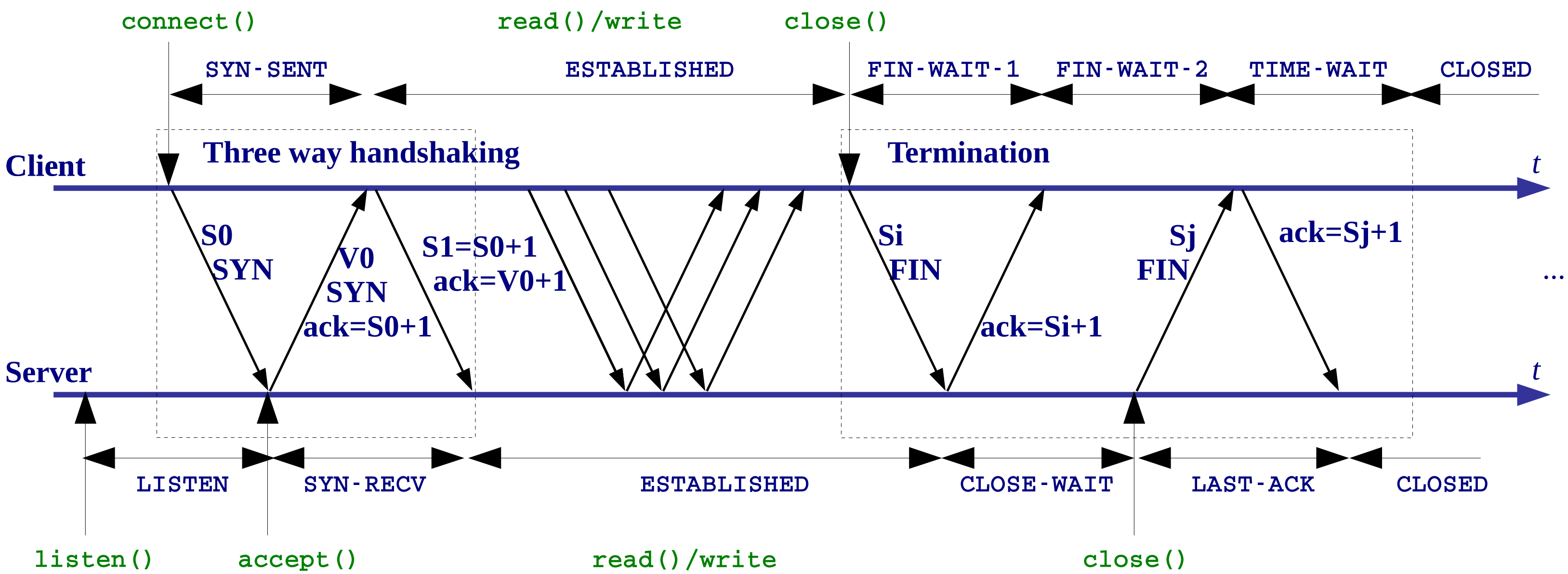
- The sequence number identifies the first payload byte.
- The ack number identifies the next byte the receiver is waiting for.



Unit 3. TCP

TCP Protocol – Connection Setup and Termination

- The client always send the 1st segment.
- Three-way handshaking segments have payload = 0.
- SYN and FIN segments consume 1 sequence number.
- Initial sequence number is random.



Unit 3. TCP

TCP Protocol – tcpdump example (web page download)

TWH

Termination

```
12:30:37.069541 IP 147.83.34.125.17788 > 147.83.32.82.80: S 3473661146:3473661146(0) win 5840 <mss
                1460,sackOK,timestamp 296476754 0,nop,wscale 7>
12:30:37.070021 IP 147.83.32.82.80 > 147.83.34.125.17788: S 544373216:544373216(0) ack 3473661147 win 5792 <mss
                1460,sackOK,timestamp 1824770623 296476754,nop,wscale 2>
12:30:37.070038 IP 147.83.34.125.17788 > 147.83.32.82.80: . ack 1 win 46 <nop,nop,timestamp 296476754
                1824770623>
12:30:37.072763 IP 147.83.34.125.17788 > 147.83.32.82.80: P 1:602(601) ack 1 win 46 <nop,nop,timestamp 296476754
                1824770623>
12:30:37.073546 IP 147.83.32.82.80 > 147.83.34.125.17788: . ack 602 win 1749 <nop,nop,timestamp 1824770627
                296476754>
12:30:37.075932 IP 147.83.32.82.80 > 147.83.34.125.17788: P 1:526(525) ack 602 win 1749 <nop,nop,timestamp
                1824770629 296476754>
12:30:37.075948 IP 147.83.34.125.17788 > 147.83.32.82.80: . ack 526 win 54 <nop,nop,timestamp 296476755
                1824770629>
12:30:53.880704 IP 147.83.32.82.80 > 147.83.34.125.17788: F 526:526(0) ack 602 win 1749 <nop,nop,timestamp
                1824787435 296476755>
12:30:53.920354 IP 147.83.34.125.17788 > 147.83.32.82.80: . ack 527 win 54 <nop,nop,timestamp 296480966
                1824787435>
12:30:56.070200 IP 147.83.34.125.17788 > 147.83.32.82.80: F 602:602(0) ack 527 win 54 <nop,nop,timestamp
                296481504 1824787435>
12:30:56.070486 IP 147.83.32.82.80 > 147.83.34.125.17788: . ack 603 win 1749 <nop,nop,timestamp 1824789625
                296481504>
```

TCP flags

timestamp | src IP addr/port | dst IP addr/port | seq. num:next seq num (bytes) | awnd

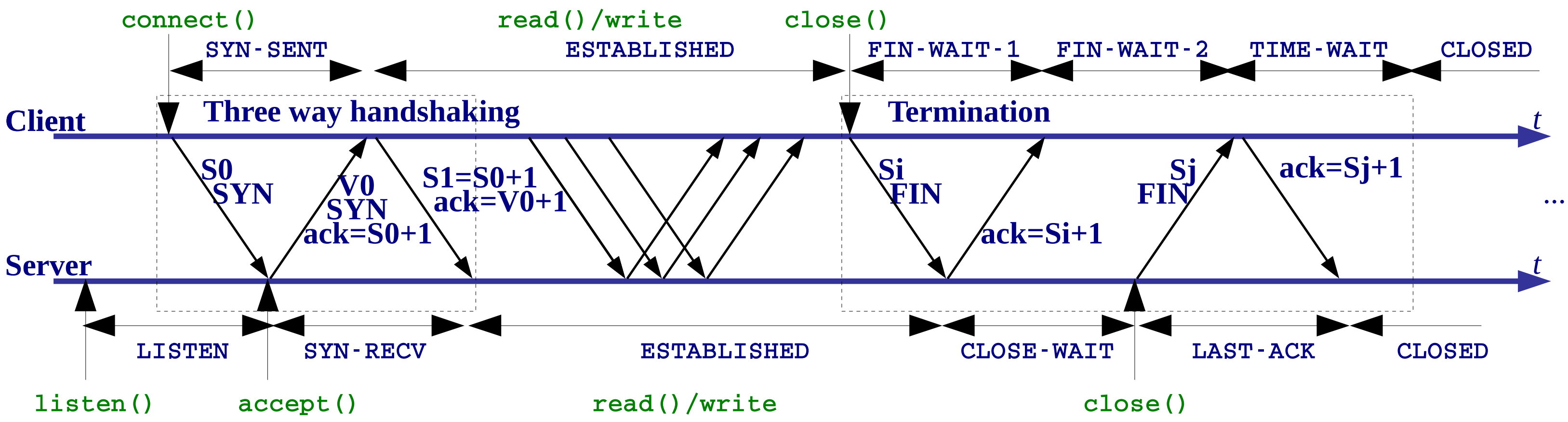
```
12:30:37.069541 IP 147.83.34.125.17788 > 147.83.32.82.80: S 3473661146:3473661146(0) win 5840
         <mss 1460,sackOK,timestamp 296476754 0,nop,wscale 7>
```

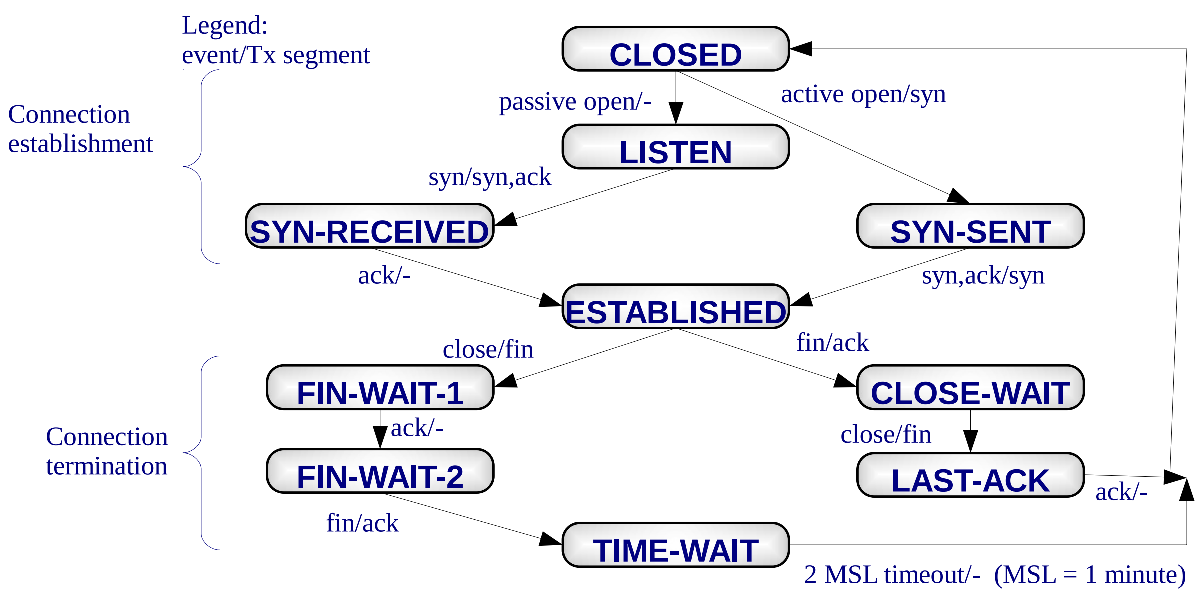
MSS | SACK | timestamp | window scale

padding

Unit 3. TCP

TCP Protocol – State diagram (simplified)





Unit 3. TCP

TCP Protocol – netstat dump

- Option -t shows tcp sockets.

```
linux# netstat -nt
Active Internet connections (w/o servers)
Proto Recv-Q Send-Q Local Address           Foreign Address         State
tcp          0   1286 192.168.0.128:29537     199.181.77.52:80        ESTABLISHED
tcp          0      0 192.168.0.128:13690     67.19.9.2:80            TIME_WAIT
tcp          0      1 192.168.0.128:12339     64.154.80.132:80        FIN_WAIT1
tcp          0      1 192.168.0.128:29529     199.181.77.52:80        SYN_SENT
tcp          1      0 192.168.0.128:17722     66.98.194.91:80         CLOSE_WAIT
tcp          0      0 192.168.0.128:14875     210.201.136.36:80       ESTABLISHED
tcp          0      0 192.168.0.128:12804     67.18.114.62:80         ESTABLISHED
tcp          0      1 192.168.0.128:25232     66.150.87.2:80          LAST_ACK
tcp          0      0 192.168.0.128:29820     66.102.9.147:80         ESTABLISHED
tcp          0      0 192.168.0.128:29821     66.102.9.147:80         ESTABLISHED
tcp          1      0 127.0.0.1:25911         127.0.0.1:80            CLOSE_WAIT
tcp          0      0 127.0.0.1:25912         127.0.0.1:80            ESTABLISHED
tcp          0      0 127.0.0.1:80            127.0.0.1:25911         FIN_WAIT2
tcp          0      0 127.0.0.1:80            127.0.0.1:25912         ESTABLISHED
```

man netstat

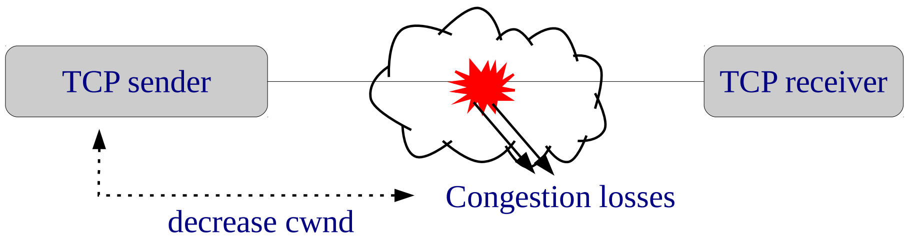
The count of bytes not acknowledged by the remote host.

The count of bytes not copied by the user program connected to this socket.

Unit 3. TCP

TCP Protocol – Congestion Control (RFC 2581)

- window = min(awnd, cwnd)
    - The advertised window (awnd) is used for flow control.
    - The congestion window (cwnd) is used for congestion control.
- TCP interprets losses as congestion:



- Basic Congestion Control Algorithm:
    - Slow Start / Congestion Avoidance (SS/CA)

Unit 3. TCP

TCP Protocol – Slow Start / Congestion Avoidance (SS/CA)

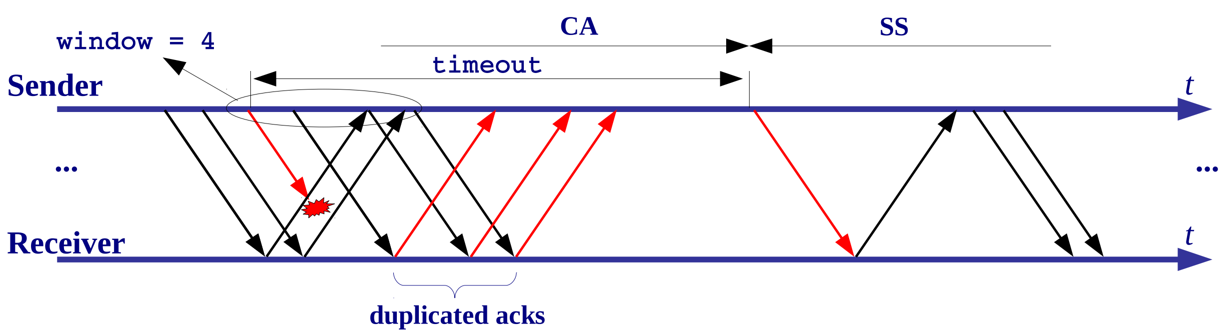
- Variables:
  - snd_una: First non ack segment (head of the TCP transmission queue).
  - ssthresh: Threshold between SS and CA.

```
Initialization:
        cwnd = MSS ; NOTE: RFC 2581 allows an initial window of 2 segments.
        ssthresh = infinity ;

Each time an ack confirming new data is received:
        if(cwnd < ssthresh) {
                cwnd += MSS ; /* Slow Start */
        } else {
                cwnd += MSS * MSS / cwnd ; /* Congestion Avoidance */
        }

When there is a time-out:
        Retransmit snd_una ;
        ssthresh = max(min(awnd, cwnd) / 2, 2 MSS) ;
        cwnd = MSS ;
```

Time-out Example:



Unit 3. TCP

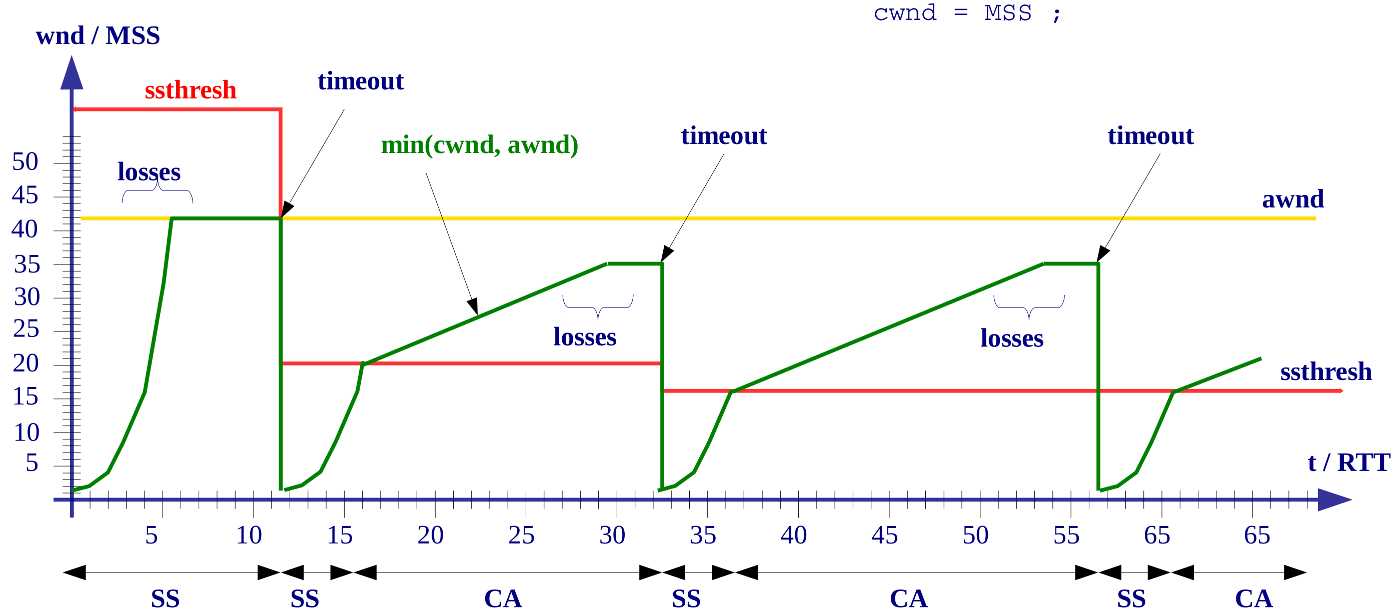
TCP Protocol – Slow Start / Congestion Avoidance (SS/CA)

- During SS cwnd is rapidly increased to the "operational point".
- During CA cwnd is slowly increased looking for more available bandwidth.

```
Initialization:
        cwnd = MSS ;
        ssthresh = infinit ;

Each time an ack confirming new data is received:
        if(cwnd < ssthresh) {
                cwnd += MSS ; /* SS */
        } else {
                cwnd += MSS * MSS / cwnd ; /* CA */
        }

When there is a time-out:
        Retransmit snd_una ;
        ssthresh = max(min(awnd, cwnd) / 2, 2 MSS) ;
        cwnd = MSS ;
```

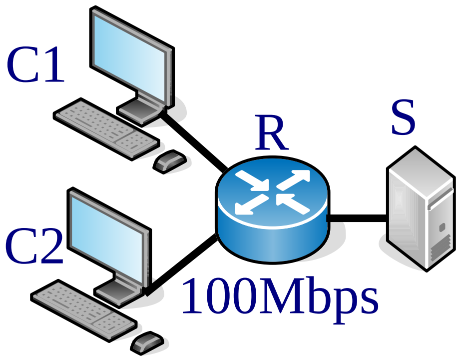


Unit 3. TCP

TCP Protocol – Evaluation without losses

- Preliminaries:
    - TCP sends the entire window, W (in several segments)
    - The segments accumulate in the queues of the interfaces where there are bottlenecks
    - Steady state: the TCP connection started time ago
    - In general, we can assume that, on the average, is fulfilled vef = W / RTT
    - If there are no losses, W will be awnd, otherwise W follows a "saw tooth"

- Example: C1 and C2 send to S, each with a TCP connection, awnd=64kB.
    - The bottleneck is the link R-S
    - For each connection vef = 100/2 = 50 Mbps
    - Since propagation delays in the links are negligible, if no losses occur in the queue of the router there will be 128 kB (the 2 TCP windows)
    - The RTT is the time in the queue of the router:
        - RTT=128 kB/100 Mbps = 10,24 ms
    - Check that vef=W/RTT = 64 kB/10,24 ms = 50 Mbps



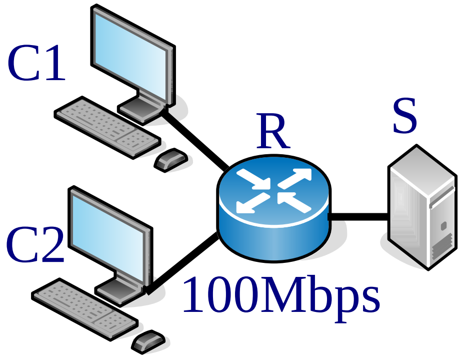
Unit 3. TCP

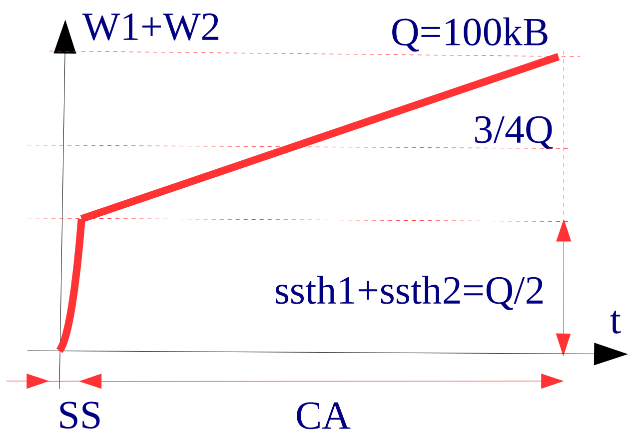
TCP Protocol – Evaluation with losses

- Example with losses: C1 and C2 send to S, each with a TCP connection, awnd=64kB. Assume now that the interface queue of the router is limited to Q=100 kB
  - The bottleneck is the link R-S
  - For each connection vef = 100/2 = 50 Mbps
  - There will be losses, because when both TCP windows add to 100kB, there will be no space left in the router queue.
  - The figure shows a possible evolution of the queue in the router, which stores the window of both connections: W1+W2. When the queue is full, both connections have losses and reduce the ssth to the half. Therefore, the average queue size in the router will be, approximately:

    (Q/2+Q)/2=3/4Q=75 kB
  - Thus, the average RTT will be:
    - $\overline{\text{RTT}}$=75 kB/100 Mbps = 6 ms
  - Note that the average window of each connection will be:

    $\overline{\text{W1}}$=$\overline{\text{W2}}$=75 kB/2=37,5 kB
  - Check that vef=$\overline{\text{W}}$/$\overline{\text{RTT}}$ = 37,5 kB/6 ms = 50 Mbps





Unit 3. TCP

TCP Protocol – Retransmission time-out (RTO)

- Activation:
  - RTO is active whenever there are pending acks.
  - When RTO is active, it is continuously decreased, and a ReTx occurs when RTO reaches zero.
  - Each time an ack confirming new data arrives:
    - RTO is computed.
    - RTO is restarted if there are pending acks, otherwise, RTO is stopped.
- Computation:
  - The TCP sender measures the RTT mean (srtt) and variance (rttvar).
  - The retransmission time-out is given by: RTO = srtt + 4 x rttvar.
  - RTO is duplicated each retransmitted segment (exponential backoff).
- RTT measurements:
  - Using “slow-timer tics” (coarse).
  - Using the TCP timestamp option.

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TCP Protocol – Retransmission time-out (RTO)