# Computer Networks - *Xarxes de Computadors*

## Outline

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

# Unit 4. TCP

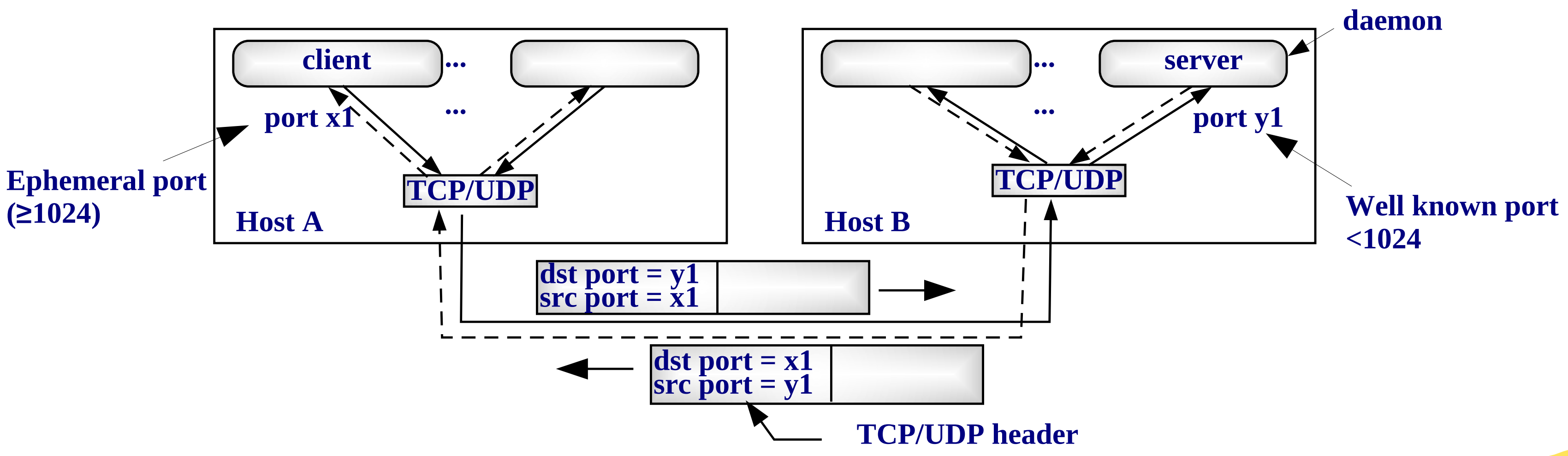
## Outline

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

# Unit 4. 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 4. 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 4. TCP

## UPD Protocol – UDP Header

- Fixed size of 8 bytes.
- The checksum is computed using the header and the payload.

```
 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

# Unit 4. TCP

## Outline

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

# Unit 4. 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:**

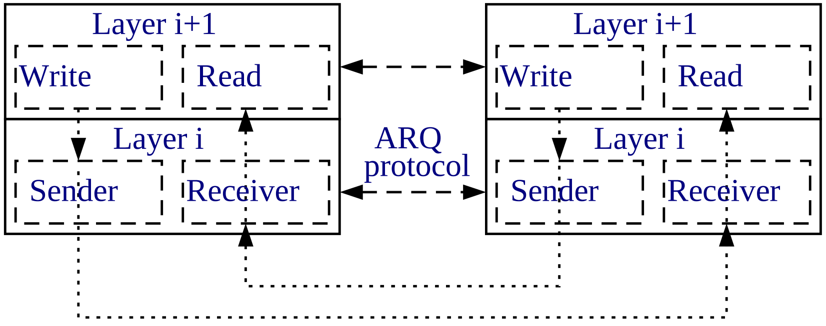
- Stop & Wait
- Go Back N
- Selective Retransmission

# Unit 4. TCP

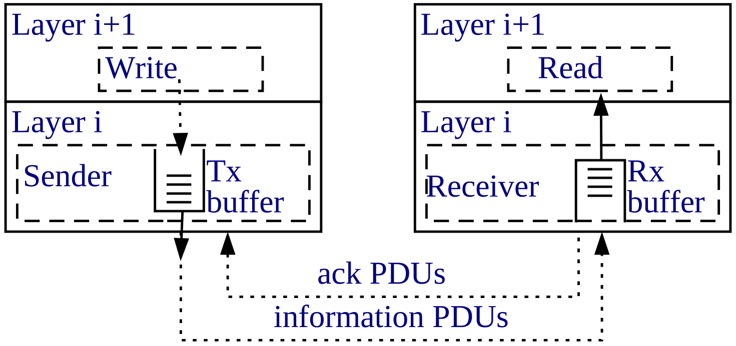
## ARQ protocols - Introduction

### 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

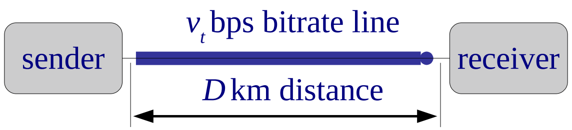



ARQ Protocol Implementation (one way)

# Unit 4. TCP

## ARQ Protocols - Assumptions

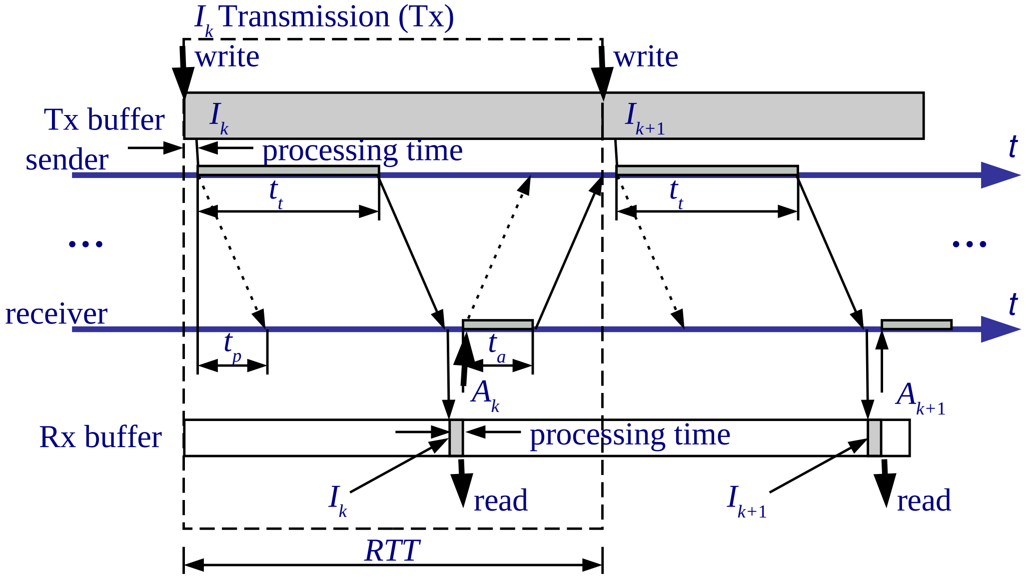
- We shall focus on the the transmission in one direction.
- We shall assume a saturated source: There is always information ready to send.
- We shall assume full duplex links.
- Protocol over a line of $D$ m distance and $v_t$ bps bitrate.
- Propagation speed of $v_p$ m/s, thus, propagation delay of $D/v_p$ 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.



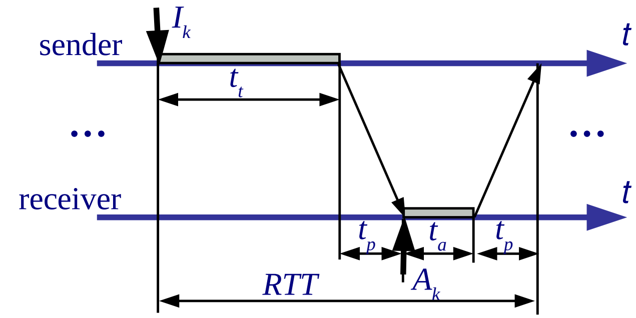
# Unit 4. TCP

## 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

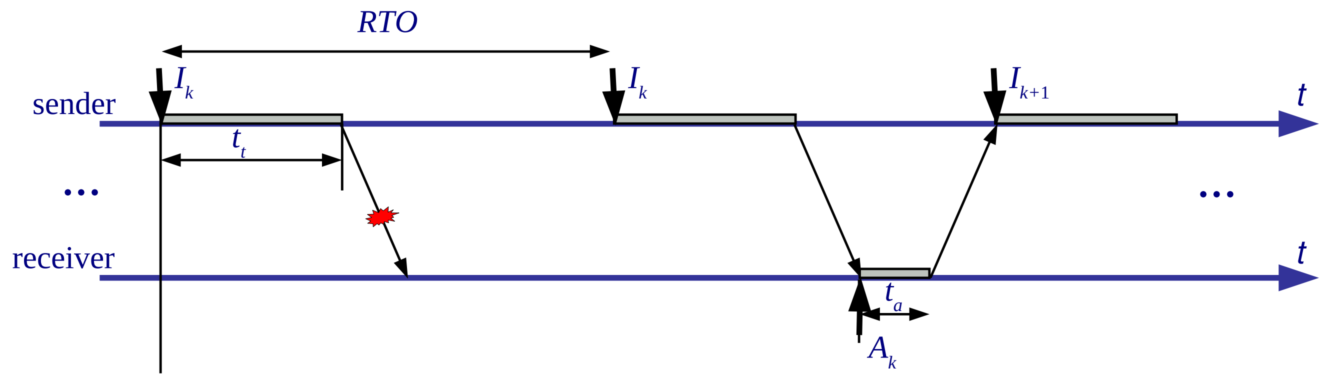



Simplified time diagram

# Unit 4. TCP

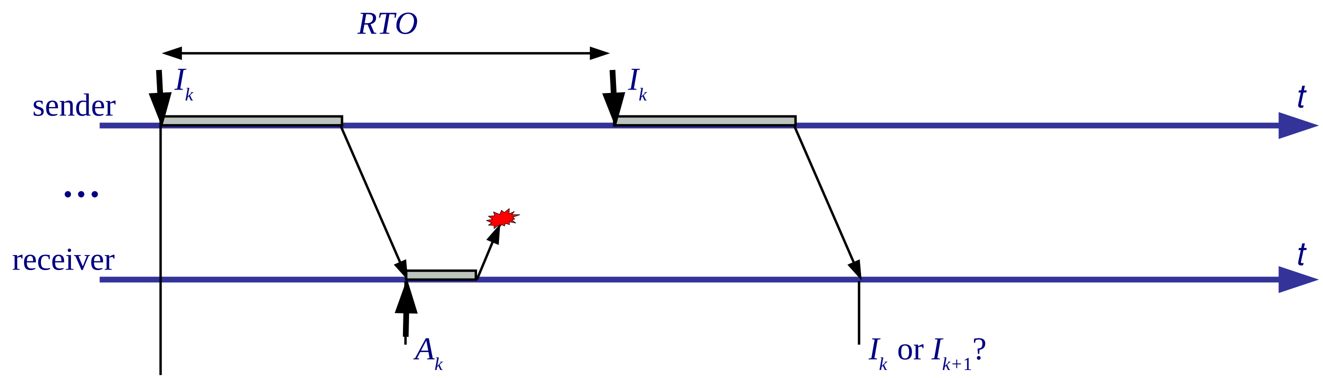
## ARQ Protocols - Stop & Wait Retransmission

- 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.

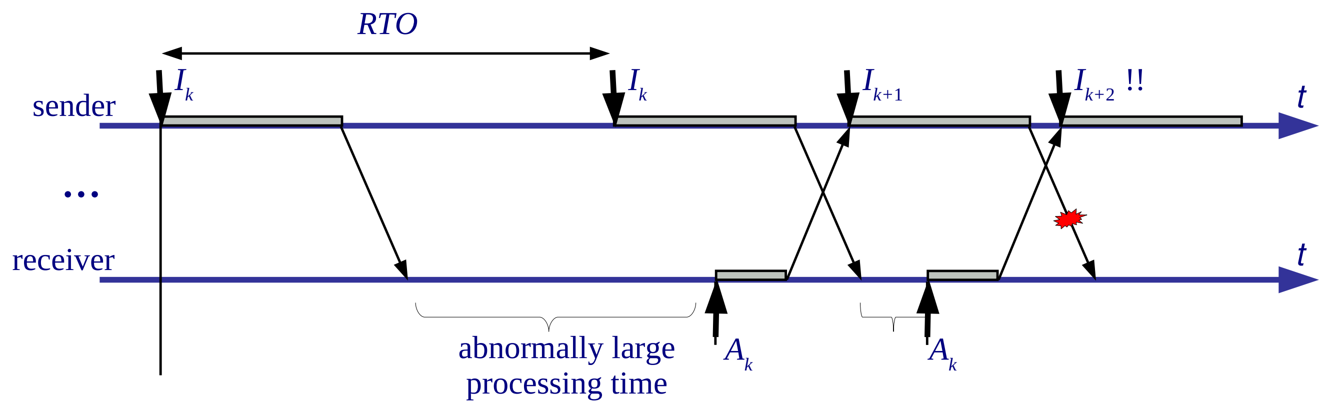


# Unit 4. TCP

## ARQ Protocols – Why sequence numbers are needed?




Need to number information PDUs

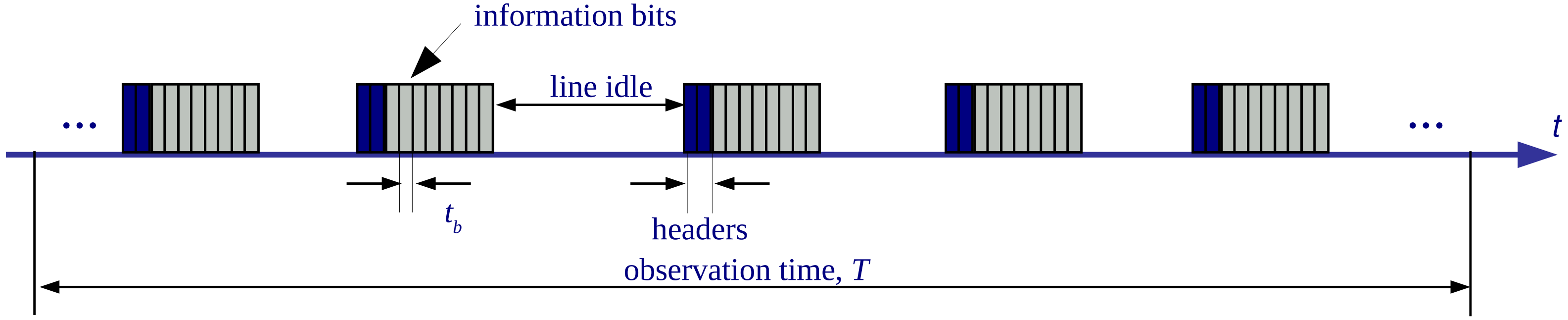



Need to number ack PDUs

# Unit 4. 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)

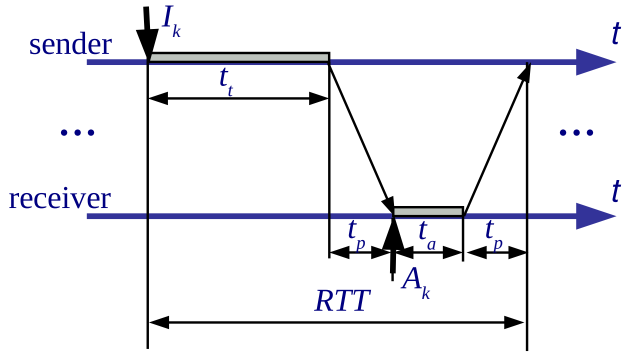



$$E = \frac{v_{ef}}{v_t} = \frac{\#\text{info bits}/T}{1/t_b} = \begin{cases} \dfrac{\#\text{info bits} \times t_b}{T} = \dfrac{\text{time Tx information}}{T} \\ \dfrac{\#\text{info bits}}{T/t_b} = \dfrac{\#\text{info bits}}{\#\text{bits at line bitrate}} \end{cases}$$

# Unit 4. TCP

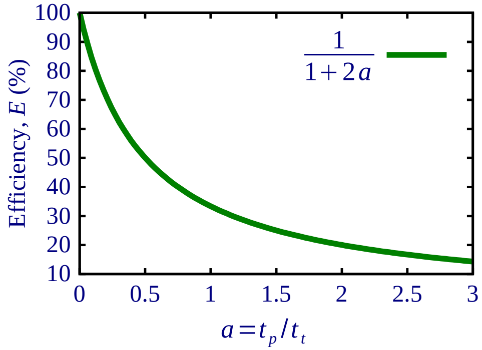
## ARQ Protocols – Stop & Wait efficiency

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




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

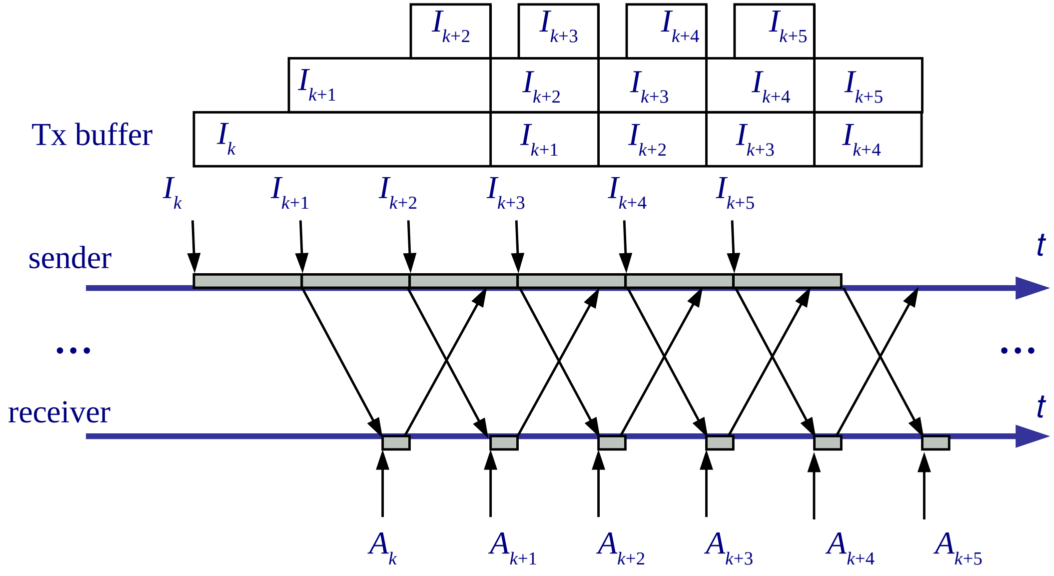
$$\frac{t_t}{t_t + 2t_p} \simeq \frac{1}{1+2a}, \text{ where } a = \frac{t_p}{t_t}$$



# Unit 4. TCP

## ARQ Protocols – Continuous Tx Protocols

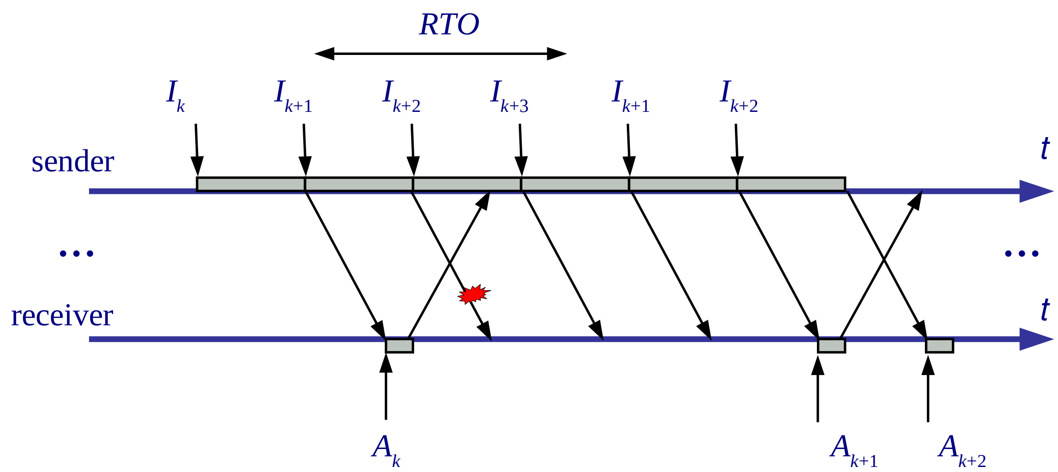
- Goal: Allow high efficiency independently of propagation delay.
- Without errors: $E$ = 100 %



# Unit 4. TCP

## ARQ Protocols – Go Back N

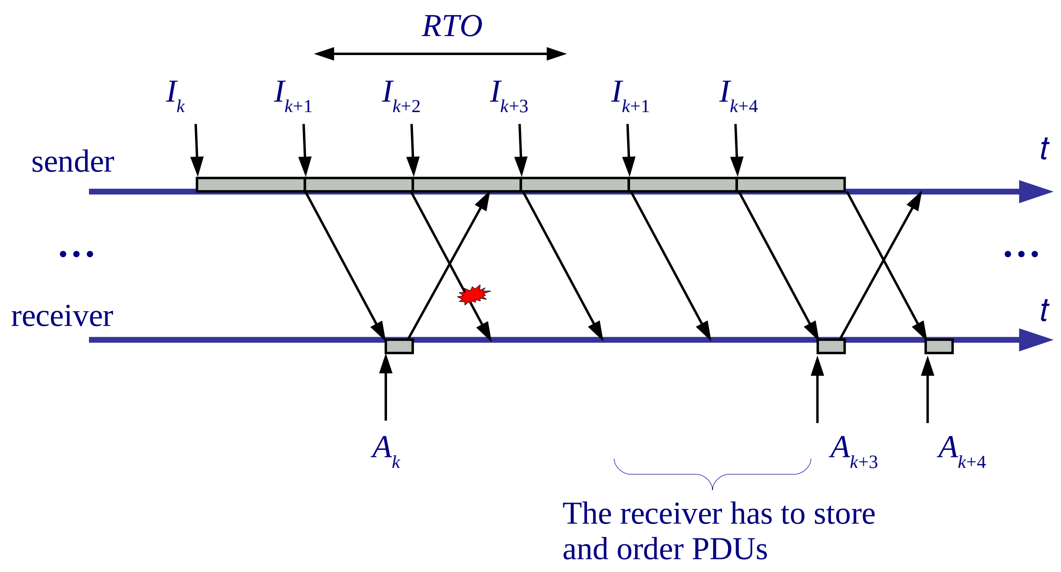
- Cumulative acks: $A_k$ confirm $I_i$, $i \le k$
- If the sender receives an error or out of order PDU: Do not send acks, discards all PDU until the expected PDU arrives. Thus, the receiver does not store out of order PDUs.
- When a retransmission timeout RTO occurs, the sender *go back* and starts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



# Unit 4. TCP

## ARQ Protocols – Selective ReTx.

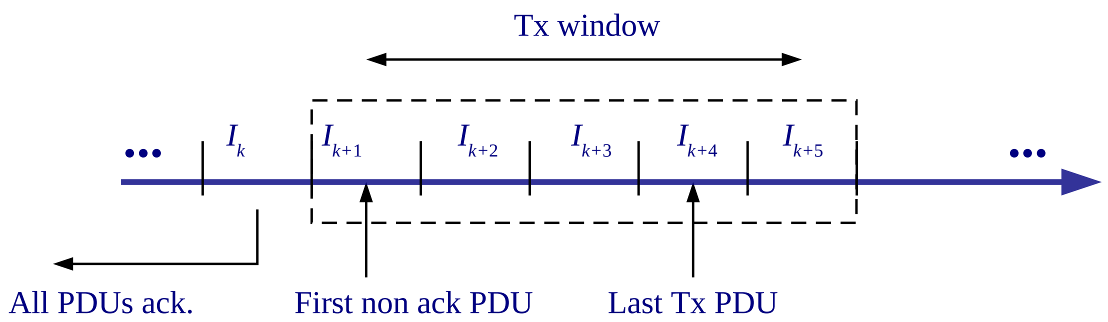
- The same as Go Back N, but:
  - The sender only ReTx a PDU when a RTO occurs.
  - The receiver stores out of order PDUs, and ack all stored PDUs when missing PDUs arrive.



# Unit 4. TCP

## ARQ Protocols – Flow Control and Window Protocols

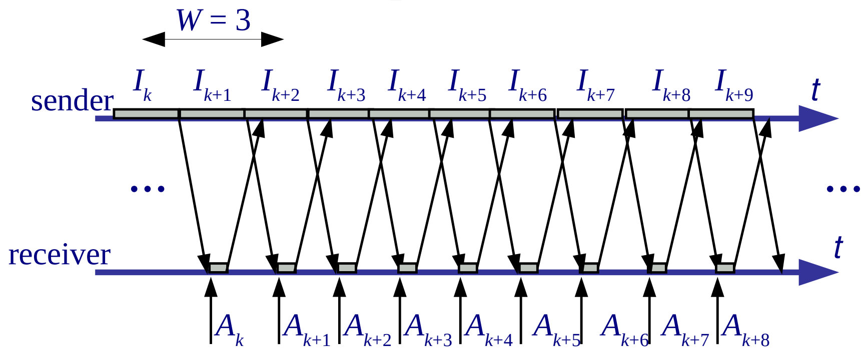
- ARQ are also used for flow control. Flow control consists on avoiding the sender to Tx at higher PDU rate than can be consumed by the receiver.
- With Stop & Wait, if the receiver is slower, acks are delayed and the sender reduces the throughput.
- With continuous Tx protocols: A *Tx window* is used. 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.



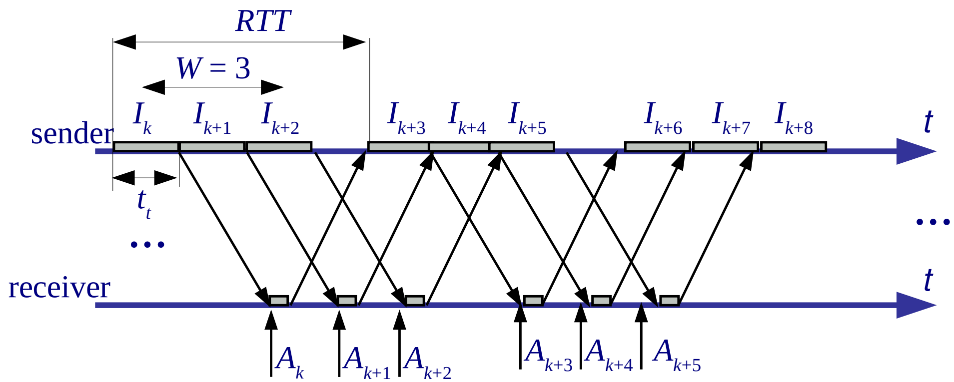
# Unit 4. TCP

## 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:

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

# Unit 4. TCP

## Outline

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

# Unit 4. TCP

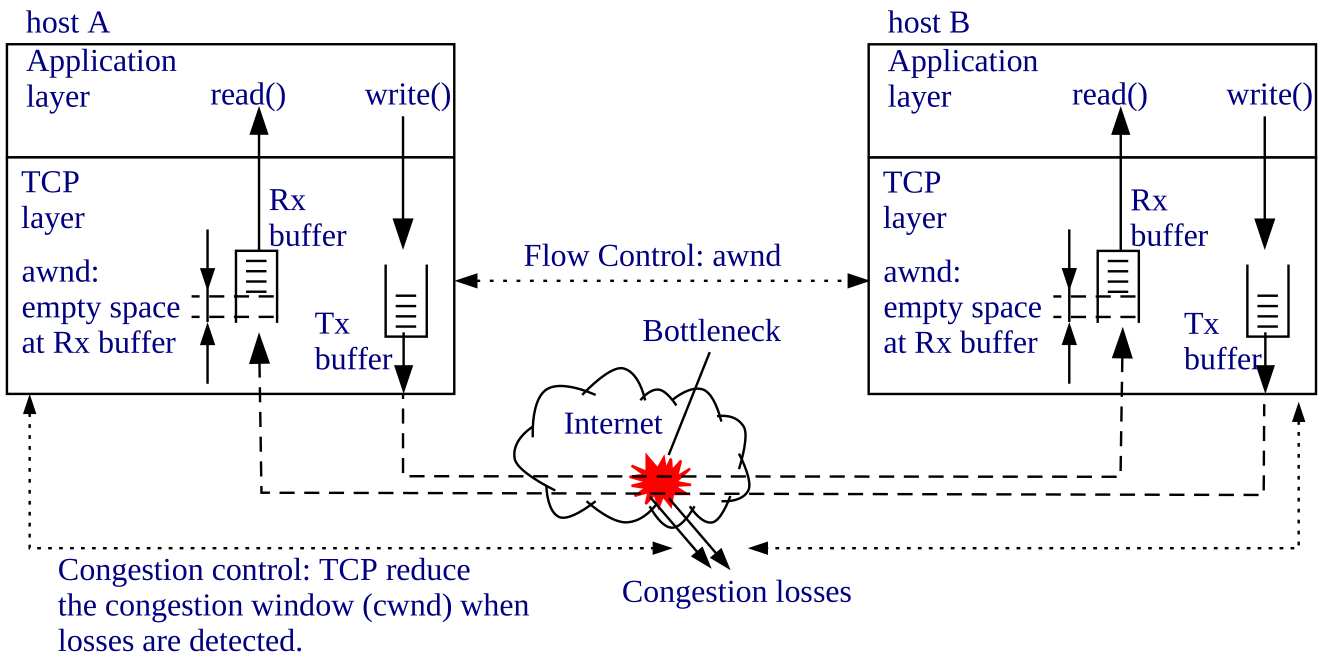
## TCP Protocol – Description (RFC 793)

- 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 4. 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 4. TCP

## TCP Protocol – Delayed acks

- TCP connections can be classified as:
  - Bulk: (e.g. web, ftp) There are always bytes to send. TCP send MSS bytes.
  - Interactive: (eg. telnet, ssh) The user interacts with the remote host.
- In bulk connections sending an ack every data segment can unnecessarily send too many small segments. Solution: Delayed acks.

Delayed ack. It is used to reduce the amount of acks. Consists of sending 1 ack each 2 MSS segments, or 200 ms. Acks are always sent in case of receiving out of order segments.

tcpdump example (bulk transfer):

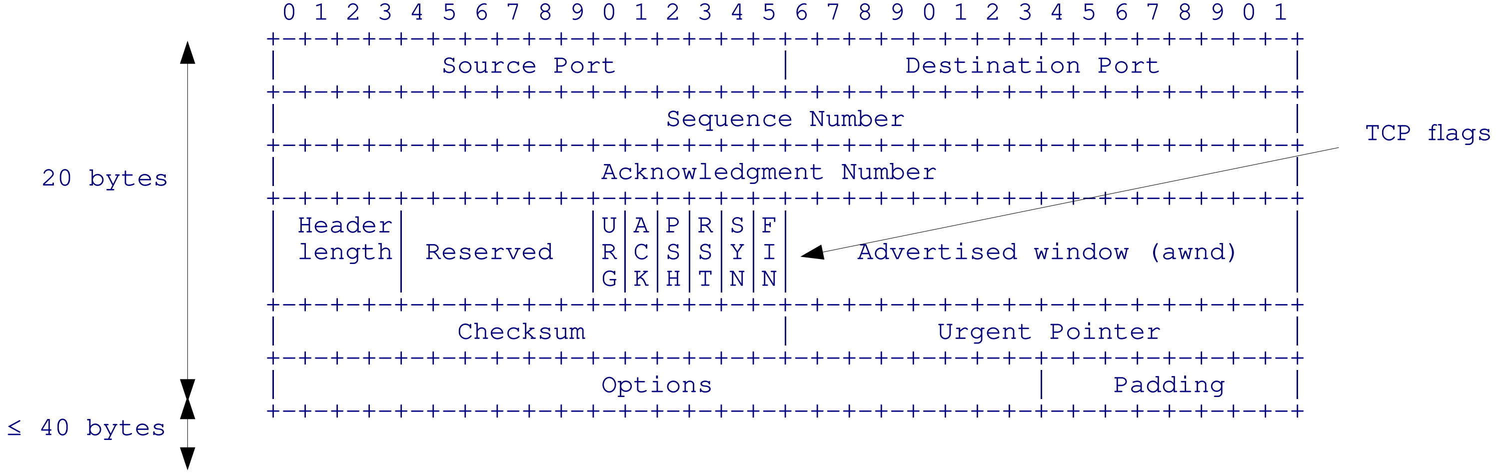
```
...
11:27:13.798849 147.83.32.14.ftp > 147.83.35.18.3020: P 9641:11089(1448) ack 1 win 10136 (DF)
11:27:13.800174 147.83.32.14.ftp > 147.83.35.18.3020: P 11089:12537(1448) ack 1 win 10136 (DF)
11:27:13.800191 147.83.35.18.3020 > 147.83.32.14.ftp: . 1:1(0) ack 12537 win 31856 (DF)
11:27:13.801405 147.83.32.14.ftp > 147.83.35.18.3020: P 12537:13985(1448) ack 1 win 10136 (DF)
11:27:13.802771 147.83.32.14.ftp > 147.83.35.18.3020: P 13985:15433(1448) ack 1 win 10136 (DF)
11:27:13.802788 147.83.35.18.3020 > 147.83.32.14.ftp: . 1:1(0) ack 15433 win 31856 (DF)
...
```

| timestamp | src IP addr/port | | dst IP addr/port | TCP flags | seq. num:next seq num (bytes) | ack | awnd | DF flag in IP header set. |
|---|---|---|---|---|---|---|---|---|
| 11:27:13.798849 | 147.83.32.14.ftp | > | 147.83.35.18.3020: | P | 9641:11089(1448) | ack 1 | win 10136 | (DF) |

# Unit 4. TCP

## TCP Protocol – TCP Header

- Variable size: Fixed fields of 20 bytes + options (15x4 = 60 bytes max.).
- Like UDP, the checksum is computed using the header and the payload.



# Unit 4. 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 4. 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 4. TCP

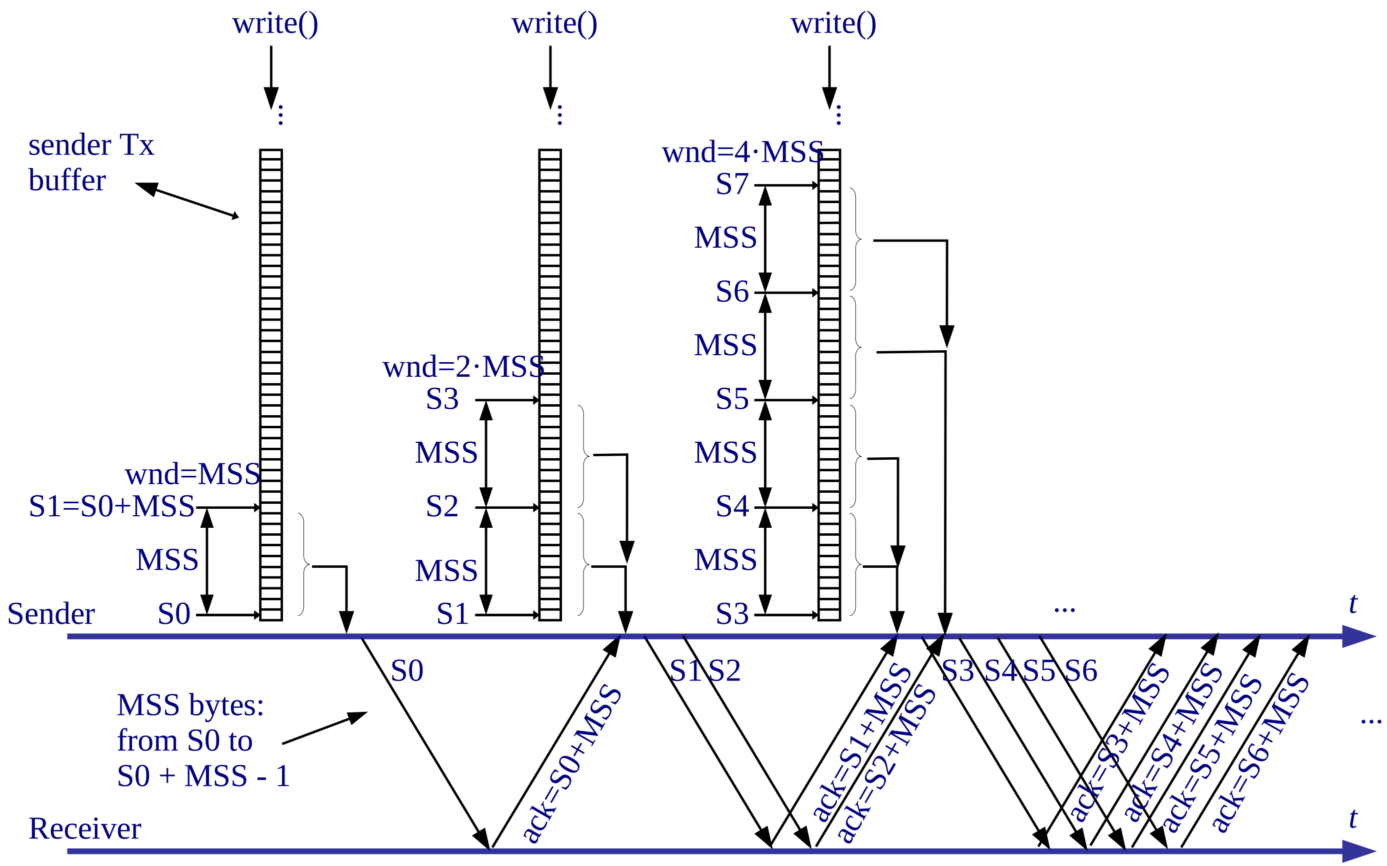
## TCP Protocol – TCP Options

- 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 4. TCP

## TCP Protocol – TCP Sequence Numbers

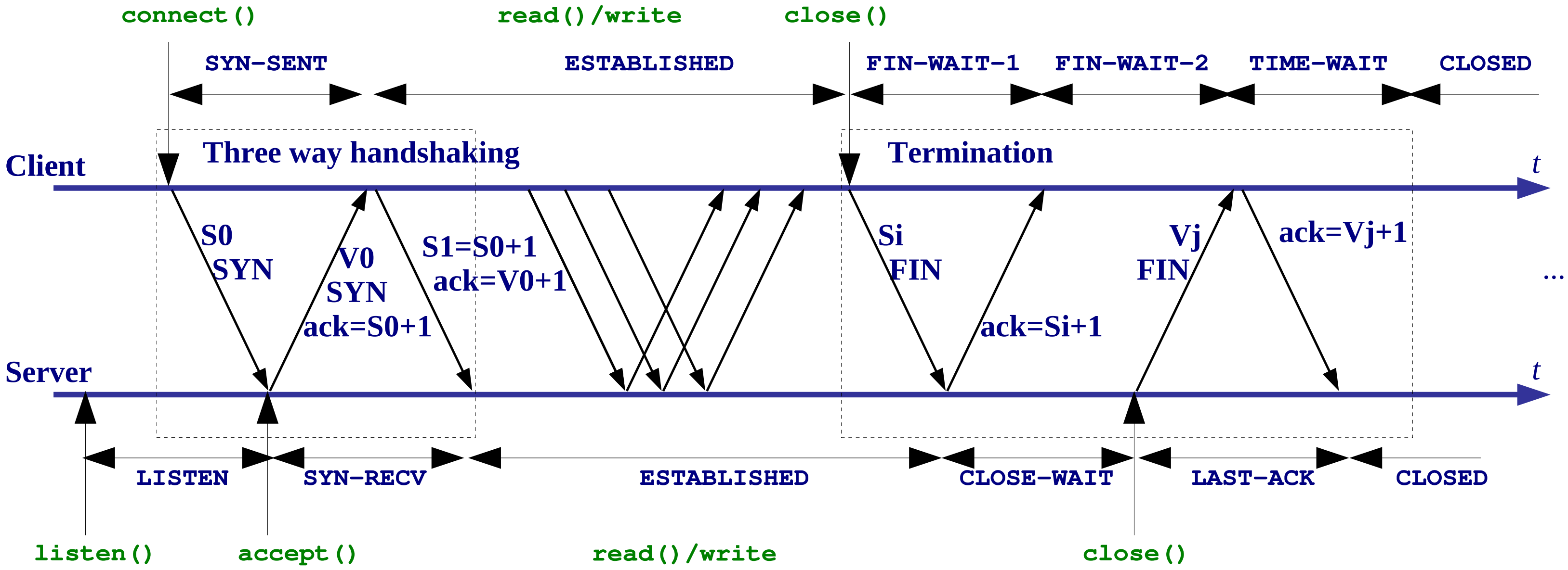
- The sequence number identifies the first payload byte.
- The ack number identifies the next byte the receiver is waiting for.



# Unit 4. 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 4. TCP

## TCP Protocol – tcpdump example (web page download)

TWH

```
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>
```

Termination

```
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

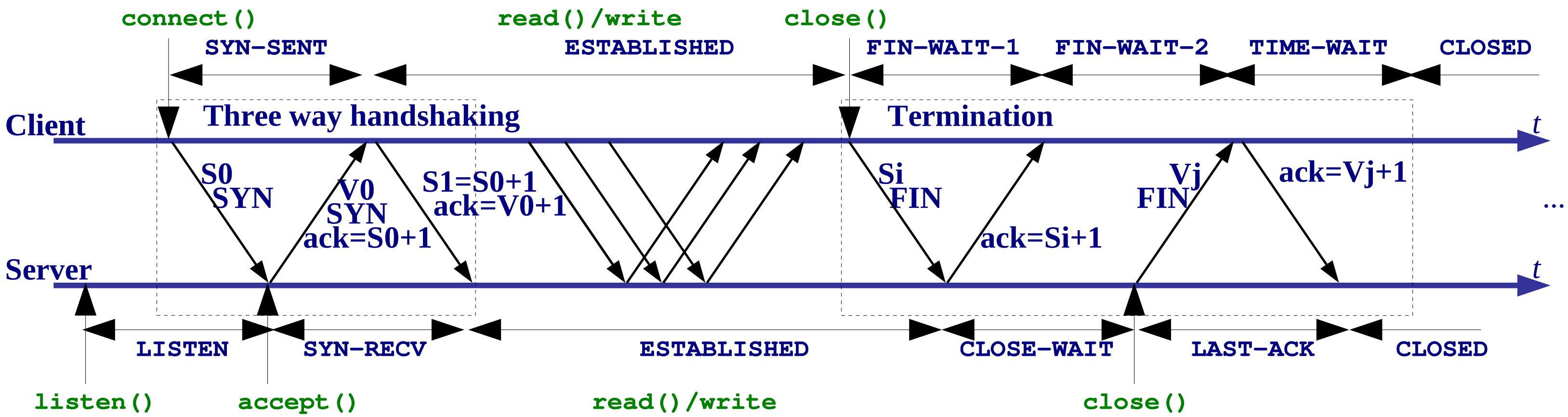
```
12:30:37.069541 IP 147.83.34.125.17788 > 147.83.32.82.80: S 3473661146:3473661146(0) win 5840
          <mss 1460,sackOK,timestamp 296476754 0,nop,wscale 7>
```

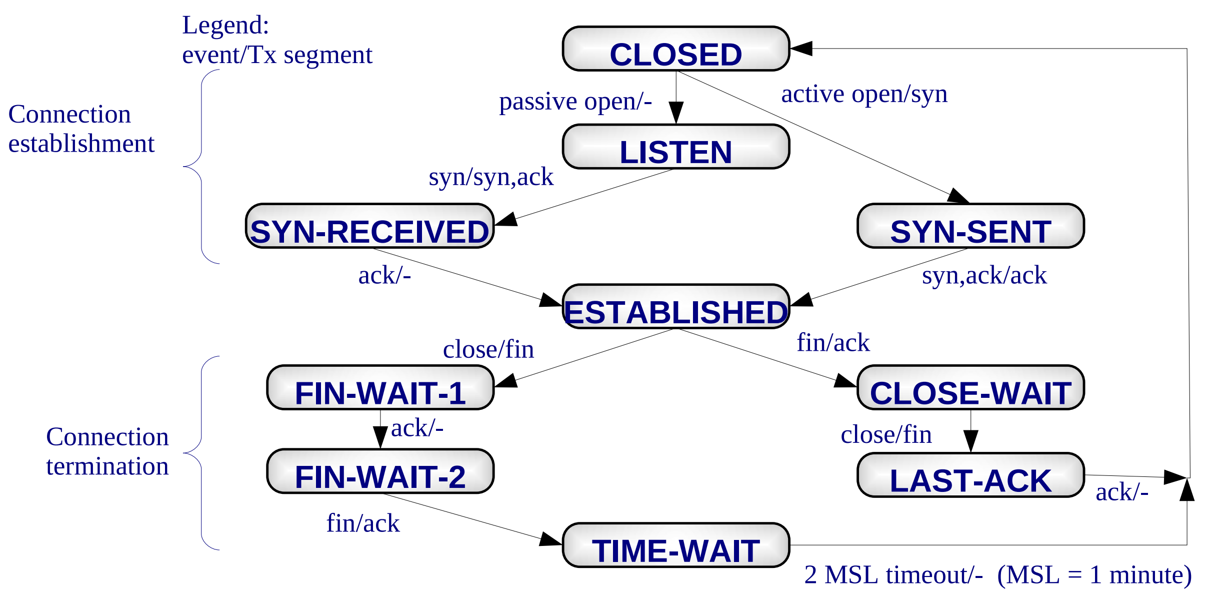
MSS — SACK — timestamp — window scale

padding

# Unit 4. TCP

## TCP Protocol – State diagram (simplified)



# Unit 4. 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
```

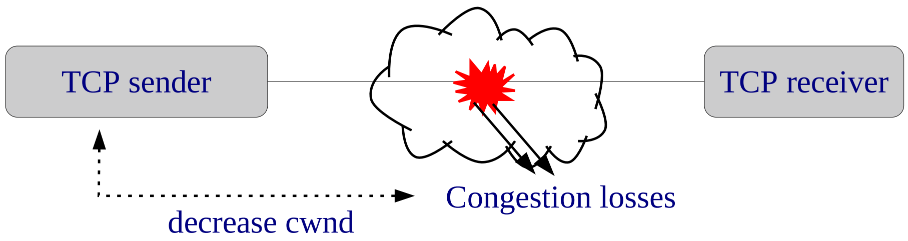
man netstat:

- Send-Q: The count of bytes not acknowledged by the remote host.
- Recv-Q: The count of bytes not copied by the user program connected to this socket.

# Unit 4. 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 4. TCP

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

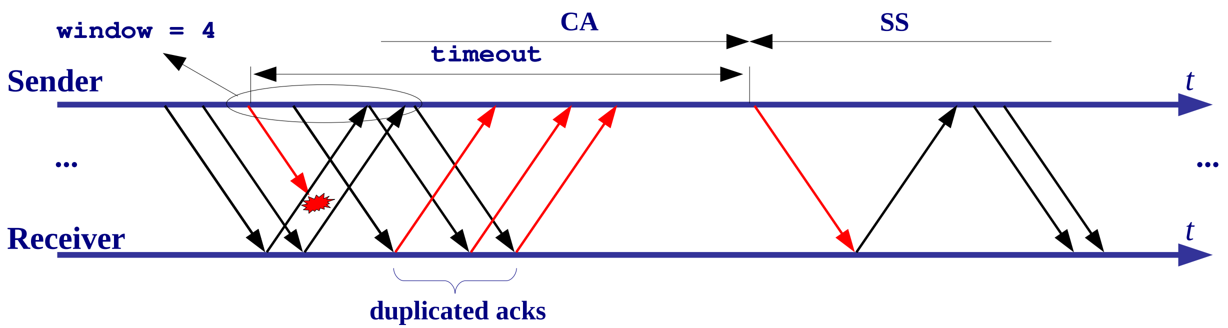
- Variables:
  - snd_una: First non ack segment (head of the TCP transmission queue).
  - ssthresh: Threshold between SS and CA.

```
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 4. TCP

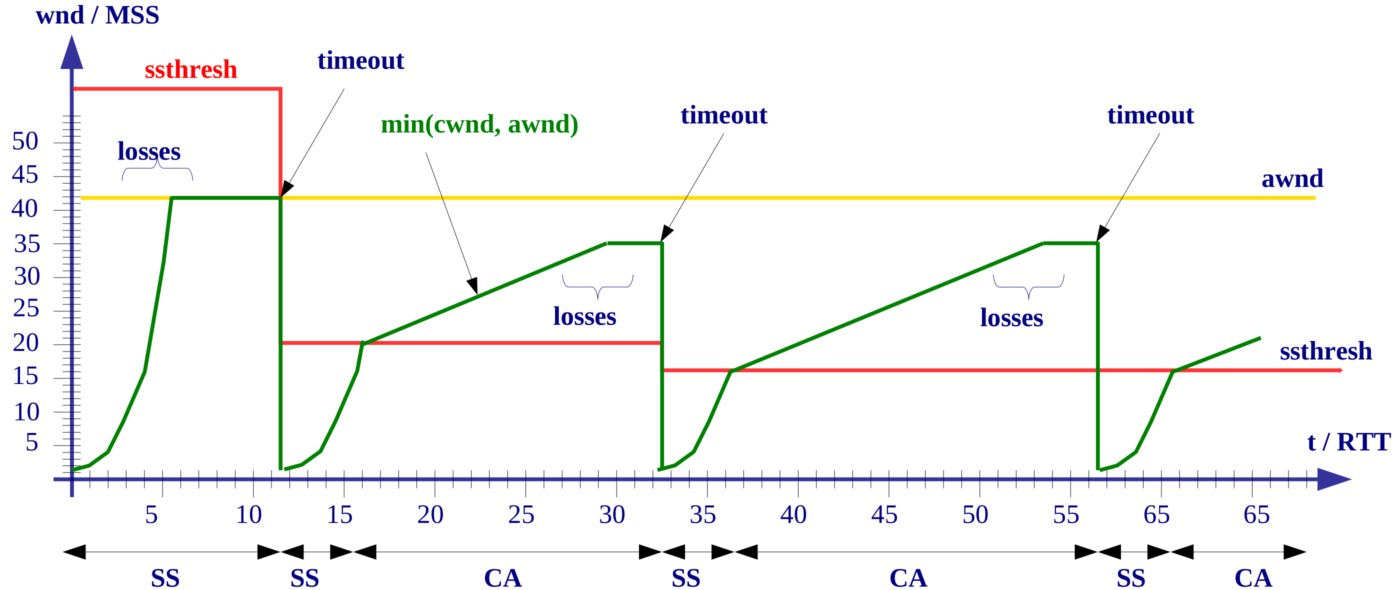
## TCP Protocol – Slow Start / Congestion Avoidance (SS/CA)

- 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 ;
```

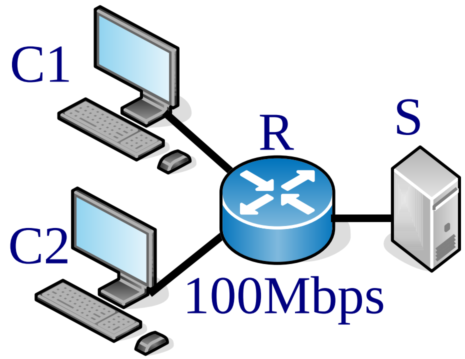


# Unit 4. TCP

## 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



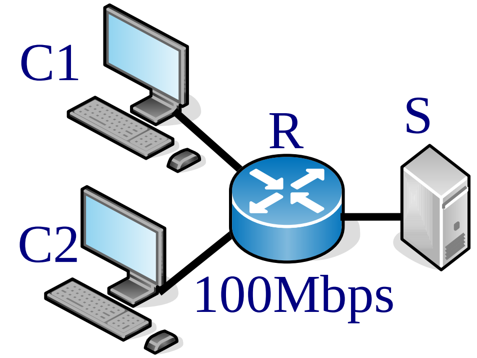
# Unit 4. TCP

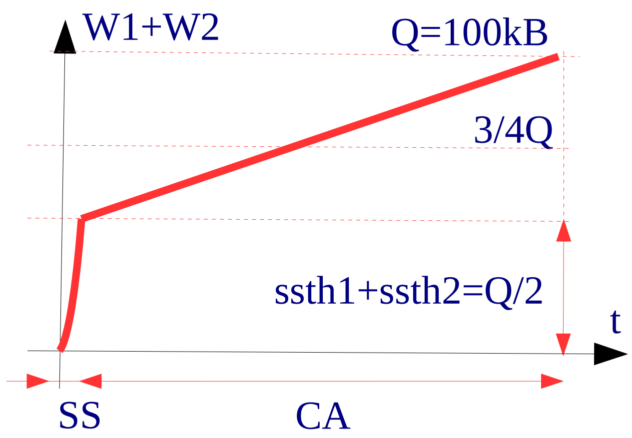
## TCP Protocol – Evaluation with losses

- 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:
    - $\overline{RTT}$=75 kB/100 Mbps = 6 ms
  - Note that the average window of each connection will be:

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



# Unit 4. 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.

# Unit 4. TCP

## TCP Protocol – Retransmission time-out (RTO)