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Data Link Layer

Introduction
Synchronization
Error Detection
Flow Control
Error Control (via Retransmission)

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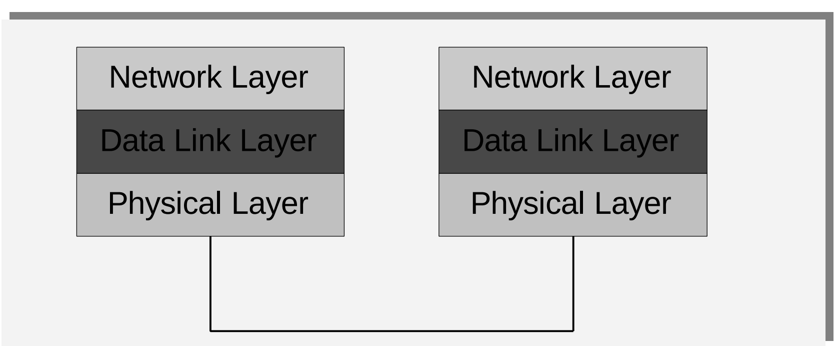
Introduction

Main Task of the data link layer:

- Provide error-free transmission over a link



Introduction

- The PDU at the Data Link Layer (DL-PDU) is typically called a Frame. A Frame has a header, a data field, and a trailer
- Example

01111110 8bits	Address 8bits	Control 8bits	Data >=0	Checksum 16bits	01111110 8bits
Header				Trailer	

Framing

- Problem: Identify the beginning and the end of a frame in a bit stream
- Solution (bit-oriented Framing): A special bit pattern (flag) signals the beginning and the end of a frame (e.g., "01111110")

01111110	Data	01111110

- Problem:
  - The sequence '01111110' must not appear in the data of the frame

Bit-Oriented Framing and Bit Stuffing

- 'Bit stuffing': If the sender detects five consecutive '1' it adds a '0' bit into the bit stream. The receiver removes the '0' from each occurrence of the sequence '111110'

Original bit sequence: 0110111111111111111100

After stuffing bits at sender: 011011111 0 11111 0 11111 0 100

Stuffed bits

After stuffing bits are removed by receiver: 0110111111111111111100

- Note: The flags itself are not bit-stuffed.

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Error Control

Two basic approaches to handle bit errors:

- Error-correcting codes
  - Used if retransmission of the data is not possible
  - Data are encoded with sufficient redundancy to correct bit errors
  - **Examples**: Hamming Codes, Reed Solomon Codes, etc.

- Error-detecting codes plus retransmission
  - Used if retransmission of corrupted data is feasible
  - Receiver detects error and requests retransmission of a frame.

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Error Detection Techniques

- Error Detection Techniques:
  - Parity Checks
  - Cyclic Redundancy Check

Parity Checks

General Method:

- Append a parity bit to the end of each character in a frame such that the total number of '1' in a character is:
  - even (even parity) or
  - odd (odd parity)

- **Example:** With ASCII code, a parity bit can be attached to an 7-bit character
  - ASCII "G" = **1 1 1 0 0 0 1**
  - with even parity =
  - with odd parity =

Cyclic-Redundancy Codes (CRC)

General Method:

- The transmitter generates an **n-bit check sequence number** from a given **k-bit frame** such that the resulting (k+n)-bit frame is divisible by some number
- The receiver divides the incoming frame by the same number
- If the result of the division does not leave a remainder, the receiver assumes that there was no error

Cyclic-Redundancy Codes (CRC)

- CRC is used by all advanced data link protocols, for the following reasons:
  - Powerful error detection capability
  - CRC can be efficiently implemented in hardware
- We discuss the CRC method in five easy steps:
  1. **Prerequisites**
  2. **CRC Encoding Method**
  3. **Example**
  4. **Error Detection with CRC**
  5. **Capabilities of CRC**

Step 1: Prerequisites

- Modulo-2 Arithmetic:

+	1	0
1	0	0
0	1	0

*	1	0
1	1	0
0	0	0

- Examples of polynomials based on Modulo-2 operations:
  1. $(x+1)(x+1) =$
  2. $(x^2+1)(x^3+x+1) =$
  3. If $F(x)$ contains $(x+1)$ as a factor, then $F(1) = 0$

Step 2: CRC Encoding Method

- Let us view each block of data as a polynomial with binary coefficients:

  1 0 1 1 0 1 is viewed as $x^5 + x^3 + x^2 + 1$

Define:

- M(x) Data block is a polynomial (= Message, Frame)
- P(x) "Generator Polynomial" which is known to both sender and receiver (degree of P(x) is n)

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Step 2: CRC Encoding Method

(I) Append n zeros to M(x), i.e., $M(x)\,x^n$

(II) Divide $M(x)\,x^n$ by P(x) and obtain:

$$M(x)\,x^n = Q(x)\,P(x) + R(x)$$

(III) Set $T(x) = M(x)\,x^n + R(x)$. T(x) is the encoded message

Note: T(x) is divisible by P(x). Therefore, if the received message does not contain an error then it can be divided by P(x).

- **Exercise:** Encode the frame **1 1 0 1 0 1 1 0 1 1**

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Step 3: Encoding

$M(x) = x^9 + x^8 + x^6 + x^4 + x^3 + x + 1$

- Generator polynomial is $P(x) = x^4 + x + 1$
- Degree of P(x) is 4

(I) $M(x)\,x^4 = x^{13} + x^{12} + x^{10} + x^8 + x^7 + x^5 + x^4$

(II) $M(x)\,x^4 = Q(x)\,P(x) + R(x)$
$=(x^9 + x^8 + x^3 + x)\,P(x) + x^3 + x^2 + x$

(III) $T(x) = M(x)\,x^4 + R(x)$
$= x^{13} + x^{12} + x^{10} + x^8 + x^7 + x^5 + X^4 + x^3 + x^2 + x$

Transmitted Bit Sequence: **1 1 0 1 0 1 1 0 1 1** 1 1 1 0

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Step 4: Error Detection with CRC

- Errors can be expressed as Error Polynomials
- For example,

Sent Message:	**1 0 1 1 1 0 1**
Received Message:	**1 1 1 1 0 0 1**
Error:	**0 1 0 0 1 0 0**

- In the example, the Error Polynomial E(x) is given by:

$$\mathbf{E(x) = x^{5} + x^{2}}$$

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Step 5: Error Detection Capability of CRC

Note:

- Errors will not be detected by CRC if

  E(x) / P (x) = B (x) + 0,

  i.e., E(x) contains P(x) as a factor

- Observe the following trade-off:
  - Large values of n introduce a lot of overhead, but improve the error detection capability.

Step 5: Error Detection Capability of CRC

- All single-bit errors are detected, if P(x) has a factor with at least 2 terms:

  $E(x) = x^i$

  If $P(x) = (x+1)P'(x)$, then x^i cannot contain $(x+1)$
- All double-bit errors are detected if P(x) has a factor with at least 3 terms

  $E(x) = x^i + x^j = x^j (x^k+1)$ (for $k = i-j$, $j<i$)

- If P(x) does not divide $(x^k + 1)$ for any k up to the max. frame length then all double errors can be detected.

  $P(x)= x^{15}+ x^{14} +1$ will not divide $E(x)= x^k + 1$ for any $k \leq 32{,}768$

Step 5: Error Detection Capability of CRC

- If P(x) contains (x+1) as a factor then all errors with "odd" number of bits are detected.
  - CRC detects 50% of all errors

- A CRC with n check bits will detect all burst errors of length ≤ n bits.

  Burst Error of Length k: $E(x)=x^i(x^{k-1}+ .... +1)$

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Additional Facts on CRC

- CRC can be efficiently implemented in hardware by a set of XOR gates and a shift register
- The following generator polynomials are widely used:

CRC-12: **P(x) =** $x^{12} + x^{11} + x^3 + x^2 + x + 1$

CRC-16: **P(x) =** $x^{16} + x^{15} + x^2 + 1$

CRC-CCITT: **P(x) =** $x^{16} + x^{12} + x^5 + 1$

CRC-32: P(x) = $x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$

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Flow Control

- Flow Control is a technique for speed-matching of transmitter and receiver. Flow control ensures that a transmitting station does not overflow a receiving station with data
- We will discuss two protocols for flow control:
  - **Stop-and-Wait Protocol**
  - **Sliding Window Protocol**
- For the time being, we assume that we have a perfect channel between sender and receiver (**no errors)**

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Stop-and-Wait Flow Control

- Simplest form of flow control
- In Stop-and-Wait flow control, the receiver indicates its readiness to receive data for each frame
- **Operations:**

    1. **Sender:** Transmit a single frame

    2. **Receiver:** Transmit acknowledgment (ACK)

    3. Goto 1.

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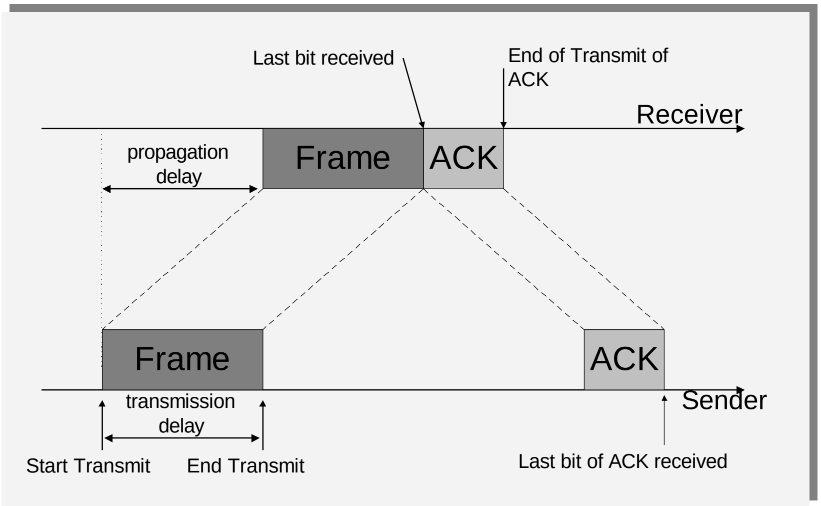
Analysis of Stop-and-Wait



Analysis of Stop-and-Wait

- **Transmission delay** is the time that the sender needs to transmit a frame
- Transmission delay is dependent on the size of a frame and the maximum data rate

Example:

Frame Size = 1000 bit
Data rate of network = 1 Mbps

Transmission delay = 1000 bit / 1 Mbps = 1 msec

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Analysis of Stop-and-Wait

- **Propagation delay** is the time that a transmitted bit needs to travel from sender to the receiver
- Propagation delay is only dependent on the speed of the transmission medium and the distance between sender and receiver.

  Speed of light: 300,000 km/sec,
  Speed in guided media (approx.): 200,000 km/sec

Example:

Distance = 1000 km
Propagation delay = 1000 km / (200,000 km/sec)
= 5 msec

Analysis of Stop-and-Wait

- **Notation**:

C	= Channel capacity in bps
I	= Propagation delay
H	= Number of bits in a frame header
D	= Number of data bits in a frame
F	= Total length of a frame (F= D+H)
A	= Total length of an ACK frame
F/C	= Transmission delay for a frame

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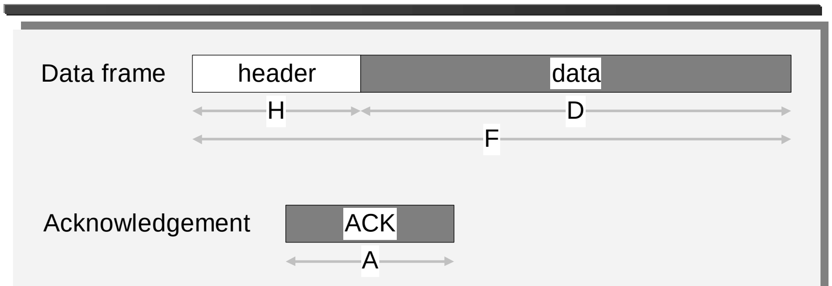
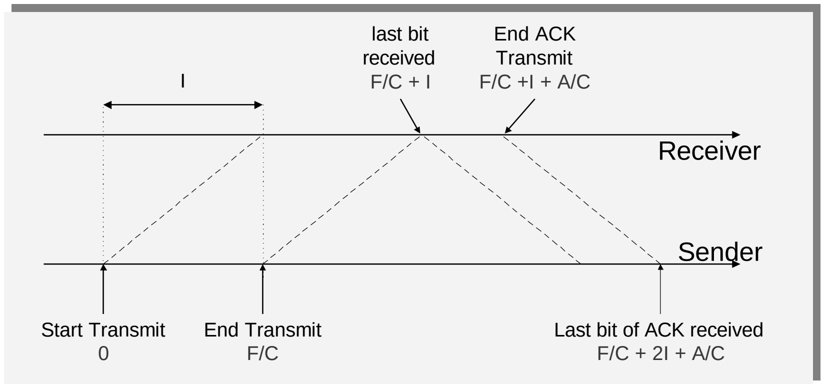
Analysis of Stop-and-Wait



$$a = \frac{propagation \quad delay}{transmission \quad delay} = \frac{I}{F/C}$$

Analysis of Stop-and-Wait

- Transmission of a frame (in Stop-and-Wait):



Analysis of Stop-and-Wait

- **Efficiency** of a protocol is the maximum fraction of time when the protocol is transmitting data
- Efficiency of Stop-and-Wait Flow Control:

$$efficiency = \frac{D/C}{F/C + A/C + 2I} = \frac{D}{F + A + 2IC}$$

- Assuming that H and A are negligible we obtain:

$$normalized\ efficiency = \frac{D}{D + 2IC} = \frac{1}{1 + 2a}$$

Exercise 1

Satellite Link

- Roundtrip propagation delay is 270 ms
- Data rate is 56 kbps
- Frame length is 4,000 bits (including header)
- Lengths of ACK frames are negligible

- What is the value of “a”?
- What is the efficiency of the satellite link if Stop-and-Wait is used?

Exercise 2

Local Area Network (LAN)

- Data rate is 10 (100) Mbps
- Propagation rate is 200,000 km/sec
- Length of the LAN is 10 km
- Frame size is 500 bits (including header)
- Length of ACK frames are negligible

- What are the values of “a” for the 10 and 100 Mbps LANs?
- How efficient are these LANs?
- What is the minimum frame size in the LANs to reach an efficiency of at least 80%?

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Sliding Window Flow Control

- **Major Drawback of Stop-and-Wait Flow Control:**
  - Only one frame can be in transmission at a time
  - This leads to inefficiency if a>1

- **Sliding Window Flow Control**
  - Allows transmission of multiple frames
  - Assigns each frame a k-bit sequence number
  - Range of sequence number is [0..2^k-1], i.e., frames are counted modulo 2^k

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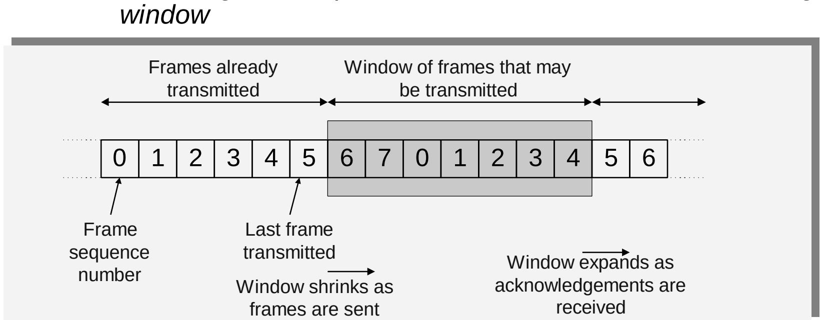
Operation of Sliding Window

- **Sending Window:**
  - At any instant, the sender is permitted to send frames with sequence numbers in a certain range
  - The range of sequence numbers is called the *sending window*



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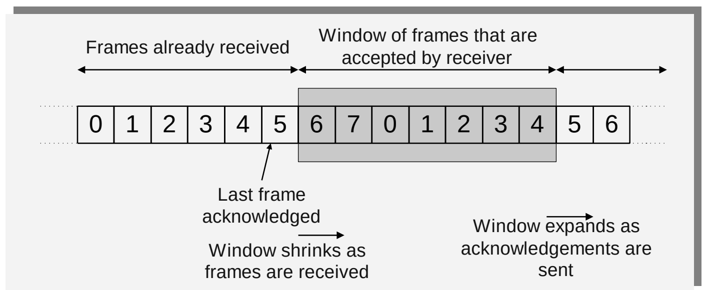
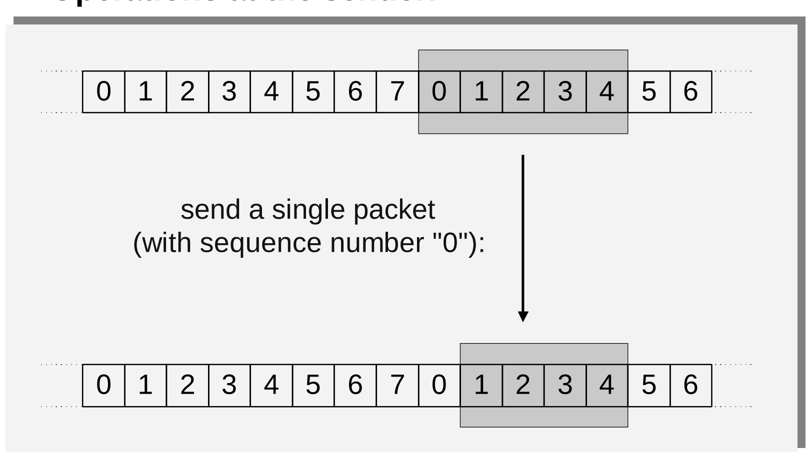
Operation of Sliding Window

- **Receiving Window:**
  - The receiver maintains a *receiving window* corresponding to the sequence numbers of frames that are accepted



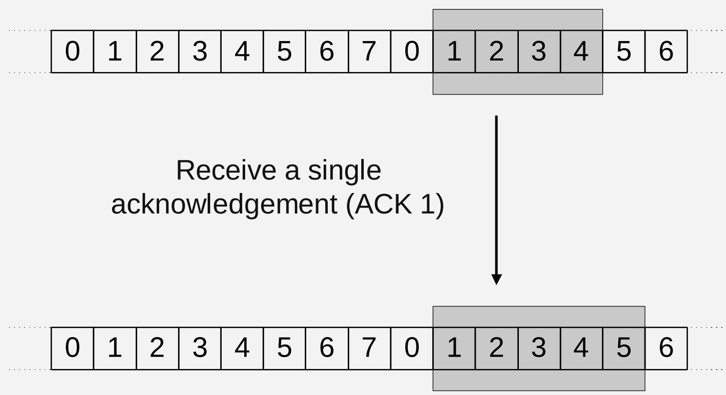
Operation of Sliding Window

- **Operations at the sender:**



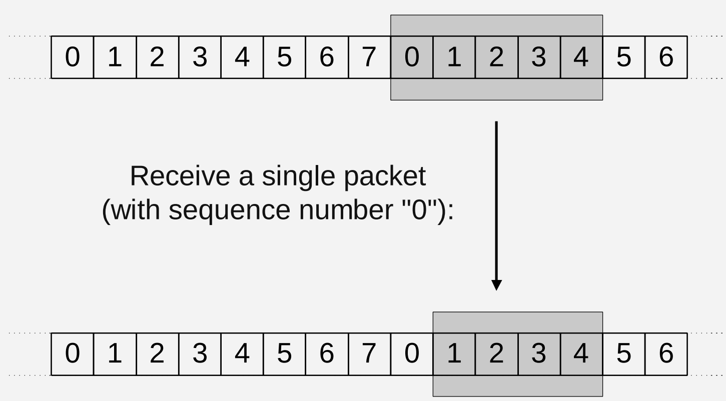
Operation of Sliding Window

- **Operations at the sender:**



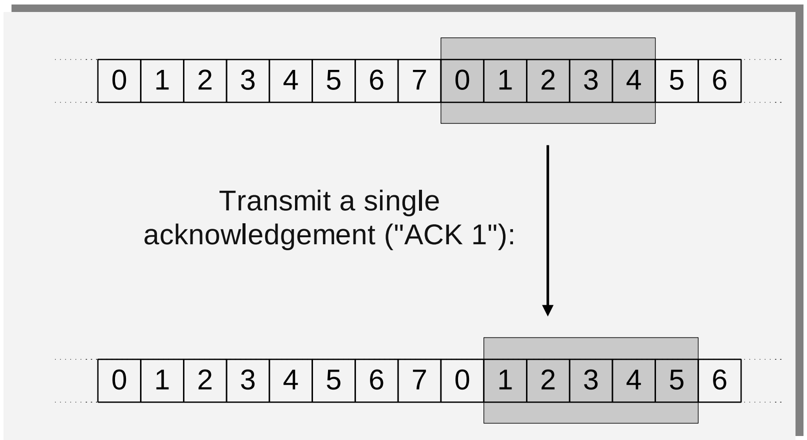
Operation of Sliding Window

- **Operations at the receiver:**



Operation of Sliding Window

- **Operations at the receiver:**



Operation of Sliding Window

- **How is “flow control” achieved?**
  - Receiver can control the size of the sending window
  - By limiting the size of the sending window data flow from sender to receiver can be limited
- **Interpretation of *ACK N* message:**
  - Receiver acknowledges all packets until (but not including) sequence number N

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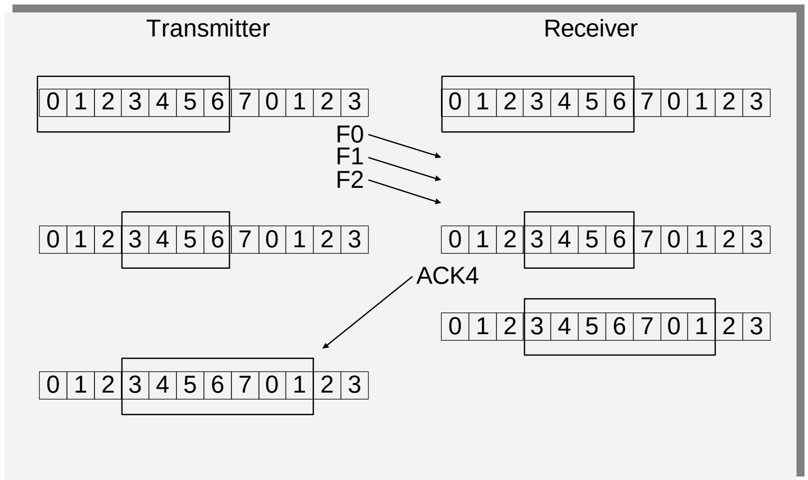
Example



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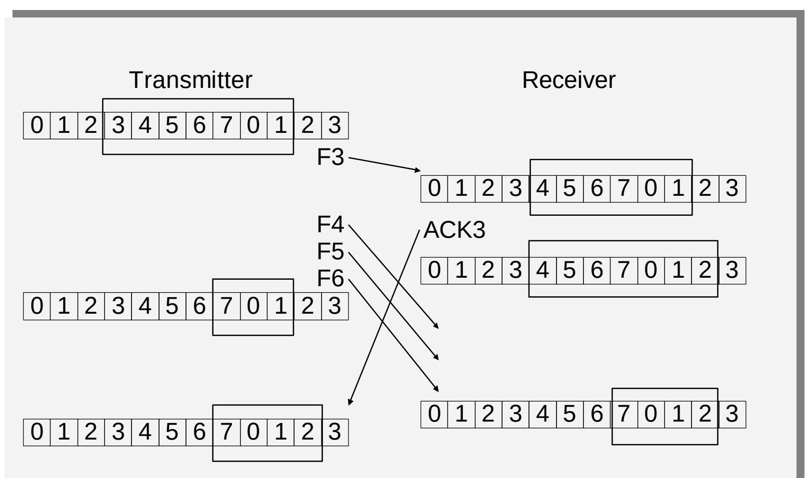
Example Continued



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Analysis of Sliding Windows

- **Define:**
  - We use the same parameters for as in Stop-and-Wait
  - To simplify notation we set:
    F/C = 1
    I = a (Normalization)
  - W = Maximum window size (iddentical for sender and receiver)

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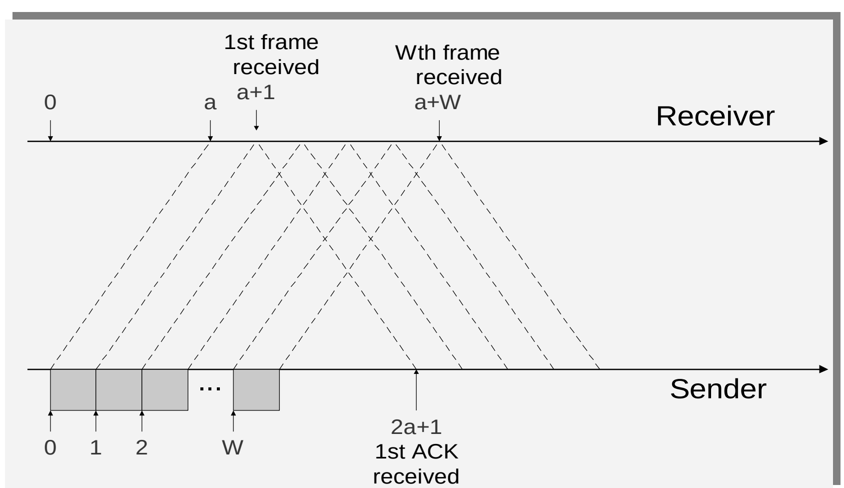
Analysis of Sliding Windows



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Analysis of Sliding Windows

- If the window size is sufficiently large the sender can continuously transmit packets:
- **W** $\geq$ **2a+1**: Sender can transmit continuously

$$normalized\ efficiency = 1$$

- **W** $<$ **2a+1**:Sender can transmit *W* frames every *2a+1* time units

$$normalized\ efficiency = \frac{W}{1+2a}$$

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ARQ Error Control

- **Two types of errors:**
  - Lost frames
  - Damaged Frames
- Most Error Control techniques are based on (1) Error Detection Scheme (e.g., Parity checks, CRC), and (2) Retransmission Scheme
- Error control schemes that involve error detection and retransmission of lost or corrupted frames are referred to as ***Automatic Repeat Request*** (***ARQ***) error control

ARQ Error Control

- All retransmission schemes use all or a subset of the following procedures:
  - Receiver sends an **acknowledgment (ACK**) if a frame is correctly received
  - Receiver sends a **negative acknowledgment (NAK**) if a frame is not correctly received
  - The sender retransmits a packet if an ACK is not received within a **timeout** interval
  - All retransmission schemes (using ACK, NAK or both) rely on the use of timers

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ARQ Error Control

- **Note:** Once retransmission is used, a sequence number is required for every data packet to prevent duplication of packets
- Both **ACK**s and **NAK**s can be sent as special frames, or be attached to data frames going in the opposite direction (**Piggybacking**)

01111110	Address	Control	Data	Checksum	01111110

0	Send Seq.-No.	P/F	Recv Seq.-No.

For piggybacking

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ARQ Schemes

- The most common ARQ retransmission schemes:
  - Stop-and-Wait ARQ
  - Go-Back-N ARQ
  - Selective Repeat ARQ
- The protocol for sending ACKs in all ARQ protocols are based on the sliding window flow control scheme

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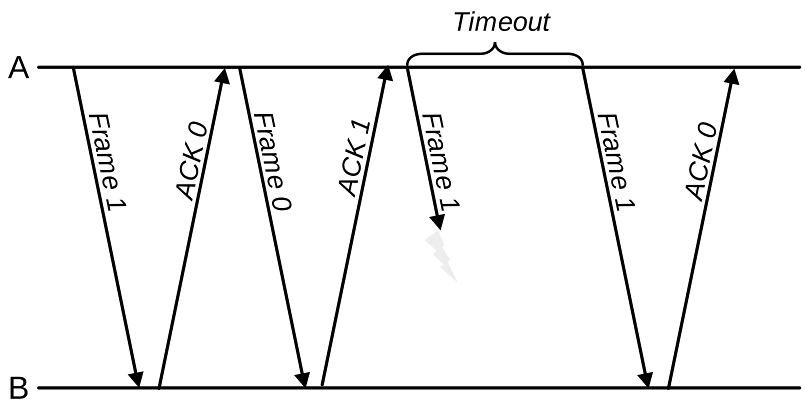
Stop-and-Wait ARQ

- **Stop-and-Wait ARQ** is an addition to the Stop-and-Wait flow control protocol:

- Frames have 1-bit sequence numbers (*SN* = 0 or 1)
- Receiver sends an *ACK (1-SN)* if frame *SN* is correctly received
- Sender waits for an *ACK (1-SN)* before transmitting the next frame with sequence number *1-SN*
- If sender does not receive anything before a timeout value expires, it retransmits frame SN

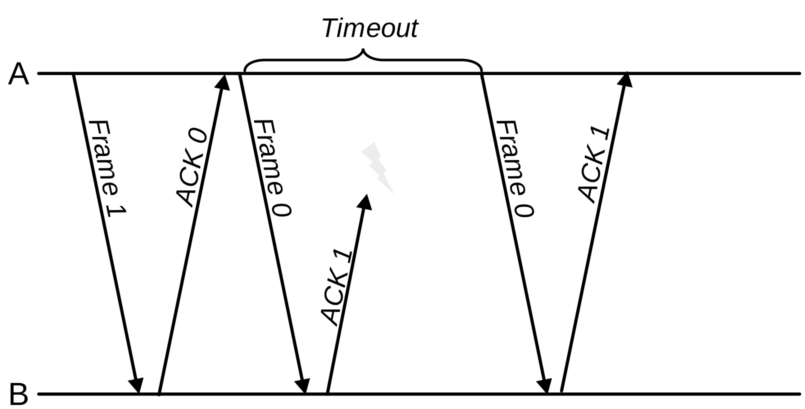
Stop-and-Wait ARQ

- Lost Frame



Stop-and-Wait ARQ

- Lost ACK

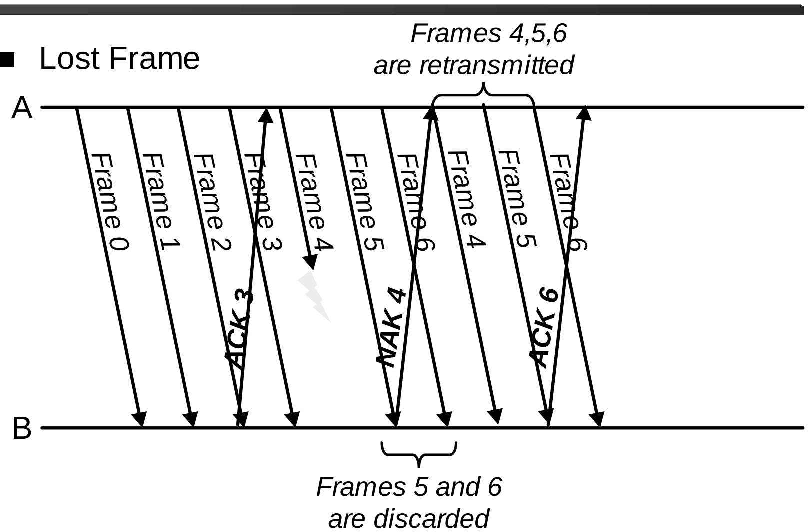


Go-Back-N ARQ

- Go-Back-N uses the sliding window flow control protocol. If no errors occur the operations are identical to Sliding Window
- **Operations:**
  - A station may send multiple frames as allowed by the window size
  - Receiver sends a ***NAK i*** if frame ***i*** is in error. *After that, the receiver discards all incoming frames until the frame in error was correctly retransmitted*
  - *If sender receives a **NAK i** it will retransmit frame **i** and all packets **i+1, i+2,...** which have been sent, but not been acknowledged*

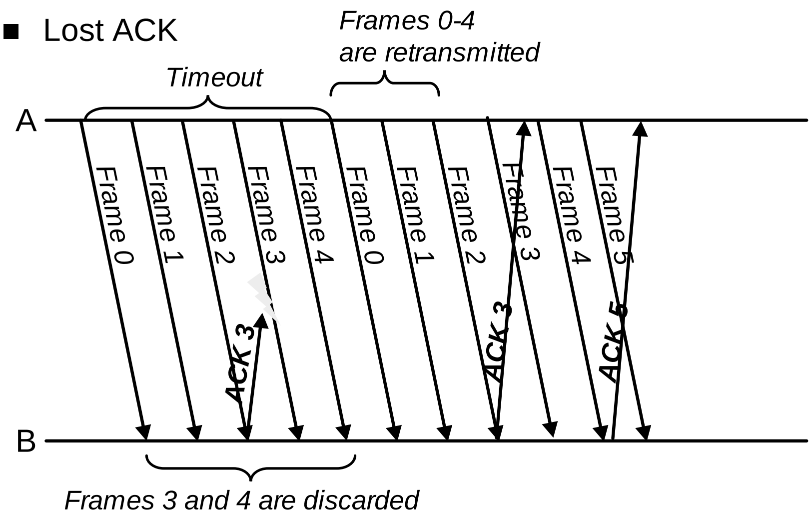
Go-Back-N ARQ

- Lost Frame



Go-Back-N ARQ

- Lost ACK



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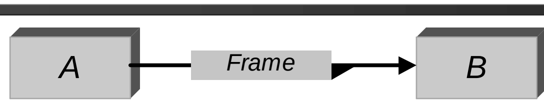
Details Go-Back-N ARQ



- <u>Scenario 1:</u>
  A transmits *frame i*, and B detects error in *frame i,* but has received *frames i-1, i-2,...* correctly

  ➔ B sends **NAK***i*

- <u>Scenario 2:</u>
  Frame i is lost or B does not recognize *frame i*
  Assume that A sends *frame i+1* and B receives it

  ➔ B sends **NAK***i*, or A will timeout and retransmit *frame i* and all subsequent frames

Details Go-Back-N ARQ

<u>Scenario 3:</u> B receives *frame i* and sends **ACK***(i+1)* which is lost

➔ B may send an **ACK(***i+k)* later which also acknowledges all frames <*i+k* (**ACK**s are "cumulative")

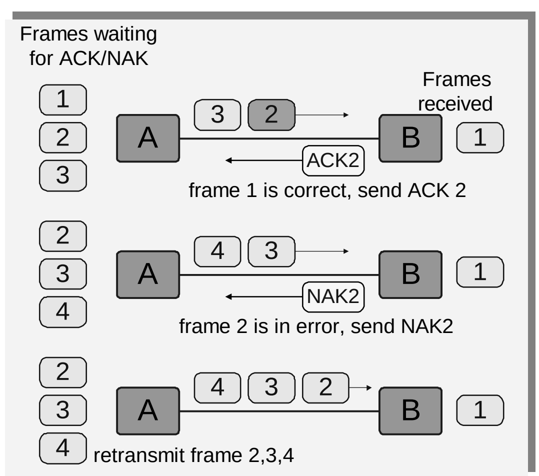
or

A retransmits *frame i* and all subsequent frames

<u>Scenario 4:</u> NAK*i* is lost

➔ A will eventually time out

Example of Go-Back-N ARQ



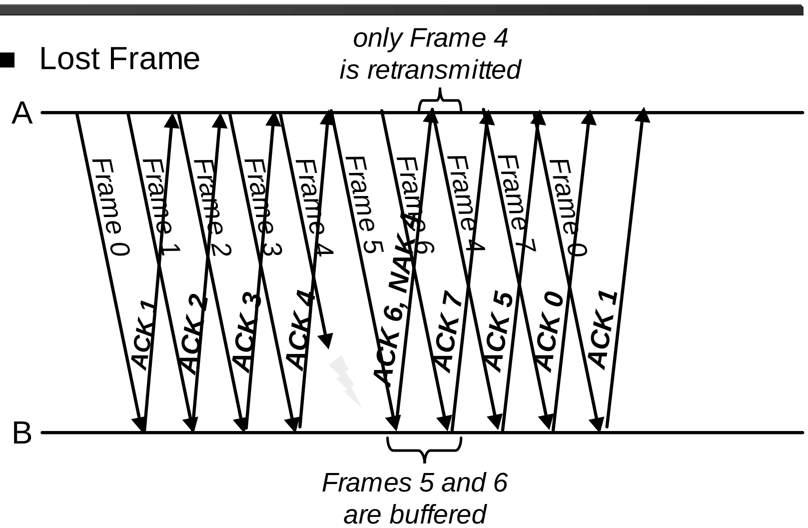
- In Go-back-N, if frames are correctly delivered, they are delivered in the correct sequence
- Therefore, the receiver does not need to keep track of `holes' in the sequence of delivered frames

Selective-Repeat ARQ

- Similar to Go-Back-N ARQ. However, the sender only retransmits frames for which a **NAK** is received
- **Advantage over Go-Back-N:**
  - Fewer Retransmissions.
- **Disadvantages:**
  - More complexity at sender and receiver
  - Each frame must be acknowledged individually (no cumulative acknowledgements)
  - Receiver may receive frames out of sequence

Selective-Repeat ARQ

- Lost Frame



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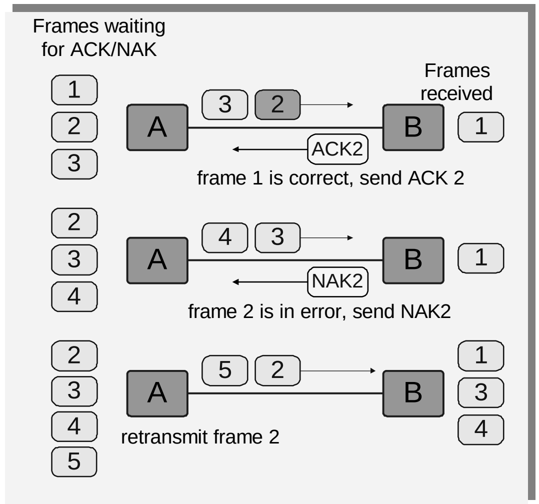
Example of Selective-Repeat ARQ



- Receiver must keep track of `holes' in the sequence of delivered frames
- Sender must maintain one timer per outstanding packet

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Analysis of ARQ Protocols

- **What is the efficiency of the discussed ARQ protocols?**
- A number of assumptions:
  - **ACK**s and **NAK**s are never lost, and frames are not dropped.
  - Sizes of **ACK**s, **NAK**s, and frame headers are negligible.

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Analysis of Stop-and-Wait ARQ

- **Parameters:**

  U= efficiency
  T_t= F/C   transmission delay of a frame
  I= propagation delay
  a= I/T_t
  P = Probability that a frame is in error

- Without Errors (P=0):

$$U = \frac{T_t}{T_t + 2I}$$

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Analysis of Stop-and-Wait ARQ

- With Errors:
- Probability that k transmission attempts are needed to successfully transmit a frame

$$\text{P[k attempts needed]} = P^{k-1} \cdot (1\text{-}P)$$

- Expected number of attempts (=E[A]):

$$E[A] = \sum_{i=1}^{\infty} i\, P^{i-1} \times (1-P) = \frac{1}{1-P}$$

- Expected efficiency with errors

$$U = \frac{T_t}{E[A] \cdot (T_t + 2I)} = \frac{(1-P) \cdot T_t}{T_t + 2I} = \frac{1-P}{1+2a}$$

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Analysis of Go-Back-N ARQ

Without Errors	With Errors
■ $W\,T_t > 2l + T_t$ $U = 1$	■ $W\,T_t > 2l + T_t$ $U = 1 - P$
■ $W\,T_t < 2l + T_t$ $U = \frac{W}{1+2a}$	■ $W\,T_t < 2l + T_t$ $U = \frac{W \cdot (1-P)}{1+2a}$

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Analysis of ARQ Protocols - Results

$P=10^{-3}$

Example DL Protocol: XModem

- ***XModem*** is a simple data link protocol which used to be popular for communications over modems
- **Xmodem** uses Stop-and-Wait ARQ

SOH	NUM	CNUM	Data	CKS
1byte	1	1	<=128	1

- **SOH:** frame delimiter (start of header, “00000001”)
- **NUM:** 8-bit sequence number
- **CNUM:** bitwise complement of NUM
- **Data:** up to 128 bytes
- **CKS:** checksum = sum of the data field without overflow bit

CS 457 - Computer Networks

University of Virginia

XModem

- **NAK:** **“00010101”** sent every 15 sec when data is not received
- **ACK:** **“00000110”** sent if CKS is correct
- **EOT:** **“00000100”** end of transmission

- **Variations of XModem:**
  - XModem-CRC : uses CRC
  - YModem: allows to send 1,024 bytes of data in a frame. Also: allows batch file transfers
  - ZModem

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