Flow Control and Error Control

EP1100 Data Communications and Computer Networks

Illustrations in this material are collected from

Behrouz A Forouzan, *Data Communications and Networking*, 3rd edition, McGraw-Hill.

Outline

- Introduction
- Flow control
  - Stop and wait
  - Sliding window
- Error detection
  - Parity
  - Checksums
  - Cyclic redundancy check (CRC)
- Error handling
  - Error correction
  - Retransmission (*Automatic Repeat Request* ARQ)
    - Stop and wait
    - Go-back-N
    - Selective reject (selective repeat)

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Data Link Layer: Background

- Physical layer provides means to transfer *frames* over a link
- Remaining problems to be solved
  - Adapt sender to receiver rate
  - Errors in frames and loss of frames should be detected and managed
  - …

8-bit flag	Header— address and control	Data	Trailer— error control	8-bit flag

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Why Flow Control?

- Problem: Sender can overload receiver
  - Frames arrive too fast
    - In many cases, the receiver is more complicated than the sender
    - Error detection, frame/packet analysis, address lookup
  - Frames are stored in a buffer before they are processed
    - Receiver buffers can overflow and frames be lost
  - Prevent loss of frames
- Control mechanisms
  - Stop and wait
  - Sliding window
- We don't worry about frame errors and loss for now
  - Will discuss that shortly…

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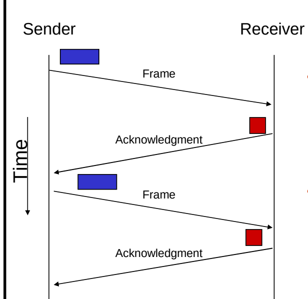
Stop and Wait



- Sender sends one frame
  - Waits for acknowledgment
  - Next frame sent after acknowledgment
- Receiver sends acknowledgment
  - When ready to receive next frame

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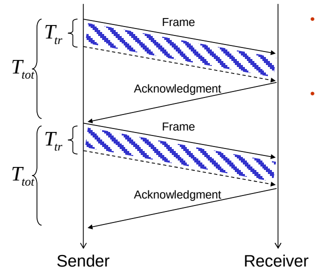
Link Utilization

T_{tr} Transmission time

T_{tot} Total time

$$U = \frac{T_{tr}}{T_{tot}}$$



- Transmission time
  - Time between first and last bit of a frame
    - Frame length (bits) divided by link capacity
    - [b] / [b/s] = [s]
- Total time
  - Time from first bit is sent until acknowledgment arrives
    - How long before sender can start sending again
- Assumptions
  - Zero transmission time for acknowledgments
  - Zero processing time in sender and receiver

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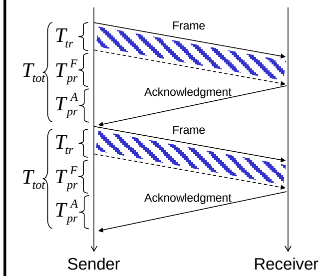
Link Utilization

$$U = \frac{T_{tr}}{T_{tr} + T_{pr}^{F} + T_{pr}^{A}}$$



- Propagation time
  - Time for one bit to propagate over the link
    - Link length divided by propagation speed
    - [m] / [m/s] = [s]

T_{pr}^{F} Propagation time for frame

T_{pr}^{A} Propagation time for acknowledgment

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Link Utilization—Symmetrical Links

For symmetrical links:

$$T_{pr}^{F} = T_{pr}^{A} = T_{pr}$$

$$U = \frac{T_{tr}}{T_{tr} + 2T_{pr}} = \frac{1}{1+2a}, \text{ where } a = \frac{T_{pr}}{T_{tr}}$$

- The parameter a is the ratio between the length of the link and length of a frame (in time)
  - $T_{pr} < T_{tr}$ ($a < 1$): max one frame fits on the link
  - $T_{pr} > T_{tr}$ ($a > 1$): multiple frames on the link
- "Length" of a bit
  - Signal propagation speed divided by link capacity
    - [m/s] / [b/s] = [m/b]
  - Speed of light in optical fiber is about 2×10^{8} m/s
    - 1 kb/s: 200 km per bit
    - 1 Mb/s: 200 m per bit
    - 1 Gb/s: 20 cm per bit

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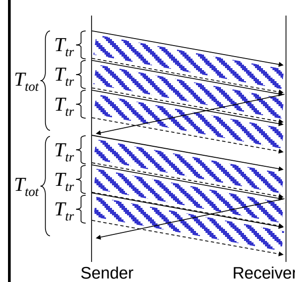
Sliding Window



- Send *N* frames before waiting
  - *N* is "window size"
    - Matched by buffer space at receiver
  - Choose N to get utilization close to 100%
- Sequence numbers
  - All frames, both data and ACKs
  - Acknowledgments
    - Sequence number of the next frame the receiver is ready to accept
    - ACK of all frames with lower sequence numbers

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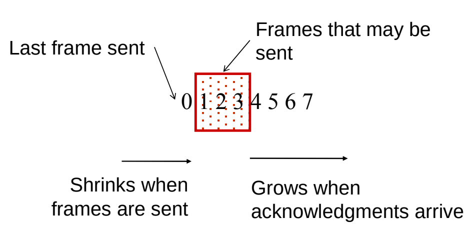
How Does it Work?

At the sender (N = 3)



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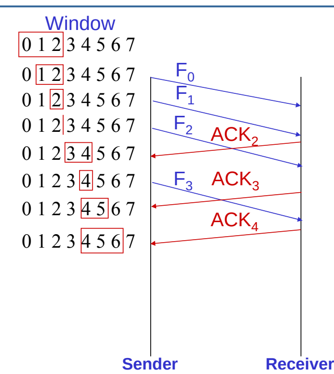
Example (N = 3)



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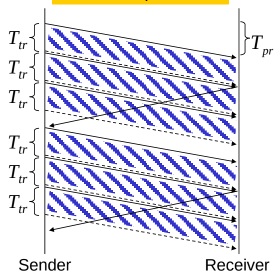
Sliding Window Utilization

$$U = \frac{NT_{tr}}{T_{tr} + 2T_{pr}} = \frac{N}{1+2a}$$



- $U \geq 1$
  - Sender receives acknowledgment before window is closed
  - Sender may send without stopping
  - True utilization can never be more than 100%
- $U < 1$
  - Window closes after N frames
  - Sender must stop and wait for acknowledgment
  - Utilization is the fraction of the time when the sender does not wait

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How Large Window?

- N = 1 ⇒ stop-and-wait
- Small a ⇒ small N
  - Local area network: N = 8 ⇒ 3 bits
- Large a ⇒ large N
  - TCP uses 32-bit sequence number
    - Byte number
    - Propagation times for global distances

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Acknowledgments

- Types of acknowledgments
  - Positive
    - ACK (*acknowledgment*)
      - HDLC: RR (receiver ready)
  - Negative
    - NACK (*negative acknowledgment*)
      - HDLC: RNR (receiver not ready)
- Indicates sequence number of next expected frame
  - Cumulative acknowledgment of all frames with lower sequence number
- When and how is the acknowledgment sent?
  - As a separate frame
  - Together with data from the receiver to the sender
    - "Piggybacking"

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Error control

Automatic Repeat Request (ARQ)

- Error control—when frames or acknowledgments are lost
  - Based on flow control
- Stop-and-wait flow control
  - Stop-and-wait ARQ
  - "Alternating Bit Protocol"
    - Two sequence numbers—0 and 1
- Sliding window flow control
  - Go-back-N ARQ
  - Selective-reject ARQ

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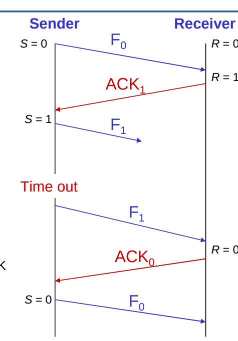
Stop-and-wait ARQ

- Sender
  - Variable *S*: sequence number of last frame sent
  - Keeps a copy of last frame sent
  - Starts a timer when a frame is sent
  - Stops timer when ACK is received
  - Retransmits frame if time out (restarts timer)
- Receiver
  - Variable *R*: next expected sequence number
  - When a frame is received, sends an ACK with next expected sequence number
    - Ready to receive
    - Not ready to receive (flow control)
  - Drops received packet if wrong sequence number



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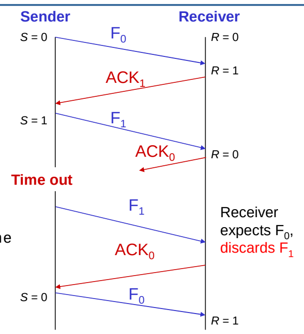
Stop-and-wait ARQ: Lost Acknowledgment

- No ACK received
  - Sender times out
  - Retransmits frame
- Receiver receives wrong sequence number
  - Discards frame
  - Sends ACK with expected sequence number (0)
- Sender may send next frame



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Continuous ARQ

- Stop-and-wait ARQ is simple but inefficient
  - same reason as for stop-and-wait flow control
- Continuous ARQ
  - Sequence numbers with sliding window
  - ACK and NACK
  - Time out

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Go-back-N ARQ

- Based on sliding window flow control
- Sender
  - May send *N* frames without acknowledgment
    - Copies of all unacknowledged frames kept in a buffer
  - Time out
    - retransmits *all* unacknowledged frames
- Receiver
  - Discards frames with unexpected sequence numbers

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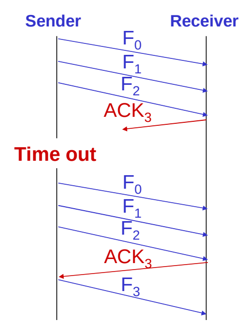
Example: Lost Acknowledgment (*N* = 3)



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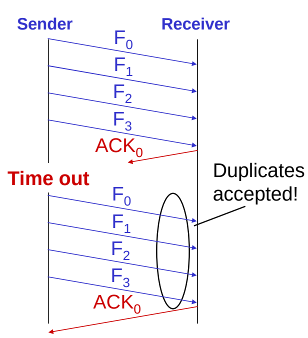
Window Size Versus Sequence Numbers

- With *k*-bit sequence numbers, window size can be at most 2^k-1
- Otherwise frames can be duplicated at receiver
- For example:
  - Sequence numbers 0-3 (*k* = 2)
  - Window size 2^k = 4 (incorrectly)



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Selective Repeat ARQ

- Sometimes also called Selective Reject ARQ (SREJ)
- Only retransmit frames that are lost
  - Negative acknowledgment NAK (SREJ)
  - Time out
- Receiver has a receiver window
  - Only frames with sequence number within receive window are accepted
  - Sorts accepted frame into correct order

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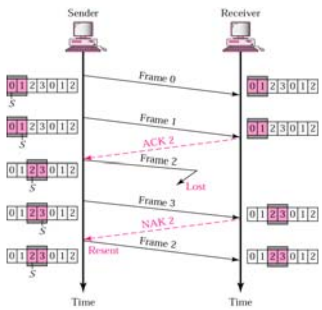
Selective Repeat ARQ



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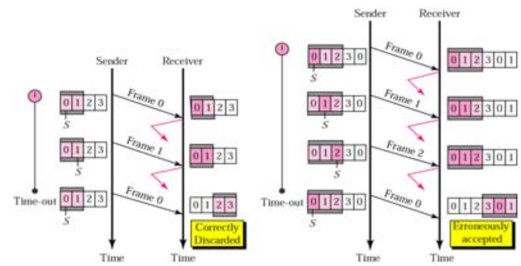
Window Size in Selective Repeat ARQ



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Transmission Errors

- Lost frame
  - Framing error
- Corrupted frame (bit errors)
  - Single bit error
  - Burst errors
    - Whole sequences of bits are corrupted
    - External noise, for example power surges

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Error Detection—Basic Idea

Data	*f*(Data)

- Add extra (redundant) information for detecting errors
  - Parity check
  - Checksum
  - Cyclic redundancy check (CRC)
- Sender computes function over data, and appends result
- Receiver computes same function, and compares the results
- If the results differ, there was an error

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Parity Check

1 0 0 1 0 1 0 0 | 1 —— Parity bit (even parity)

- Simple parity check
  - Extra bit (parity bit) is added to the data unit
  - Numbers of 1s should be even ("even parity") or odd ("odd parity")
  - Receiver checks the number of 1s
- Advantages
  - Simple: $P= 1 \oplus 0 \oplus 0 \oplus 1 \oplus ... \oplus 1 \oplus 0$ for even parity
  - Inexpensive: only one extra bit per data unit
- Disadvantage
  - Only detects single bit errors, and burst errors with odd number of bit errors

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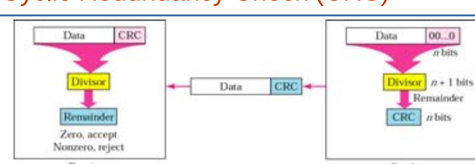
Cyclic Redundancy Check (CRC)



- The data M is treated as a sequence of bits
- Predefined binary word P (generator) of length n+1
- Sender generates M' by adding n CRC bits to M
  - Such that M' is evenly divided by P
  - M' is sent
- Receiver receives M''
  - If remainder of M'' divided by P is zero then $M'' = M'$
  - Otherwise: bit error detected, discard the data

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CRC Calculation Using Binary Division

- Append '00' to *M*
- Binary subtraction (xor) of 3 bits
  - If first bit is '1'
    - subtract *P*
    - (Put '1' in quotient)
    - Copy down next bit
  - If first bit is '0'
    - subtract '000'
    - (Put '0' in quotient)
    - Copy down next bit
- Append remainder to data as checksum

```
          10110
    101 | 1001100
          101
           011
           000
            111
            101
             100
             101
              010
              000
               10
```

n = 2
P = 101
M = 10011

M´ = 1001110

CRC Control at Receiver

- Divide received data with *P*
- If remainder is '00', data is OK
  - Strip off CRC bits
- Otherwise discard data

```
          10110
    101 | 1001110
          101
           011
           000
            111
            101
             101
             101
              000
              000
               00
```

n = 2
P = 101
M = 10011

M´ = 1001110

Generator Polynomials

- Binary numbers can be represented as polynomials
  - Bit value is coefficient of a term
  - Exponent indicates the bit position, starting at 0
  - Example: 100111 $\Rightarrow$

$P(X) = 1 \times X^5 + 0 \times X^4 + 0 \times X^3 + 1 \times X^2 + 1 \times X + 1 \times X^0$

$P(X) = X^5 + X^2 + X + 1$

- Standard polynomials

ITU-16: $X^{16} + X^{12} + X^5 + 1$

ITU-32: $X^{32} + X^{26} + X^{23} + X^{22} + X^{16} + X^{12} + X^{11} + X^{10} + X^8 + X^7 + X^5 + X^4 + X^2 + X + 1$

CRC

- Effective error detection
  - All burst errors that affect an odd number of bits
  - All burst errors of length less than or equal to degree of polynomial
  - With high probability longer errors
- Simple implementation in hardware
  - Shift register circuit
  - CRC often appended to the data (trailer)

Checksum

- Treat the data as a sequence of integer numbers in binary format
- Compute the sum of the integer numbers
  - (In ones complement arithmetic)
  - Use the result for error detection

Checksum

- Less effective than CRC
  - Easier to implement in software
- Detects
  - all errors involving an odd number of bits
  - Most errors involving an even number of bits
    - Two opposite bit inversions may balance out each other
- Used in IP, TCP and UDP

Correction of Errors

- Forward Error Correction (FEC)
  - Error-correcting codes
  - Replace CRC, checksum etc with a code that can automatically correct the error
  - Needs more redundancy bits
- Retransmission (ARQ)
  - Can be used both for bit errors and frame loss
  - A frame with bit errors is dropped (lost)

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Data Link Example: HDLC

- High-level Data Link Control
  - ISO standard
- Data encapsulation method on synchronous serial links
- Point-to-point and multipoint links

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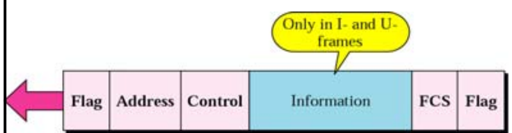
HDLC Frame Format



- Flag
  - Start and end
  - Binary 01111110
    - $7E_{16}$
- Address
- Control
- Information
  - User data
  - Management information
- FCS field
  - 2- or 4-byte CRC

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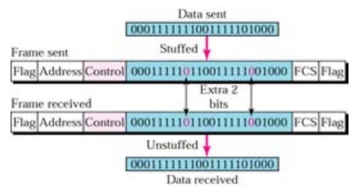
HDLC Bit Stuffing

- Data may contain flag pattern 01111110
- Sender: insert (”stuff”) an extra 0 after five 1s
- Receiver: remove 0 after five 1s



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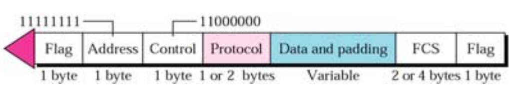
Data Link Example: (PPP)

- Point-to-point Protocol
- Control and management of data transfer over physical (point-to-point) links
  - Dedicated link with two stations
  - Traditional modem, DSL, etc
- Based on HDLC frame format



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PPP Protocol Family

- Link Control Protocol (LCP)
  - Establish, disconnect link
  - Negotiate options—maximum receive unit, authentication, compression
- Authentication
  - Password Authentication Protocol (PAP)
  - Challenge Handshake Authentication Protocol (CHAP)
- Network Control Protocol (NCP)
  - Internetwork Protocol Control Protocol (IPCP)

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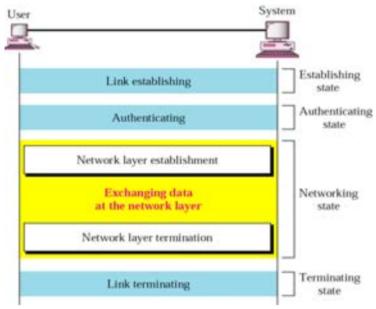
PPP Example



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Summary

- Flow control
  - Stop and wait
  - Sliding window
- Bit error detection
  - Parity control
  - Checksum
  - Cyklic redundancy check (CRC)
- Detecting frame loss: sequence numbers
- Error control: retransmission (ARQ)
  - Stop and wait ARQ
  - Go-back-N ARQ
  - Selective reject ARQ
- Two examples:
  - HDLC
  - PPP

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