King Fahd University of Petroleum & Minerals Computer Engineering Dept

COE 341 – Data and Computer Communications

Term 112

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Lecture Contents

1. Flow Control
   a. Stop-and-Wait flow control
   b. Sliding-Window flow control
2. Error Control
   a. Stop-and-Wait ARQ
   b. Go-Back-N ARQ
   c. Selective-Reject ARQ
3. High-Level Data Link (HDLC)
4. Other Data Link Control Protocols

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What is Data Link Control

- The logic or procedures used to convert the raw stream of bits provided by the physical layer into a "*reliable*" connection
- Requirements and Objectives:
  - Frame synchronization
  - Flow control
  - Error control
  - Addressing
  - Multiplexing data and control on connection
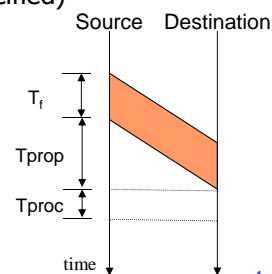 - Link management

Flow Control

- A scheme to ensure that transmitter does not overwhelm receiver with data
- Transmission of one frame:
  - T_f: time to transmit frame
  - Tprop: time for signal to propagate
  - Tproc: time for destination to process received frame – small delay (usually ignored if not specified)
- Tproc may be ignored if not specified

$$T_f = \frac{\text{Frame Size (bits)}}{\text{Transmission Speed (bits/sec)}}$$

$$T_{prop} = \frac{\text{Distance (meters)}}{\text{Propagation Speed (meters/sec)}}$$
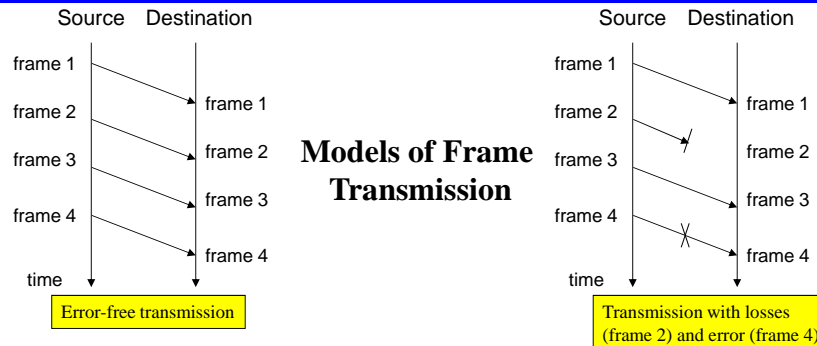
Flow Control (2)

Source	Destination		Source	Destination
frame 1			frame 1	
frame 2	frame 1		frame 2	frame 1
frame 3	frame 2	**Models of Frame Transmission**	frame 3	frame 2
frame 4	frame 3		frame 4	frame 3
time	frame 4		time	frame 4

Error-free transmission

Transmission with losses (frame 2) and error (frame 4)

- The destination has a limited buffer space. How will the source know that destination is ready to receive the next frame?
- In case of errors or lost frame, the source need to retransmit frames – i.e. a copy of transmitted frames must be kept. How will the source know when to discard copies of old frames?
- Etc.

Stop-and-Wait Protocol

- Protocol:
  - Source transmits a frame
  - After the destination receives frame, it sends ACK
  - Source, upon the receipt of ACK, can now send the next frame
- Destination can stop source by withholding the ACK
- Simple
- Animation for Stop-and-Wait
- NOTE: ONLY one frame can be in transit at any time

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Stop-and-Wait Protocol: Efficiency

- After every frame, source must wait till acknowledgment ➔ Hence link propagation time is significant
- Total time to for one frame:

  $T\_total = Tf + 2Tprop + Tproc + Tack$

  if we ignore Tproc and Tack (usually very small)

  $T\_total = Tf + 2Tprop$
- Link utilization, U is equal to

  $U = Tf/ (T\_total)$, or

  $= 1 / (1+2(Tprop/Tf)) = 1 / (1 + 2 a)$

  where $a = Tprop/Tf$ = length of link in bits

- If a < 1 (i.e. Tf > Tprop – when 1st transmitted bit reaches destination, source will still be transmitting ➔ U is close 100%
- If a > 1 (i.e. Tf < Tprop – frame transmission is completed before 1st bit reaches destination ➔U is low
- See figure 7.2

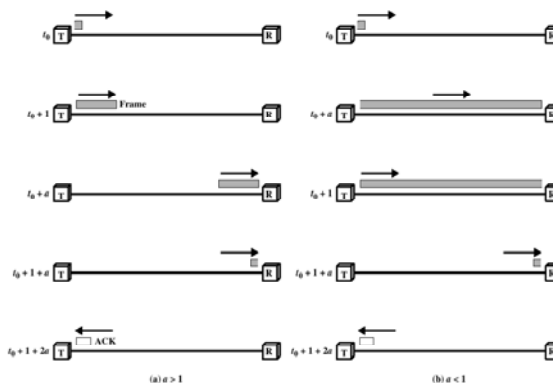Source   Destination

T_f

Tprop

Tproc

Tprop

Tack

time
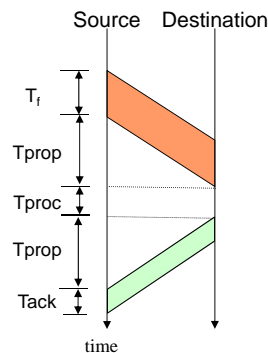
Stop-and-Wait Protocol: Efficiency (2)

- Remember: $a = Tprop/Tf$ = length of link in bits

- If a < 1 (i.e. Tf > Tprop – when 1st transmitted bit reaches destination, source will still be transmitting ➔ U is close 100%
- If a > 1 (i.e. Tf < Tprop – frame transmission is completed before 1st bit reaches destination ➔U is low
- Stop-and-Wait is efficient for links where a << 1 (long frames compared to propagation time)

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

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Sliding Window Protocol

- Stop-and-Wait can be very inefficient when a > 1
- Protocol:
  - Assumes full duplex line
  - Source A and Destination B have buffers each of size W frames
  - For k-bit sequence numbers:
    - Frames are numbered: 0, 1, 2, …, 2^k-1, 0, 1, … (modulo 2^k)
    - ACKs (RRs) are numbered: 0, 1, 2, …, 2^k-1, 0, 1, … (modulo 2^k)
  - A is allowed to transmit up to W frames without waiting for an ACK
  - B can receive up to W consecutive frames
  - ACK J (or RR J), where $0<=J<= 2^k$-1, sent by B means B is have received frames up to frame J-1 and is ready to receive frame J
  - B can also send RNR J: B have received all frames up to J-1 and is not ready to receive any more
- Window size, W can be less or equal to 2^k-1
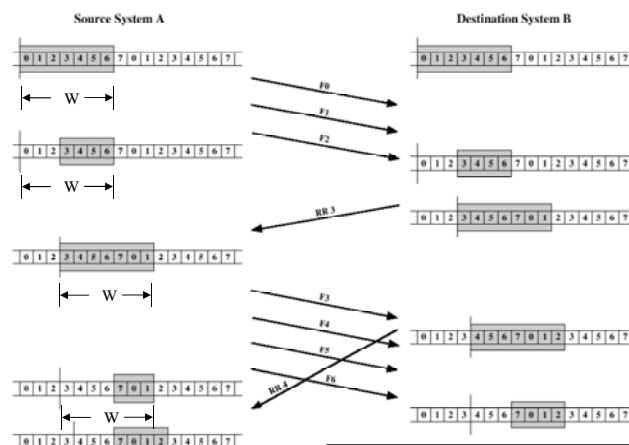
Sliding Window Protocol (2)

- Example of Sliding-Window-Protocol: k = 3 bits, W = 7

Observations:

- A may tx W = 7 frames (F0, F1, …, F6)
- After F0, F1, & F2 are tx-ed, window is shrunk (i.e. can not transmit except F3, F4, …, F6)
- When B sends RR3, A knows F0, F1 & F2 have been received and B is ready to receive F3
- Window is advanced to cover 7 frames (starting with F3 up to F1)
- A sends F3, F4, F5, & F6
- B responds with RR4 when F3 is received – A advances the window by one position to include F2

W = distance between first unacknowledged frame and last frame that can be sent

Sliding Window Protocol - Piggybacking

- When using sliding window protocol in full duplex connections:
  - Node A maintains its own transmit window
  - Node B maintains its own transmit window
  - A frame contains: data field + ACK field
  - There is a sequence number for the data field, and a sequence number for the ACK field

Sliding Window Protocol - Efficiency

- Again we can distinguish two cases:

- Case 1: $W \geq 2a + 1$

- Case 2: $W < 2a + 1$

Sliding Window Protocol - Efficiency - Case 1

- Assume k=3, W = 7
  (ignoring Tack)

- Source can continuously keep transmitting!!
  - Because the ACK can arrive to source before the window is completed

- Utilization = 100%
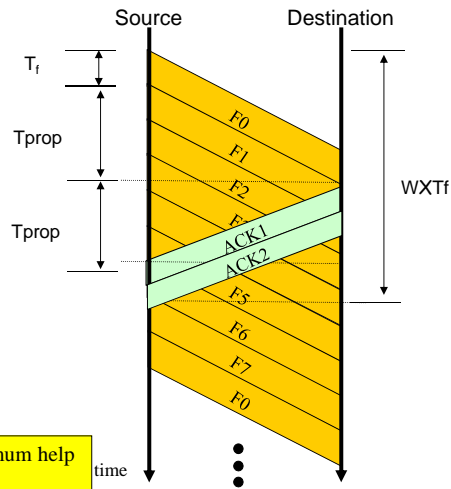
Sending ACK0 as soon as F0 is received is the maximum help the destination can do to increase utilization

Source   Destination

T_f

Tprop

Tprop

F0
F1
F2
ACK1
ACK2
F5
F6
F7
F0

WXTf

time
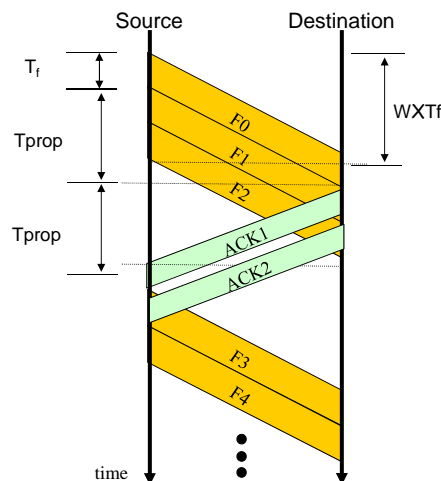
Sliding Window Protocol - Efficiency - Case 2

- Assume k = 3, W = 3 (ignoring Tack)
- Source can NOT continuously keep transmitting!!

  - Because the ACK can NOT arrive to source before the window is completed

- Utilization = $\dfrac{W \times T_f}{T_f + 2 \times T_{prop}}$

  $= \dfrac{W}{1 + 2a}$

Source   Destination

T_f

Tprop

Tprop

F0
F1
F2
ACK1
ACK2
F3
F4

WXTf

time

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Sliding Window Protocol - Efficiency

- Refer to Appendix A
- When window size is W (for error free), link utilization, U, is given by

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

where a = Tprop/Tf or length of link in bits

- Sliding window protocol can achieve 100% utilization if W >= (2a + 1)

Sliding Window Protocol

- Animation for Sliding Window protocol
- Sliding Window Protocol Simulation (http://www.cs.stir.ac.uk/~kjt/software/comms/jasper/SWP3.html)

Error Control

- Types of Errors:
    - Lost frame
    - Damaged frame
- Error control Techniques (Automatic Repeat Request - ARQ):
    - Error detection – discussed previously
    - +ve ACK
    - Retransmission after timeout
    - -ve ACK and retransmission
- ARQ Procedures: convert an unreliable data link into a reliable one.
    - Stop-and-wait
    - Go-back-N
    - Selective-reject

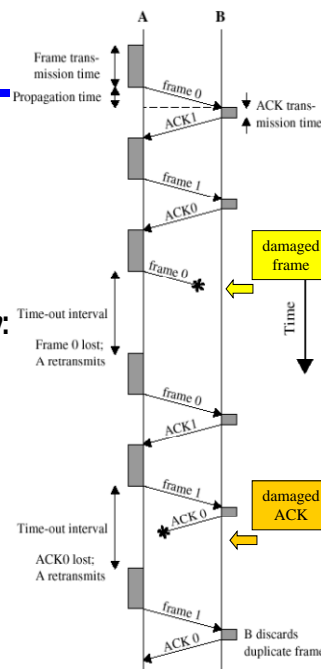# Stop-and-Wait ARQ

- Based on the stop-and-wait control flow procedure - Stop-and-Wait Protocol slide
- Two types of errors:
    1. Frame lost or damaged – *Solution*: timeout timer
    2. Damaged or lost ACK – The timeout timer solves this problem

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Go-Back-N ARQ

- Based on the sliding-window flow control procedure - Sliding Window Protocol slide
- Three types of errors:
  1. i^{th} frame damaged:
     a. If A send subsequent frames (i+1, i+2, …), B responds with REJ i ➔ A must retransmit i^{th} frame and ***all subsequent frames***
     b. If A does not send subsequent frames and B does not respond with RR or REJ (since frame was damaged) ➔ timeout timer at A expires – send a POLL signal to B; B sends an RR i, i.e. it expect the ith frame – A sends the ith frame again

     <div style="border:1px solid; background:yellow; display:inline-block">Check for status of B before resending the frame</div>
  2. Damaged RR (B receives i^{th} frame and sends RR i+1 which is lost or damaged):
     a. Since ACKs are cumulative – A may receive a subsequent RR j (j >i+1) before A times out
     b. If A times out, it sends a POLL signal to B – if B fails to respond (i.e. down) or its response is damaged subsequent POLLs are sent; procedure repeated certain number of time before link reset
  3. Damaged REJ – same as 1.b

Selective-Reject ARQ

- In contrast to Go-Back-N, the only frames retransmitted are those that receive –ve ACK (called SREJ) or those that time out
- More efficient:
  - Rx-er must have large enough buffer to save *post-*SREJ frames
  - Buffer manipulation – re-insertion of out-of-order frames

Window Size for Selective-Reject ARQ – Why?

- Window size: should less or equal to half range of sequence numbers
  - For n-bit sequence numbers, Window size is $\leq 2^{n-1}$ (remember sequence numbers range from 0,1, …, 2^n-1)
- Why? See next example

Window Size for Selective-Reject ARQ – Why? (2)

- Example: Consider 3-bit sequence number and window size of 7

NODE A

0 1 2 3 4 5 6 7 0 1 2

Transmitter can only advance its transmit window with the frames it sent are acknowledged

NODE B

0 1 2 3 4 5 6 7 0 1 2

Frame 0
Frame 1
Frame 2
Frame 3
Frame 4
Frame 5

timeout for frame 0

Frame 6

Receiver advances its receive window

RR7

0 1 2 3 4 5 6 7 0 1 2

Frame 0

Receiver is now confused!
This frame zero – is it the new frame or a resend of the old one?
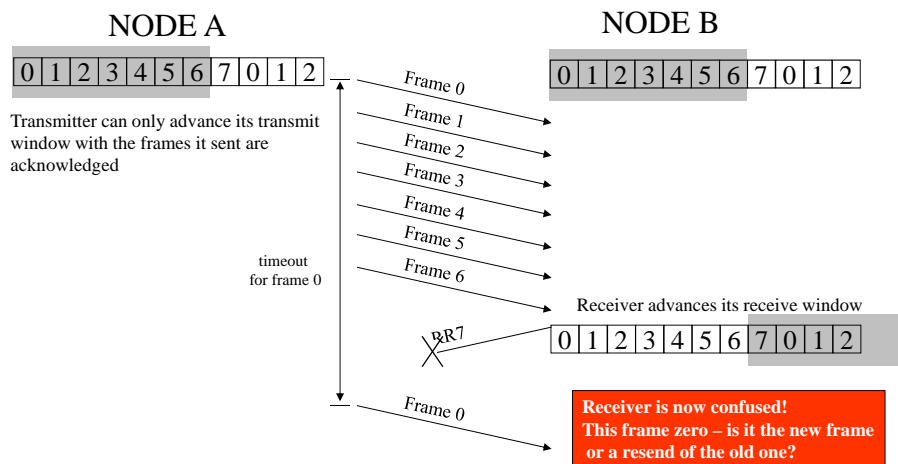
Go-Back-N/Selective-Reject ARQ Examples

- With Go-back-N frames 4,5 and 6 are retransmitted
- With Selective-Reject only frame 4 is retransmitted

Did this lost RR7 affect flow? How did the link recover?

A   B

frame 0
frame 1
frame 2   RR 2
frame 3
frame 4   RR 4
frame 5   ✱
frame 6   REJ 4   } discarded by receiver
frame 4
frame 5   RR 5
frame 6
frame 7   RR 7
frame 0   ✱
Timeout
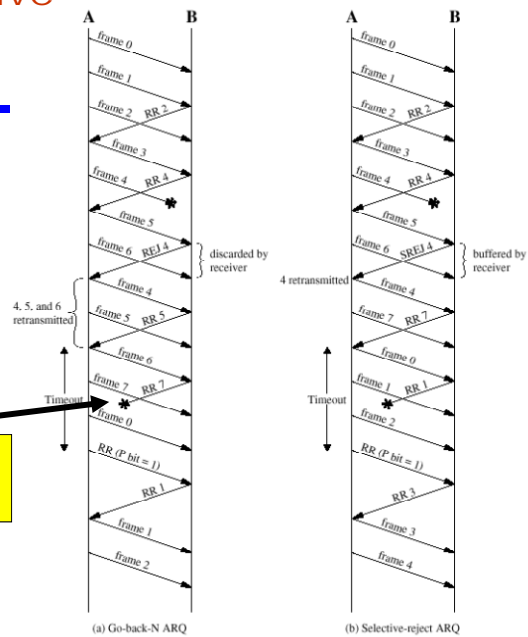RR (P bit = 1)
RR 1
frame 1
frame 2

4, 5, and 6 retransmitted

(a) Go-back-N ARQ

A   B

frame 0
frame 1
frame 2   RR 2
frame 3
frame 4   RR 4
frame 5   ✱
frame 6   SREJ 4   } buffered by receiver
frame 4
frame 7   RR 7
frame 0
frame 1   RR 1
frame 2   ✱
Timeout
RR (P bit = 1)
RR 3
frame 3
frame 4

4 retransmitted

(b) Selective-reject ARQ

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Example: Problem 7-9

7-9: Two neighboring nodes A and B use a sliding-window protocol with a 3-bit sequence numbers. As the ARQ mechanism, go-back-N is used with a window size of 4. Assuming A is transmitting and B is receiving, show the window positions for the following succession of events:

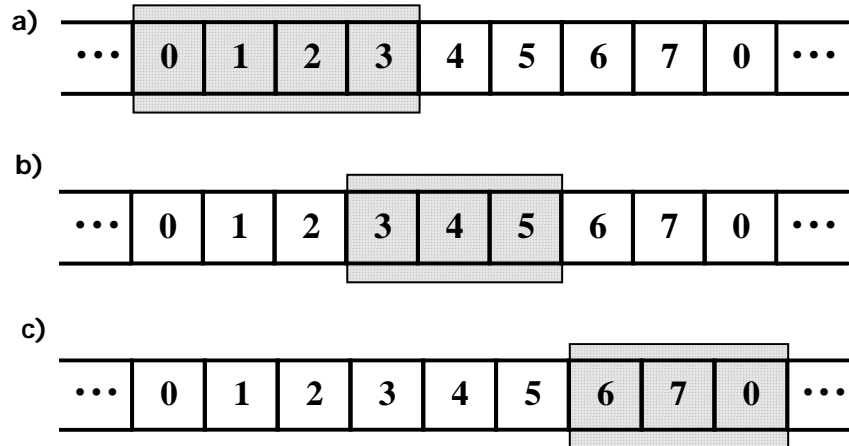a) Before A sends any frames

b) After A sends frame 0, 1, 2 and B acknowledges 0, 1 and the ACKs are received by A

c) After A sends frames 3, 4, and 5 and B acknowledges 4 and the ACK is received by A

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Example: Problem 7-9 - Solution

a)

···	0	1	2	3	4	5	6	7	0	···

b)

···	0	1	2	3	4	5	6	7	0	···

c)

···	0	1	2	3	4	5	6	7	0	···

High-Level Data Link Control Protocol (HDLC)

- One of the most important data link control protocols
- Basic Characteristics:
    - Primary Station: issues *commands*
    - Secondary Station: issues *responses* – operates under the control of a primary station
    - Combined Station: issues commands and responses
- Two link configurations are defined:
    - Unbalanced: one primary plus one or more secondary
    - Balanced: two combined (functions as primary and/or secondary) stations

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High-Level Data Link Control Protocol (HDLC) (2)

- Three transfer modes are defined:
  - Normal Response Mode (NRM) – used in unbalanced conf.; secondary may only tx data in response to a command from primary
  - Asynchronous Balanced Mode (ABM) – used in balanced conf.; either combined station may tx data without receiving permission from other station
  - Asynchronous Response Mode (ARM) – used in unbalanced conf.; Secondary may initiate data tx without explicit permission; primary still retains line control (initialization, error recovery, …)
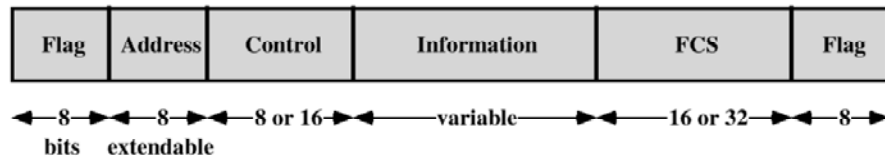- Animation for HDLC

HDLC - Applications

- NRM:
  - Point-multi-point (multi-drop line): one computer (primary) polls multiple terminals (secondary stations)
  - Point-to-point: computer and a peripheral
- ABM: most widely used (no polling involved)
  - Full duplex point-to-point
- ARM: rarely used

HDLC – Frame Structure – Flag Field

Flag	Address	Control	Information	FCS	Flag

◄—8—► ◄—8—► ◄—8 or 16—► ◄——variable——► ◄——16 or 32—► ◄—8—►
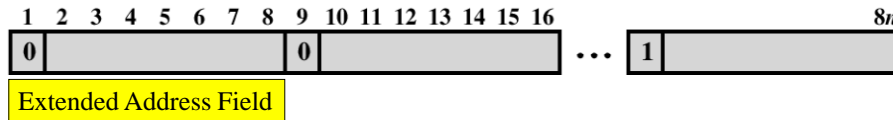bits   extendable

- Flag Field: unique pattern 01111110
  - Used for synchronization
  - To prevent this pattern form occurring in data ➔ *bit stuffing*
    - Tx-er inserts a 0 after each 5 1s
    - Rx-er, after detecting flag, monitors incoming bits – when a pattern of 5 1s appears; the $6^{th}/7^{th}$ bit are checked:
      - If 0, it is deleted
      - If 10, this is a flag
      - If 11, this is an ABORT
- Pitfalls of bit stuffing: one bit errors can split one frame into two or merge two frames into one

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HDLC – Frame Structure - Address Field

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16   8n

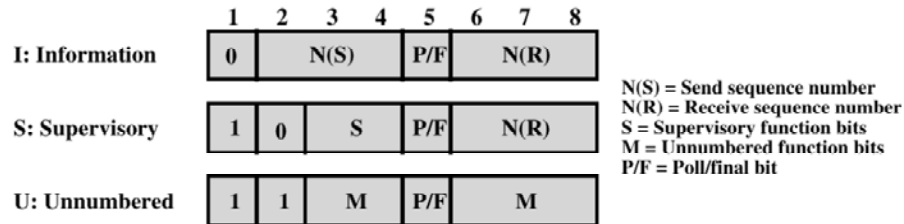| 0 | | 0 | | ... | 1 | |

Extended Address Field

- Address field identifies the secondary station that transmitted or is to receive frame
- Not used (but included for uniformity) for point-to-point links
- Extendable – by prior arrangement
- Address = 11111111 (single octet) used for broadcasting; i.e. received by all secondary stations

HDLC – Frame Structure - Control Field

	1	2	3	4	5	6	7	8
I: Information	0	N(S)			P/F	N(R)		
S: Supervisory	1	0	S		P/F	N(R)		
U: Unnumbered	1	1	M		P/F	M		

N(S) = Send sequence number
N(R) = Receive sequence number
S = Supervisory function bits
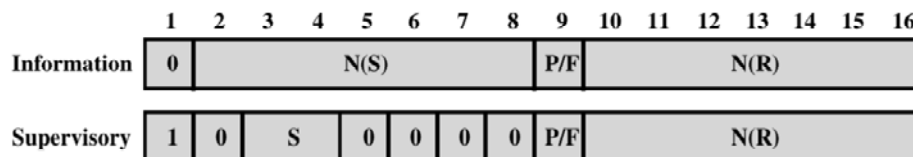M = Unnumbered function bits
P/F = Poll/final bit

- First 2 bits of field determine the type of frame
  - Information frame (I): carry user data (upper layers) – flow and error control info is piggybacked on these frames as well
  - Supervisory frame (S): carry flow and error control info when there is no user data to tx
  - Unnumbered frame (U): provide supplementary link control
- Poll/Final (P/F) bit:
  - In command frames (P): used to solicit response from peer entity
  - In response frames (F): indicate response is the result of soliciting command

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HDLC – Frame Structure - Control Field   (2)

|	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Information	0	N(S)							P/F	N(R)						
Supervisory	1	0	S	0	0	0	0		P/F	N(R)						

- "Set-mode" command ➔ extends control field to 16 bit for S and I frames
- Extension: 7-bit sequence numbers rather than 3-bit ones
- Unnumbered frames always use 3-bit sequence numbers

HDLC – Frame Structure – Information/FCS Fields

Flag	Address	Control	Information	FCS	Flag

8 bits — 8 extendable — 8 or 16 — variable — 16 or 32 — 8
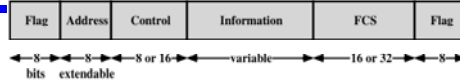
- Information field:
  - Present ONLY in I-frames and some U-frames
  - Contains integer number of octets
  - Length is variable – up to some system defined maximum

- FCS field:
  - Error detecting code
  - Calculated from *ALL* remaining bits in frame
  - Normally 16 bits (CRC-CCITT polynomial = $X^{16}+X^{12}+X^5+1$)
  - 32-bit optional FCS

HDLC Operation

- Initialization
  - One side signals to the other the need for initialization
  - Specifies which of the three modes to use: NRM, ABM, or ARM
  - Specifies 3- or 7-bit sequence numbers
  - The other side can accept by sending unnumbered acknowledgment (UA)
  - The other side can reject by sending - A disconnected mode (DM) frame is sent
- Data Transfer
  - Exchange of I-frames: data and can perform flow/error control
  - S-frames can be used as well: RR, RNR, REJ, or SREJ
- Disconnect
  - DISC frame ➔ UA
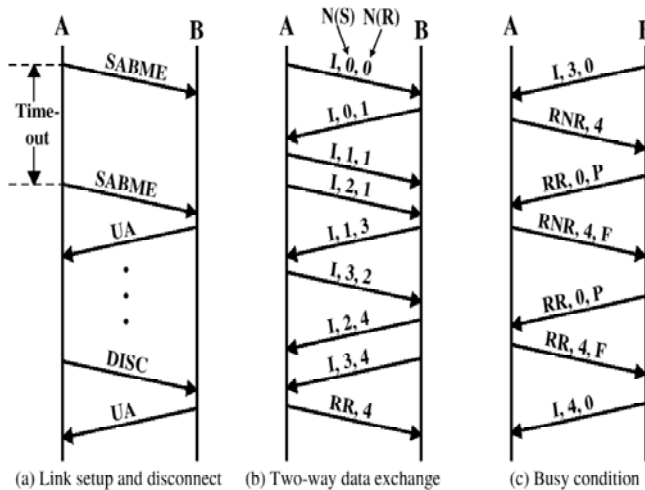
HDLC – Operation

a) Link Setup & Disconnect:
- SABM command – starts timer
- B responds with UA (or DM if not interested)
- A receives UA and initializes its variables
- To disconnect: issue DISC command

b) Two-Way Data Exchange:
- Full-duplex exchange of I-frames

c) Busy Condition:
- Note the use of the P and F bits

(a) Link setup and disconnect (b) Two-way data exchange (c) Busy condition


HDLC – Operation (2)

a) Reject Recovery:
- I-frame 4 was lost
- B receives I-frame 5 (out of order) – responds with REJ 4
- A resend I-frame 4 and all subsequent frames (Go-back-N)

b) Timeout Recovery:
- A sends I-frame 3 – but it is lost
- Timer expires before acknowledgement arrives
- A polls Node B
- B responds indicating it is still waiting for frame 3 – B set the F bit because this a response to A's solicitation

(d) Reject recovery (e) Timeout recovery
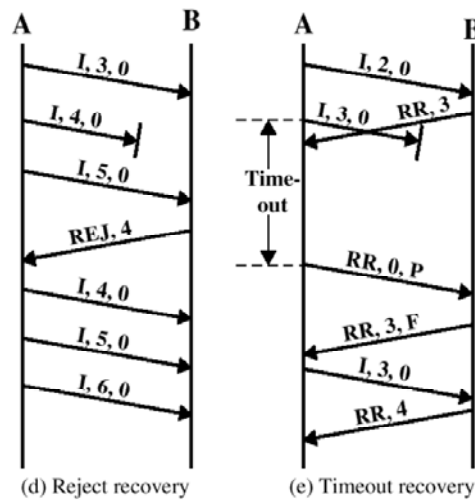
Other Data Link Control Protocols

- Link Access Procedure – Balanced (LAPB):
  - Part of X.25 packet-switching interface standard
  - Subset of HDLC – only ABM is provided
  - Designed for point-to-point
  - Frame format is same as HDLC
- Link Access Procedure – D-Channel (LAPD):
  - Part of ISDN – functions on the D-channel
  - 7-bit sequence numbers only
  - FCS field is always 16-bit
  - 16-bit address fields (two sub-addresses)

Other Data Link Control Protocols (2)

- Logical Link Control (LLC):
  - Part of IEEE802 family for LANs
  - Different frame format than HDLC
- Link Access Control Protocol for Frame-Mode Bearer Service (LAPF):
  - Designed for Frame Relay Protocol
  - Provides only ABM mode
  - Only 7-bit sequence numbers
  - Only 16-bit CRC field
  - Address field is 16, 24, or 32 bits long – containing a 10-bit, 16-bit, or 23-bit data link connection identifier (DLCI)
  - No control field – I.e. CANNOT do flow or error control (remember that frame relay was designed for fast and reliable connections!)

Other Data Link Control Protocols (3)

- Asynchronous Transfer Mode (ATM):
  - Like frame relay designed for fast and reliable links
  - NOT based on HDLC
  - New frame format – called CELL (53 bytes: 48 Bytes for payload or user data and 5 Bytes for overhead)
  - Cell has minimal overhead
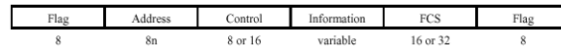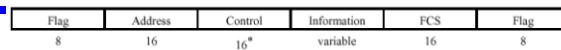 - NO error control for payload

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Other Data Link Control Protocols (4)

- Frame Formats

Flag	Address	Control	Information	FCS	Flag
8	8n	8 or 16	variable	16 or 32	8

(a) HDLC, LAPB

Flag	Address	Control	Information	FCS	Flag
8	16	16*	variable	16	8

(b) LAPD

MAC control	Dest. MAC address	Source MAC address	DSAP	SSAP	LLC control	Info.	FCS
variable	16 or 48	16 or 48	8	8	16*	variable	32

(c) LLC/MAC

Flag	Address	Control	Information	FCS	Flag
8	16, 24, or 32	16*	variable	16	8

(d) LAPF (control)

Flag	Address	Information	FCS	Flag
8	16, 24, or 32	variable	16	8

(e) LAPF (core)

Generic flow control	Virtual path identifier	Virtual channel identifier	Control bits	Header error control	Information
4	8	16	4	8	384

(f) ATM

Textbook Problems of INTEREST

- **Textbook:**