# Data Link Layer

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Based in part upon the slides of Prof. Raj Jain (OSU)

## Overview

- ❑ The data link layer problem
- ❑ Error detection and correction
- ❑ Simple datalink protocols
- ❑ Sliding window protocols
- ❑ Example datalink protocols

## Links

Sometimes you install your own

| | |
|---|---|
| Category 5 twisted pair | 10-100Mbps, 1 |
| 50-ohm coax (ThinNet) | 10-100Mbps, 2 |
| 75-ohm coax (ThickNet) | 10-100Mbps, 5 |
| Multimode fiber | 100Mbps, 2km |
| Single-mode fiber | 100-2400Mbps |

Sometimes leased from the phone company

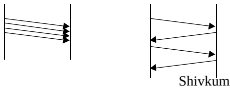
| Service to ask for | Bandwidth you get |
|---|---|
| ISDN | 64 Kbps |
| T1 | 1.544 Mbps |
| T3 | 44.736 Mbps |
| STS-1 | 51.840 Mbps |
| STS-3 | 155.250 Mbps |
| STS-12 | 622.080 Mbps |
| STS-24 | 1.244160 Gbps |
| STS-48 | 2.488320 Gbps |

# The data link layer problem

- How to provide a ***"reasonable" link abstraction*** to the higher layers ?
  - I.e., accept "frames" from many higher layer protocols and compensate for link errors or lack of destination buffers …
  - Other types of "abstractions" possible too
- Problems:
  - Framing, protocol multiplexing
  - Error Control
  - Flow Control

# Datalink Layer Services

- Unacknowledged connectionless service
  - No acks, no connection
  - Error recovery up to higher layers
  - For low error-rate links or voice traffic
- Acknowledged connectionless service
  - Acks improve reliability
  - For unreliable channels. E.g.: Wireless Systems



# Datalink Services (Cont)

- Acknowledged connection-oriented service
  - Equivalent of reliable bit-stream
  - Connection establishment
  - Packets Delivered In-Order
  - Connection Release
  - Inter-Router Traffic
- Typically implemented by network adaptor
  - Adaptor fetches (deposits) frames out of (into) host memory

# Framing

- ❑ Framing = How to break a bit-stream into frames
- ❑ Need for framing: Error Detection/Control work on chunks and not on bit streams of data
- ❑ Framing methods:
  - ❑ ***Timing*** : risky. No network guarantees.
  - ❑ ***Character count:*** may be garbled by errors
  - ❑ ***Character delimiter and stuffing:*** Delimit frame with special characters
  - ❑ ***Bit stuffing:*** delimit frame with bit pattern
  - ❑ Physical layer ***coding violations***

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# Character Stuffing

- ❑ Delimit with DLE STX or DLE ETX character flags
- ❑ Insert 'DLE' before accidental 'DLE' in data
- ❑ Remove stuffed character at destination

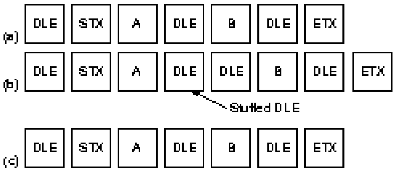

Fig 3-4

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# Bit Stuffing

- ❑ Delimit with special bit pattern (bit flags)
- ❑ Stuff bits if pattern appears in data
- ❑ Remove stuffed bits at destination

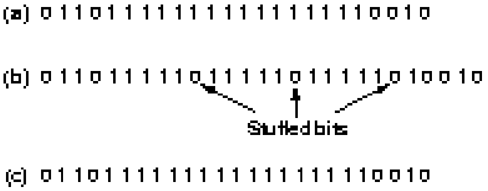
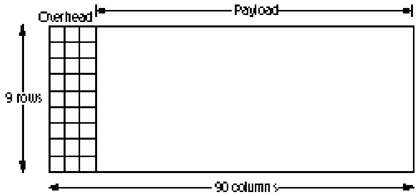


Fig 3-5

# Clock-Based Framing

- SONET: Synchronous Optical Network
- ITU standard for transmission over fiber
- STS-1 (51.84 Mbps)



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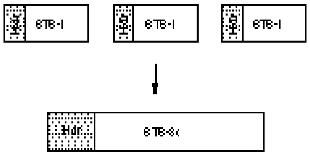
- Byte-interleaved multiplexing



- Each frame is 125µs long (remember, 1/8000 ?)

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# Error Detection and Correction

- Single bit-errors vs Burst Errors
  110101 → 100101 vs 100001
- n-bit codeword = m message bits + r check bits
- Hamming Distance = # of different bits
  1010101
  <u>1001010</u>
  0011111 ⇒ Hamming distance = 5
- Distance d code = minimum Hamming distance between any two code words written in the code
- To detect d-bit errors, distance d+1 code required
- To correct d-bit errors, distance 2d+1 code required

# Parity Checks

```
1 0 1 1 1 0 1 0 _
1 2 3 4 5 6 7 8 9
```

❑ Odd Parity

```
1 0 1 1 1 0 1 0 0      0 0 1 1 1 0 1 0 0
1 2 3 4 5 6 7 8 9      1 2 3 4 5 6 7 8 9
                          1-bit error
0 0 0 1 0 0 1 0 0      0 0 0 1 1 0 1 0 0
1 2 3 4 5 6 7 8 9      1 2 3 4 5 6 7 8 9
    3-bit error           2-bit error
```

q Even Parity

```
1 0 1 1 1 0 1 1 0
1 2 3 4 5 6 7 8 9
```

# Check Digit Method

❑ Make number divisible by 9

**Example**: 823 is to be sent

1. Left-shift: 8230
2. Divide by 9, find remainder: 4
3. Subtract remainder from 9: 9-4=5
4. Add the result of step 5 to step 1: 8235
5. Check that the result is divisible by 9.

Detects all single-digit errors: 7235, 8335, 8255, 8237

Detects several multiple-digit errors: 8765, 7346

Does not detect some errors: 7335, 8775, ...

# Modulo 2 Arithmetic

```
  1111     11001        1100
 +1010   ×    11   11  | 10101
 --------  --------     / 11
  0101     11001        -------
         11001            x11
         ---------         11
         101011          ------
                           x00
                            00
                           -----   010   2
                             x01   011   3
                              00   ----  --
                            ----   001   1  Mod 2
                              x1   101   5  Binary
```

# Cyclic Redundancy Check (CRC)

- ***Binary Check Digit Method***
- Make number divisible by P=110101 (n+1=6 bits)

**Example**: M=1010001101 is to be sent

1. Left-shift M by n bits $2^n$M= 101000110100000

2. Divide $2^n$M by P, find remainder: R=01110

~~3. Subtract remainder from P~~ ← Not required in Mod 2

4. Add the result of step 2 to step 1 : T=101000110101110

5. Check that the result T is divisible by P.

---

# Modulo 2 Division

```
       Q=1101010110
P=110101)101000110100000=2^nM
         110101                 010110
          111011                000000
          110101                 101100
           011101                110101
           000000                 110010
            111010                110101
            110101                 001110
             011111                000000
             000000                 01110 = R
              111110
              110101
```

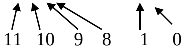
---

# Checking At The Receiver

```
       1101010110
110101)101000110101110
       110101
        111011             010111
        110101             000000
         011101             101111
         000000             110101
          111010             110101
          110101             110101
           011111             00000
           000000
            111110
            110101
```

# Polynomial Representation

- Number the bits 0, 1, ..., from right
  $b_n b_{n-1} b_{n-2} .... b_3 b_2 b_1 b_0$
  $b_n x^n + b_{n-1} x^{n-1} + b_{n-2} x^{n-2} + ... + b_3 x^3 + b_2 x^2 + b_1 x + b_0$
- Example:
  543210
  ↓↓↓↓↓
  110101 = $x^5+x^4+x^2+1$
  1101 1001 0011 = $x^{11}+x^{10}+x^8+x^7+x^4+x+1$



# Cyclic Redundancy Check (CRC)

***Polynomial Division Method***

Make $T(x)$ divisible by $P(x) = x^5+x^4+x^2+1$ (Note: $n$=5)

**Example**: M=1010001101 is to be sent
$M(x) = x^9+x^7+x^3+x^2+1$

1. Multiply M(x) by $x^n$, $x^nM(x)= x^{14}+x^{12}+x^8+x^7+x^5+$ ....
2. Divide $x^nM(x)$ by $P(x)$, find remainder: $R(x)$=01110=$x^3+x^2+x$

# CRC (Cont)

- 3. Add the remainder $R(x)$ to $x^nM(x)$ :
  $T(x)= x^{14}+x^{12}+x^8+x^7+x^5+x^3+x^2+x$
- 4. Check that the result $T(x)$ is divisible by $P(x)$.
- Transmit the bit pattern corresponding to $T(x)$:
  101000110101110

## Popular CRC Polynomials

- CRC-12: $x^{12}+x^{11}+x^3+x^2+x+1$
- CRC-16: $x^{16}+x^{15}+x^2+1$
- CRC-CCITT: $x^{16}+x^{12}+x^5+1$
- CRC-32: Ethernet, FDDI, ...
  $x^{32}+x^{26}+x^{23}+x^{22}+x^{16}+x^{12}+x^{11}$
  $+x^{10}+x^8+x^7+x^5+x^4+x^2+x+1$

Even number of terms in the polynomial
⇒ Polynomial is divisible by 1+x
⇒ Will detect all odd number of bit errors

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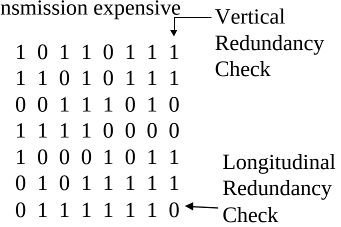
## Error Correcting Codes (ECC)

- Example: VRC+LRC will correct all single bit errors
- Forward error correction (FEC)
  Used if retransmission expensive



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 |
| 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |

Fig 4.5b Stallings

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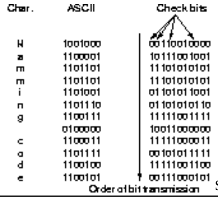
## Error-Correcting Codes

- Enough redundant information in a frame to detect and correct the error
- Lower limit on number of check bits to correct 1 error: $(m+r+1) <= 2^r$
- Hamming's method: (corrects 1-bit errors)
  - Check bits in positions in powers of 2 (1,2,4 ...)
  - Each data bit included in several check bits
    E.g., data bit 11 included in check bits 1, 2, 8
  - Other bit positions data

# Burst Error Correction

- ❑ Arrange code words as matrix
- ❑ Transmit one column at a time
- ❑ Uses kr check bits to immunize blocks of km data bits to single burst error of length k or less



| Char. | ASCII | Check bits |
|---|---|---|
| H | 1001000 | 00110010000 |
| a | 1100001 | 10111001001 |
| m | 1101101 | 11101010101 |
| m | 1101101 | 11101010101 |
| i | 1101001 | 01101011001 |
| n | 1101110 | 01101010110 |
| g | 1100111 | 11111001111 |
|  | 0100000 | 10011000000 |
| c | 1100011 | 11111000011 |
| o | 1101111 | 00101011111 |
| d | 1100100 | 11111001100 |
| e | 1100101 | 00111000101 |

Fig 3-6

# Internet Checksum Algorithm

Idea: view message as a sequence of 16-bit integers. Add these integers together using 16-bit ones complement arithmetic, and then take the ones complement of the result. That 16-bit number is the checksum.

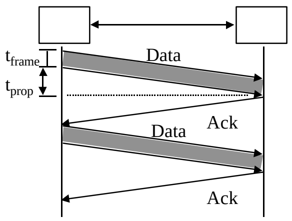
# Flow Control

- ❑ Flow Control = Sender does not flood the receiver, but maximizes throughput
- ❑ Sender throttled until receiver grants permission

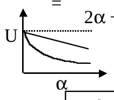
## Sliding Window Protocols

- Window = Set of sequence numbers to send/receive
- Sender window
  - Sender window increases when ack received
  - Packets in sender window must be buffered at source
  - Sender window may grow in some protocols

## Stop and Wait Flow Control



$$U = \frac{t_{frame}}{2t_{prop}+t_{frame}} = \frac{1}{2\alpha + 1}$$



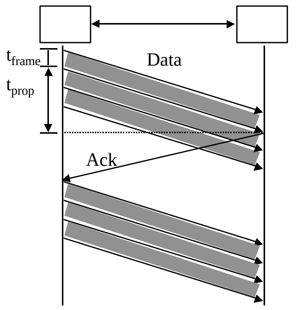
Light in vacuum
= 300 m/µs
Light in fiber
= 200 m/µs
Electricity
= 250 m/µs

$$\alpha = \frac{t_{prop}}{t_{frame}} = \frac{\text{Distance/Speed of Signal}}{\text{Frame size /Bit rate}} = \frac{\text{Distance} \times \text{Bit rate}}{\text{Frame size} \times \text{Speed of Signal}}$$

## Utilization: Examples

- ***Satellite Link:*** Propagation Delay $t_{prop}$ = 270 ms
  Frame Size = 4000 bits = 500 bytes
  Data rate = 56 kbps ⇒ $t_{frame}$ = 4/56 = 71 ms
  $\alpha = t_{prop}/t_{frame} = 270/71 = 3.8$
  U = 1/(2α+1) = ***0.12*** (too low !!)
- ***Short Link:*** 1 km = 5 µs,
  Rate=10 Mbps,
  Frame=500 bytes ⇒ $t_{frame}$= 4k/10M= 400 µs
  $\alpha=t_{prop}/t_{frame}=5/400=0.012$ ⇒ U=1/(2α+1)= ***0.98*** (great!)

# Sliding Window Protocol



$$U = \frac{Nt_{frame}}{2t_{prop}+t_{frame}}$$

$$= \begin{cases} \frac{N}{2\alpha+1} \\ 1 \text{ if } N>2\alpha+1 \end{cases}$$

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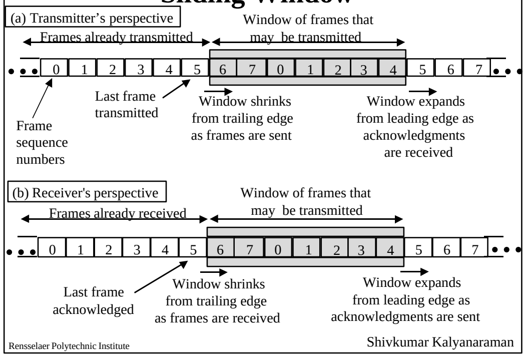
# Sliding Window


(a) Transmitter's perspective

Frames already transmitted

Window of frames that may be transmitted

Frame sequence numbers

Last frame transmitted

Window shrinks from trailing edge as frames are sent

Window expands from leading edge as acknowledgments are received

(b) Receiver's perspective

Frames already received

Window of frames that may be transmitted

Last frame acknowledged

Window shrinks from trailing edge as frames are received

Window expands from leading edge as acknowledgments are sent

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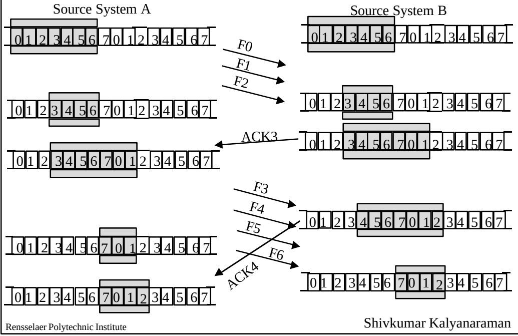
# Sliding Window: Example



# Effect of Window Size

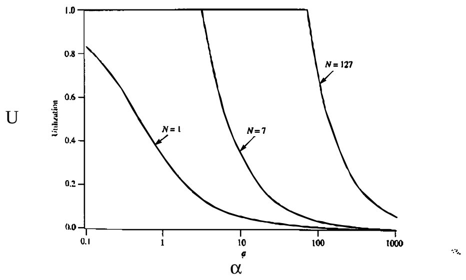


Fig 5.9 Stallings

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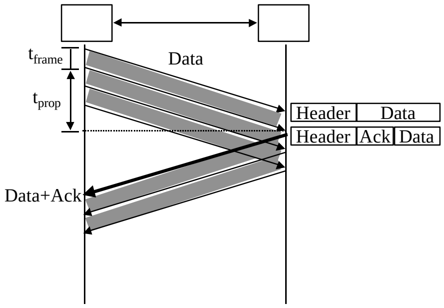
# Piggybacking



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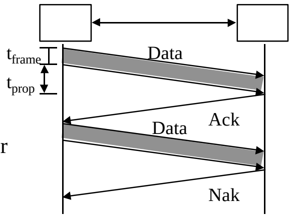
# Packet-error Control

- Error Control = Deliver frames without error, in the proper order to network layer
- Error control Mechanisms:
  - ***Ack/Nak:*** Provide sender some feedback about other end
  - ***Time-out:*** for the case when entire packet or ack is lost
  - ***Sequence numbers:*** to distinguish retransmissions from originals, and to identify what is acked/nacked

# Packet-error Control

- Automatic Repeat Request (ARQ)
  - Error detection
  - Acknowledgment
  - Retransmission after timeout
  - Negative Acknowledgment



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# Stop-and-Wait ARQ

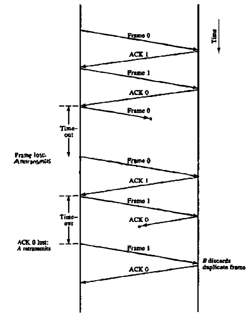

Fig 5.10

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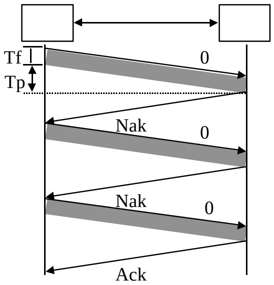
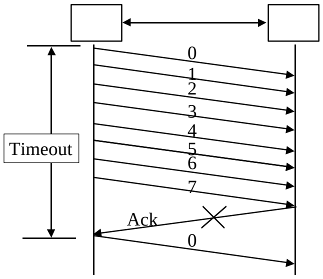
# Performance: Stop-and-Wait ARQ

- P=Probability of Frame Error
- $\alpha = T_p/T_f$
- $U=T_f/[N_r(T_f+2T_p)]$ $= 1/[N_r(1+2\alpha)]$
- $N_r=\Sigma\ i\ P^{i-1}(1-P)$ $=1/(1-P)$
- $\mathbf{U=(1-P)/(1+2\alpha)}$



# Selective Repeat: Window Size



Sequence number space ≥ 2 window size

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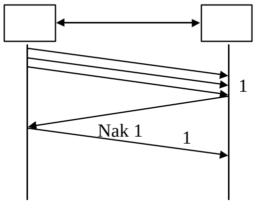
# Performance: Selective Repeat



- ❑ Error Free:
  $U=1$ if $N>2\alpha+1$
  $N/(2\alpha+1)$ otherwise
- ❑ With Errors:
  $N_r=\Sigma\ i\ P^{i-1}(1-P)$
  $=1/(1-P)$
- ❑ **$U=(1-P)$ if $N>(1+2\alpha)$**
  **$N(1-P)/(1+2\alpha)$** otherwise

Note that we have simply divided the error-free sliding window result by Nr, where, Nr = E [# transmitted frames to successfully transmit one frame] = 1-P in this case...

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# Go Back n: Example

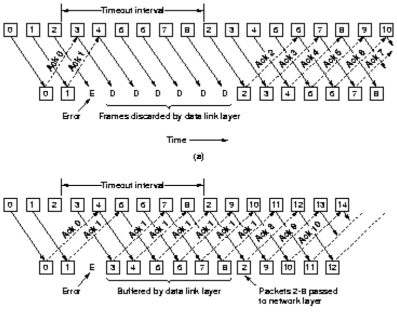

Fig 3-15

# Go-back-N

- ❑ Damaged Frame
  - ❑ Frame received with error
  - ❑ Frame lost
  - ❑ Last frame lost
- ❑ Damaged Ack
  - ❑ One ack lost, next one makes it
  - ❑ All acks lost
- ❑ Damaged Nak

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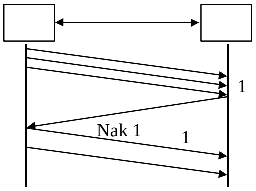
# Performance: Go-back-N



- ❑ Frames Retransmitted = 2α+1 if N>2α+1
  N otherwise
- ❑ U = (1-P)/(1+2αP) if N>2α+1
  N(1-P)/[(2α+1)(1-P+NP)] otherwise

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# Selective-Repeat ARQ

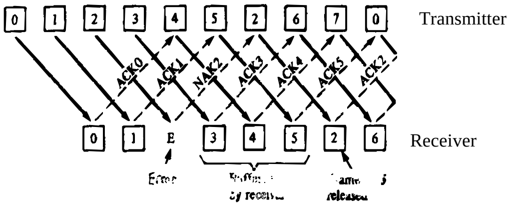

Fig 5.11b

# Performance Comparison

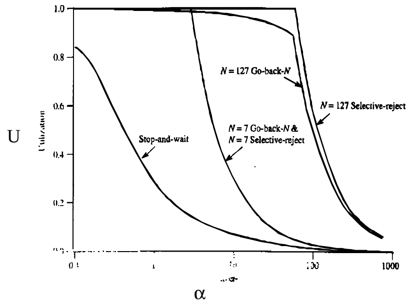

Fig 5.12

# HDLC Family

- ❑ Synchronous Data Link Control (SDLC): IBM
- ❑ **High-Level Data Link Control (HDLC): ISO**
- ❑ Link Access Procedure-Balanced (LAPB): X.25
- ❑ Link Access Procedure for the D channel (LAPD): ISDN
- ❑ Link Access Procedure for modems (LAPM): V.42
- ❑ Link Access Procedure for half-duplex links (LAPX): Teletex
- ❑ **Point-to-Point Protocol (PPP): Internet**
- ❑ **Logical Link Control (LLC): IEEE**
- ❑ Advanced Data Communications Control Procedures (ADCCP): ANSI
- ❑ V.120 and Frame relay also use HDLC

# HDLC

- ❑ High-level Data Link Control
- ❑ Bit-oriented, bit-stuffing for transparency
- ❑ Control field for seq numbers, acks etc
- ❑ Data field arbitrarily long (practical limits: checksum efficiency)
- ❑ CRC using CRC-CCITT generator polynomial

| Bits | 8 | 8 | 8 | ≥0 | 16 | 8 |
|---|---|---|---|---|---|---|
| | 01111110 | Address | Control | Data | Checksum | 01111110 |

# HDLC Frame Types

- ❑ Information, Supervisory, Unnumbered frames
- ❑ Sliding window with 3-bit sequence number, piggybacked acks
- ❑ New: Conn’n Management through supervisory frames

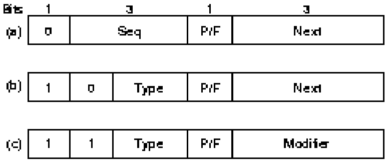

Fig 3-25

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# HDLC Frames

- ❑ Information Frames: User data
  - ❑ Piggybacked Acks: Next frame expected
  - ❑ Poll/Final = Command/Response
- ❑ Supervisory Frames: Flow and error control
  - ❑ Go back N and Selective Reject
  - ❑ Final ⇒ No more data to send
- ❑ Unnumbered Frames: Control *(bla, bla, bla …)*
  - ❑ Mode setting commands and responses
  - ❑ Information transfer commands and responses
  - ❑ Recovery commands and responses
  - ❑ Miscellaneous commands and responses

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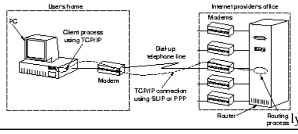
# Data Link Layer in the Internet

- ❑ Point-to-Point link scenarios
- ❑ Router-router leased line (PPP)
- ❑ dial-up host-router connection (old SLIP, now PPP)
- ❑ SLIP: Not an approved Internet Standard ⇒ incompatibilities
- ❑ PPP: Official Internet Standard.



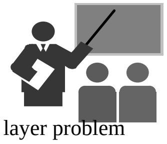
## Serial IP (SLIP)

- Simple: only framing = Flags + byte-stuffing
- Compressed headers (CSLIP) for efficiency on low speed links for interactive traffic.
- Problems:
  - Need other end’s IP address a priori (can’t dynamically assign IP addresses)
  - No “type” field => no multi-protocol encapsulation
  - No checksum => all errors detected/corrected by higher layer.
- RFCs: 1055, 1144

## PPP

- Frame format similar to HDLC
- Multi-protocol encapsulation, CRC, dynamic address allocation possible
  - key fields: flags, protocol, CRC (fig 2.3)
- Asynchronous and synchronous communications possible
- Link and Network Control Protocols (LCP, NCP) for flexible control & peer-peer negotiation
- Can be mapped onto low speed (9.6Kbps) and high speed channels (SONET)
- RFCs: 1548, 1332

## Summary



- The data link layer problem
- Framing methods
- Error and Flow Control: Sliding Window
- HDLC, SLIP, PPP.