The Data Link Layer

Chapter 3

Data Link Layer Design Issues

- Services offered to Network layer
- Framing
- Error control
- Flow control

Data Link Layer

- Algorithms for achieving:
  - Reliable,
  - Efficient communication of a whole units – frames (as opposed to bits – Physical Layer) between two machines.
- Two machines are connected by a communication channel that acts conceptually like a wire (e.g., telephone line, coaxial cable, or wireless channel).
- Essential property of a channel that makes it “wire-like” connection is that the bits are delivered in exactly the same order in which they are sent.

Data Link Layer

- For ideal channel (no distortion, unlimited bandwidth and no delay) the job of data link layer would be trivial.
- However, limited bandwidth, distortions and delay makes this job very difficult.

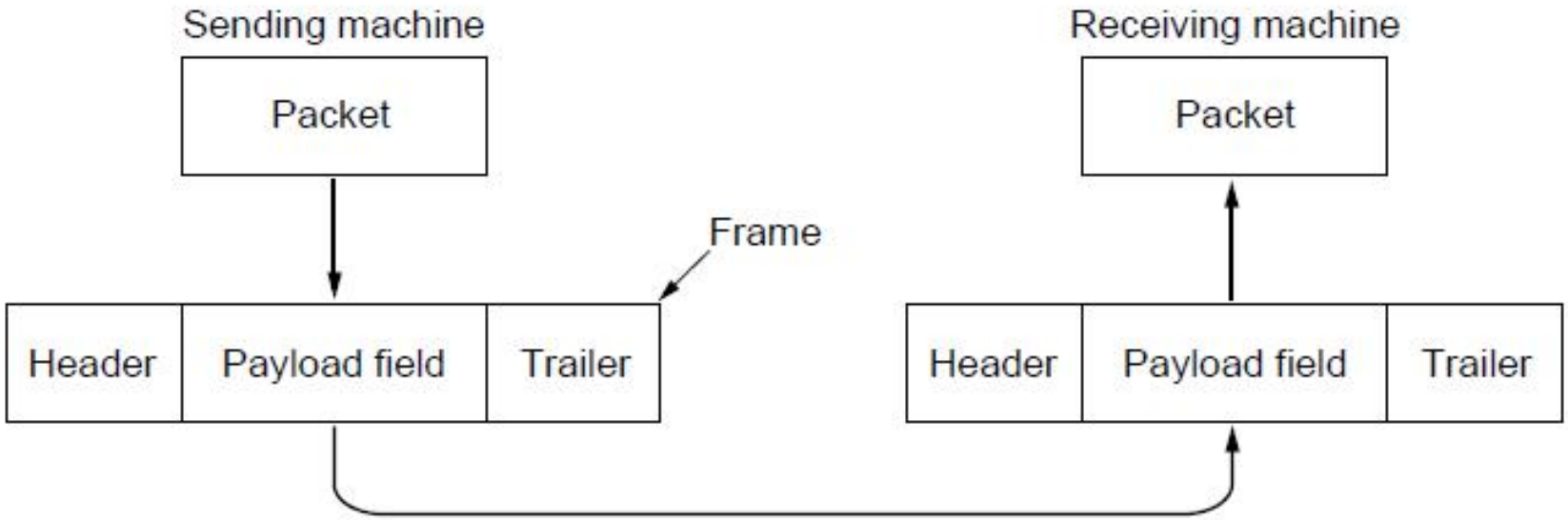
Data Link Layer Design Issues

- Physical layer delivers bits of information to and from data link layer. Thus, functions of Data Link Layer are:
  1. Providing a well-defined service interface to the network layer.
  2. Dealing with transmission errors.
  3. Regulating the flow of data so that slow receivers are not swamped by fast senders.
- Data Link layer
  - Takes the packets from Network layer, and
  - Encapsulates them into **frames**

Data Link Layer Design Issues

- Each frame has a
  - frame header – fields for holding the packet, and
  - frame trailer.
- Frame Management is what Data Link Layer does.

Packets and Frames

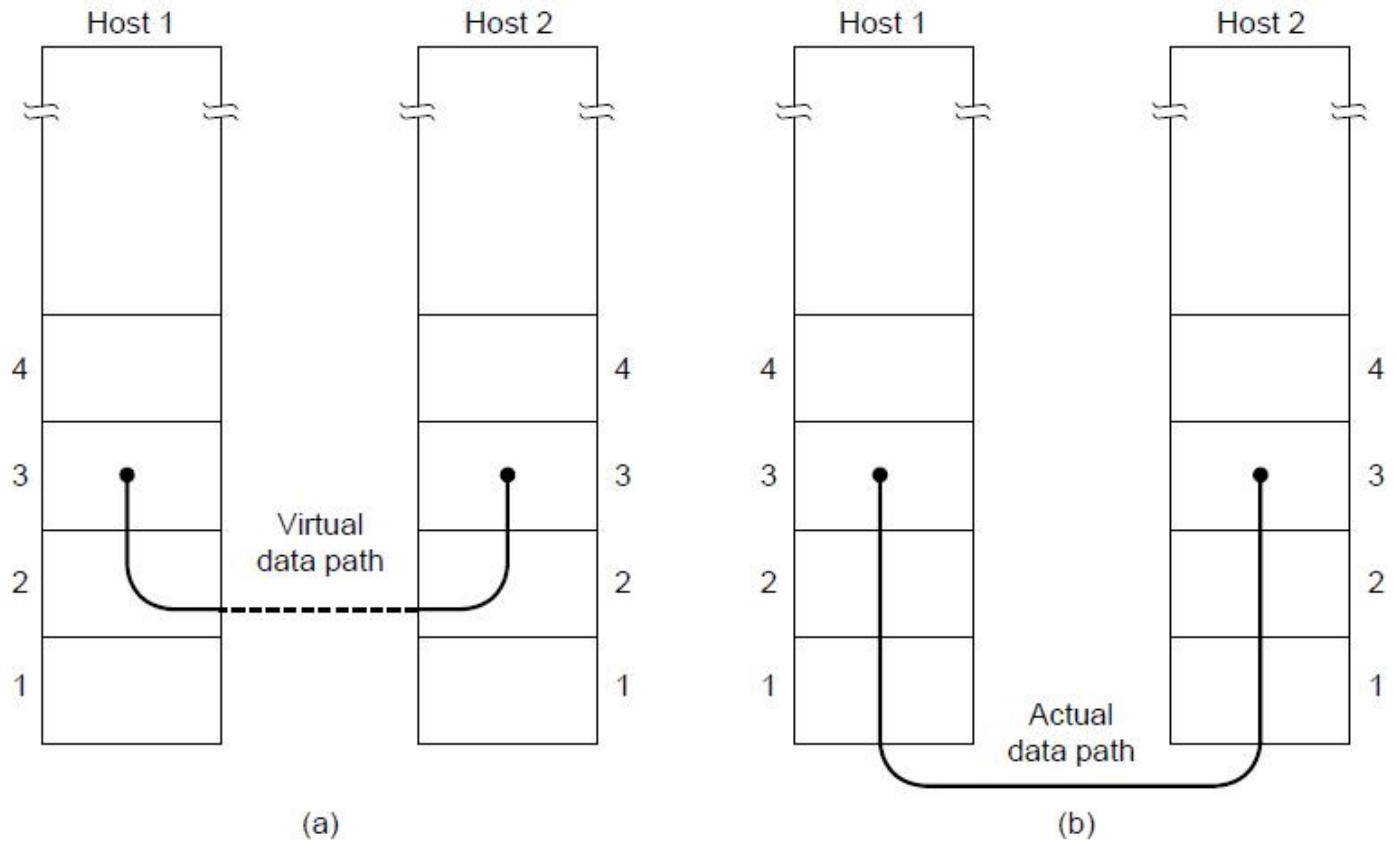


Relationship between packets and frames.

Services Provided to the Network Layer

- Principal Service Function of the data link layer is to transfer the data from the network layer on the source machine to the network layer on the destination machine.
  - Process in the network layer hands some bits (packet) to the data link layer for transmission.
  - Job of data link layer is to transmit the packet to the destination machine so they can be handed over to the network layer process there

Network Layer Services



(a) Virtual communication. (b) Actual communication.

Possible Services Offered

- Unacknowledged connectionless service.
- Acknowledged connectionless service.
- Acknowledged connection-oriented service.

Unacknowledged Connectionless Service

- It consists of having the source machine send independent frames to the destination machine without having the destination machine acknowledge them.
- In all the communication channel where real time operation is more important than quality of transmission.
- Example: Ethernet, Voice over IP, etc.

Acknowledged Connectionless Service

- Each frame sent by the Data Link layer is acknowledged and the sender knows if a specific frame has been received or lost.
- Typically the protocol uses a specific time period that if has passed without getting acknowledgment it will re-send the frame.
- This service is useful for commutation when an unreliable channel is being utilized (e.g., 802.11 WiFi).

Acknowledged Connection Oriented Service

- Source and Destination establish a connection first.
- Each frame sent is numbered
  - Data link layer guarantees that each frame sent is indeed received.
  - It guarantees that each frame is received only once and that all frames are received in the correct order.
- Examples:
  - Satellite channel communication

Acknowledged Connection Oriented Service

- Three distinct phases:
  1. Connection is established by having both side initialize variables and counters needed to keep track of which frames have been received and which ones have not.
  2. One or more frames are transmitted.
  3. Finally, the connection is released – freeing up the variables, buffers, and other resources used to maintain the connection.

Framing

- To provide service to the network layer, the data link layer must use the service provided to it by physical layer.
- Stream of data bits provided to data link layer is not guaranteed to be without errors.
- Errors could be:
  - Number of received bits does not match number of transmitted bits (deletion or insertion)
  - Alteration of bit Value
- It is up to data link layer to correct the errors if necessary.

Framing

- Transmission of the data link layer starts with breaking up the bit stream
  - into discrete frames
  - Computation of a checksum for each frame, and
  - Include the checksum into the frame before it is transmitted.
- Receiver computes its checksum error for a receiving frame and if it is different from the checksum that is being transmitted will have to deal with the error.
- Framing is more difficult than one could think!

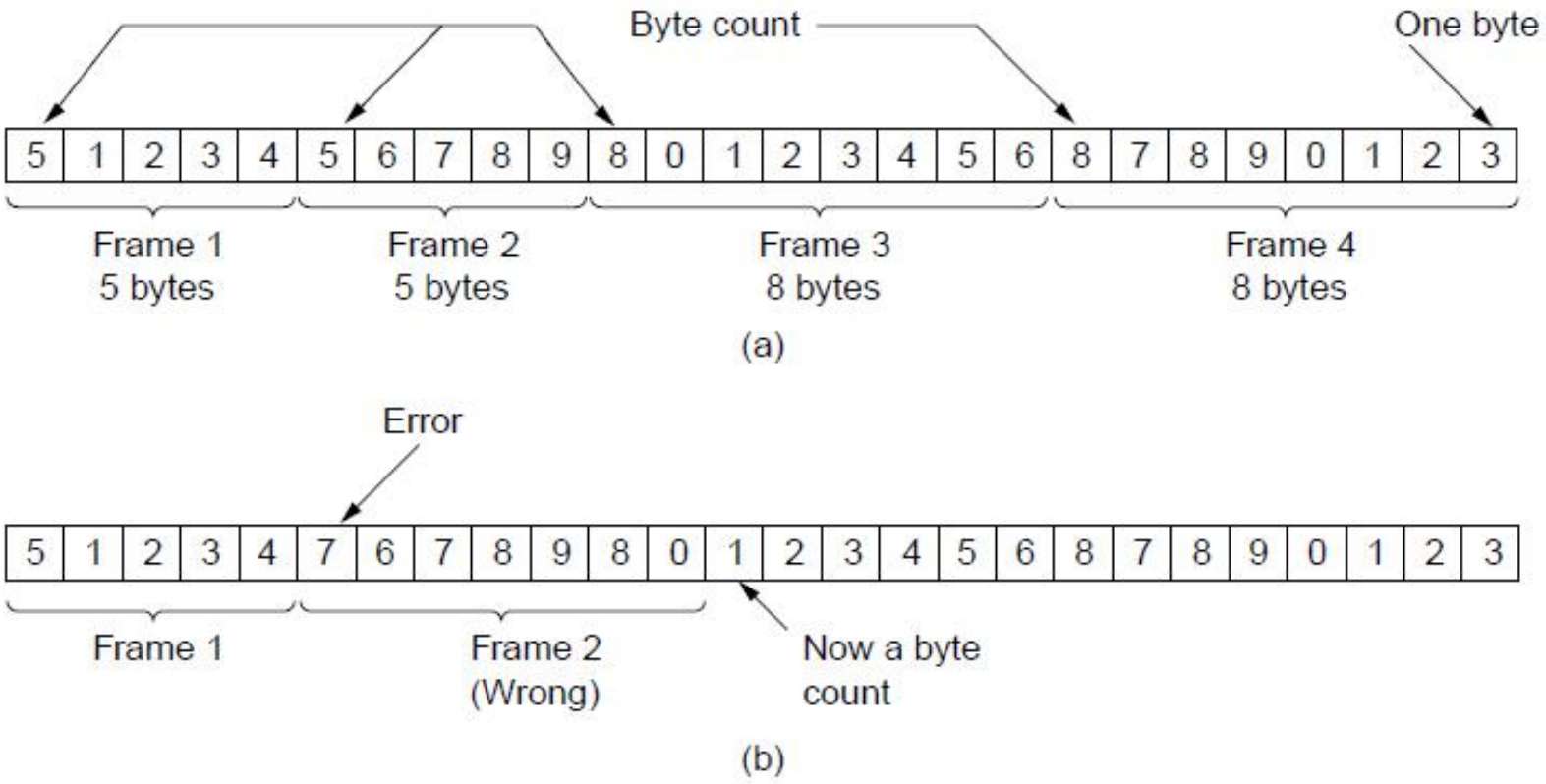
Framing Methods

- Byte count.
- Flag bytes with byte stuffing.
- Flag bits with bit stuffing.
- Physical layer coding violations.

Byte Count Framing Method

- It uses a field in the header to specify the number of bytes in the frame.
- Once the header information is being received it will be used to determine end of the frame.
- See figure in the next slide:
- Trouble with this algorithm is that when the count is incorrectly received the destination will get out of synch with transmission.
  - Destination may be able to detect that the frame is in error but it does not have a means (in this algorithm) how to correct it.

Framing (1)

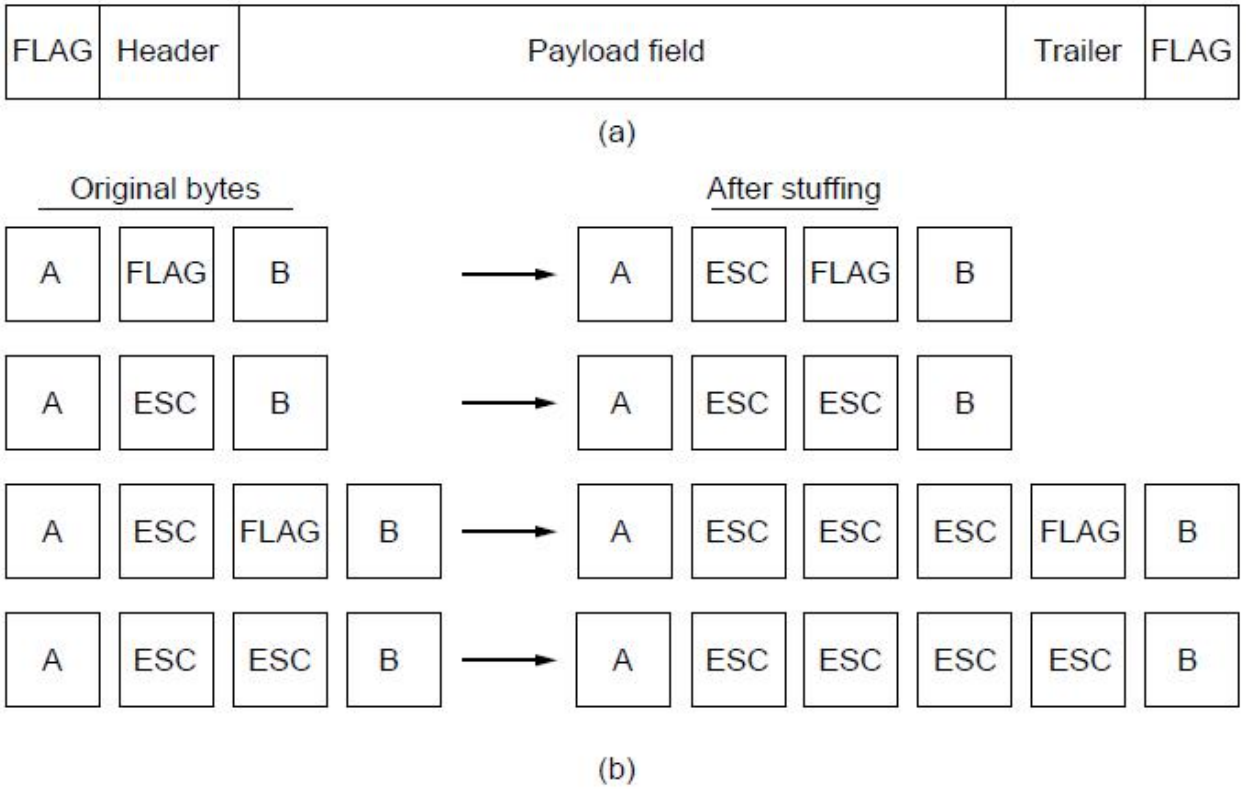


A byte stream. (a) Without errors. (b) With one error.

Flag Bytes with Byte Stuffing Framing Method

- This methods gets around the boundary detection of the frame by having each frame appended by the start and end special bytes.
- If they are the same (beginning and ending byte in the frame) they are called **flag byte**.
- If the actual data contains a byte that is identical to the FLAG byte (e.g., picture, data stream, etc.) the convention that can be used is to have escape character inserted just before the “FLAG” character.

Framing (2)



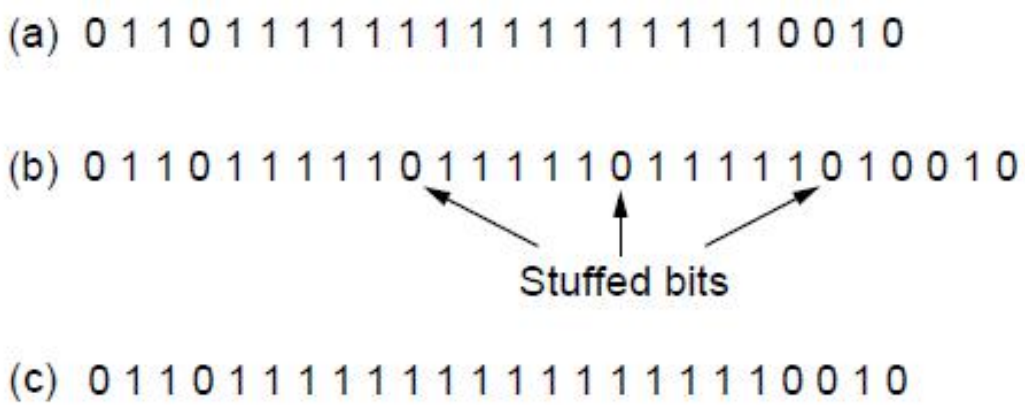
a) A frame delimited by flag bytes.

b) Four examples of byte sequences before and after byte stuffing.

Flag Bits with Bit Stuffing Framing Method

- This methods achieves the same thing as Byte Stuffing method by using Bits (1) instead of Bytes (8 Bits).
- It was developed for High-level Data Link Control (HDLC) protocol.
- Each frames begins and ends with a special bit pattern:
  - 01111110 or 0x7E <- Flag Byte
  - Whenever the sender's data link layer encounters five consecutive 1s in the data it automatically stuffs a 0 bit into the outgoing bit stream.
  - USB uses bit stuffing.

Framing (3)



Bit stuffing. (a) The original data. (b) The data as they appear on the line. (c) The data as they are stored in the receiver's memory after destuffing.

Framing

Violating Physical Layer encoding:

- Many networks uses encoding techniques like manchestor, differential manchestor encoding.
- These techniques have transition in middle of each bit.
- Violating this and using a high-high or low-low pair for indicating beginning or end of frame

Error Control

- After solving the marking of the frame with start and end the data link layer has to handle eventual errors in transmission or detection.
  - Ensuring that all frames are delivered to the network layer at the destination and in proper order.
- Unacknowledged connectionless service: it is OK for the sender to output frames regardless of its reception.
- Reliable connection-oriented service: it is NOT OK.

Error Control

- Reliable connection-oriented service usually will provide a sender with some feedback about what is happening at the other end of the line.
  - Receiver Sends Back Special Control Frames.
  - If the Sender Receives positive Acknowledgment it will know that the frame has arrived safely.
- Timer and Frame Sequence Number for the Sender is Necessary to handle the case when there is no response (positive or negative) from the Receiver .

Flow Control

- Important Design issue for the cases when the sender is running on a fast powerful computer and receiver is running on a slow low-end machine.
- Two approaches:
  1. Feedback-based flow control
  2. Rate-based flow control
  3. Credit-based flow control

Feedback-based Flow Control

- Receiver sends back information to the sender giving it permission to send more data, or
- Telling sender how receiver is doing.
- Most data link layer protocols uses feedback-based flow control

Rate-based Flow Control

- Built in mechanism that limits the rate at which sender may transmit data, without the need for feedback from the receiver.
- ABR service in ATM uses rate-based flow control

Credit-based Flow Control

- Sender is given explicit credit by the receiver. Utilize the credits on each byte. Transmit at any rate till the credits are available. Pause when the credits are over and wait for more credits to come.
- TCP implements credit based flow control

Error Detection and Correction

- Two basic strategies to deal with errors:
  1. Include enough redundant information to enable the receiver to deduce what the transmitted data must have been.

     Error correcting codes.

  2. Include just enough redundancy to allow the receiver to deduce that an error has occurred (but not which error).

     Error detecting codes.

Error Detection and Correction

- Error codes are examined in Link Layer because this is the first place that we have run up against the problem of reliably transmitting groups of bits.
- Error codes have been developed after long fundamental research conducted in mathematics.
- Many protocol standards get codes from the large field in mathematics.

Error Detection & Correction Code

- All the codes add redundancy to the information that is being sent.
- A frame consists of
  - m data bits (message) and
  - r redundant bits (check).
- n – total length of a block (i.e., $n = m + r$)
- n – bit ***codeword*** containing n bits.
- (n, m) – code
- m/n – code rate (range ½ for noisy channel and close to 1 for high-quality channel).

Error Detection & Correction Code

- Number of bit positions in which two codewords differ is called ***Hamming Distance***. It shows that two codes are ***d*** distance apart, and it will require ***d*** errors to convert one into the other.
- ***Example***

  Transmitted: 10001001

  Received: 10110001

  XOR operation gives number of bits that are different.

  XOR: 00111000

Error Detection & Correction Code

- All 2^m possible data messages are legal, but due to the way the check bits are computed not all 2^n possible code words are used.
- Only small fraction of $2^m/2^n=1/2^r$ ***will be legal codewords.***
- The error-detecting and error-correcting codes of the block code depend on this Hamming distance.
- To reliably detect d error, one would need a distance $d+1$ code.
- To correct d error, one would need a distance $2d+1$ code.

Error Detection & Correction Code

Example:

- 4 valid codes:
  - 0000000000
  - 0000011111
  - 1111100000
  - 1111111111
- Minimal Distance of this code is 5 => can correct double errors and it detect quadruple errors.
- 0000000111 => single or double – bit error. Hence the receiving end must assume the original transmission was 0000011111.
- 0000000000 => had triple error that was received as 0000000111 it would be detected in error.

Error Detection & Correction Code

- One cannot perform double error correction and at the same time detect quadruple errors.
- Error correction requires evaluation of each candidate codeword which may be time consuming search.
- Through design this search time can be minimized.
- In theory if n = m + r, this requirement becomes:
  - $(m + r + 1) \leq 2^r$

Hamming Code

- Codeword: b1 b2 b3 b4 ….
- Check bits: The bit positions that are powers of 2 (p1, p2, p4, p8, p16, …).
- The rest of bits (m3, m5, m6, m7, m9, …) are filled with m data bits.
- Example of the Hamming code with $m = 7$ data bits and $r = 4$ check bits is given in the next slide.

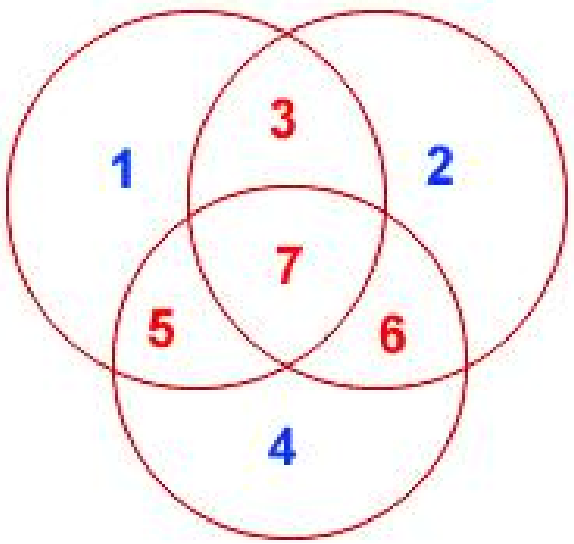
The Hamming Code

- A message having four data bits (D)
- 3 error correcting bits will make it a 7-bit codeword.
- This would be called a (7,4) code.
- The three bits to be added are three EVEN Parity bits (P), where the parity of each is computed on different subsets of the message bits as shown below.

7	6	5	4	3	2	1	
D_4	D_3	D_2	P_4	D_1	P_2	P_1	7-BIT CODEWORD
D_4	-	D_2	-	D_1	-	P_1	(EVEN PARITY)
D_4	D_3	-	-	D_1	P_2	-	(EVEN PARITY)
D_4	D_3	D_2	P_4	-	-	-	(EVEN PARITY)

Hamming Code

- **Why Those Bits?** - The three parity bits (1,2,4) are related to the data bits (3,5,6,7) as shown at right. In this diagram, each overlapping circle corresponds to one parity bit and defines the four bits contributing to that parity computation. For example, data bit 3 contributes to parity bits 1 and 2. Each circle (parity bit) encompasses a total of four bits, and each circle must have EVEN parity. Given four data bits, the three parity bits can easily be chosen to ensure this condition.



- It can be observed that changing any one bit numbered 1..7 uniquely affects the three parity bits. Changing bit 7 affects all three parity bits, while an error in bit 6 affects only parity bits 2 and 4, and an error in a parity bit affects only that bit. The location of any single bit error is determined directly upon checking the three parity circles.

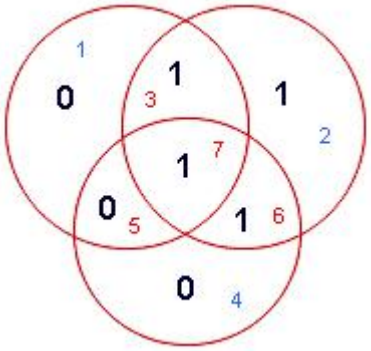
Hamming Code

- For example, the message 1101 would be sent as 1100110, since:

7	6	5	4	3	2	1	
1	1	0	0	1	1	0	7-BIT CODEWORD
1	-	0	-	1	-	**0**	(EVEN PARITY)
1	1	-	-	1	**1**	-	(EVEN PARITY)
1	1	0	**0**	-	-	-	(EVEN PARITY)

Hamming Codes

- When these seven bits are entered into the parity circles, it can be confirmed that the choice of these three parity bits ensures that the parity within each circle is EVEN, as shown here.



Hamming Code

- It may now be observed that if an error occurs in any of the seven bits, that error will affect different combinations of the three parity bits depending on the bit position.

- For example, suppose the above message 1100110 is sent and a single bit error occurs such that the codeword 1110110 is received:

transmitted message		received message
1 1 0 0 1 1 0	---------->	1 1 1 0 1 1 0
BIT: 7 6 5 4 3 2 1		BIT: 7 6 5 4 3 2 1

The above error (in bit 5) can be corrected by examining which of the three parity bits was affected by the bad bit:

Hamming Code

7	6	5	4	3	2	1			
1	1	1	**0**	1	**1**	**0**	7-BIT CODEWORD		
1	-	1	-	1	-	0	(EVEN PARITY)	**NOT!**	**1**
1	1	-	-	1	1	-	(EVEN PARITY)	**OK!**	**0**
1	1	1	0	-	-	-	(EVEN PARITY)	**NOT!**	**1**

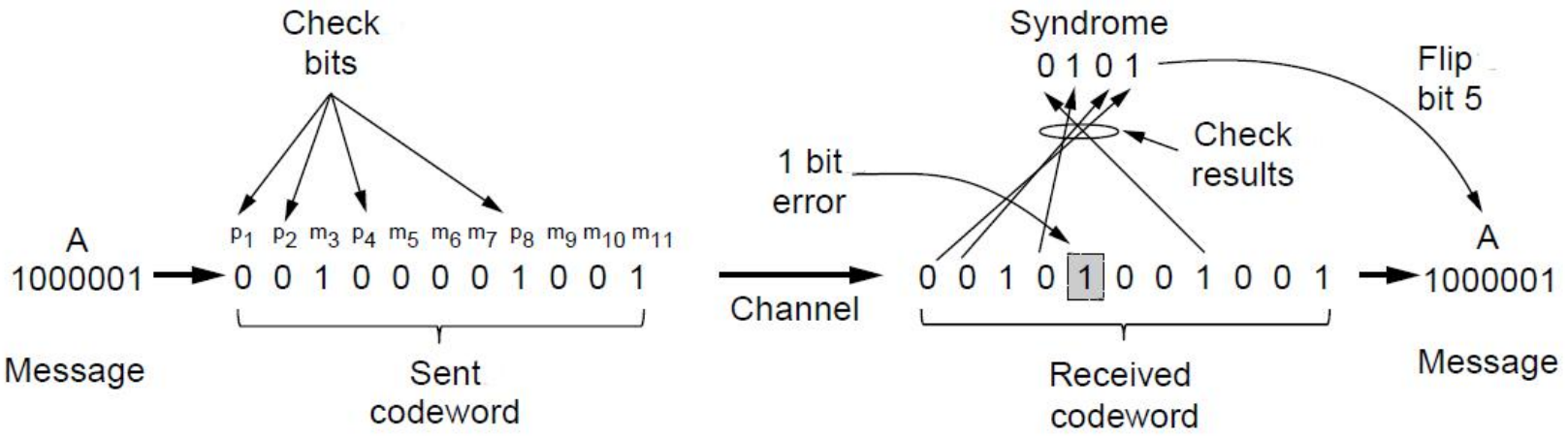
Hamming Code

- *In fact, the bad parity bits labeled **101** point directly to the bad bit since **101** binary equals **5**.* Examination of the 'parity circles' confirms that any single bit error could be corrected in this way.
- The value of the Hamming code can be summarized:

1. Detection of 2 bit errors (assuming no correction is attempted);
2. Correction of single bit errors;
3. Cost of 3 bits added to a 4-bit message.

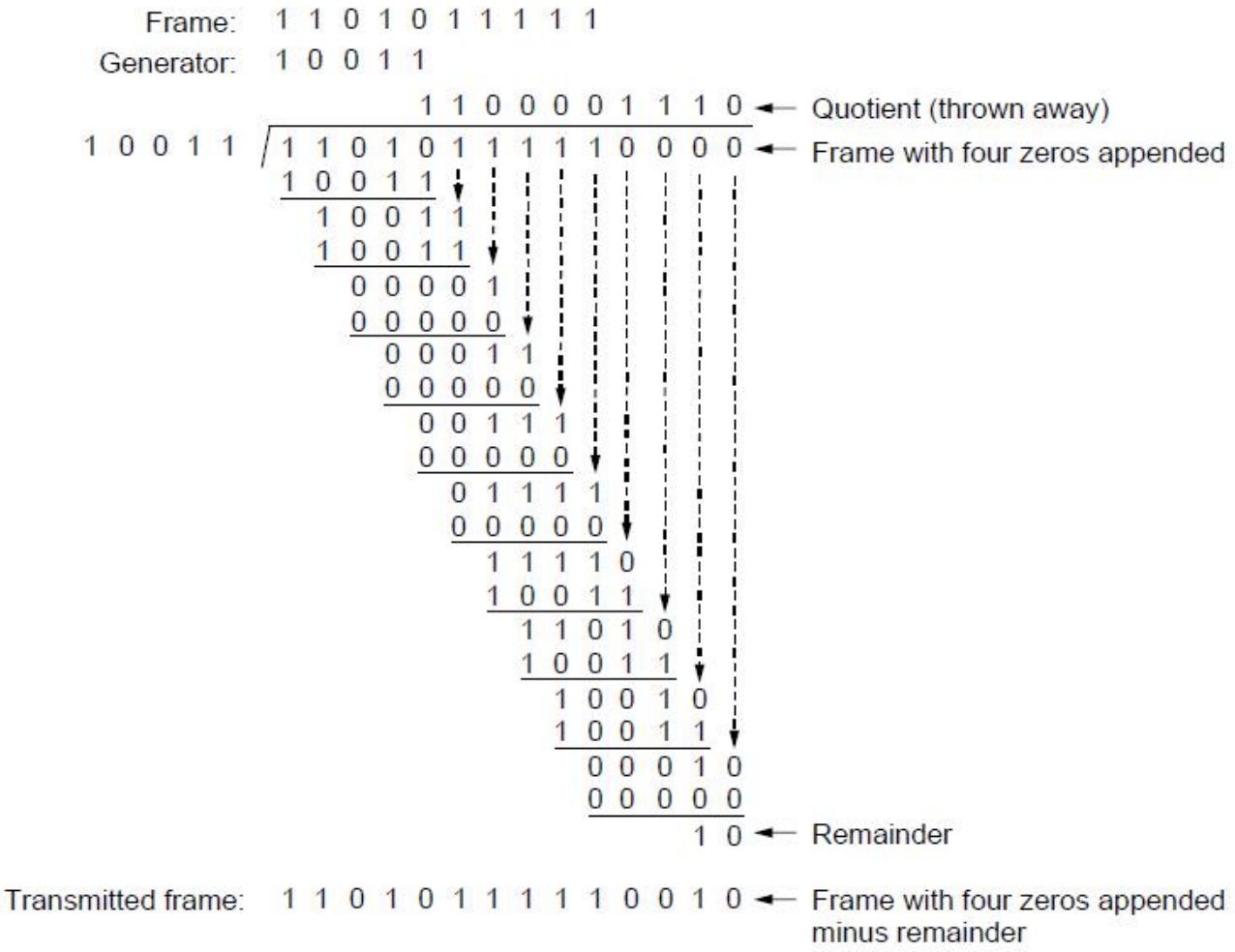
- The ability to correct single bit errors comes at a cost which is less than sending the entire message twice. (Recall that simply sending a message twice accomplishes no error correction.)

Error Detection Codes



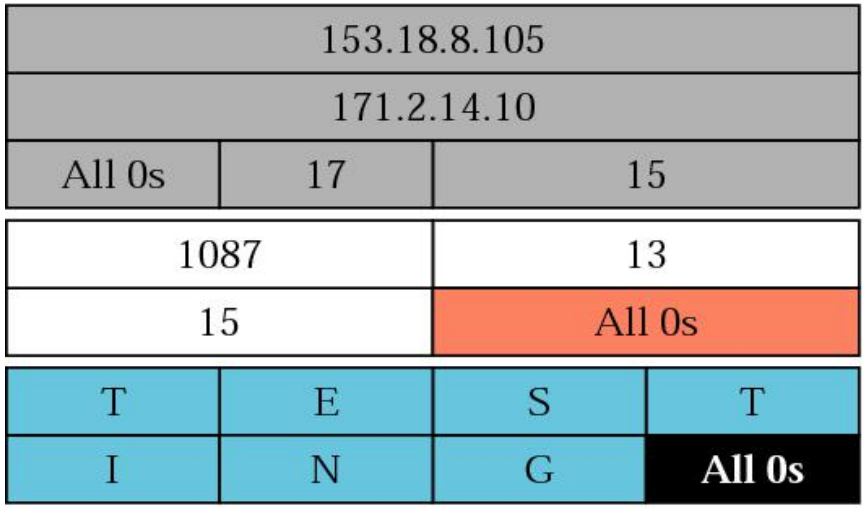
Example of an (11, 7) Hamming code correcting a single-bit error.

Error-Detecting Codes - CRC



Example calculation of the CRC

Error-Detecting Codes - Checksum



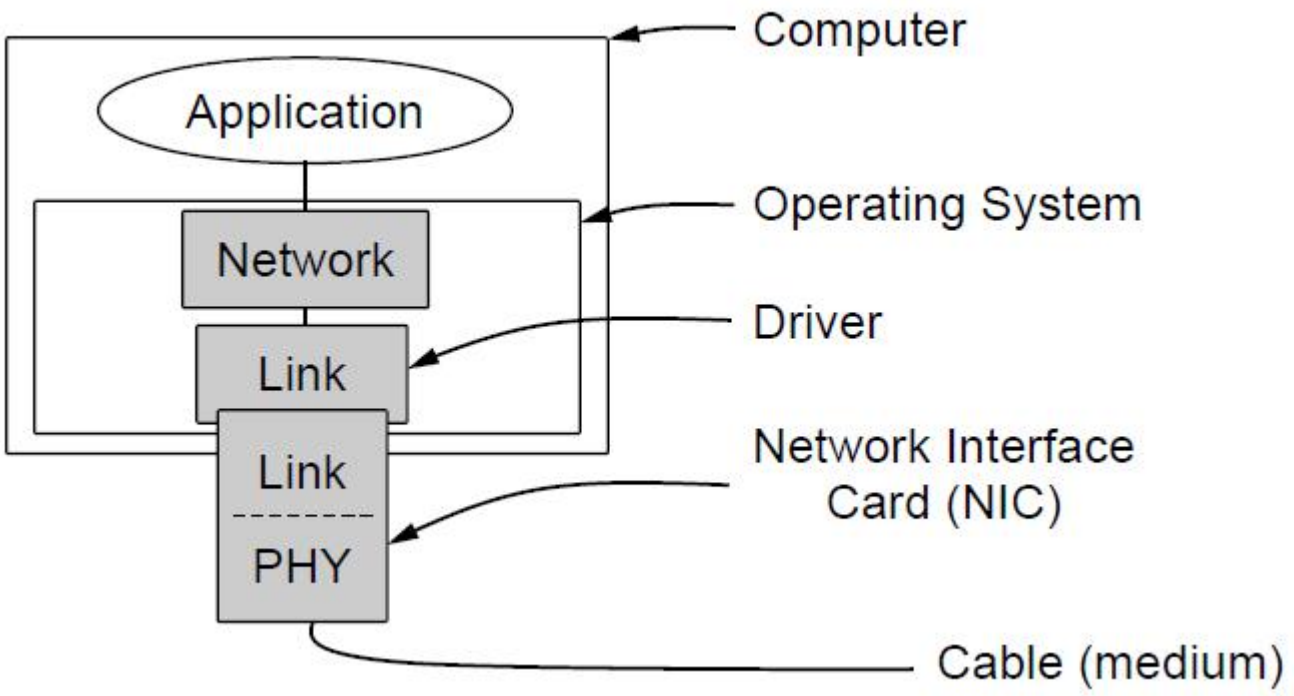
10011001 00010010	153.18
00001000 01101001	8.105
10101011 00000010	171.2
00001110 00001010	14.10
00000000 00010001	0 and 17
00000000 00001111	15
00000100 00111111	1087
00000000 00001101	13
00000000 00001111	15
00000000 00000000	0 (checksum)
01010100 01000101	T and E
01010011 01010100	S and T
01001001 01001110	I and N
01000111 00000000	G and 0 (padding)
10010110 11101011	Sum
01101001 00010100	Checksum

Example calculation (in UDP) of the Checksum

Elementary Data Link Protocols (1)

- Utopian Simplex Protocol
- Simplex Stop-and-Wait Protocol
  - Error-Free Channel
- Simplex Stop-and-Wait Protocol
  - Noisy Channel

Elementary Data Link Protocols (2)



Implementation of the physical, data link, and network layers

- The PHY process and some of the data link layer process run on dedicate hardware called a NIC
- The rest of the link layer process and the network layer process run on the main CPU as part of the OS, with the software for the link layer process often taking the form of a device driver

Key Assumptions

- Machine A wants to send a long stream of data to machine B, using a reliable, connection-oriented service
- A is assumed to have an infinite supply of data ready to send and never has to wait for data to be produced
- Machines do not crash

Elementary Data Link Protocols (3)

```
#define MAX_PKT 1024                                        /* determines packet size in bytes */

typedef enum {false, true} boolean;                         /* boolean type */
typedef unsigned int seq_nr;                                /* sequence or ack numbers */
typedef struct {unsigned char data[MAX_PKT];} packet;       /* packet definition */
typedef enum {data, ack, nak} frame_kind;                   /* frame_kind definition */

typedef struct {                                            /* frames are transported in this layer */
  frame_kind kind;                                          /* what kind of frame is it? */
  seq_nr seq;                                               /* sequence number */
  seq_nr ack;                                               /* acknowledgement number */
  packet info;                                              /* the network layer packet */
} frame;
```

. . .

Some definitions needed in the protocols to follow. These definitions are located in the file *protocol.h.*

Elementary Data Link Protocols (4)

```
/* Wait for an event to happen; return its type in event. */
void wait_for_event(event_type *event);

/* Fetch a packet from the network layer for transmission on the channel. */
void from_network_layer(packet *p);

/* Deliver information from an inbound frame to the network layer. */
void to_network_layer(packet *p);

/* Go get an inbound frame from the physical layer and copy it to r. */
void from_physical_layer(frame *r);

/* Pass the frame to the physical layer for transmission. */
void to_physical_layer(frame *s);

/* Start the clock running and enable the timeout event. */
void start_timer(seq_nr k);

/* Stop the clock and disable the timeout event. */
void stop_timer(seq_nr k); . . .
```

Some definitions needed in the protocols to follow. These definitions are located in the file *protocol.h.*

Elementary Data Link Protocols (5)

```
/* Start an auxiliary timer and enable the ack_timeout event. */
void start_ack_timer(void);

/* Stop the auxiliary timer and disable the ack_timeout event. */
void stop_ack_timer(void);

/* Allow the network layer to cause a network_layer_ready event. */
void enable_network_layer(void);

/* Forbid the network layer from causing a network_layer_ready event. */
void disable_network_layer(void);

/* Macro inc is expanded in-line: increment k circularly. */
#define inc(k) if (k < MAX_SEQ) k = k + 1; else k = 0
```

Some definitions needed in the protocols to follow. These definitions are located in the file *protocol.h.*

Utopian Simplex Protocol (1)

```
/* Protocol 1 (Utopia) provides for data transmission in one direction only, from
   sender to receiver. The communication channel is assumed to be error free
   and the receiver is assumed to be able to process all the input infinitely quickly.
   Consequently, the sender just sits in a loop pumping data out onto the line as
   fast as it can. */

typedef enum {frame_arrival} event_type;
#include "protocol.h"

void sender1(void)
{
  frame s;                          /* buffer for an outbound frame */
  packet buffer;                    /* buffer for an outbound packet */

  while (true) {
      from_network_layer(&buffer);  /* go get something to send */
      s.info = buffer;              /* copy it into s for transmission */
      to_physical_layer(&s);        /* send it on its way */
  }                                 /* Tomorrow, and tomorrow, and tomorrow,
                                       Creeps in this petty pace from day to day
                                       To the last syllable of recorded time.
                                           – Macbeth, V, v */
}
```

. . .

A utopian simplex protocol.

Utopian Simplex Protocol (2)

```
void receiver1(void)
{
  frame r;
  event_type event;                    /* filled in by wait, but not used here */

  while (true) {
       wait_for_event(&event);         /* only possibility is frame_arrival */
       from_physical_layer(&r);        /* go get the inbound frame */
       to_network_layer(&r.info);      /* pass the data to the network layer */
  }
}
```

A utopian simplex protocol.

Key Assumptions

- Drop the most unrealistic restriction used in protocol 1:
  - The ability of the receiving network layer to process incoming data infinitely quickly

or

  - The presence in the receiving data link layer of an infinite amount of buffer space in which to store all incoming frames while they are waiting their respective turns

Simplex Stop-and-Wait Protocol (1)

```
/* Protocol 2 (Stop-and-wait) also provides for a one-directional flow of data from
   sender to receiver. The communication channel is once again assumed to be error
   free, as in protocol 1. However, this time the receiver has only a finite buffer
   capacity and a finite processing speed, so the protocol must explicitly prevent
   the sender from flooding the receiver with data faster than it can be handled. */

typedef enum {frame_arrival} event_type;
#include "protocol.h"

void sender2(void)
{
  frame s;                              /* buffer for an outbound frame */
  packet buffer;                        /* buffer for an outbound packet */
  event_type event;                     /* frame_arrival is the only possibility */

  while (true) {
      from_network_layer(&buffer);      /* go get something to send */
      s.info = buffer;                  /* copy it into s for transmission */
      to_physical_layer(&s);            /* bye-bye little frame */
      wait_for_event(&event);           /* do not proceed until given the go ahead */
  }
}    . . .
```

A simplex stop-and-wait protocol.

Simplex Stop-and-Wait Protocol (2)

```
void receiver2(void)
{
  frame r, s;                          /* buffers for frames */
  event_type event;                    /* frame_arrival is the only possibility */
  while (true) {
      wait_for_event(&event);          /* only possibility is frame_arrival */
      from_physical_layer(&r);         /* go get the inbound frame */
      to_network_layer(&r.info);       /* pass the data to the network layer */
      to_physical_layer(&s);           /* send a dummy frame to awaken sender */
  }
}
```

A simplex stop-and-wait protocol.

Positive Acknowledgement with Retransmission

- Normal situation of a communication channel that makes errors
- Frames may be either damaged or lost completely
- Assume that if a frame is damaged in transit, the receiver hardware will detect this when it computes the checksum
- It seem that a variation of protocol 2 would work: adding a timer where timeout will retransmit a frame

Positive Acknowledgement with Retransmission

Consider

a)The network layer on A gives packet 1 to its data link layer. The packet is correctly received at B and passed to the network layer on B. B sends an acknowledgement frame back to A.

b)The acknowledgement frame gets lost completely.

c)The data link layer on A eventually times out and sends the frame containing packet 1 again

d)The duplicate frame also arrives at the data link layer on B perfectly and sent to network layer.

The protocol will fail. Some way for the receiver to be able to distinguish a frame that it is seeing for the first time from a retransmission is needed

Positive Acknowledgement with Retransmission

- Since a small frame header is desirable, the question arises: What is the minimum number of bits needed for the sequence number?
- The only ambiguity in this protocol is between a frame, m, and its direct successor, m + 1.
- If frame m is lost or damaged, the receiver will not acknowledge it, so the sender will keep trying to send it.
- Once it has been correctly received, the receiver will send an acknowledgement to the sender.
- Depending upon whether the acknowledgement frame gets back to the sender correctly or not, the sender may try to send m or m + 1.
- A 1-bit sequence number (0 or 1) is therefore sufficient

Simplex Stop-and-Wait Protocol for a Noisy Channel (1)

```
/* Protocol 3 (PAR) allows unidirectional data flow over an unreliable channel. */

#define MAX_SEQ 1                                   /* must be 1 for protocol 3 */
typedef enum {frame_arrival, cksum_err, timeout} event_type;
#include "protocol.h"

void sender3(void)
{
  seq_nr next_frame_to_send;                        /* seq number of next outgoing frame */
  frame s;                                          /* scratch variable */
  packet buffer;                                    /* buffer for an outbound packet */
  event_type event;

     . . .
```

A positive acknowledgement with retransmission protocol.

Simplex Stop-and-Wait Protocol for a Noisy Channel (2)

```
next_frame_to_send = 0;                    /* initialize outbound sequence numbers */
from_network_layer(&buffer);               /* fetch first packet */
while (true) {
    s.info = buffer;                       /* construct a frame for transmission */
    s.seq = next_frame_to_send;            /* insert sequence number in frame */
    to_physical_layer(&s);                 /* send it on its way */
    start_timer(s.seq);                    /* if answer takes too long, time out */
    wait_for_event(&event);                /* frame_arrival, cksum_err, timeout */
    if (event == frame_arrival) {
        from_physical_layer(&s);           /* get the acknowledgement */
        if (s.ack == next_frame_to_send) {
            stop_timer(s.ack);             /* turn the timer off */
            from_network_layer(&buffer);   /* get the next one to send */
            inc(next_frame_to_send);       /* invert next_frame_to_send */
        }
    }
}
```

. . .

A positive acknowledgement with retransmission protocol.

Simplex Stop-and-Wait Protocol for a Noisy Channel (3)

```
void receiver3(void)
{
  seq_nr frame_expected;
  frame r, s;
  event_type event;

  frame_expected = 0;
  while (true) {
      wait_for_event(&event);                  /* possibilities: frame_arrival, cksum_err */
      if (event == frame_arrival) {            /* a valid frame has arrived */
          from_physical_layer(&r);             /* go get the newly arrived frame */
          if (r.seq == frame_expected) {       /* this is what we have been waiting for */
              to_network_layer(&r.info);       /* pass the data to the network layer */
              inc(frame_expected);             /* next time expect the other sequence nr */
          }
          s.ack = 1 – frame_expected;          /* tell which frame is being acked */
          to_physical_layer(&s);               /* send acknowledgement */
      }
  }
}
```

A positive acknowledgement with retransmission protocol.

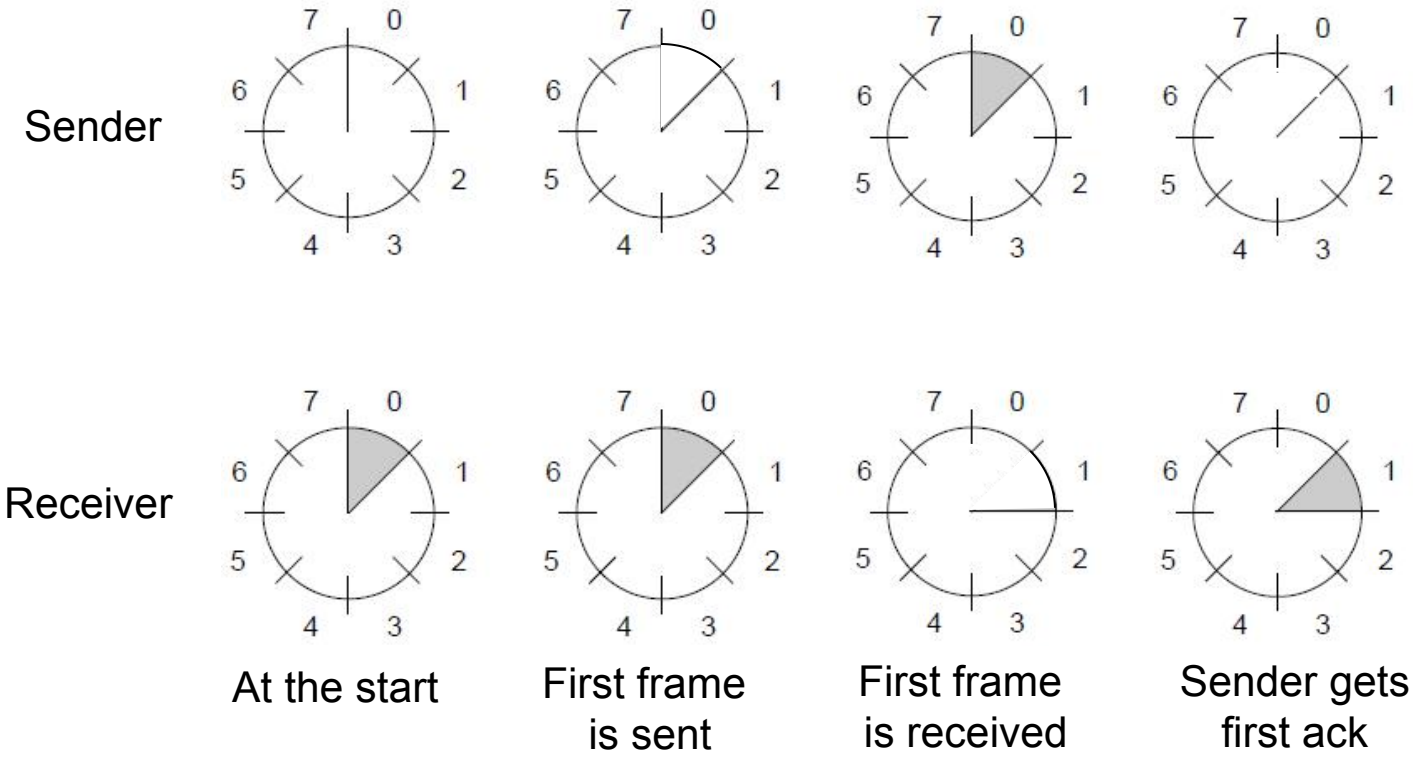
Sliding Window Protocol

- Assuming duplex communication, both sides transmits to each other
- When machine A sends to data to B, it also hooks up the acknowledgement to be sent to B with data packet. It is called as piggybacking
- Wait for some time before sending ack so that if data frame generated can be sent with ack
- How long to wait? If too long other side will timeout and retransmit and too short, leads to overhead of sending separate ack and data

Sliding Window concept (2)

A sliding window advancing at the sender and receiver

- Ex: window size is 1, with a 3-bit sequence number.



One-Bit Sliding Window (1)

a) Transfers data in both directions with stop-and-wait
   - Piggybacks acks on reverse data frames for efficiency
   - Handles transmission errors, flow control, early timers

Each node is sender and receiver (p4):

```
void protocol4 (void) {
  seq_nr next_frame_to_send;
  seq_nr frame_expected;
  frame r, s;
  packet buffer;
  event_type event;
  next_frame_to_send = 0;
  frame_expected = 0;
  from_network_layer(&buffer);
  s.info = buffer;
  s.seq = next_frame_to_send;
  s.ack = 1 – frame_expected;
  to_physical_layer(&s);
  start_timer(s.seq);
```

Prepare first frame

Launch it, and set timer

. . .

One-Bit Sliding Window (2)

Wait for frame or timeout

If a frame with new data then deliver it

If an ack for last send then prepare for next data frame

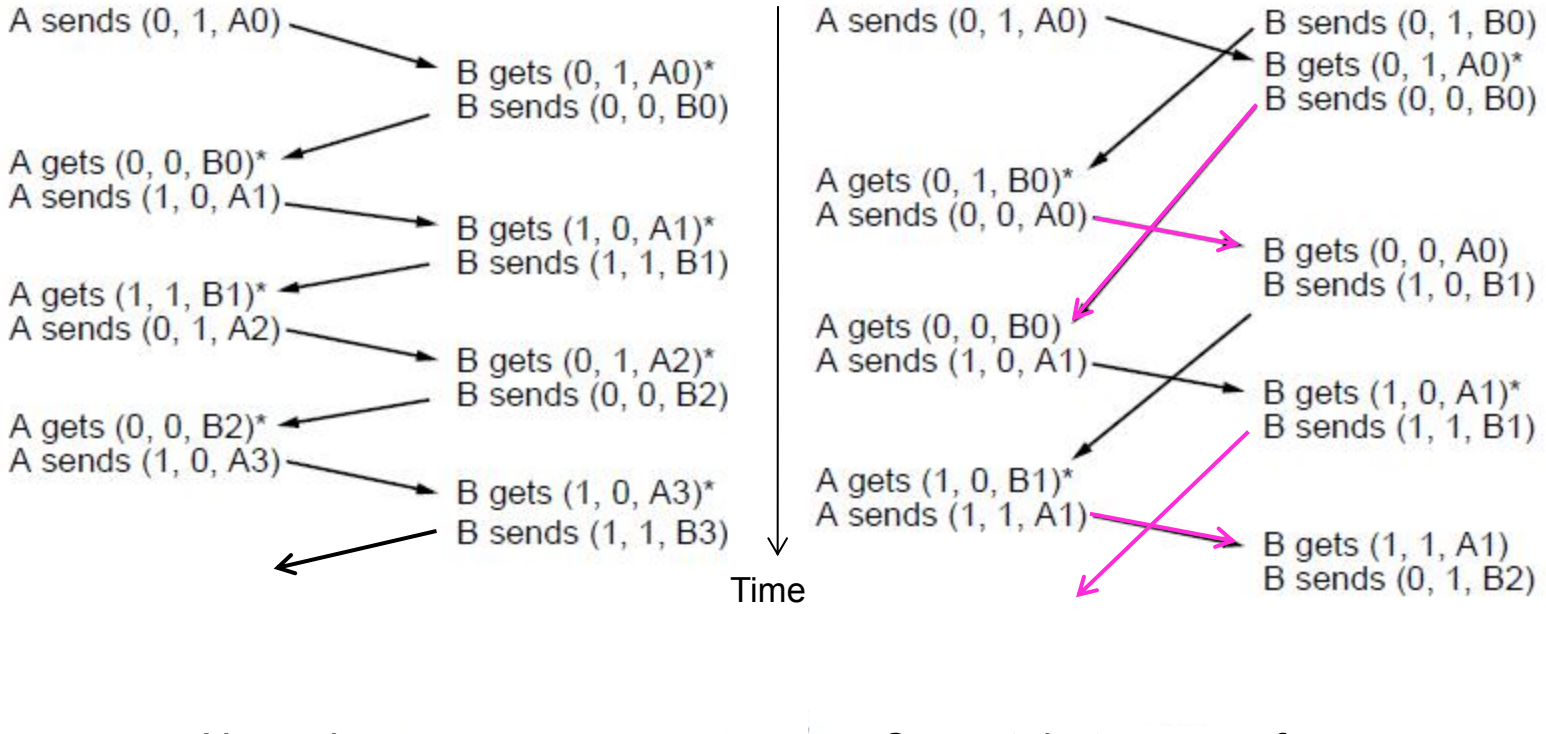
(Otherwise it was a timeout)

Send next data frame or retransmit old one; ack the last data we received

. . .

```
while (true) {
    wait_for_event(&event);
    if (event == frame_arrival) {
        from_physical_layer(&r);
        if (r.seq == frame_expected) {
            to_network_layer(&r.info);
            inc(frame_expected);
        }
        if (r.ack == next_frame_to_send) {
            stop_timer(r.ack);
            from_network_layer(&buffer);
            inc(next_frame_to_send);
        }
    }
    s.info = buffer;
    s.seq = next_frame_to_send;
    s.ack = 1 – frame_expected;
    to_physical_layer(&s);
    start_timer(s.seq);
  }
}
```

One-Bit Sliding Window Protocol (4)



Normal case

Correct, but poor performance

Two scenarios for protocol 4. (a) Normal case. (b) Abnormal case.

The notation is (seq, ack, packet number). An asterisk indicates where a network layer accepts a packet

- Simultaneous start [right] causes correct but slow operation compared to normal [left] due to duplicate transmissions.

Sliding Window concept (3)

Consider a 50-kbps satellite channel with a 500-msec round-trip propagation delay. Let us imagine trying to use protocol 4 to send 1000-bit frames via the satellite. At t = 0 the sender starts sending the first frame. At t = 20 msec the frame has been completely sent. Not until t = 270 msec has the frame fully arrived at the receiver, and not until t = 520 msec has the acknowledgement arrived back at the sender, under the best of circumstances

What is the efficiency?

The sender was blocked 500/520 or 96% of the time. In other words, only 4% of the available bandwidth was used

The solution is in permitting the sender to send w frames, instead of 1, before blocking for acknowledgement

Appropriate value of w is 2BD + 1

Sliding Window concept (3)

Larger windows enable pipelining for efficient link use

- Stop-and-wait (w=1) is inefficient for long links
- Best window (w) depends on bandwidth-delay (BD)
- Want $w \geq 2BD+1$ to ensure high link utilization

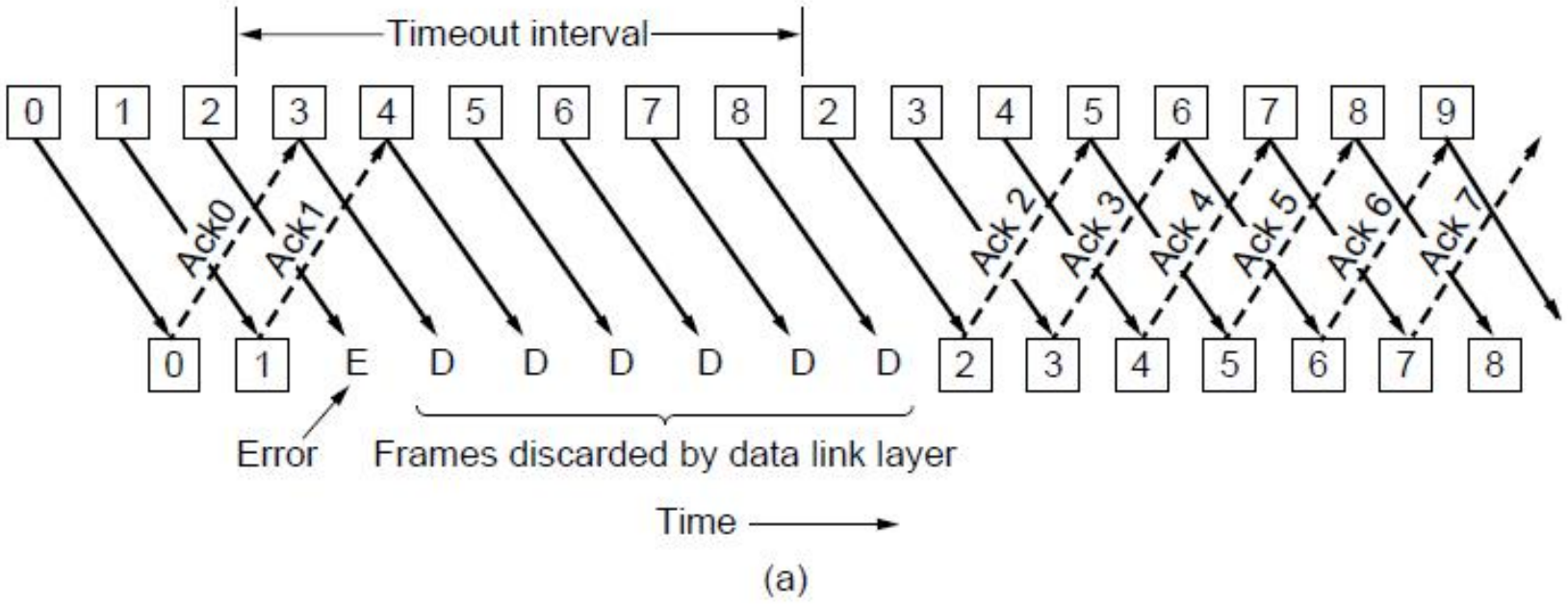
Pipelining leads to different choices for errors/buffering

- We will consider Go-Back-N and Selective Repeat

Protocol Using Go-Back-N (1)

Receiver only accepts/acks frames that arrive in order:

- Discards frames that follow a missing / corrupted frame
- Sender times out and resends all outstanding frames



Pipelining and error recovery. Effect of an error when (a) receiver's window size is 1

Protocol Using Go-Back-N (3)

Tradeoff made for Go-Back-N:

- Simple strategy for receiver; needs only 1 frame
- Wastes link bandwidth for errors with large windows; entire window is retransmitted

Implemented as p5 (see code in next slides)

Protocol Using Go-Back-N (3)

Window Size:

- Is the maximum number of frames that can be outstanding
- Actual sequence number space is MAX_SEQ + 1 (eg. 0...7)
- What if the window size is MAX_SEQ + 1
  1. The sender sends frames 0 through 7.
  2. A piggybacked acknowledgement for 7 comes back to the sender.
  3. The sender sends another eight frames, again with sequence numbers 0 through 7.
  4. Now another piggybacked acknowledgement for frame 7 comes in.

  did all eight frames belonging to the second batch arrive successfully, or did all eight get lost? Conclude

  So Window size in Go-Back-N is MAX_SEQ and not MAX_SEQ +1

Protocol Using Go-Back-N (3)

```
/* Protocol 5 (Go-back-n) allows multiple outstanding frames. The sender may transmit up
   to MAX_SEQ frames without waiting for an ack. In addition, unlike in the previous
   protocols, the network layer is not assumed to have a new packet all the time. Instead,
   the network layer causes a network_layer_ready event when there is a packet to send. */

#define MAX_SEQ 7
typedef enum {frame_arrival, cksum_err, timeout, network_layer_ready} event_type;
#include "protocol.h"

static boolean between(seq_nr a, seq_nr b, seq_nr c)
{
/* Return true if a <= b < c circularly; false otherwise. */
  if (((a <= b) && (b < c)) || ((c < a) && (a <= b)) || ((b < c) && (c < a)))
        return(true);
    else
        return(false);
}
  . . .
```

A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (4)

```
static void send_data(seq_nr frame_nr, seq_nr frame_expected, packet buffer[])
{
/* Construct and send a data frame. */
  frame s;                                        /* scratch variable */

  s.info = buffer[frame_nr];                      /* insert packet into frame */
  s.seq = frame_nr;                               /* insert sequence number into frame */
  s.ack = (frame_expected + MAX_SEQ) % (MAX_SEQ + 1); /* piggyback ack */
  to_physical_layer(&s);                          /* transmit the frame */
  start_timer(frame_nr);                          /* start the timer running */
}
```

. . .

A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (5)

```
void protocol5(void)
{
  seq_nr next_frame_to_send;          /* MAX_SEQ > 1; used for outbound stream */
  seq_nr ack_expected;                /* oldest frame as yet unacknowledged */
  seq_nr frame_expected;              /* next frame expected on inbound stream */
  frame r;                            /* scratch variable */
  packet buffer[MAX_SEQ + 1];         /* buffers for the outbound stream */
  seq_nr nbuffered;                   /* number of output buffers currently in use */
  seq_nr i;                           /* used to index into the buffer array */
  event_type event;

  . . .
```

A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (6)

```
enable_network_layer();                /* allow network_layer_ready events */
ack_expected = 0;                      /* next ack expected inbound */
next_frame_to_send = 0;                /* next frame going out */
frame_expected = 0;                    /* number of frame expected inbound */
nbuffered = 0;                         /* initially no packets are buffered */

while (true) {
  wait_for_event(&event);              /* four possibilities: see event_type above */
```

. . .

A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (7)

```
switch(event) {
  case network_layer_ready:                /* the network layer has a packet to send */
       /* Accept, save, and transmit a new frame. */
       from_network_layer(&buffer[next_frame_to_send]); /* fetch new packet */
       nbuffered = nbuffered + 1;          /* expand the sender's window */
       send_data(next_frame_to_send, frame_expected, buffer);/* transmit the frame */
       inc(next_frame_to_send);            /* advance sender's upper window edge */
       break;

  case frame_arrival:                      /* a data or control frame has arrived */
       from_physical_layer(&r);            /* get incoming frame from physical layer */

       if (r.seq == frame_expected) {
            /* Frames are accepted only in order. */
            to_network_layer(&r.info);     /* pass packet to network layer */
            inc(frame_expected);           /* advance lower edge of receiver's window */
       }
```

. . .

A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (8)

```
        /* Ack n implies n – 1, n – 2, etc.  Check for this. */
        while (between(ack_expected, r.ack, next_frame_to_send)) {
                /* Handle piggybacked ack. */
                nbuffered = nbuffered – 1;          /* one frame fewer buffered */
                stop_timer(ack_expected);           /* frame arrived intact; stop timer */
                inc(ack_expected);                  /* contract sender's window */
        }
        break;

    case cksum_err: break;                          /* just ignore bad frames */

    case timeout:                                   /* trouble; retransmit all outstanding frames */
        next_frame_to_send = ack_expected;          /* start retransmitting here */
        for (i = 1; i <= nbuffered; i++) {
                send_data(next_frame_to_send, frame_expected, buffer);/* resend frame */
                inc(next_frame_to_send);            /* prepare to send the next one */
        }

}
```

. . .

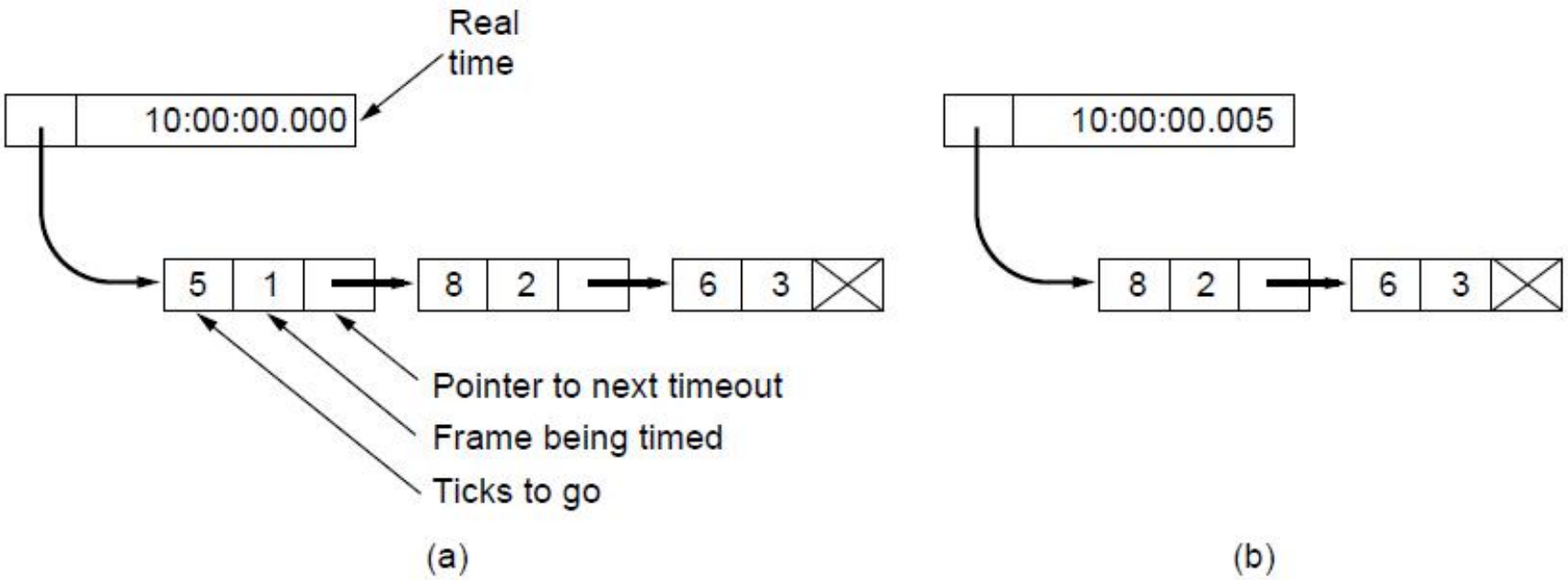
A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (9)

```
    if (nbuffered < MAX_SEQ)
            enable_network_layer();
    else
            disable_network_layer();
  }
}
```

A sliding window protocol using go-back-n.

Protocol Using Go-Back-N (10)



Simulation of multiple timers in software. (a) The queued timeouts (b) The situation after the first timeout has expired.

Protocol Using Selective Repeat (1)

```
/* Protocol 6 (Selective repeat) accepts frames out of order but passes packets to the
   network layer in order. Associated with each outstanding frame is a timer. When the timer
   expires, only that frame is retransmitted, not all the outstanding frames, as in protocol 5. */

#define MAX_SEQ 7                                   /* should be 2^n – 1 */
#define NR_BUFS ((MAX_SEQ + 1)/2)
typedef enum {frame_arrival, cksum_err, timeout, network_layer_ready, ack_timeout} event_type;
#include "protocol.h"
boolean no_nak = true;                              /* no nak has been sent yet */
seq_nr oldest_frame = MAX_SEQ + 1;                  /* initial value is only for the simulator */

static boolean between(seq_nr a, seq_nr b, seq_nr c)
{
/* Same as between in protocol 5, but shorter and more obscure. */
  return ((a <= b) && (b < c)) || ((c < a) && (a <= b)) || ((b < c) && (c < a));
}
```

. . .

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (2)

```
static void send_frame(frame_kind fk, seq_nr frame_nr, seq_nr frame_expected, packet buffer[])
{
/* Construct and send a data, ack, or nak frame. */
  frame s;                                        /* scratch variable */

  s.kind = fk;                                    /* kind == data, ack, or nak */
  if (fk == data) s.info = buffer[frame_nr % NR_BUFS];
  s.seq = frame_nr;                               /* only meaningful for data frames */
  s.ack = (frame_expected + MAX_SEQ) % (MAX_SEQ + 1);
  if (fk == nak) no_nak = false;                  /* one nak per frame, please */
  to_physical_layer(&s);                          /* transmit the frame */
  if (fk == data) start_timer(frame_nr % NR_BUFS);
  stop_ack_timer();                               /* no need for separate ack frame */
}
```

. . .

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (3)

```
void protocol6(void)
{
  seq_nr ack_expected;                /* lower edge of sender's window */
  seq_nr next_frame_to_send;          /* upper edge of sender's window + 1 */
  seq_nr frame_expected;              /* lower edge of receiver's window */
  seq_nr too_far;                     /* upper edge of receiver's window + 1 */
  int i;                              /* index into buffer pool */
  frame r;                            /* scratch variable */
  packet out_buf[NR_BUFS];            /* buffers for the outbound stream */
  packet in_buf[NR_BUFS];             /* buffers for the inbound stream */
  boolean arrived[NR_BUFS];           /* inbound bit map */
  seq_nr nbuffered;                   /* how many output buffers currently used */
  event_type event;
```

. . .

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (4)

```
enable_network_layer();                                  /* initialize */
ack_expected = 0;                                        /* next ack expected on the inbound stream */
next_frame_to_send = 0;                                  /* number of next outgoing frame */
frame_expected = 0;
too_far = NR_BUFS;
nbuffered = 0;                                           /* initially no packets are buffered */
for (i = 0; i < NR_BUFS; i++) arrived[i] = false;
```

. . .

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (5)

```
while (true) {
  wait_for_event(&event);                    /* five possibilities: see event_type above */
  switch(event) {
    case network_layer_ready:                /* accept, save, and transmit a new frame */
         nbuffered = nbuffered + 1;          /* expand the window */
         from_network_layer(&out_buf[next_frame_to_send % NR_BUFS]); /* fetch new packet */
         send_frame(data, next_frame_to_send, frame_expected, out_buf);/* transmit the frame */
         inc(next_frame_to_send);            /* advance upper window edge */
         break;

  . . .
```

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (6)

```
case frame_arrival:                          /* a data or control frame has arrived */
     from_physical_layer(&r);                /* fetch incoming frame from physical layer */
     if (r.kind == data) {
          /* An undamaged frame has arrived. */
          if ((r.seq != frame_expected) && no_nak)
             send_frame(nak, 0, frame_expected, out_buf); else start_ack_timer();
          if (between(frame_expected,r.seq,too_far) && (arrived[r.seq%NR_BUFS]==false)) {
               /* Frames may be accepted in any order. */
               arrived[r.seq % NR_BUFS] = true;      /* mark buffer as full */
               in_buf[r.seq % NR_BUFS] = r.info;     /* insert data into buffer */
. . .
```

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (7)

```
        while (arrived[frame_expected % NR_BUFS]) {
            /* Pass frames and advance window. */
            to_network_layer(&in_buf[frame_expected % NR_BUFS]);
            no_nak = true;
            arrived[frame_expected % NR_BUFS] = false;
            inc(frame_expected);     /* advance lower edge of receiver's window */
            inc(too_far);            /* advance upper edge of receiver's window */
            start_ack_timer();       /* to see if a separate ack is needed */
        }
    }
}
. . .
```

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (8)

```
    if((r.kind==nak) && between(ack_expected,(r.ack+1)%(MAX_SEQ+1),next_frame_to_send))
        send_frame(data, (r.ack+1) % (MAX_SEQ + 1), frame_expected, out_buf);

    while (between(ack_expected, r.ack, next_frame_to_send)) {
        nbuffered = nbuffered – 1;          /* handle piggybacked ack */
        stop_timer(ack_expected % NR_BUFS);     /* frame arrived intact */
        inc(ack_expected);                  /* advance lower edge of sender's window */
    }
    break;
case cksum_err:
    if (no_nak) send_frame(nak, 0, frame_expected, out_buf); /* damaged frame */
    break;
. . .
```

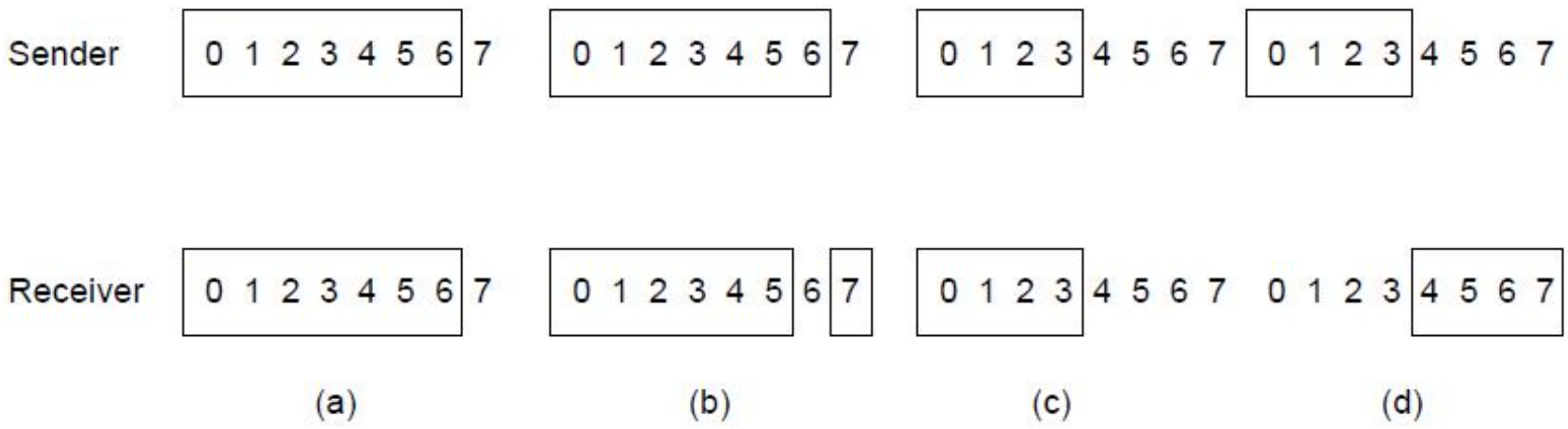
A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (9)

```
        case timeout:
                send_frame(data, oldest_frame, frame_expected, out_buf); /* we timed out */
                break;
        case ack_timeout:
                send_frame(ack,0,frame_expected, out_buf);      /* ack timer expired; send ack */
    }
    if (nbuffered < NR_BUFS) enable_network_layer(); else disable_network_layer();
  }
}
```

A sliding window protocol using selective repeat.

Protocol Using Selective Repeat (10)



- Initial situation with a window of size 7

a) After 7 frames sent and received

b) Acknowledgement is lost.

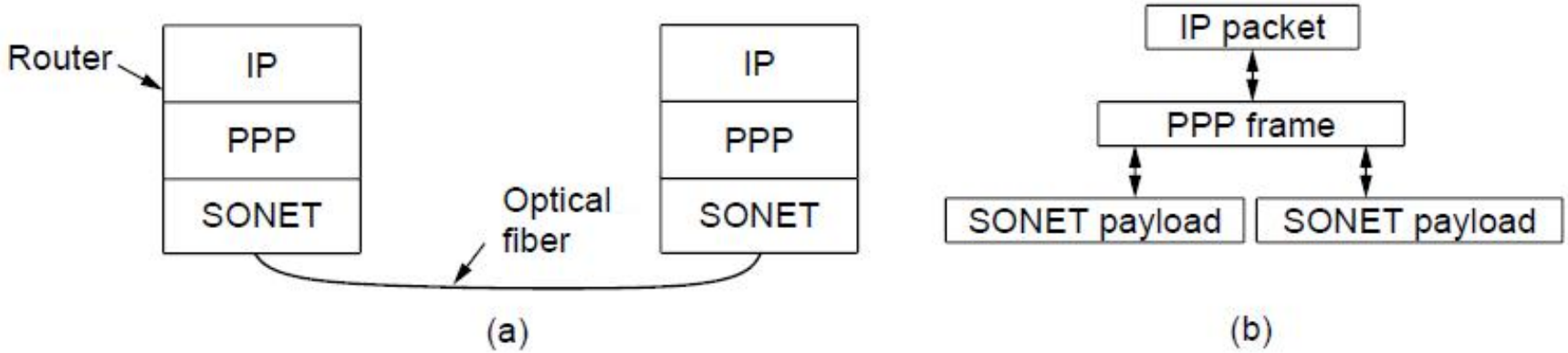
c) Initial situation with a window size of 4.

d) After 4 frames sent and received but not acknowledged.

Example Data Link Protocols

- Packet over SONET
- ADSL (Asymmetric Digital Subscriber Loop)

Packet over SONET (1)



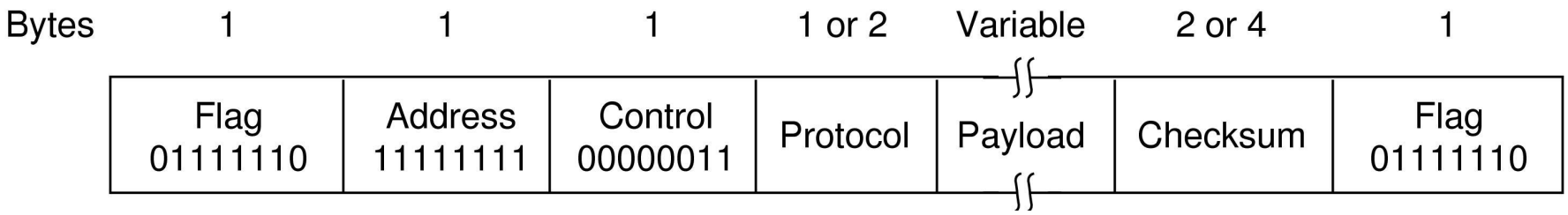
Packet over SONET. (a) A protocol stack. (b) Frame relationships

Packet over SONET (2)

PPP Features

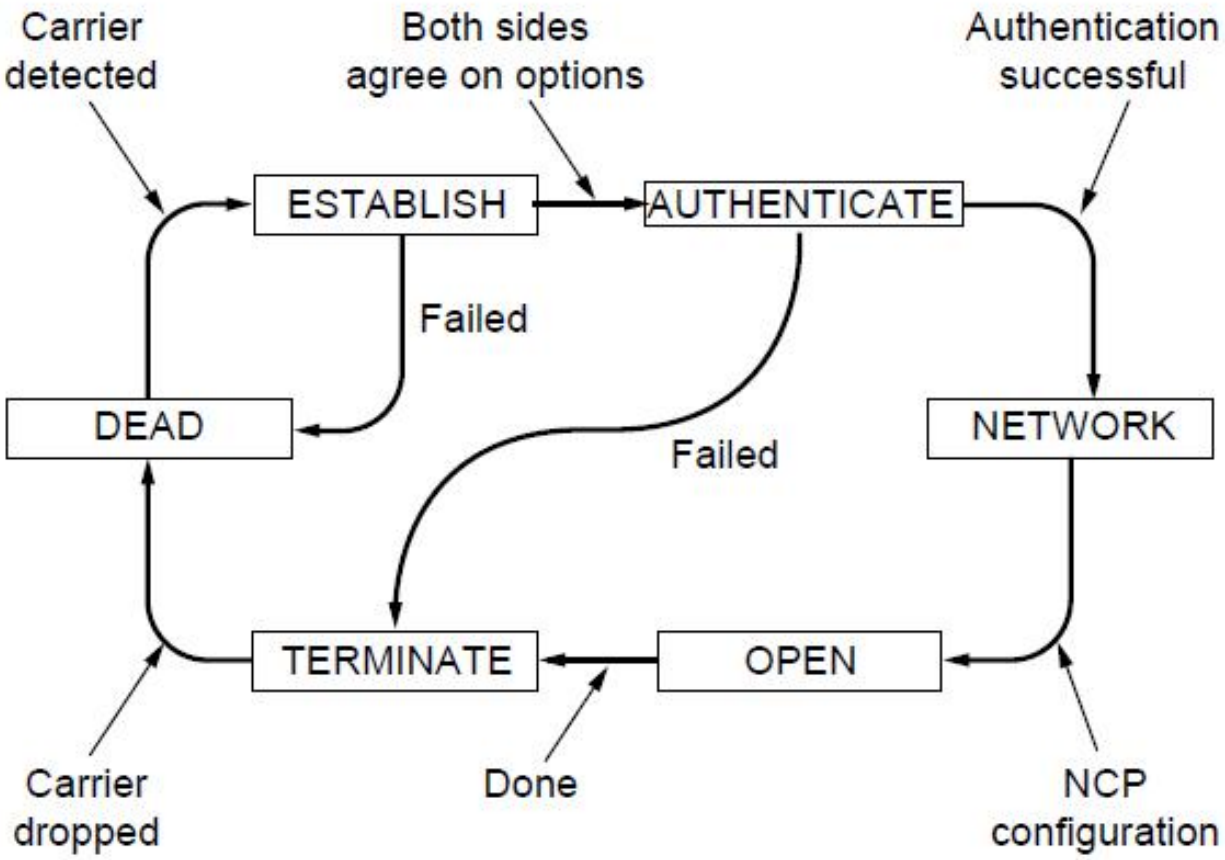
- Separate packets, error detection
- Link Control Protocol
- Network Control Protocol

Packet over SONET (3)



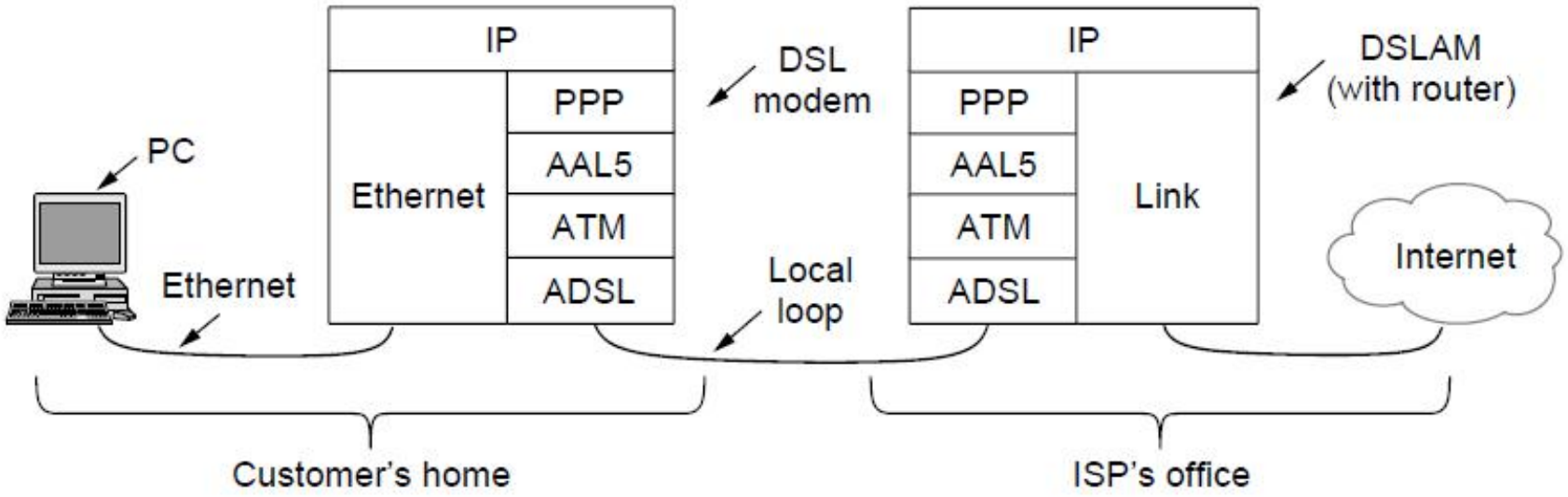
The PPP full frame format for unnumbered mode operation

Packet over SONET (4)



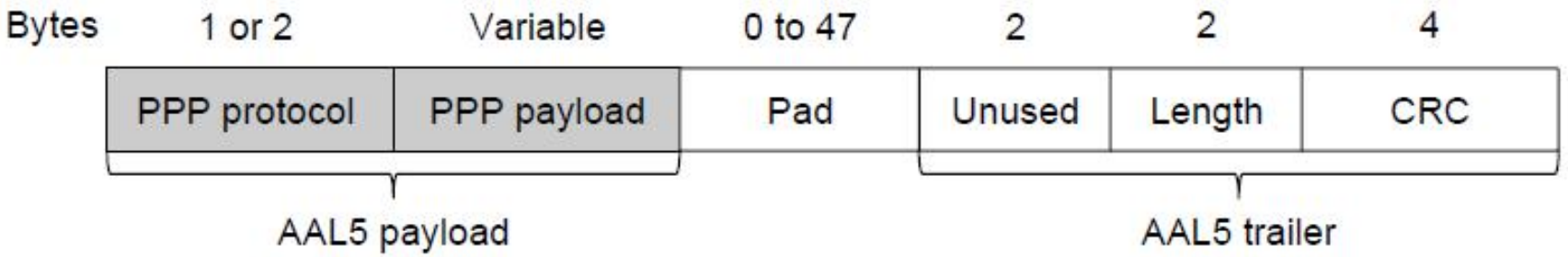
State diagram for bringing a PPP link up and down

ADSL (Asymmetric Digital Subscriber Loop) (1)



ADSL protocol stacks.

ADSL (Asymmetric Digital Subscriber Loop) (1)



AAL5 frame carrying PPP data

End

Chapter 3