3

THE DATA LINK LAYER

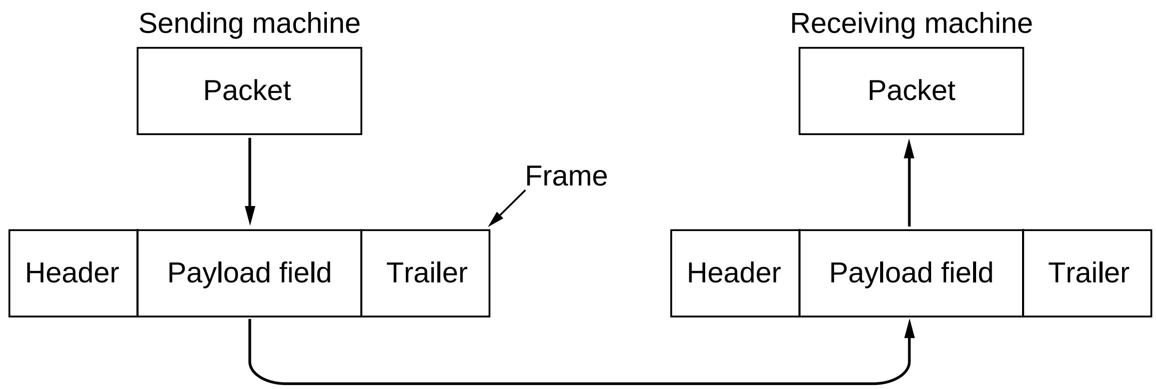


Fig. 3-1. Relationship between packets and frames.

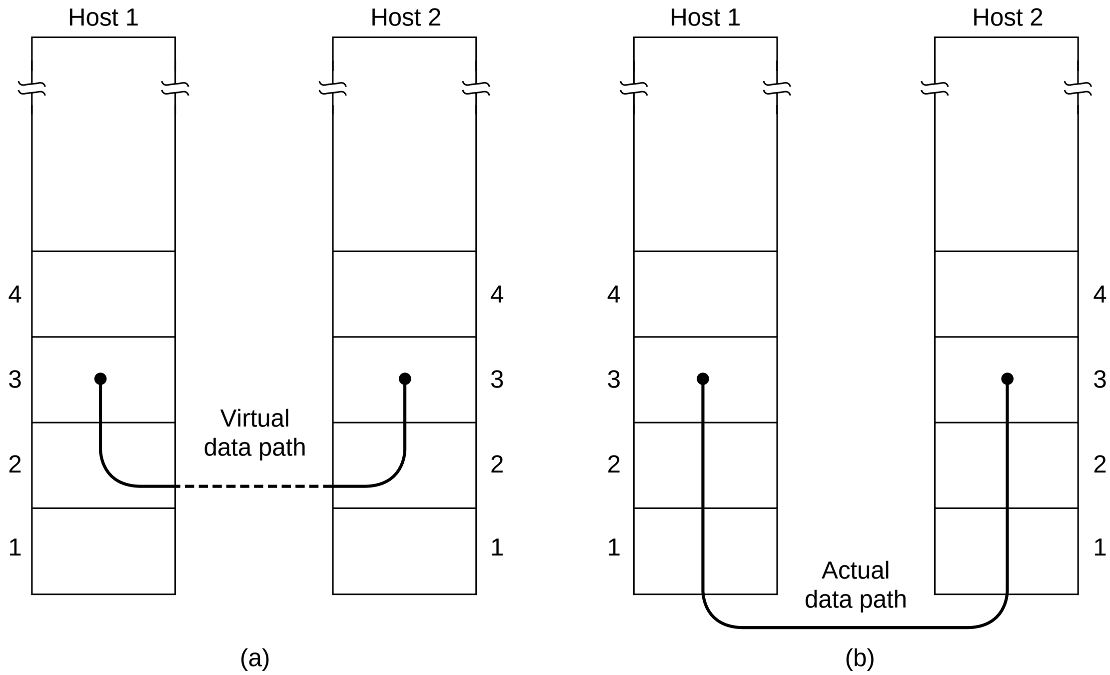


Fig. 3-2. (a) Virtual communication. (b) Actual communication.

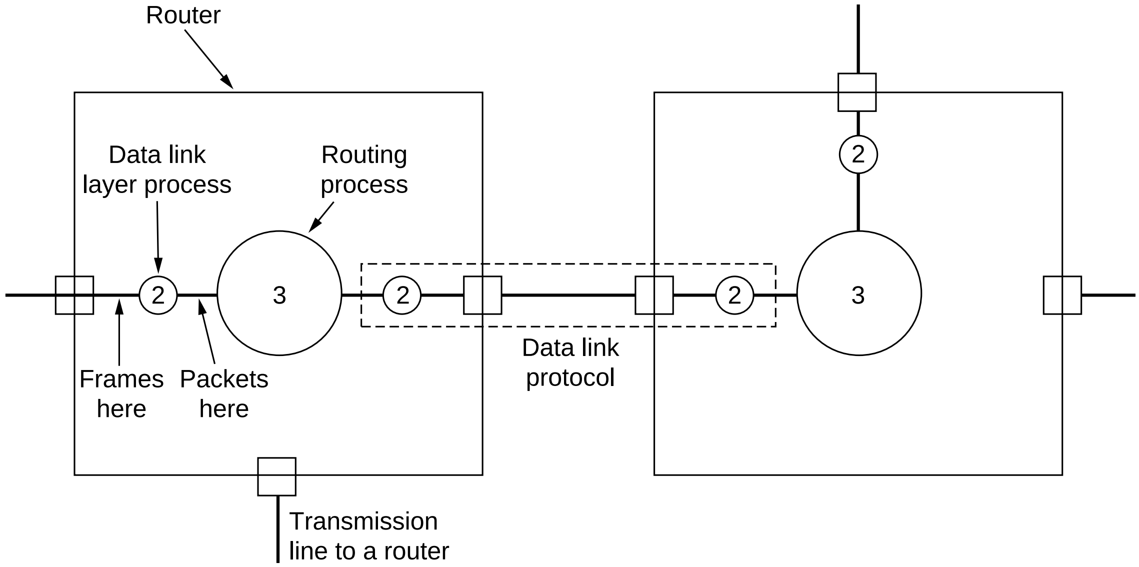


Fig. 3-3. Placement of the data link protocol.

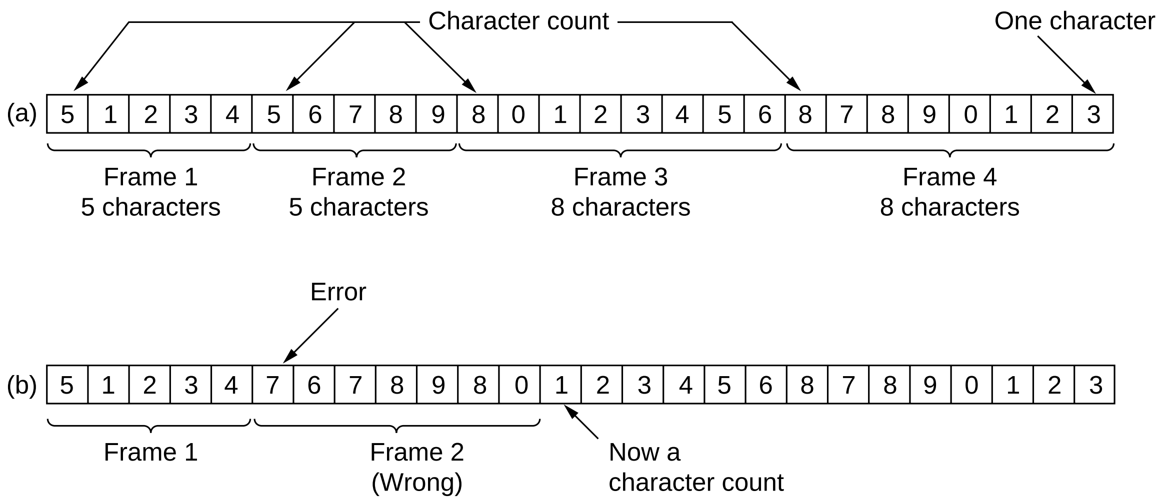


Fig. 3-4. A character stream. (a) Without errors. (b) With one error.

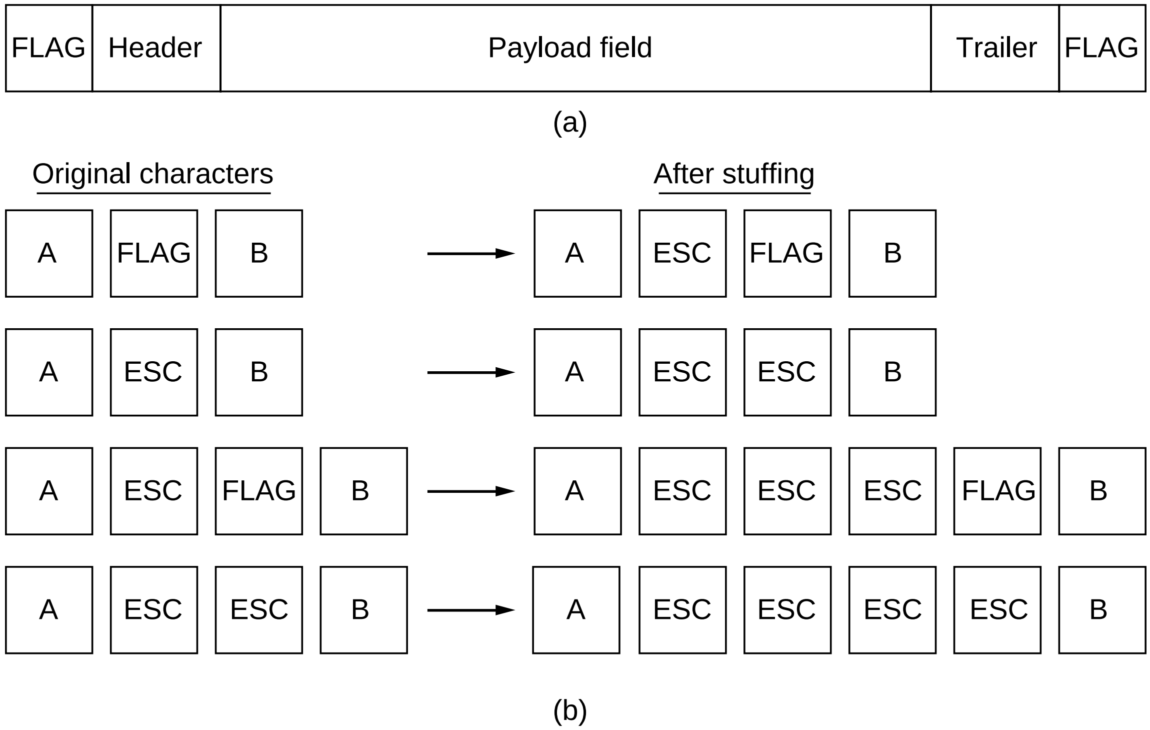


Fig. 3-5. (a) A frame delimited by flag bytes. (b) Four examples of byte sequences before and after byte stuffing.

(a) 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

(b) 0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0

Stuffed bits

(c) 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

Fig. 3-6. 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.

Char.	ASCII	Check bits
H	1001000	00110010000
a	1100001	10111001001
m	1101101	11101010101
m	1101101	11101010101
i	1101001	01101011001
n	1101110	01101010110
g	1100111	01111001111
	0100000	10011000000
c	1100011	11111000011
o	1101111	10101011111
d	1100100	11111001100
e	1100101	00111000101

Order of bit transmission

Fig. 3-7. Use of a Hamming code to correct burst errors.

Frame : 1 1 0 1 0 1 1 0 1 1

Generator: 1 0 0 1 1

Message after 4 zero bits are appended: 1 1 0 1 0 1 1 0 1 1 0 0 0 0

```
                  1 1 0 0 0 0 1 0 1 0
        ____________________________
1 0 0 1 1 | 1 1 0 1 0 1 1 0 1 1 0 0 0 0
            1 0 0 1 1
            ---------
              1 0 0 1 1
              1 0 0 1 1
              ---------
                0 0 0 0 1
                0 0 0 0 0
                ---------
                  0 0 0 1 0
                  0 0 0 0 0
                  ---------
                    0 0 1 0 1
                    0 0 0 0 0
                    ---------
                      0 1 0 1 1
                      0 0 0 0 0
                      ---------
                        1 0 1 1 0
                        1 0 0 1 1
                        ---------
                          0 1 0 1 0
                          0 0 0 0 0
                          ---------
                            1 0 1 0 0
                            1 0 0 1 1
                            ---------
                              0 1 1 1 0
                              0 0 0 0 0
                              ---------
                                1 1 1 0   <- Remainder
```

Transmitted frame: 1 1 0 1 0 1 1 0 1 1 1 1 1 0

Fig. 3-8. Calculation of the polynomial code checksum.

```
#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 a frame is it? */
  seq_nr seq;                                 /* sequence number */
  seq_nr ack;                                 /* acknowledgement number */
  packet info;                                /* the network layer packet */
} frame;

/* 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);

/* 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
```

Fig. 3-9. Some definitions needed in the protocols to follow. These definitions are located in the file *protocol.h*.

```
/* 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 */
}


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 */
  }
}
```

Fig. 3-10. An unrestricted simplex protocol.

```
/* 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 */
  }
}

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 */
  }
}
```

Fig. 3-11. A simplex stop-and-wait protocol.

```
/* 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;

  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 */
              }
       }
  }
}

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 */
       }
  }
}
```

Fig. 3-12. A positive acknowledgement with retransmission protocol.

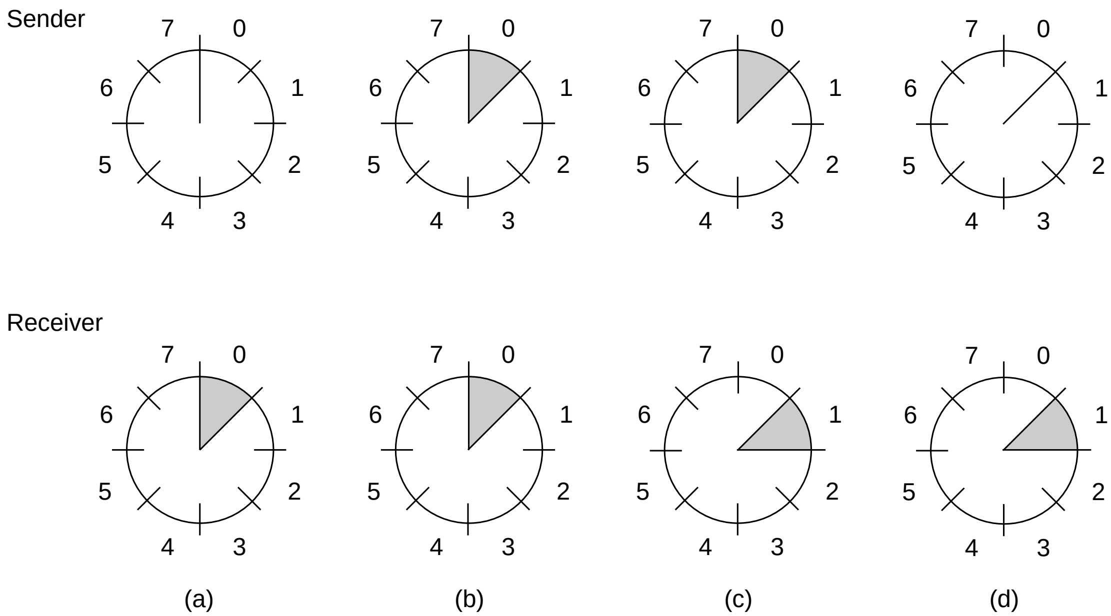


Fig. 3-13. A sliding window of size 1, with a 3-bit sequence number. (a) Initially. (b) After the first frame has been sent. (c) After the first frame has been received. (d) After the first acknowledgement has been received.

```
/* Protocol 4 (sliding window) is bidirectional. */

#define MAX_SEQ 1                               /* must be 1 for protocol 4 */
typedef enum {frame_arrival, cksum_err, timeout} event_type;
#include "protocol.h"

void protocol4 (void)
{
  seq_nr next_frame_to_send;                    /* 0 or 1 only */
  seq_nr frame_expected;                        /* 0 or 1 only */
  frame r, s;                                   /* scratch variables */
  packet buffer;                                /* current packet being sent */
  event_type event;

  next_frame_to_send = 0;                       /* next frame on the outbound stream */
  frame_expected = 0;                           /* frame expected next */
  from_network_layer(&buffer);                  /* fetch a packet from the network layer */
  s.info = buffer;                              /* prepare to send the initial frame */
  s.seq = next_frame_to_send;                   /* insert sequence number into frame */
  s.ack = 1 – frame_expected;                   /* piggybacked ack */
  to_physical_layer(&s);                        /* transmit the frame */
  start_timer(s.seq);                           /* start the timer running */

  while (true) {
      wait_for_event(&event);                   /* frame_arrival, cksum_err, or timeout */
      if (event == frame_arrival) {             /* a frame has arrived undamaged. */
            from_physical_layer(&r);            /* go get it */

            if (r.seq == frame_expected) {      /* handle inbound frame stream. */
                  to_network_layer(&r.info);    /* pass packet to network layer */
                  inc(frame_expected);          /* invert seq number expected next */
            }

            if (r.ack == next_frame_to_send) {/* handle outbound frame stream. */
                  stop_timer(r.ack);            /* turn the timer off */
                  from_network_layer(&buffer);          /* fetch new pkt from network layer */
                  inc(next_frame_to_send);      /* invert sender's sequence number */
            }
      }
      s.info = buffer;                          /* construct outbound frame */
      s.seq = next_frame_to_send;               /* insert sequence number into it */
      s.ack = 1 – frame_expected;               /* seq number of last received frame */
      to_physical_layer(&s);                    /* transmit a frame */
      start_timer(s.seq);                       /* start the timer running */
  }
}
```

Fig. 3-14. A 1-bit sliding window protocol.

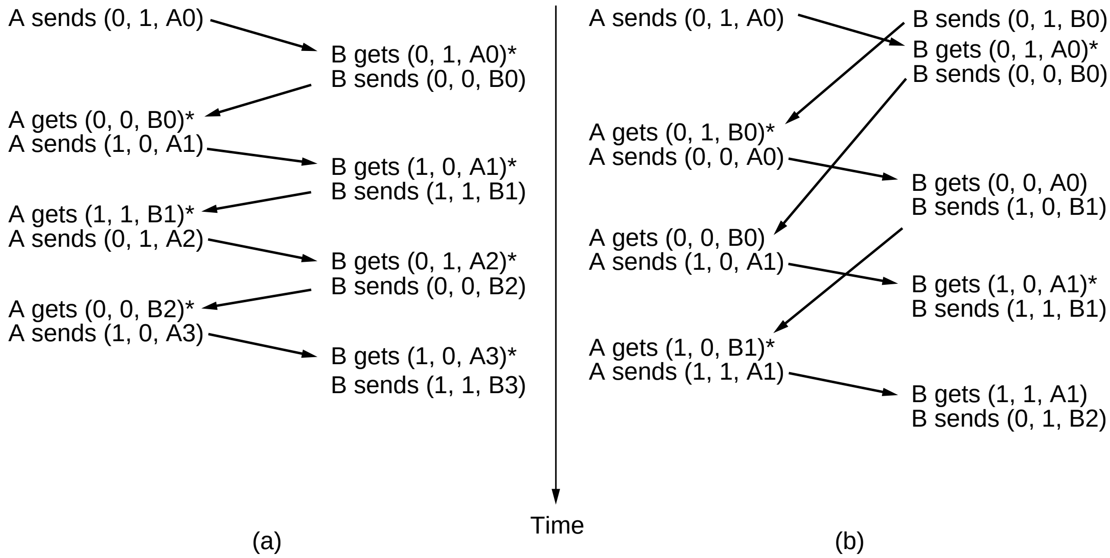


Fig. 3-15. Two scenarios for protocol 4. (a) Normal case. (b) Abnormal case. The notation is (seq, ack, packet number). An asterisk indicates where a network layer accepts a packet.

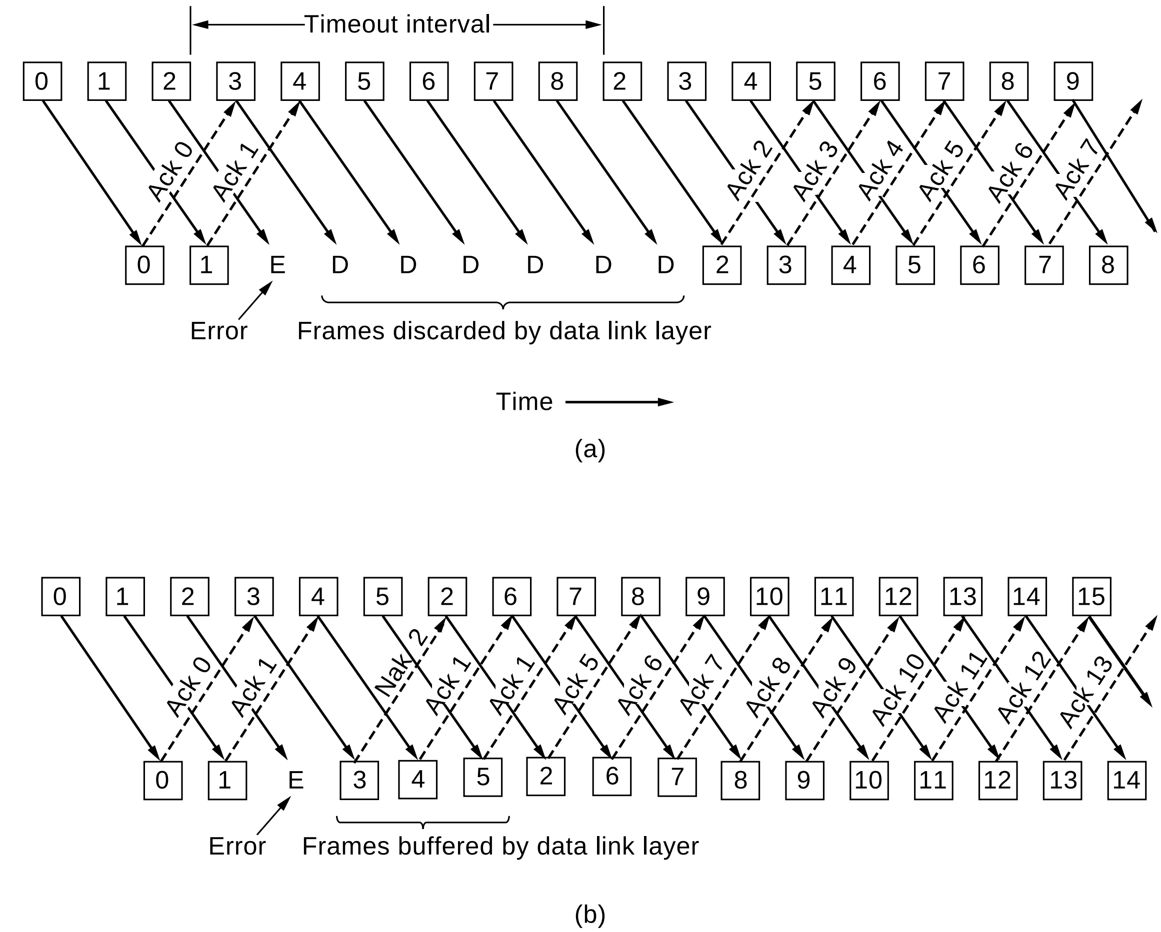


Fig. 3-16. Pipelining and error recovery. Effect of an error when (a) receiver's window size is 1 and (b) receiver's window size is large.

```
/* 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                          /* should be 2^n - 1 */
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);
}

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 */
}

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;                        /* # output buffers currently in use */
  seq_nr i;                                /* used to index into the buffer array */
  event_type event;

  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 */

    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 */
             }

             /* 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 */
            }

    }

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

Fig. 3-17. A sliding window protocol using go back n.

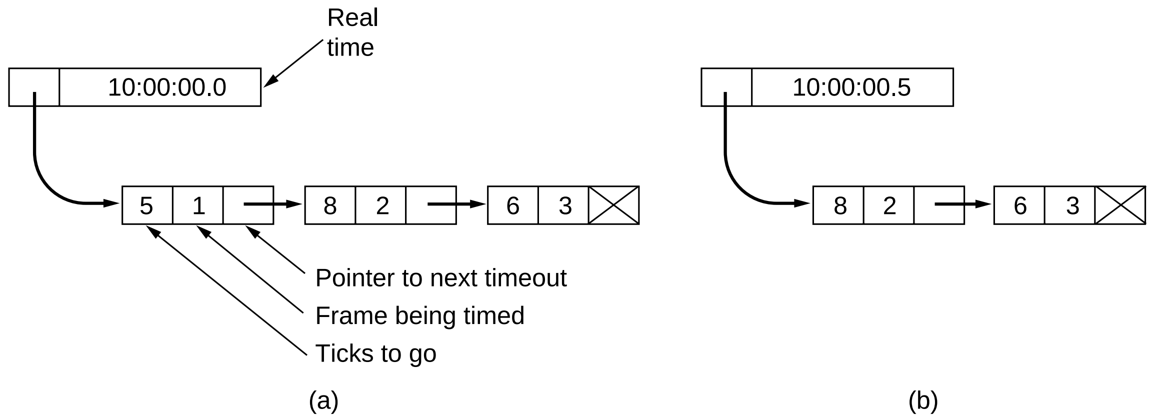


Fig. 3-18. Simulation of multiple timers in software.

```
/* 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 protocol5, but shorter and more obscure. */
  return ((a <= b) && (b < c)) || ((c < a) && (a <= b)) || ((b < c) && (c < a));
}

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 */
}

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;

  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;
```

```
  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;

      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 */
                        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 */
                        }
                  }
            }
            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;

      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();
  }
}
```

Fig. 3-19. A sliding window protocol using selective repeat.

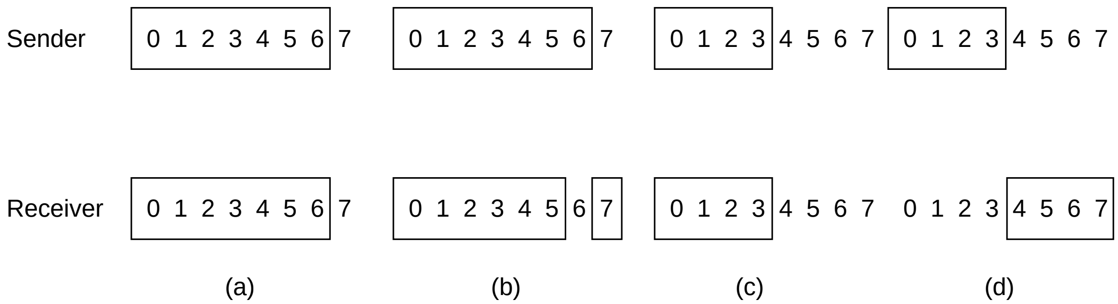
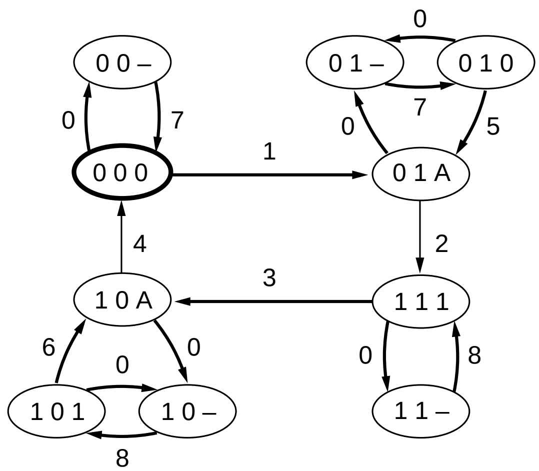


Fig. 3-20. (a) Initial situation with a window of size seven. (b) After seven frames have been sent and received but not acknowledged. (c) Initial situation with a window size of four. (d) After four frames have been sent and received but not acknowledged.



(a)

Transition	Who runs?	Frame accepted	Frame emitted	To network layer
0	–	(frame lost)		–
1	R	0	A	Yes
2	S	A	1	–
3	R	1	A	Yes
4	S	A	0	–
5	R	0	A	No
6	R	1	A	No
7	S	(timeout)	0	–
8	S	(timeout)	1	–

(b)

Fig. 3-21. (a) State diagram for protocol 3. (b) Transitions.

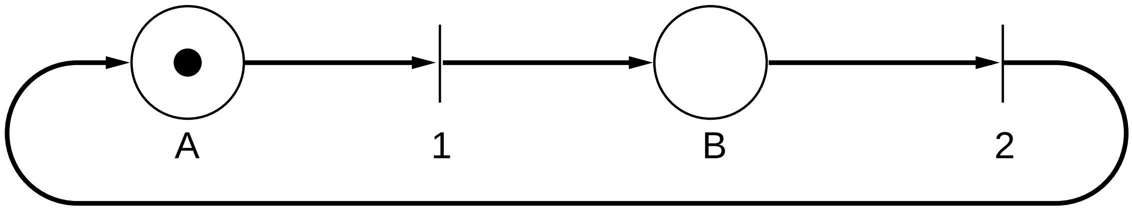


Fig. 3-22. A Petri net with two places and two transitions.

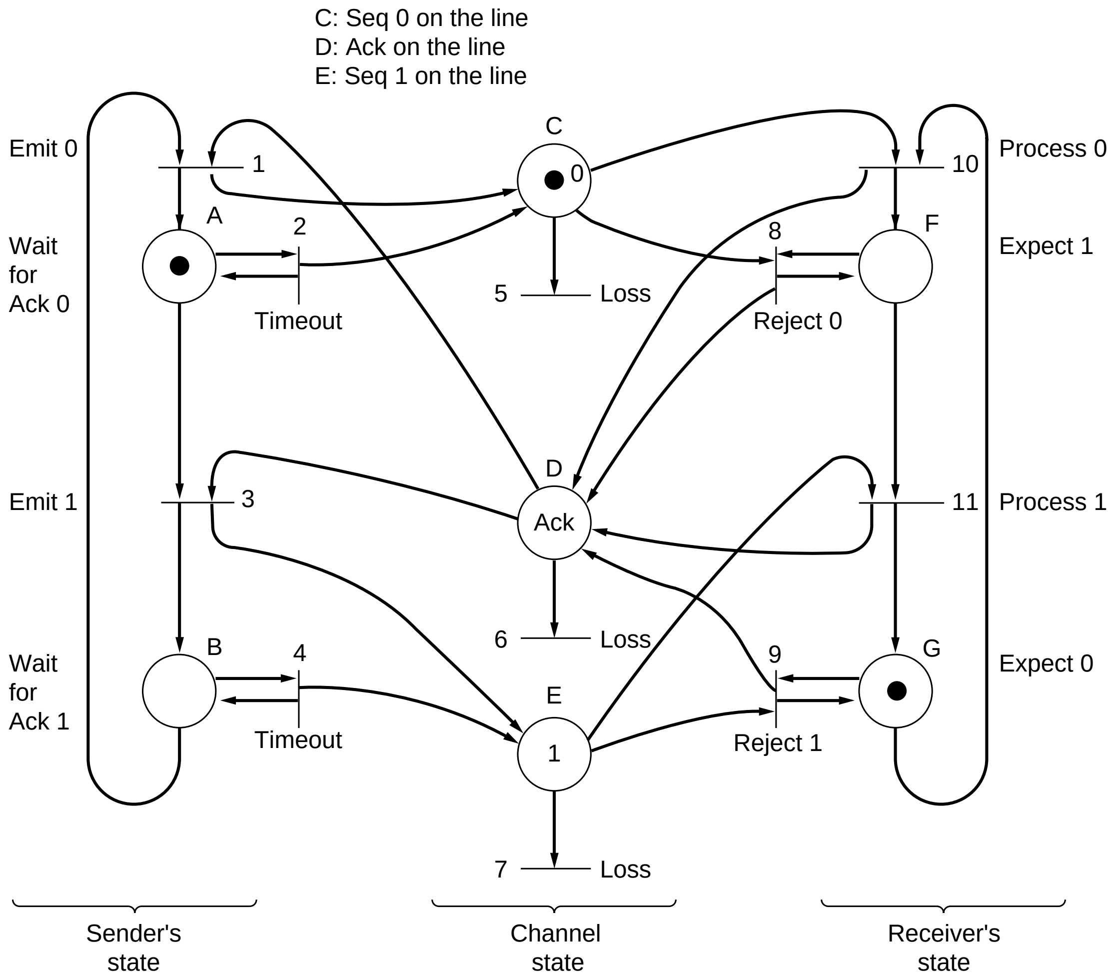


Fig. 3-23. A Petri net model for protocol 3.

Bits	8	8	8	⩾ 0	16	8
	0 1 1 1 1 1 1 0	Address	Control	Data	Checksum	0 1 1 1 1 1 1 0

Fig. 3-24. Frame format for bit-oriented protocols.

Bits	1	3		1	3
(a)	0	Seq		P/F	Next
(b)	1	0	Type	P/F	Next
(c)	1	1	Type	P/F	Modifier

Fig. 3-25. Control field of (a) an information frame, (b) a supervisory frame, (c) an unnumbered frame.

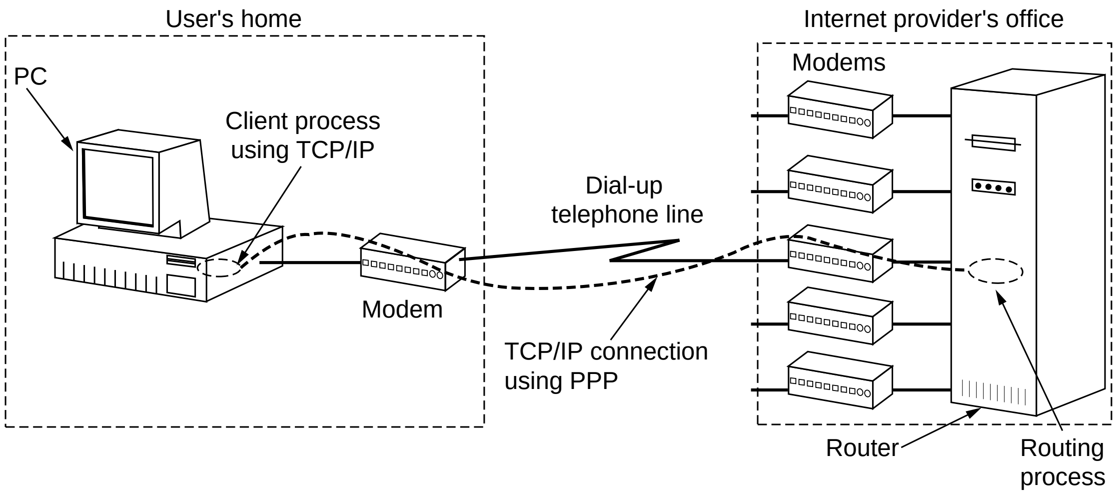


Fig. 3-26. A home personal computer acting as an Internet host.

Bytes	1	1	1	1 or 2	Variable	2 or 4	1
	Flag 01111110	Address 11111111	Control 00000011	Protocol	Payload	Checksum	Flag 01111110

Fig. 3-27. The PPP full frame format for unnumbered mode operation.

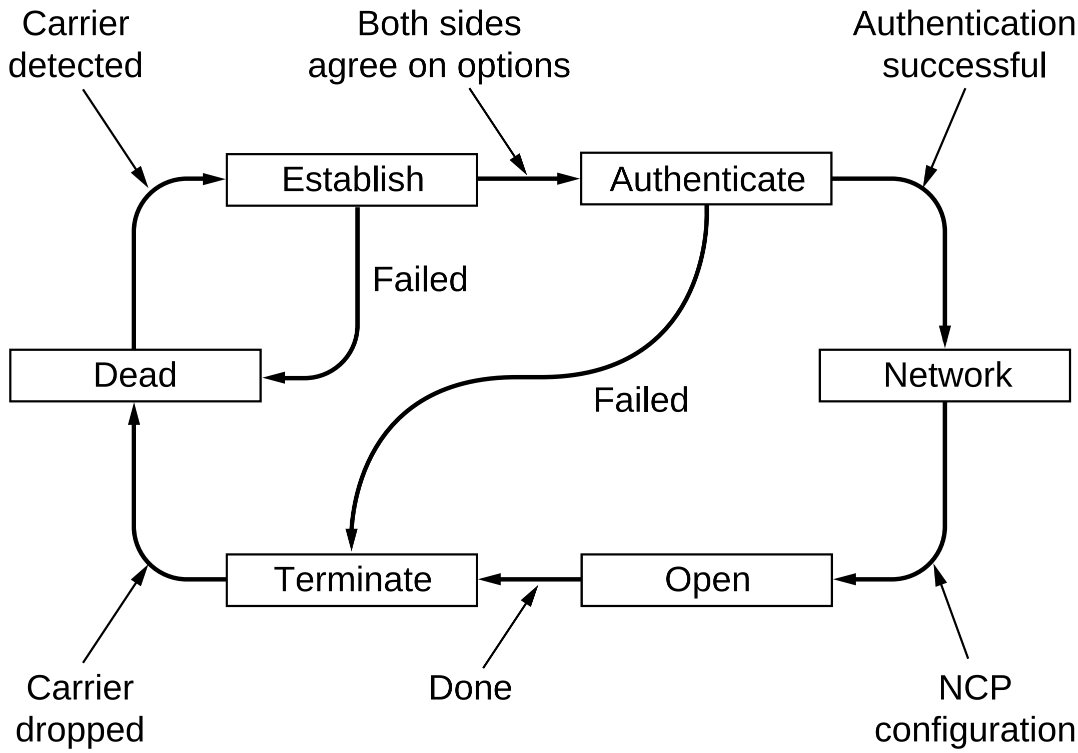


Fig. 3-28. A simplified phase diagram for bringing a line up and down.

Name	Direction	Description
Configure-request	I → R	List of proposed options and values
Configure-ack	I ← R	All options are accepted
Configure-nak	I ← R	Some options are not accepted
Configure-reject	I ← R	Some options are not negotiable
Terminate-request	I → R	Request to shut the line down
Terminate-ack	I ← R	OK, line shut down
Code-reject	I ← R	Unknown request received
Protocol-reject	I ← R	Unknown protocol requested
Echo-request	I → R	Please send this frame back
Echo-reply	I ← R	Here is the frame back
Discard-request	I → R	Just discard this frame (for testing)

Fig. 3-29. The LCP frame types.