Data Link Layer
Data Link Layer Outline

- Parallelism between Transport and Data Link Layer
- Tanenbaum’s Treatment/Model of Data Link Layer
  - Protocol 1: Utopia
  - Protocol 2: Stop-and-Wait
  - Protocol 3: Positive Acknowledgment with Retransmission [PAR]
    - Old ‘flawed’ version
    - Newer version
DL Layer Outline (cont)

- Pipelining and Sliding Windows
- Protocol 4: One Bit Sliding Window
- Protocol 5: Go Back N
- Protocol 6: Selective Repeat
- Further Details and Decisions
Reliable Protocols at Two Layers

Leon-Garcia & Widjaja: Communication Networks

End to End

Transport Layer

Hop by Hop

Data Link Layer

Computer Networks  Data Link Layer
To achieve control when sending data, a layer of logic, the **Data Link Layer protocol** is added above the Physical layer.

To manage data exchange over a link, DL layer protocol needs:

- frame synchronization
- flow control
- error control
- addressing
- control and data
- link management
Data Link Layer

- Provides a *well-defined service interface* to the network layer.
- Determines how the bits of the physical layer are grouped into frames (framing).
- Deals with transmission errors (CRC and ARQ).
- Regulates the flow of frames.
- Performs general link layer management.
Tanenbaum’s DL Layer Treatment

- Concerned with communication between two adjacent nodes in the subnet (node to node).

- Assumptions:
  - The bits are delivered in the order sent.
  - A rigid interface between the Host and the node ➔ the communications policy and the Host protocol (with OS effects) can evolve separately.
  - He uses a simplified model.
Tanenbaum’s Data Link Layer Model

Assume the sending Host has infinite supply of messages. A node constructs a frame from a single packet message. The CRC is automatically appended in the hardware. The protocols are developed in increasing complexity to help students understand the data link layer issues.
Basic Elements of ARQ

Packet sequence

Transmitter

Information frames

Receiver

Error-free packet sequence

Control frames

Transmitter

Station A

Information packet

Header

CRC

Station B

Control frame

Information Frame

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Tanenbaum’s Protocol Definitions

Figure 3-9. Some definitions needed in the protocols to follow. These are located in the file protocol.h.
Packet and Frame Definitions

- **Packet**
  - Buffer
  - Frame
    - Info
    - Ack
    - Seq
    - Kind

- **Physical Layer**
  - Postamble
  - CRC
  - preamble

- **Data Link Layer**
  - Network Layer
  - Physical Layer

- **Computer Networks**
  - Data Link Layer
Figure 3-9. Some definitions needed in the protocols to follow. These are located in the file protocol.h.

/* 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
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 */
    }
}

/* 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. */
Simplex Stop-and-Wait Protocol

Figure 3-11

typedef enum {frame_arrival} event_type;

void receiver2(void)
{
    frame r, s;
    // event type event:
    while (true) {
        // from network layer(&r.info);
        // to physical layer(&r.info);
        wait_for_event(&event);
        wait_for_network_layer(&event);
    }
}

void sender2(void)
{
    frame s;
    // packet_buffer;
    // event_type event:
    while (true) {
        // from network layer(&buffer);
        // to physical layer(&s.info);
        // wait_for_event(&event);
        wait_for_network_layer(&event);
    }
}

/* buffers for frames */
/* get the inbound frame */
/* pass the data to the network layer */
/* send a dummy frame to awaken sender */
/* only possibility is frame_arrival */
/* get something to send */
/* copy it into the transmission */
/* do not proceed until given the go ahead */
/* buffer for an outbound frame */
/* frame_arrival is the only possibility */
/* buffer for an outbound packet */
/* frame_arrival is the only possibility */

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. *
Stop-and-Wait Scenarios

Figure 2.17 Timeline showing four different scenarios for the stop-and-wait algorithm. (a) The ACK is received before the timer expires; (b) the original frame is lost; (c) the ACK is lost; (d) the timeout fires too soon {premature timeout!!}
In parts (a) and (b) transmitting station A acts the same way, but part (b) receiving station B accepts frame 1 twice.
Protocol 3: Positive Acknowledgement with Retransmissions [PAR]

Introduce Noisy Channels

- This produces:
  1. Damaged and lost frames
  2. Damaged and lost ACKs

PAR Protocol

- Tools and issues:
  - Timers
  - Sequence numbers
  - Duplicate frames
```c
#define MAX_SEQ 1
typedef enum {frame_arrival, cksum_err, timeout} event_type;
include "protocol.h"

void sender_par (void) {
    seq_nr next_frame_to_send;
    frame s;
    packet buffer;
    event_type event;
    next_frame_to_send = 0;
    from_network_layer (&buffer);
    while (true) {
        s.info = buffer;
        s.seq = next_frame_to_send;
        to_physical_layer (&s);
        start_timer (s.seq);
        wait_for_event (&event);
        if (event == frame_arrival) {
            stop_timer (s.seq);
            from_network_layer (&buffer);
            inc (next_frame_to_send); }
    }
}
```
void receiver_par (void)
{
    seq_nr next_frame_to_send;
    frame r, s;
    event_type event;
    frame_expected = 0;
    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);
            }
        }
        to_physical_layer (&s); /* Note - no sequence number on ACK */
    }
}
Ambiguities occur when ACKs are not numbered.

Transmitting station A misinterprets duplicate ACKs.

This protocol is broken!!
/* 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"

int 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);
        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 Simplex Protocol for a Noisy Channel

```c
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) {
            from_physical_layer(&r);
            if (r.seq == frame_expected) {
                to_network_layer(&r.info);
                inc(frame_expected);
            }
        }
        s.ack = 1 - frame_expected;  /* tell which frame is being acked */
        to_physical_layer(&s);  /* send acknowledgement */
    }
}
```

Figure 3-12. A **Positive Acknowledgement with Retransmission protocol.**
State Machine for Stop-and-Wait

Global State: 
\((S_{\text{last}}, R_{\text{next}})\)

Error-free frame 0 arrives at receiver

ACK for frame 1 arrives at transmitter

Error-free frame 1 arrives at receiver

FSM’s used to check logic on both ends of a protocol.
Pipelined Protocols

Pipelining: sender allows multiple, “in-flight”, yet-to-be-acknowledged packets
- range of sequence numbers must be increased
- buffering at sender and/or receiver

Two generic forms of pipelined protocols: Go Back N, Selective Repeat
Sliding Window Protocols [Tanen]

- Must be able to transmit data in both directions.

- Choices for utilization of the reverse channel:
  - mix DATA frames with ACK frames.
  - **Piggyback the ACK**
    - Receiver waits for DATA traffic in the opposite direction.
    - Use the ACK field in the frame header to send the sequence number of frame being ACKed.

→ better use of the channel capacity.
Sliding Window Protocols

- ACKs introduce a new issue – how long does receiver wait before sending ONLY an ACK frame?
  - Now we need an **ACKTimer** !!
  - The sender *timeout period* needs to be set longer.

- The protocol must deal with the premature timeout problem and be “robust” under pathological conditions.
Each outbound frame must contain a **sequence number**. With $n$ bits for the sequence number field,

$$\text{maxseq} = 2^n - 1$$

and the numbers range from 0 to maxseq.

**Sliding window**: the sender has a window of frames and maintains a list of consecutive sequence numbers for frames that it is permitted to send without waiting for ACKs.
The receiver has a window of frames that has space for frames whose sequence numbers are in the range of frame sequence numbers it is permitted to accept.

Note - sending and receiving windows do NOT have to be the same size.

The windows can be fixed size or dynamically growing and shrinking (e.g., TCP uses dynamic cwnd).
The Host is oblivious to sliding windows and the message order at the transport layer is maintained.

sender’s DL window :: holds frames sent but not yet ACKed.

- new packets from the Host cause the upper edge inside the sender’s window to be incremented.
- acknowledged frames from the receiver cause the lower edge inside the sender’s window to be incremented.
Sliding Window Protocols

- All frames in the sender's window must be saved for possible retransmission and we need one timer per frame in the window.
- If the maximum sender window size is $B$, the sender needs at least $B$ buffers.
- If the sender's window gets full (i.e., it reaches the maximum window size, the protocol must shut off the Host (the network layer) until buffers become available.
Sliding Window Diagram

(a) Sender’s perspective

(b) Receiver’s perspective

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Sliding Window Protocols

receiver's DL window

- Frames received with sequence numbers outside the receiver's window are not accepted.
- The receiver's window size is normally static.
- The set of acceptable sequence numbers is rotated as “acceptable” frames arrive.

If a receiver’s window size = 1, then the protocol only accepts frames in order.

This scheme is referred to as Go Back N.
Selective Repeat :: receiver’s window size > 1.

- The receiver stores all correct frames within the acceptable window range.
- Either the sender times out and resends the missing frame, or
- Selective repeat receiver sends a NACK frame back to the sender.
1. The ACK sequence number indicates the last frame successfully received.

- OR -

2. ACK sequence number indicates the next frame the receiver expects to receive.

Both schemes can be strictly individual ACKs or represent cumulative ACKs. **Cumulative ACKs** is the most common technique used.
/* 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;
    packet buffer;
    event_type event;
    next_frame_to_send = 0; /* next frame on the outbound stream */
    frame_expected = 0; /* frame expected next */
    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);
    while (true) {
        wait_for_event(&event);
        if (event == frame_arrival) {
            from_physical_layer(&r);
            /* a frame has arrived undamaged. */
            /* go get it */
        }
        if (r.seq == frame_expected) {
            to_network_layer(&r.info);
            inc(frame_expected);
            /* handle inbound frame stream. */
            /* pass packet to network layer */
            /* 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);
            inc(next_frame_to_send);
            /* fetch new pkt from network layer */
            /* invert sender’s sequence number */
        }
    }
    s.info = buffer;
    s.seq = next_frame_to_send; /* insert sequence number into it */
    s.ack = 1 - frame_expected;
    to_physical_layer(&s);
    start_timer(s.seq);
}

Figure 3-14. A 1-bit sliding window protocol.
Timeout Occurs for frame 3!!
4 outstanding frames so go back 4

Go-Back-4:

timeout

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

Out-of-sequence frames

A A A A C C C C K K K K 1 2 3

error

ACKing next frame expected

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Go Back N

with NAK error recovery

Transmitter goes back to frame 1

Go-Back-7:

A

fr 0  fr 1  fr 2  fr 3  fr 4  fr 5  fr 6  fr 7  fr 0

B

A  C  K 1

A  NAK 1

Out-of-sequence frames

A  C  K 2

A  C  K 3

A  C  K 4

A  C  K 5

A  C  K 6

A  C  K 7

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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;
    s.info = buffer[frame_nr];
    s.seq = frame_nr;
    s.ack = (frame_expected + MAX_SEQ) % (MAX_SEQ + 1); /* piggyback ack */
    to_physical_layer(&s);
    start_timer(frame_nr);
}

void protocol5(void)
{
    seq_nr next_frame_to_send;
    seq_nr ack_expected;
    seq_nr frame_expected;
    frame r;
    packet buffer[MAX_SEQ + 1];
    seq_nr nbuffered;
    seq_nr i;
    event_type event;

    enable_network_layer();
    ack_expected = 0;
    next_frame_to_send = 0;
    frame_expected = 0;
    nbuffered = 0;
    */MAX_SEQ > 1; used for outbound stream */
    */oldest frame as yet unacknowledged */
    */next frame expected on inbound stream */
    */scratch variable */
    /* buffers for the outbound stream */
    /* # output buffers currently in use */
    /* used to index into the buffer array */
    /* allow network_layer_ready events */
    /* next ack expected inbound */
    /* next frame going out */
    /* number of frame expected inbound */
    /* 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 */
            }
            break;

        if (nbuffered < MAX_SEQ)
            enable_network_layer();
        else
            disable_network_layer();
    }
}
Sliding Window Example

Source System A

Destination System B

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Selective Repeat with NAK error recovery

Retransmit only frame 2

Cumulative ACK

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/* 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 */
    s.seq = frame_nr;
    s.ack = (frame_expected + MAX_SEQ) % (MAX_SEQ + 1);
    if (fk == nak) no_nak = false;  /* one nak per frame, please */
    to_physical_layer(&s);
    if (fk == data) start_timer(frame_nr % NR_BUFS);  /* no need for separate ack frame */

    void protocol6(void)
    {
        seq_nr ack_expected;
        seq_nr next_frame_to_send;
        seq_nr frame_expected;
        seq_nr too_far;
        int i;
        frame r;
        packet out_buf[NR_BUFS];
        packet in_buf[NR_BUFS];
        boolean arrived[NR_BUFS];
        seq_nr nbuffered;
        event_type event;

        enable_network_layer();  /* lower edge of sender's window */
        ack_expected = 0;  /* upper edge of sender's window */
        next_frame_to_send = 0;  /* lower edge of receiver's window */
        frame_expected = 0;  /* upper edge of receiver's window */
        too_far = NR_BUFS;
        nbuffered = 0;  /* index into buffer pool */
        /* scratch variable */

        /* buffers for the outbound stream */
        /* buffers for the inbound stream */
        /* inbound bit map */
        /* how many output buffers currently used */

        /* initialize */
        /* next ack expected on the inbound stream */
        /* number of next outgoing frame */

        for (i = 0; i < NR_BUFS; i++) arrived[i] = false;

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while (true) {
    wait_for_event(&event);
    switch(event) {
        case network_layer_ready:
            nbuffered = nbuffered + 1; /* accept, save, and transmit a new frame */
            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();
}

Figure 3-19. A sliding window protocol using ACK to report.
Data Link Layer Summary

- Parallelism between Transport and Data Link Layer
- Tanenbaum’s Treatment/Model of Data Link Layer
- Protocol 1: Utopia
- Protocol 2: Stop-and-Wait
- Protocol 3: Positive Acknowledgment with Retransmission [PAR]
  - Old ‘flawed version
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DL Layer Summary (cont)

- Pipelining and Sliding Windows
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