

Chapter 3

The Data Link Layer

Many protocols/algorithms discussed in this chapter apply to other layers



Functions of the Data Link Layer

- Provide service interface to the network layer
- Dealing with transmission errors.
 - Either error free or detectable
- In broadcast networks there are additional problems
 - Co-ordination (e.g. CDMA, token, central arbiter)
 - Local Addressing (within a network)
- Regulating data flow
 - Slow receivers not swamped by fast senders
 - Not always implemented at the datalink layer
 - Provided only up to the interface to network layer
 - Does not guard against packet drop in upper layer



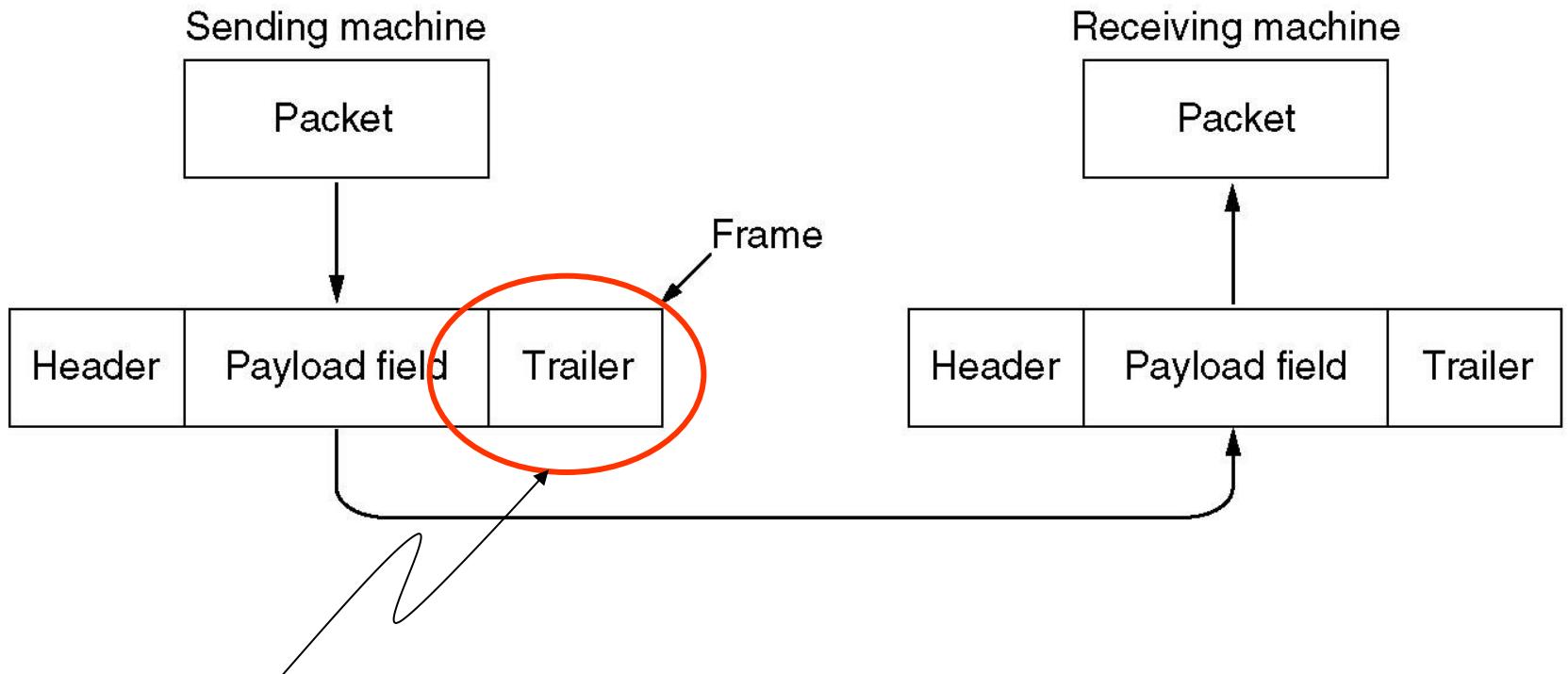
Data Link Layer Design Issues

- Services Provided to the Network Layer
 - Framing
 - Error Control
 - Flow Control
 - Local Addressing
- Many of the above functions are also provided at upper layers. E.g.
 - E.g. Error control and flow control is provided at the transport layer
 - The principle is the same in all layers



Relation Between Packets and Frames

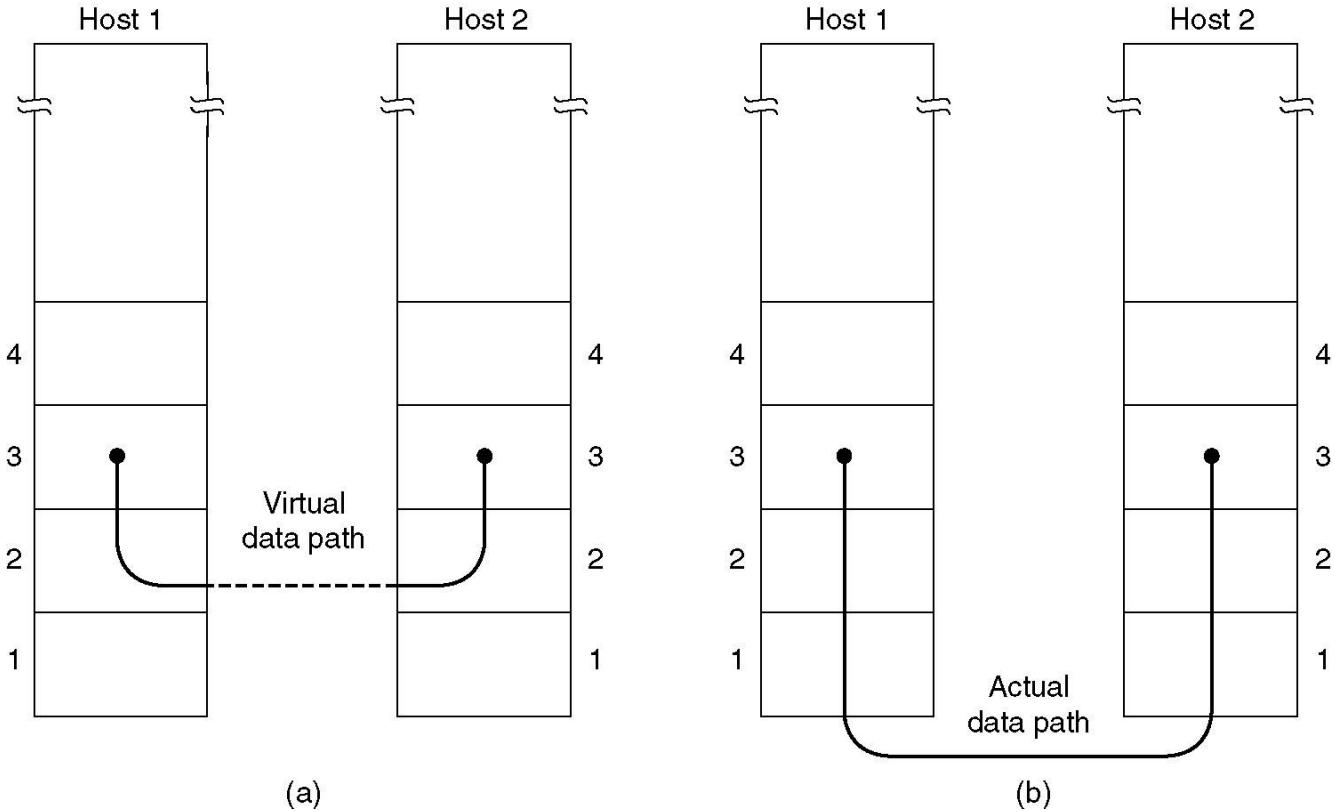
Relationship between packets and frames.



Not all datalink protocols use trailers



Services Provided to Network Layer





Types of Connections

- Unacknowledged connectionless
 - Usually on reliable links (e.g fiber).
 - Extra weight and complexity of acknowledgement not necessary
- Acknowledged connectionless
 - Good for unreliable links* (e.g. wireless)
 - Sub-optimal for reliable channels (e.g. fiber)
 - No need for connection establishment
 - Mobility and simplicity
 - No need to keep state with every peer
 - Can deliver *out of order* packets
- Connection oriented
 - Establish connection prior to sending
 - Information is acknowledged
 - Easy to provide flow control
 - Each packet gets a sequence number
 - In-order delivery
 - Easy to detect lost packet and expedite retransmit (E.g. by sending NACK)
 - PPP, HDLC



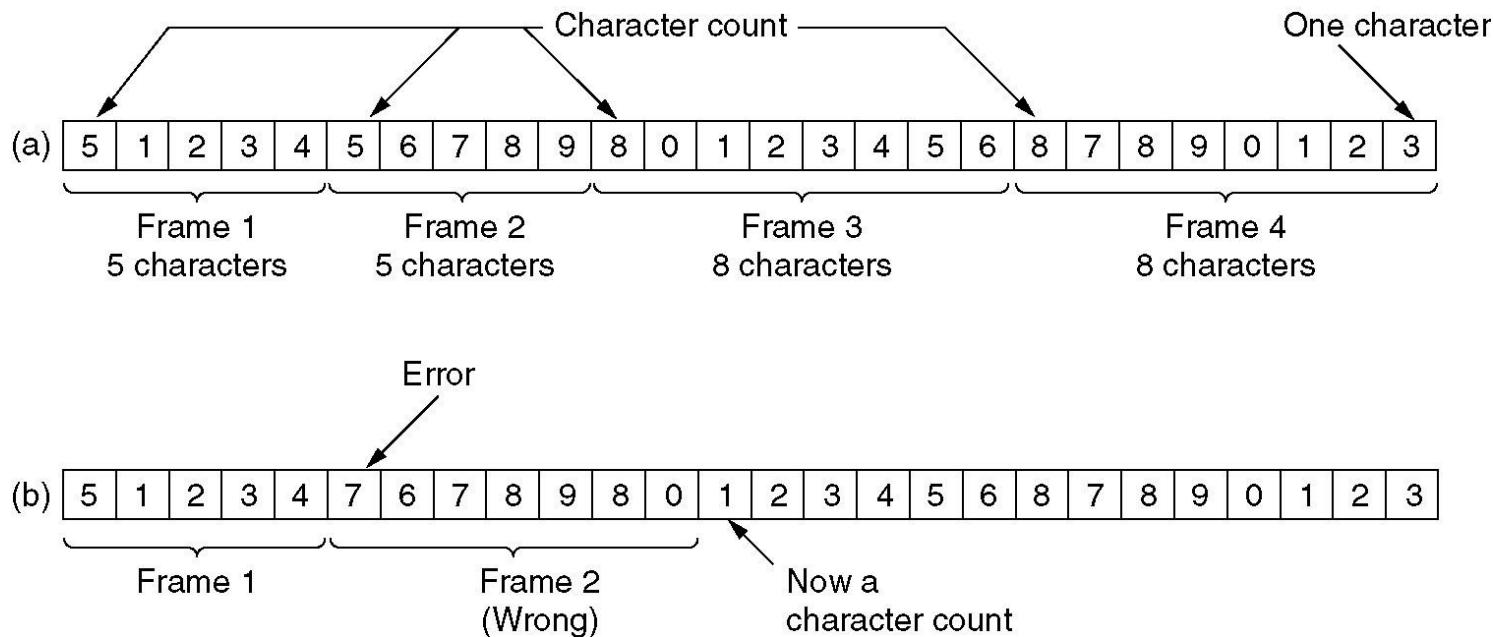
Framing

- Framing is breaking up stream of bits into well defined bounded chunks
- Good for reliability
 - Error detection/correction codes
 - Allows for Ack
- Not easy to do (Cannot rely on time gaps)
 - time gaps are not guaranteed by network
 - Time gaps may change while traveling due physical or logical condition
- We'll talk about 3 frame demarcation methods
 - Character count
 - Flag bytes with byte stuffing
 - Starting and ending flags with bit stuffing
 - Physical layer encoding violations (we will not talk about it)



Framing Using Character Count

- Idea
 - Put the character count in the header of each frame



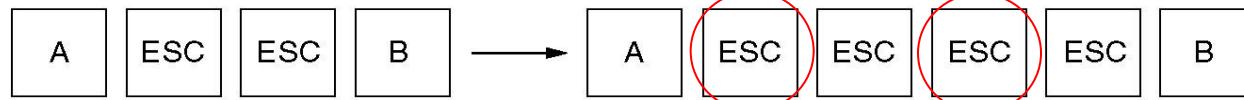
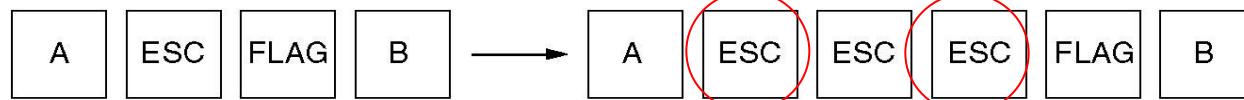
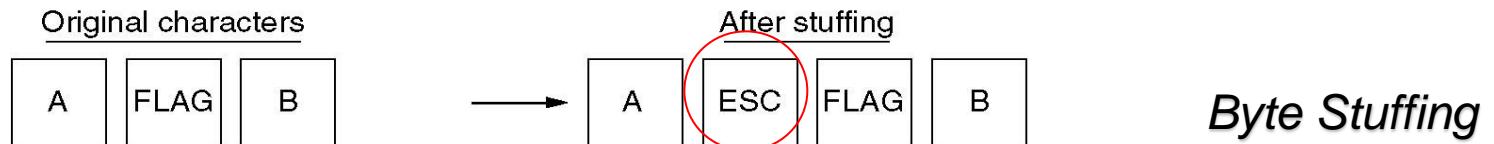
A character stream. (a) Without errors. (b) With one error.



Framing Using Flag Byte

FLAG	Header	Payload field			Trailer	FLAG
------	--------	---------------	--	--	---------	------

(a)



(b)

Flag is called Frame Sync Sequence (FSS) as in HDLC

(a) A frame delimited by FLAG bytes.

I.e. Each frame is started and ended by a FLAG byte

The Start and end FLAG bytes may be identical

Why it is better to have a FLAG byte at the beginning and the end of each frame instead of just one FLAG byte at the beginning of each frame?

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

(c) Insert ESC before **each** accidental FLAG in data stream

(d) Insert ESC before **each** accidental ESC in data stream

(e) A single FLAG is a flag. Double ESC is a single ESC

What is the disadvantage of byte stuffing?



Framing Using Bit Stuffing

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

↑
Stuffed bits

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

- Idea
 - Add (*stuff*) a bit so that the flag sequence is never transmitted inside the payload data
 - Allow the receiver to detect the “*stuffed*” bit and remove it to restore data to its original value
- Flag is 01111110
- When sender sees a sequence of 5 1's it stuffs **0** into the stream
- When receiver sees 5 1's followed by **0**, it *destuffs* the **0**
- Hence we can **never** get 01111110 in the data stream
- If stream contains 01111110, it is transmitted as 011111**0**10
- When receiver sees “011111**0**”, it removes **0** to get “011111”



Error Control

- Error control repairs frames that are received in error
 - Requires errors to be detected at the receiver
 - Typically retransmit the unacknowledged frames
 - Timer protects against lost acknowledgements
- Detecting errors and retransmissions are next topics.



Flow Control

- Prevents a fast sender from out-pacing a slow receiver
 - Receiver gives feedback on the data it can accept
 - Rare in the Link layer as NICs run at “wire speed”
 - Receiver can take data as fast as it can be sent
- Flow control is a topic in the Link and Transport layers



Error Detection and Correction

- Two main strategies
 - Error-Correcting Codes (FEC)
 - Error-Detecting Codes
- An error is a bit the value of which is reversed
 - Error sometimes is referred to as “corruption”
- Errors are usually bursty
 - Bursty errors cause less packets to be corrupted than random error
 - Much harder to correct because *many* bits are corrupted.
- FEC good for low reliability (e.g. wireless) because retransmission is frequent and may contain error itself
- Error detection is good for reliable links because it is cheaper to re-transmit the rare corrupted frames
- **What is the basic idea?**
 - *Agree on valid symbols*
 - *Add check (redundant) bits*
- **Why do we need redundant bits?**



Original Hamming Method

- Use power of 2 bit position as check bits (1, 2, 4, 8, 16)
- All other bit position are message bits
- The parity bit at position 2^k checks bits in positions having bit k set in their binary representation.
- Conversely, for instance, bit 13, i.e. 1101, is checked by bits $1000 = 8$, $0100 = 4$ and $0001 = 1$.

Error Bounds – Hamming distance

Code turns data of n bits into codewords of $n+k$ bits

Hamming distance is the minimum bit flips to turn one valid codeword into any other valid one.

- Example with 4 codewords of 10 bits ($n=2, k=8$):
 - 0000000000, 0000011111, 1111100000, and 1111111111
 - Hamming distance is 5

Bounds for a code with distance:

- $2d+1$ – can correct d errors (e.g., 2 errors above)
- $d+1$ – can detect d errors (e.g., 4 errors above)



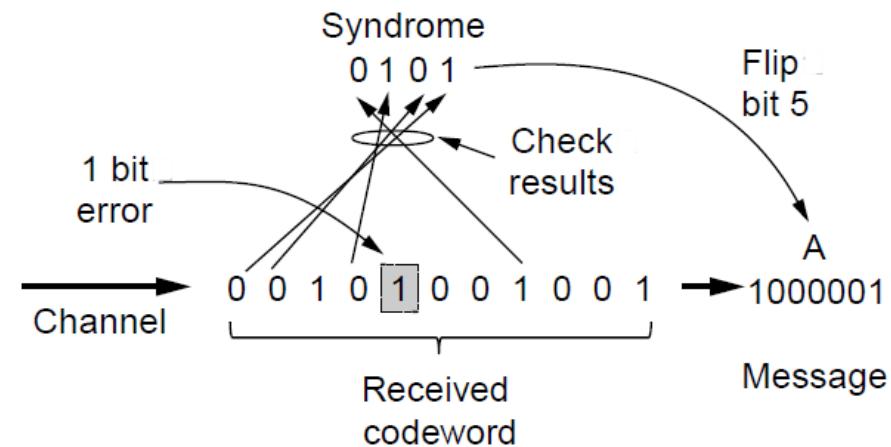
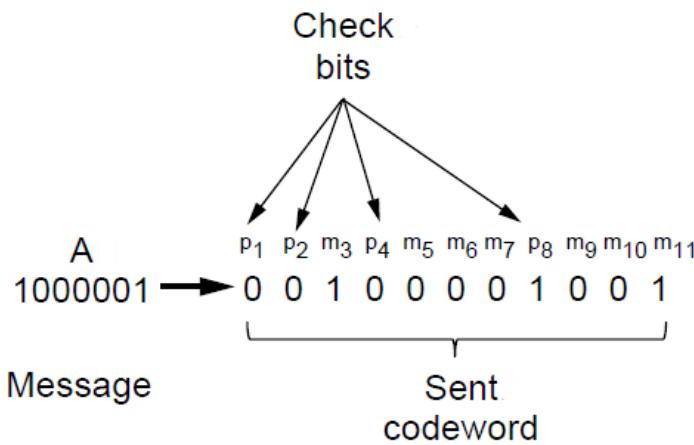
Hamming Method

- For 1-bit error-correction, message m , number of redundant r bits will be calculated as follows:
 - $(m+r+1) \leq 2^r$
 - Let $m=64$. Then we need:
$$r+65 \leq 2^r$$
Remember **powers of 2**
 - i.e. $r \geq 7$



Error Correction – Hamming code

- Hamming code gives a simple way to add check bits and correct up to a single bit error:
 - Check bits are parity over subsets of the codeword
 - Re-computing the parity sums (syndrome) gives the position of the error to flip, or 0 if there is no error



(11, 7) Hamming code adds 4 check bits and can correct 1 error

Even parity: $P_1 (m_3, m_5, m_7, m_9, m_{11}) = 0$ – $P_2 (m_3, m_6, m_7, m_{10}, m_{11}) = 0$ –
 $P_4 (m_5, m_6, m_7) = 0$ – $P_8 (m_9, m_{10}, m_{11}) = 1$



Hamming Code to Correct Burst Errors

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

- Distribute the burst over multiple code words by sending columns first
- Let the burst error size be k
- Arrange every k codeword in a matrix
- Send the k code words one *column* after the other
- When the entire matrix is received, reconstruct the matrix
- Because burst size is at most k , then there is at most one error per code word



Error-Detecting Codes

- Better for reliable channels
- Detect an error and re-transmit
- Far less redundancy bits.



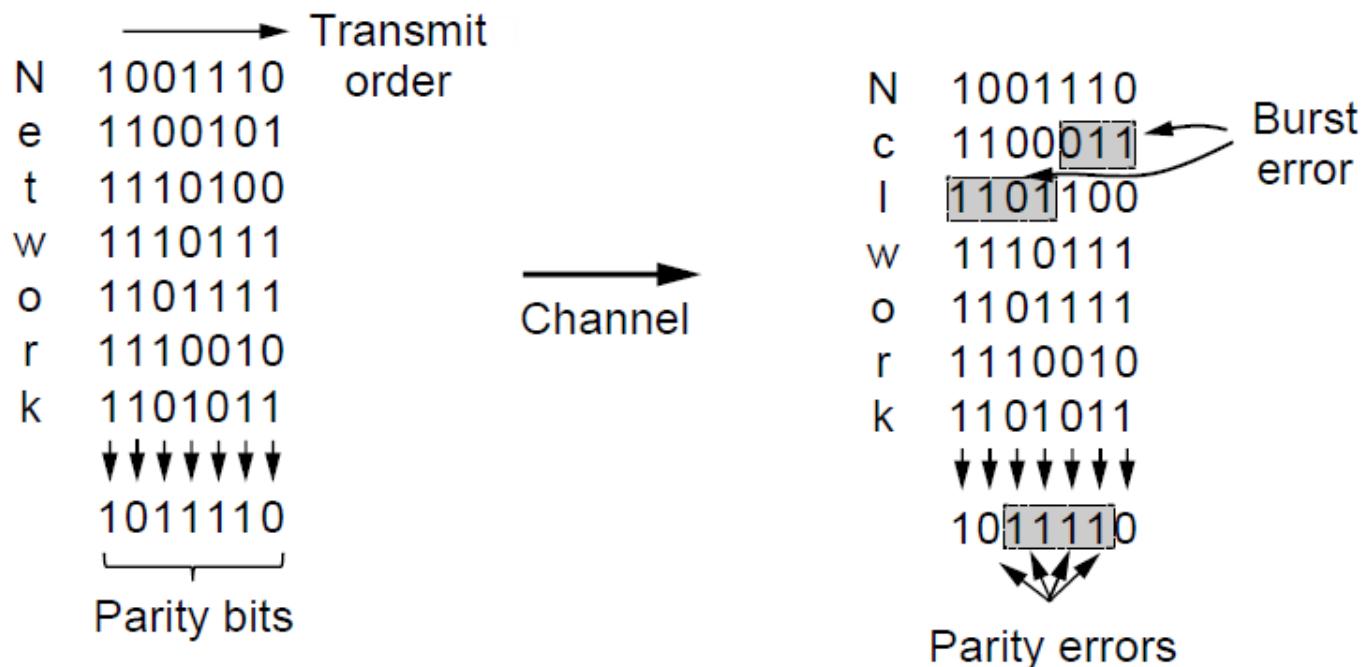
Error Detection – Parity (1)

- Parity bit is added as the modulo 2 sum of data bits
 - Equivalent to XOR; this is even parity
 - Ex: 1110000 → 11100001
 - Detection checks if the sum is wrong (an error)
- Simple way to detect an *odd* number of errors
 - Ex: 1 error, 11100101; detected, sum is wrong
 - Ex: 3 errors, 11011001; detected sum is wrong
 - Ex: 2 errors, 1110110 ; *not detected*, sum is right!
 - Error can also be in the parity bit itself
 - Random errors are detected with probability $\frac{1}{2}$



Error Detection – Parity (2)

- Interleaving of N parity bits detects burst errors up to N
 - Each parity sum is made over non-adjacent bits
 - An even burst of up to N errors will not cause it to fail





Parity Error-Detecting Codes

- Compare Parity bits with Hamming error correction
- Suppose the error rate is 10^{-6}
- Hamming error correction
 - message size is 1000 bits and we send a block of 1000 messages
 - Using $m + r + 1 \leq 2^r$, we need 10 redundant bits per message ($2^{10}=1024$).
 - Single bit error correction 10kbits per Mbits
- Parity Bits error detection + retransmission
 - Single bit burst error correction overhead is 2001 bits per Mbits
(how did we calculate this number?)



Parity Error-Detecting Codes

- 1 M of data needs 1,000 check bits.
- Once every 1000 blocks (1 M), 1 block needs to be re-transmitted (extra 1001)



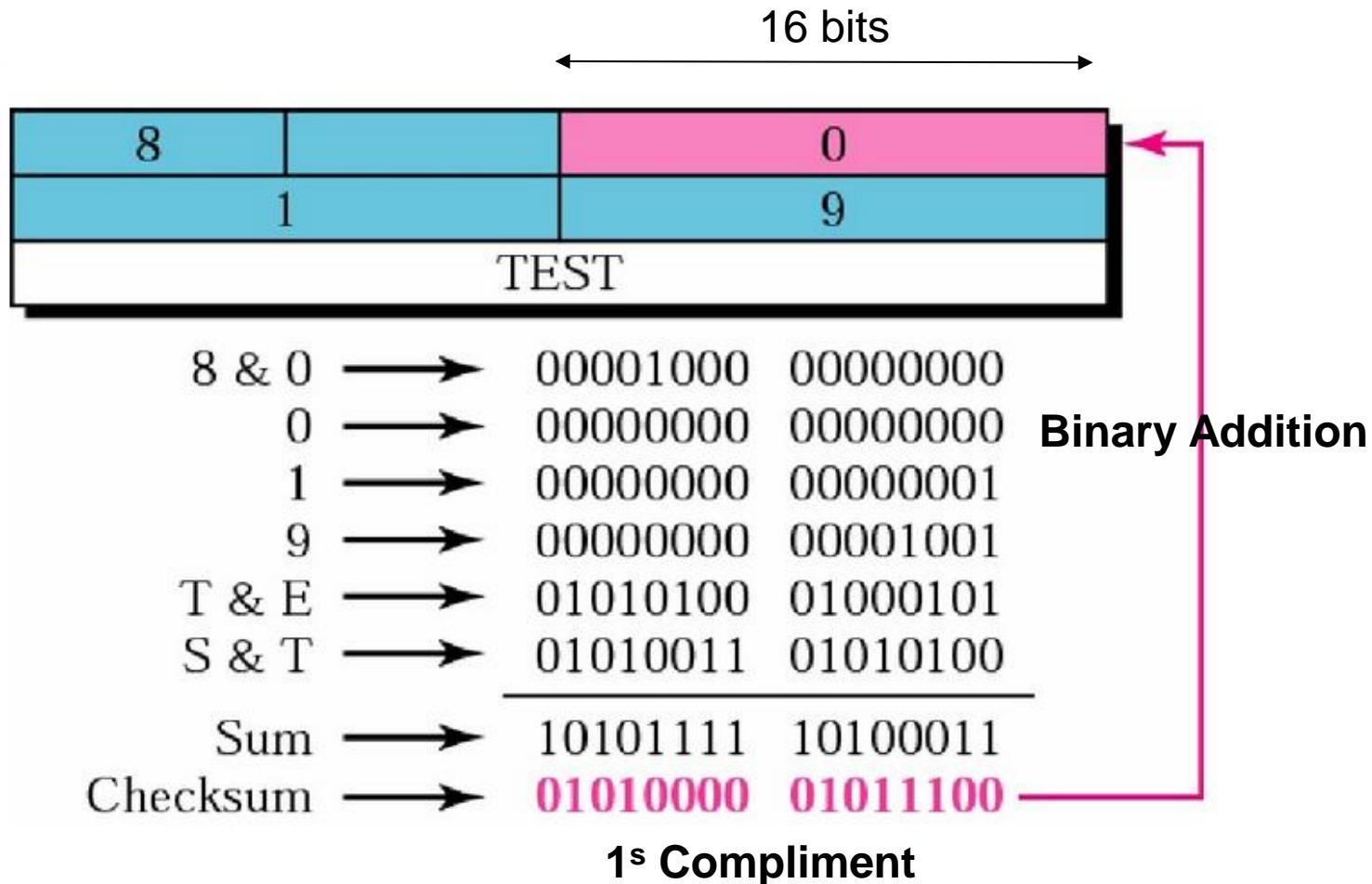
Error Detection – Checksums

- Checksum treats data as N -bit words and adds N check bits that are the modulo 2^N sum of the words
 - Ex: Internet 16-bit 1s complement checksum
 - Simply Binary Add your N -bit words and your checksum is 1s complement of the result
- Properties:
 - Improved error detection over parity bits
 - Detects bursts up to N errors
 - Detects random errors with probability $1 - 2^{-N}$
 - Vulnerable to systematic errors, e.g., added zeros



Error Detection – Checksums

Example of checksum calculation





Cyclic Redundancy Check Idea

- We all know that x divides y if remainder of y/x is 0
- Transmitter and receiver agree on **generating polynomial $G(x)$**
 - Both high and low order bits of $G(x)$ must be **1**.
 - Frame must be longer than $G(x) \Rightarrow$ The order of $M(x)$ is larger than $G(x)$
- Represent the message (i.e the frame) by the polynomial $M(x)$
- Append **checksum** bits to the message resulting in the polynomial $T(x)$. ($T(x)$ contains both $M(x)$ and the **checksum** bits)
- Checksum bits are calculated such that $G(x)$ divides $T(x)$
- Transmit the frame corresponding to $T(x)$ to the receiver
- At the receiver, compute the *received* $T(x)/G(x)$
- If $G(x)$ does **not** divide the received $T(x)$, then there is an **error**



How to Calculate Transmit Frame

- Given $G(x)$ and $M(x)$
- Let r be the degree of $G(x)$
 - ⇒ $G(x)$ has at most $(r+1)$ terms
- Let m be the maximum number of bits in the message
 - m is the size of the payload
- Append $r 0$'s to $M(x)$
 - The frame now contains $m+r$ bits
 - The frame corresponds to the polynomial $x^r M(x)$ (*Why?*)
- Divide $x^r M(x)$ by $G(x)$ using modulo 2 arithmetic
- *What is the number of bits in the remainder?*
- Subtract the remainder from $x^r M(x)$
 - Remember that *subtraction* is just **XOR**.
- $T(x)$ is the result of the subtraction.



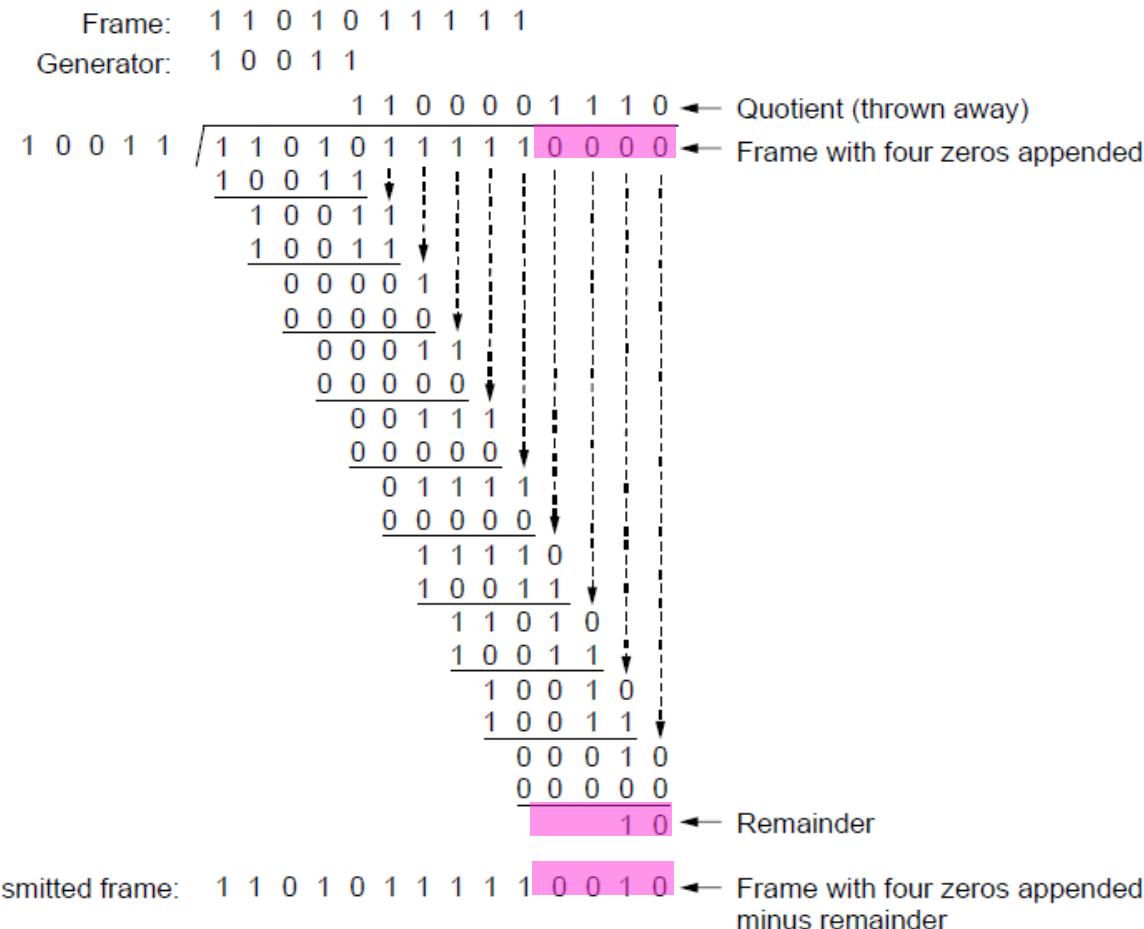
Error Detection – CRCs

- Adds bits so that transmitted frame viewed as a polynomial is evenly divisible by a generator polynomial

Start by adding
0s to frame
and try dividing

- Add zeros to end
- Simple Xor and shift
- Get the remainder

Offset by any
remainder to make it
evenly divisible





Error Detection – CRCs

- Based on standard polynomials:
 - Ex: Ethernet 32-bit CRC
$$x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x^1 + 1$$
 - Computed with simple shift/XOR circuits
- Stronger detection than checksums:
 - E.g., can detect all double bit errors
 - Not vulnerable to systematic errors



Elementary Data Link Protocols

1. An Unrestricted Simplex Protocol (UTOPIA)
 2. A Simplex Stop-and-Wait Protocol
 3. A Simplex Protocol for a Noisy Channel
- Simplex means:
 - Data can flow in one direction only
 - Control packets can flow in both directions

Variations of protocols described in this section are used in other layers



Basic Assumptions

- Assume physical, data link, and network layers are independent processes that communicate only using messages
- The physical layer does **NOT reorder** packets.
 - In general, physical wires and media do not re-order packets.
 - Reordering usually occurs in virtual channels
- **Assume network layer at endpoints want reliable connection-oriented channel**
 - In order delivery: Packets are always delivered to network layer in order
 - No duplicate packets: Never deliver duplicate packets to the network layer
 - No packets are lost: Never skip delivering a packet to the network layer.
 - No error packets: The payload delivered to the network layer of the receiver is identical to the payload sent by the network layer at the sender
 - No deadlock: Packets are delivered in a *finite amount of time*. E.g a packet never gets stuck at the sender or the receiver datalink layer
- Note: Unbounded wait time (e.g. due to strict priority) is considered finite. Hence for a protocol to be reliable it need not provide bounded time but it has to be finite*)
- Frame header is never given to network layer (to ensure layer independence)
- Assume medium is unreliable. Hence timeout mechanism is used by sender to retransmit.
- Assume timers can be (re)started and stopped at any time
- Assume receiver waits indefinitely and only wakes on events (e.g. packet arrive, received errored packet, timer expired)
- Subtraction and addition of sequence number is assumed to be *circular*
 - We *never* get negative sequence number
- Assume network layer transmitter has infinite supply of data
 - we will remove this assumption later



Protocol Definitions

```
#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 */  
  
Frame header  
  └──→ typedef struct {  
    frame_kind kind;  
    seq_nr seq;  
    seq_nr ack;  
    packet info;  
  } frame;  
    └──→ Payload  
  
The sequence number of the frame that we are sending in this packet  
The sequence number of the frame to be received
```

```
/* frames are transported in this layer */  
/* what kind of a frame is it? */  
/* sequence number */  
/* acknowledgement number */  
/* the network layer packet */
```

Continued →

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



Protocol Definitions (ctd.)

```
/* 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
```

Separate timer for each sequence number “k”

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

Circular increment



Link layer environment (2)

- Link layer protocol implementations use library functions
 - See code (`protocol.h`) for more details

Group	Library Function	Description
Network layer	<code>from_network_layer(&packet)</code> <code>to_network_layer(&packet)</code> <code>enable_network_layer()</code> <code>disable_network_layer()</code>	Take a packet from network layer to send Deliver a received packet to network layer Let network cause “ready” events Prevent network “ready” events
Physical layer	<code>from_physical_layer(&frame)</code> <code>to_physical_layer(&frame)</code>	Get an incoming frame from physical layer Pass an outgoing frame to physical layer
Events & timers	<code>wait_for_event(&event)</code> <code>start_timer(seq_nr)</code> <code>stop_timer(seq_nr)</code> <code>start_ack_timer()</code> <code>stop_ack_timer()</code>	Wait for a packet / frame / timer event Start a countdown timer running Stop a countdown timer from running Start the ACK countdown timer Stop the ACK countdown timer



Unrestricted Simplex Protocol

- Perfect world ☺
- Error free communication channel
- Sender has infinite buffer
- Receiver has infinite buffer
- Receiver can process all input infinitely fast
- Sender network layer has infinite packet supply to send
- Propagation delay is negligible



Unrestricted Simplex Protocol

- We have not initialized the fields in the header (*why?*)

```
/* 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 */
    }
}
```



Simplex Stop-and-Wait Protocol

- Semi-perfect world
- Drop the unrealistic assumption at the receiver. Assume
 - Receiver has *finite buffer*
 - Receiver has *finite processing capacity*
- Error free channel
- Sender has infinite buffer
- Sender Network layer has infinite supply of packets to send
- *What and where error can occur?*

Packet drop at the receiver side



Simplex Stop-and- Wait Protocol

- We do not need a timeout mechanism in this protocol (*Why?*)
- We do not need sequence number (*why?*)

```
/* 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;
    packet buffer;
    event_type event;

    while (true) {
        from_network_layer(&buffer);
        s.info = buffer;
        to_physical_layer(&s);
        wait_for_event(&event);
    }
}

void receiver2(void)
{
    frame r, s;
    event_type event;
    while (true) {
        wait_for_event(&event);
        from_physical_layer(&r);
        to_network_layer(&r.info);
        to_physical_layer(&s);

    }
}

/* buffer for an outbound frame */
/* buffer for an outbound packet */
/* frame_arrival is the only possibility */

/* go get something to send */
/* copy it into s for transmission */
/* bye bye little frame */
/* do not proceed until given the go ahead */

/* buffers for frames */
/* frame_arrival is the only possibility */

/* only possibility is frame_arrival */
/* go get the inbound frame */
/* pass the data to the network layer */
/* send a dummy frame to awaken sender */
```



Simplex Stop-and-Wait Protocol

- We can see from the protocol code that we do *NOT have a timeout* on the sender side. *Why don't we need a timer even though the receiver has a finite buffer and hence packets may be dropped?*
 - Actually, there is *no possibility of packet drop* because the sender will send the next packet ONLY when it receives an ACK from the receiver.
 - Because we assumed perfect channel, the packet will arrive at the receiver and the ACK will arrive at the sender
 - Hence there is no need for timeout at the sender
 - In other words, we overcome the finite CPU and buffer capacity of the receiver by having the ***receiver control the transmission***.
- We do not need a sequence number , *why?*
 - because we do not lose packets
 - Because there is no possibility of packet duplication
 - Because there is no possibility of packet reorder
- *Why doesn't the sender inspect the packet type?*



A Simplex Protocol for a Noisy Channel

- Assume *non-zero* variable *propagation delay* along the channel in both direction
- Assume possible frame damage or loss in both direction
- Assume errored packets are detected correctly (*i.e.* perfect error detection)
- Simple modification to the previous protocol
- Use a timeout at the sender
- Sender only transmits next frame if it received *correct ACK* (damaged ACK are discarded)
- **If it does not receive a correct ACK, it times-out and re-transmits the same frame**



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- *Is this correct?*



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Duplicate Frame if ACK is lost



A Simplex Protocol for a Noisy Channel

- Assume *non-zero* variable *propagation delay* along the channel in both direction
- Assume possible frame damage or loss in both direction
- Assume errored packets are detected correctly
- Assume that the propagation delay is greater than zero
- Simple modification to the previous protocol
- Use a timeout at the sender
- Sender only transmits next frame if it received *correct ACK* (damaged ACK are discarded)
- If it does not receive a correct ACK, it times-out and re-transmits the same frame
- *Is this correct?*

Duplicate Frame if ACK is lost

- We need a sequence number (*what size?*)
- Protocols where sender waits to ACK from receiver and retransmits after time out are sometimes called
 - PAR: Positive Acknowledge with Retransmit
 - **ARQ: Automatic Repeat reQuest**
 - See for example RFC3366: Advice to Link Designers on Link ARQ
- Hence the rest of the protocols in this chapter belong to the class of protocols known as ARQ



A Simplex Protocol for a Noisy Channel

A positive acknowledgement with retransmission protocol.

Why does the sender need to check the sequence number in s.ack?

I.e. Can the sender just send the next frame as soon as it receives an ACK, assuming that the physical layer drops any corrupted packet?

- Assume that an errored frame generates the event “checksum_err”. We will ignore this event.
- This is similar to assuming that physical layer discards errored packets

```
/* 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 */

    next_frame_to_send = 0;                     /* initialize outbound sequence numbers */
    from_network_layer(&buffer);             /* fetch first packet */

    while (true) {
        s.info = buffer;
        s.seq = next_frame_to_send;            /* construct a frame for transmission */
        to_physical_layer(&s);                /* insert sequence number in frame */
        start_timer(s.seq);                  /* send it on its way */
        wait_for_event(&event);              /* if answer takes too long, time out */
        if (event == frame_arrival) {          /* frame_arrival, cksum_err, timeout */
            from_physical_layer(&s);         /* get the acknowledgement */
            if (s.ack == 1 - next_frame_to_send) {
                stop_timer(s.ack);
                from_network_layer(&buffer);  /* turn the timer off */
                inc(next_frame_to_send);      /* get the next one to send */
            }
        }
    }
}
```

Circular increment

Continued →



A Simplex Protocol for a Noisy Channel (ctd.)

```
void receiver3(void)
{
    seq_nr frame_expected;
    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);
            }
            s.ack = frame_expected;
            to_physical_layer(&s);
        }
    }
}
```

```
/* possibilities: frame_arrival, cksum_err */
/* a valid frame has arrived. */
/* go get the newly arrived frame */
/* this is what we have been waiting for. */
/* pass the data to the network layer */
/* next time expect the other sequence nr */

/* tell which frame is being acked */
/* send acknowledgement */
```

- Receiver sends ACK for next expected frame
- Receiver sends ACK *every time* it receives ANY packet

- Suppose that the receiver does NOT send an ACK unless it receives a packet with the **expected sequence number**, will the protocol work correctly?



Stop-and-Wait ARQ

Cases of Operations:

1. *Normal operation*
2. *The frame is lost*
3. *The Acknowledgment (ACK) is lost*
4. *The Ack is delayed*

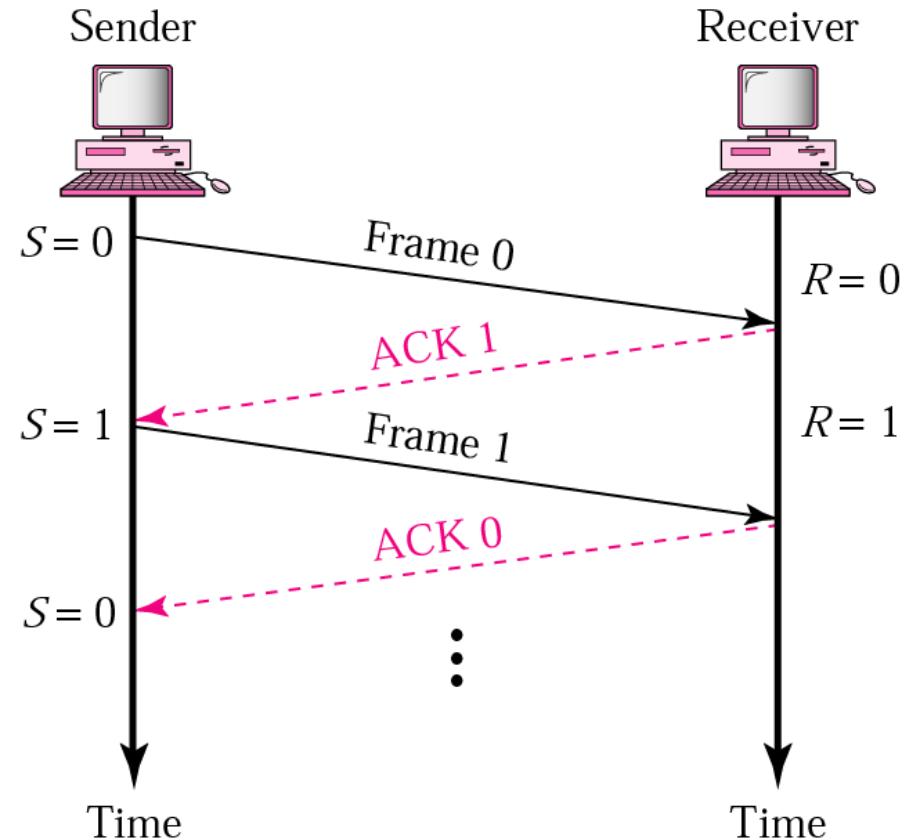
S&W + Time out + Seq. No. + Ack No.



Stop-and-Wait ARQ

1. Normal operation

- *The sender will not send the next frame until it is sure that the current one is correctly received*
- *sequence number is necessary to check for duplicated frames*

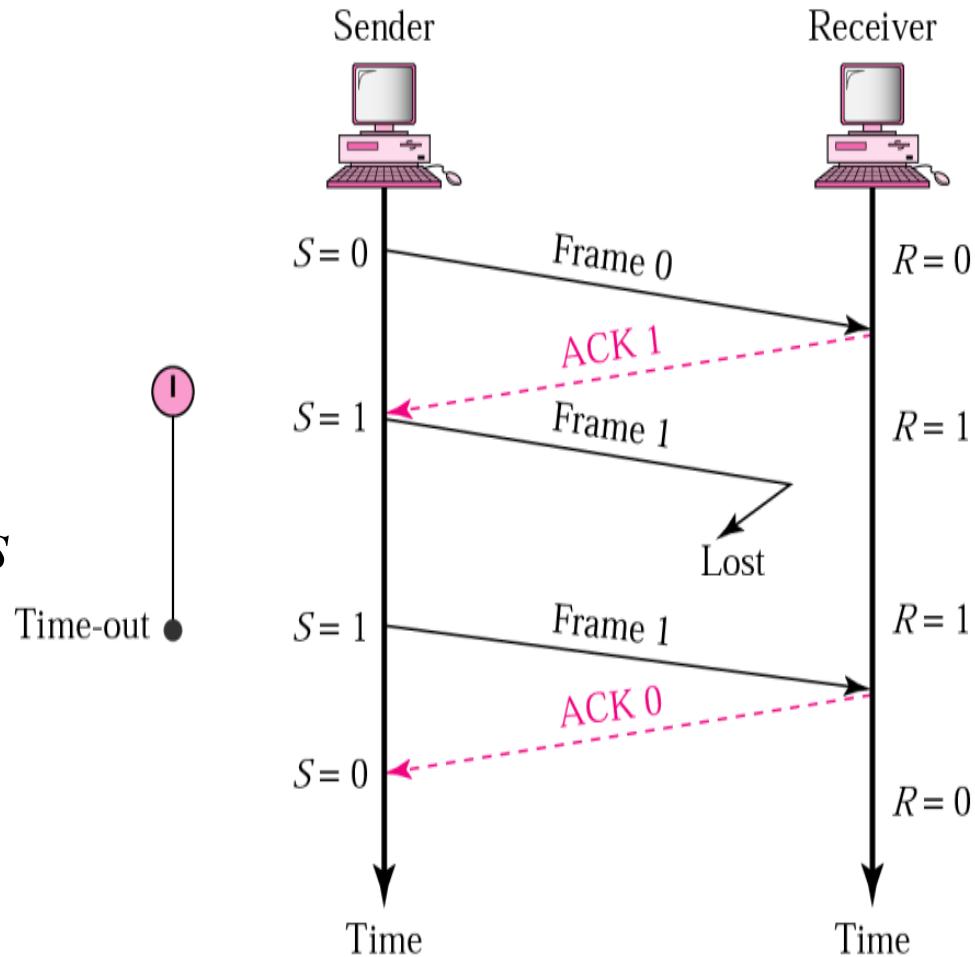
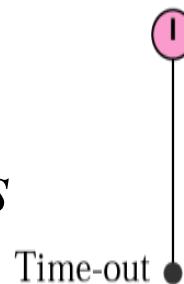




Stop and Wait ARQ

2. Lost or damaged frame

- A damage or lost frame treated by the same manner by the receiver.
- No NACK when frame is corrupted / duplicate

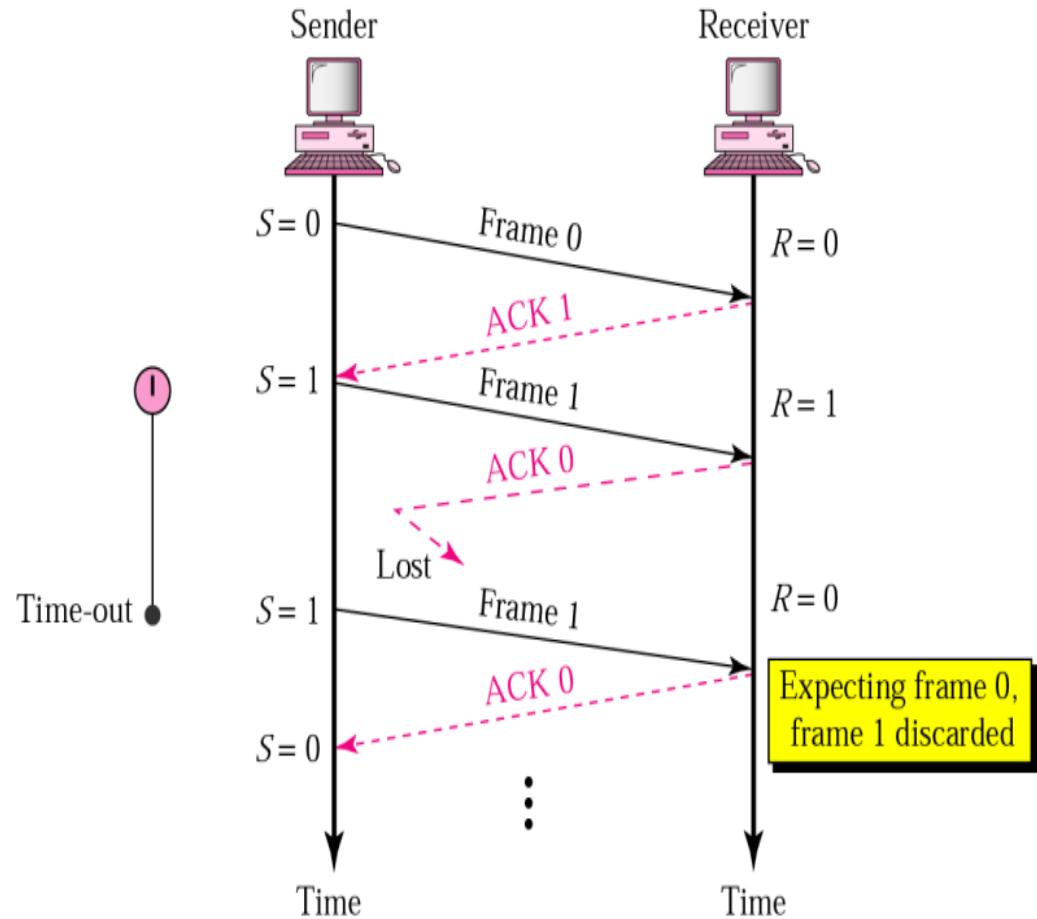




Stop-and-Wait ARQ

3. Lost ACK frame

- *Importance of frame numbering*





Note

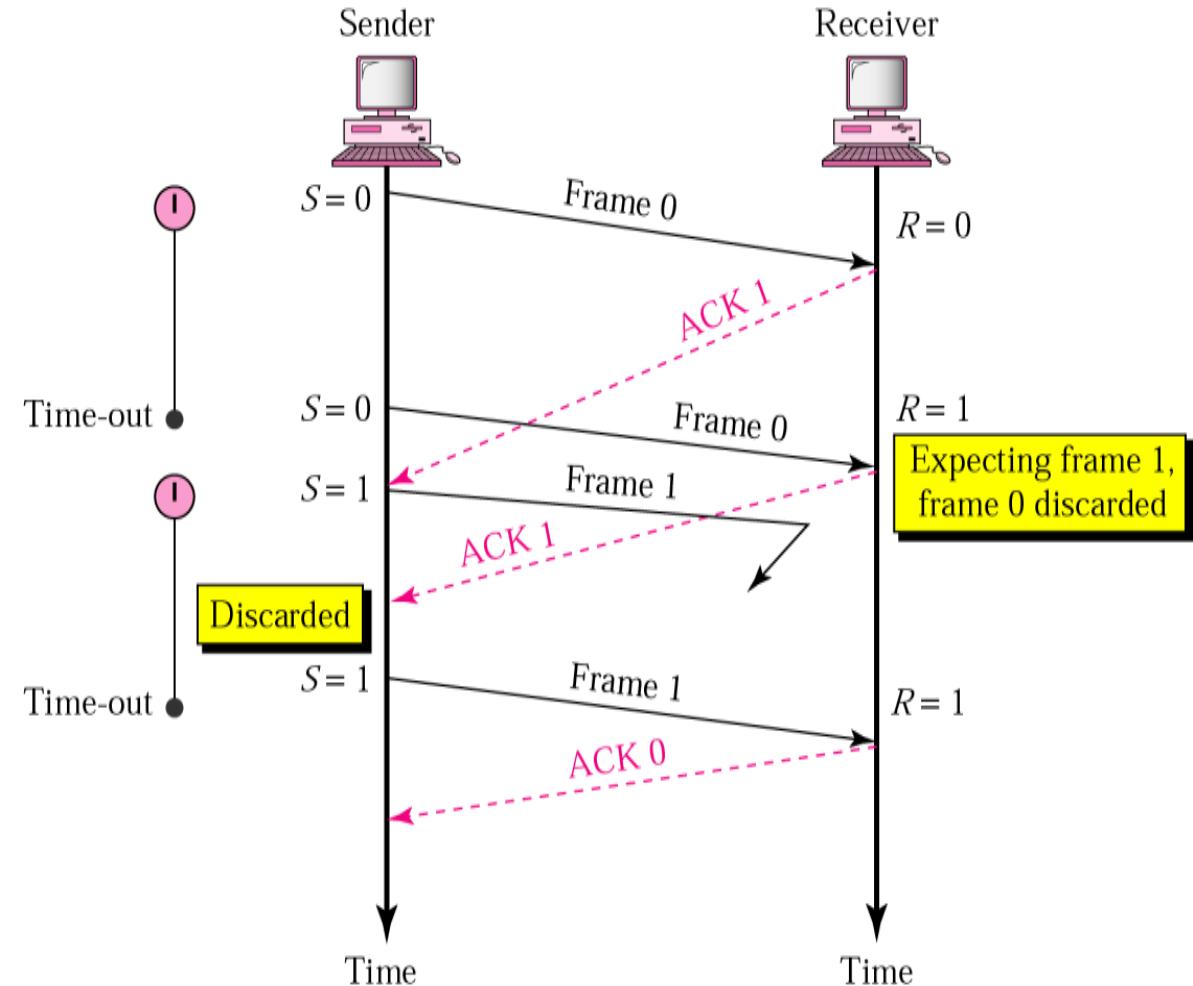
In Stop and-Wait ARQ, numbering frames prevents the retaining of duplicate frames.



Stop-and-Wait ARQ

4. Delayed ACK and lost frame

- *Importance of frame numbering*





Note

Numbered acknowledgments are needed if an acknowledgment is delayed and the next frame is lost.



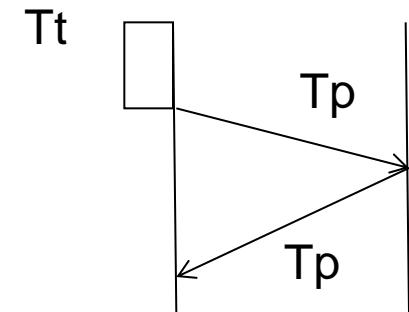
S&W Efficiency

- $\text{Efficiency} = \text{useful time} / \text{total time}$

$$= Tt / (Tt + 2 Tp)$$

$$= 1 / (1 + (2 Tp / Tt)) = 1 / (1 + 2 a) \quad a = Tp / Tt$$

$$= 1 / (1 + 2 * (d/v) * (B/L))$$



- d = distance between source and receiver, v = velocity
- B = Bandwidth
- Throughput : no. of bits sent / sec = $L / (Tt + 2Tp)$

Where L is the packet length

- Throughput is called Effective Bandwidth or Bandwidth utilization
- Effective BW = $(L * (B/B)) / (Tt + 2Tp) = [Tt / (Tt + 2Tp)] * BW$
= efficiency * B $(Tt = L/B)$



S&W Efficiency

- Example $Tt = 1 \text{ msec}$, $Tp = 1 \text{ msec}$, $B = 6 \text{ Mbps}$,
Then Efficiency is 33.3%
 $\text{Throughput} = 2 \text{ Mbps}$
 $Tt = 2 \text{ msec}$, $Tp = 1 \text{ msec}$, Efficiency is 50%,
 $\text{Throughput} = 3 \text{ Mbps}$
- For efficiency $\geq 50\%$, then $Tt \geq 2Tp$
 - Then $(L/B) \geq 2Tp$ then **L should be $\geq 2 * Tp * BW$**



S&W Efficiency

- In case of **S&W** protocol is only sending only one packet irrespective of the link bandwidth

Example: $T_t = 1 \text{ msec}$, $T_p = 1.5 \text{ msec}$

$$a = T_p / T_t = 1.5$$

$$\mathbf{S\&W \ Efficiency} = 1 / (1 + 2a) = 25\%$$



Retransmission packets in S&W ARQ protocol

- If P is the probability of loss packets
- If we want to transmit n packets then we will transmit the following:
$$\begin{aligned} & n + n(p) + (n(p))(p) + (np)p + \dots \\ & n(1 + p + p^2 + p^3 + p^4 + \dots) \\ & = n(1 / (1-p)) \end{aligned}$$
- Ex: if $n = 400$ and $p = 0.2$ then we will transmit 500 packets



A Simplex Protocol for a Noisy Channel

Discussion points

- *How can we argue that we only need 1 bit for sequence number?*
- *What anomaly could happen if the timeout at the sender is smaller (even temporarily when sending one packet only) than the round-trip delay?*
- *What is a alternative design for round-trip delay that is larger than sender timeout?*
- *Why does the sender re-send the last packet it sent when it gets duplicate ACK (I.e. what assumption is made)?*
- *Why don't we need a timeout mechanism at the receiver side? In other words, is it possible that the protocol deadlocks and the sender stops sending traffic?*
- *What is main new issue in this protocol?*
- *Why do we put $s.ack = 1 - frame_expected$*



Piggybacking

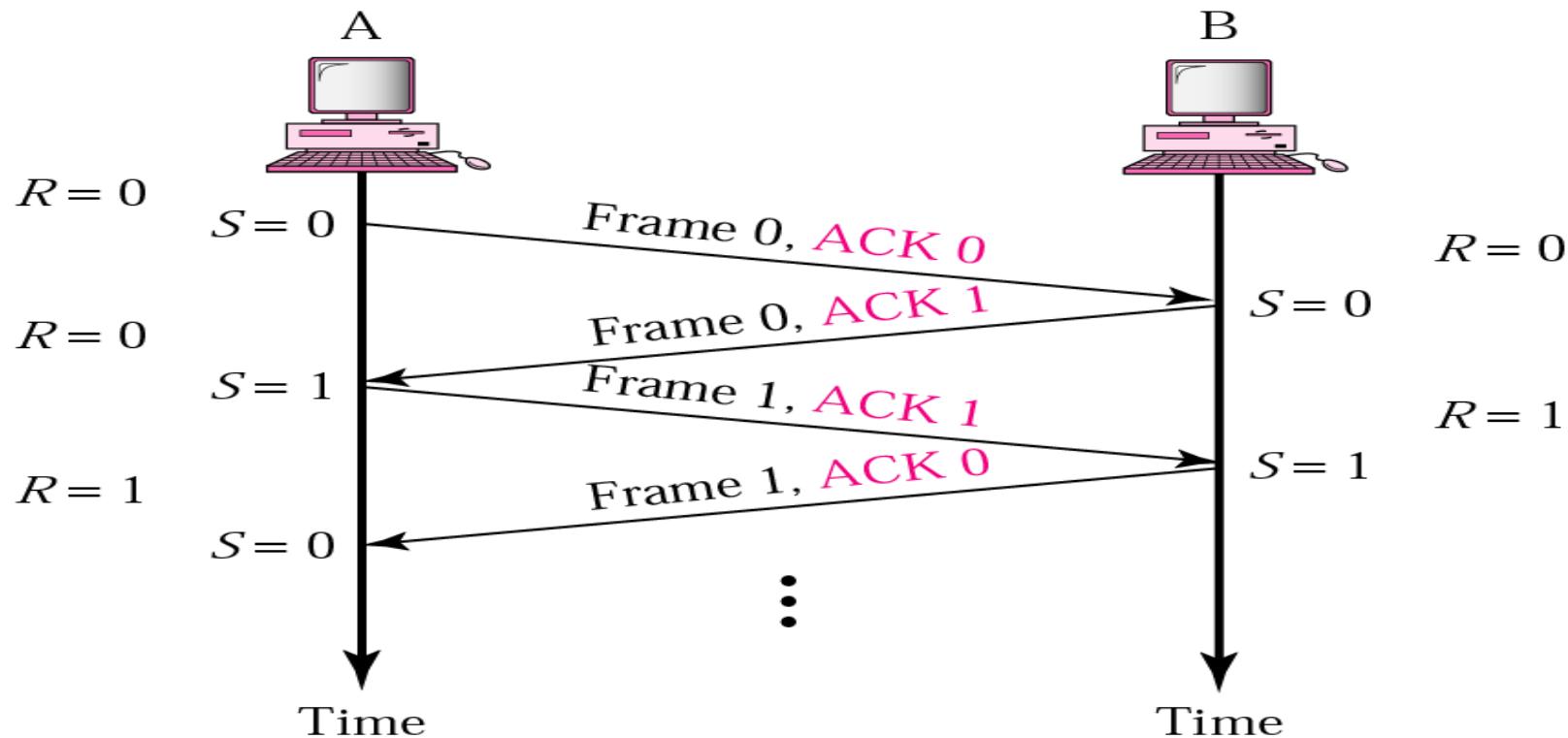
- Sending multiple types of packets in the same frame
- Example: Bidirectional channel
 - Receiver sends ACK with data
- Why
 - Saving on bandwidth
 - Saving of packet processing capacity of routers and switches
- Problem: What happens if there is no data to send?
- Use ad hoc mechanisms: e.g.
 - Wait for a short timeout
 - If no new packet arrives after a receiver ack timeout
 - ⇒ Sending a separate acknowledgement frame
 - Timeout should be smaller than other side timeout



Piggybacking (Bidirectional transmission)

Is a method to combine a data frame with an acknowledgment.

It can save bandwidth because data frame and an ACK frame can combined into just one frame





Pipelining

Pipelining: A task is begun before the previous task has ended

- ❖ ***There is no pipelining in stop and wait ARQ*** because we need to wait for a frame to reach the destination and be acknowledged before the next frame can be sent
- ❖ *Pipelining improves the efficiency of the transmission*



Link Capacity / Pipelining

- Link Capacity is dependent on BW and Propagation delay
- For a Half duplex :Capacity = $BW * T_p$
- For a full duplex: Capacity = $2 BW * T_p$
- In case of S&W he is only sending one packet irrespective of the link capacity
- With Pipelining :
 - One packet is sent in T_t , How many packets can be send in $T_t + 2T_p$? $\rightarrow (1+2a)$ packets
- Example: $T_t = 1$ msec, $T_p = 1.5$ msec, $a = T_p/T_t$
 - Efficiency for S&W = $1 / (1 + 2a) = 1/4$
 - Total time = 4msec, with pipelining you can send 3 more packets



Sliding Window Protocols

- A One-Bit Sliding Window Protocol
- A Protocol Using Go Back N
- A Protocol Using Selective Repeat
- From now on
 - protocols are *full duplex*
 - ACK is *piggy-backed* with data



Sliding window protocol

Sliding window protocols apply Pipelining

- *Sliding window protocols improve the efficiency*
- *multiple frames should be in transition while waiting for ACK. Let more than one frame to be outstanding.*
- *Outstanding frames: frames sent but not acknowledged*
- *We can send up to **W** frames and keep a copy of these frames(outstanding) until the ACKs arrive.*
- *This procedures requires additional feature to be added :**sliding window***



Sliding Window concept

Sender maintains window of frames it can send

- Needs to buffer them for possible retransmission
- Window advances with next acknowledgements

Receiver maintains window of frames it can receive

- Needs to keep buffer space for arrivals
- Window advances with in-order arrivals



Sliding Window Protocol

- Sending Window: range of sequence number sender permitted to send or already sent
- Receiving Window: Range of sequence number receiver permitted to receive or partially received
- In general, *Sending window \neq receiving Window*
- Windows need not be fixed in size
- **Sender**
 - Packet from network layer given next highest sequence number
 - ACK matching the lower end of the window advances the lower end
 - ACK may arrive out of order
 - Maximum number of packets transmitted without receiving ACK is *the window size*
 - Retransmit based on timeout (later, re-transmition will be based on other factors)
 - May shutoff link or block network layer if transmit window reaches max size



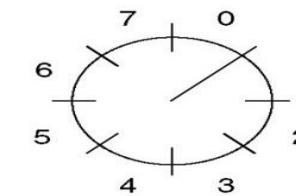
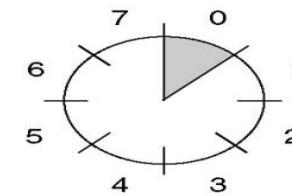
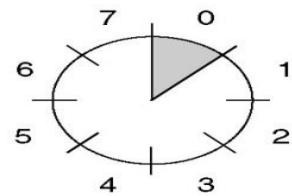
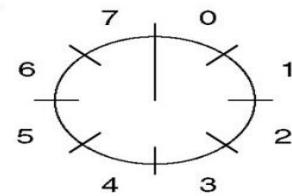
Sliding Window Protocol

- **Receiver**
 - Accepts only packets within its window (packets outside window discarded)
 - When packet matching the lower end arrives, ACK is sent
 - Packets may arrive *out of order*
 - Packets are delivered to network layer *in order*

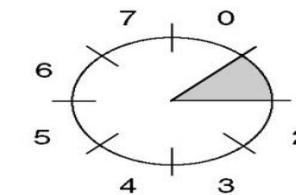
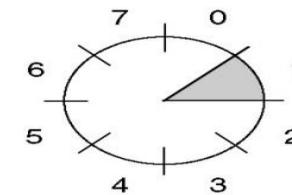
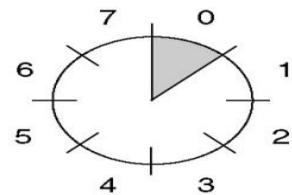
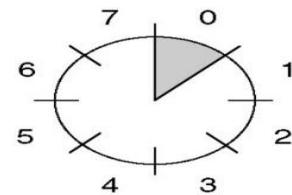


Sliding Window Protocols

Sender



Receiver



(a)

(b)

(c)

(d)

- 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.
- *Are packets delivered in order?*
 - Because the receiver window size is 1 packets, packets are always delivered in order



A One-Bit Sliding Window Protocol

```
/* 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 = frame_expected;                 /* piggybacked ack */
    to_physical_layer(&s);                  /* transmit the frame */
    start_timer(s.seq);                     /* start the timer running */
```



A One-Bit Sliding Window Protocol (ctd.)

```
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 == 1 - 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 = frame_expected;  
        to_physical_layer(&s);  
        start_timer(s.seq);  
    }  
}
```

*Can be timeout, cksum_err, or frame_arrival
Ignore all except frame_arrival*

Why do I have two variables, frame_expected and next_frame_to_send? In other words, can I calculate the value of one variable based on the value of the other?

*This is equivalent to saying that ACK is the **circular**(frame expected-1). Circular(x-1) = (x>0) ? (x--) : MAX_SEQ*

Assume calling start_timer() again restarts the timer

/ frame_arrival, cksum_err, or timeout */
/* a frame has arrived undamaged. */
/* go get it */
/* handle inbound frame stream. */
/* pass packet to network layer */
/* invert seq number expected next */
/* handle outbound frame stream. */
/* turn the timer off */
/* fetch new pkt from network layer */
/* invert sender's sequence number */
/* construct outbound frame */
/* insert sequence number into it */
/* seq number of last received frame */
/* transmit a frame */
/* start the timer running */*

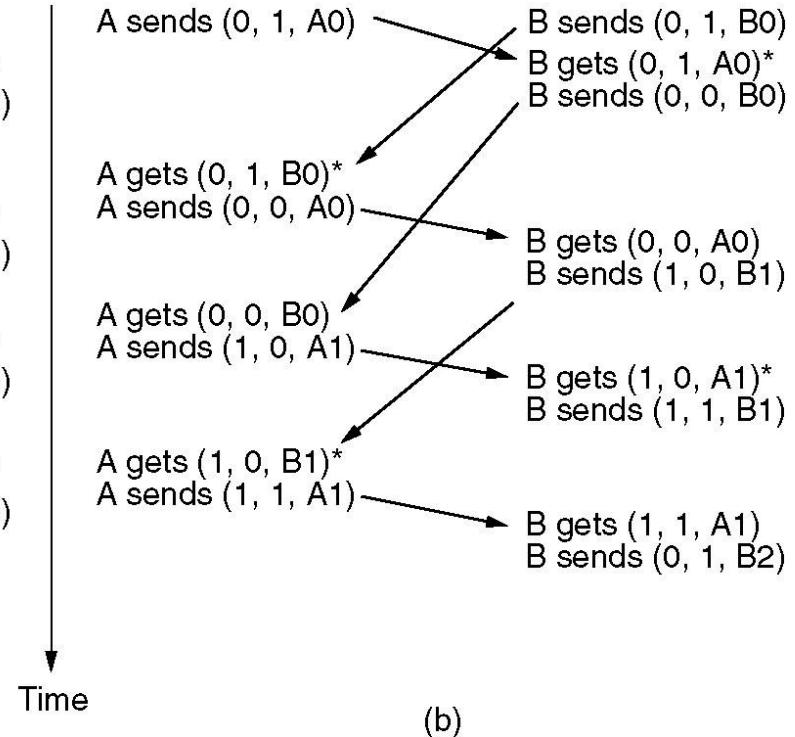
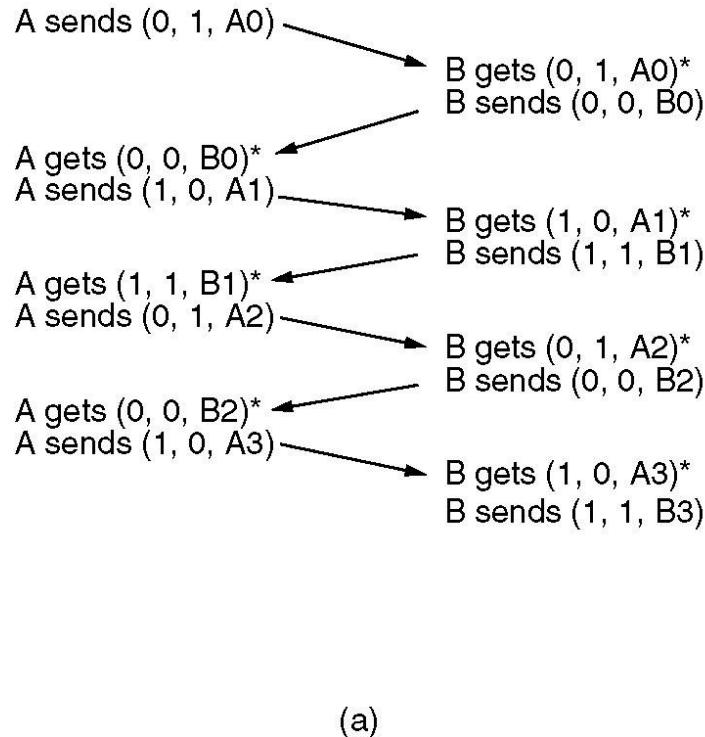


A One-Bit Sliding Window Protocol Correctness

- Protocol is correct
 - In order packet delivery to network layer
 - No packets are skipped
 - No deadlocking. Not stuck packet or keep sending the same packet forever
 - No duplicate packets delivered to network layer because of sequence number
- The protocol looks like we have intermixed sender and receiver of the “simplex protocol in a noisy channel”. *But it is not !!*
 - Piggy backing ACK on transmitted packets has side effects
 - Remember that this is a ***feedback*** system \Rightarrow *small changes can cause significant results*
- If one side sends a packet and is received before the other side sends a packet, the protocol works perfectly
- If both sides send at the same time and the frames cross,
 - Half of the packets contain duplicates
 - Protocol is still correct, but bandwidth is wasted



A One-Bit Sliding Window Protocol (ctd.)



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.



A One-Bit Sliding Window Protocol Disadvantages

- Certain synchronization situation can result in continuous packet duplication
- Timeouts needs to be tuned carefully, otherwise multiple re-transmission can occur

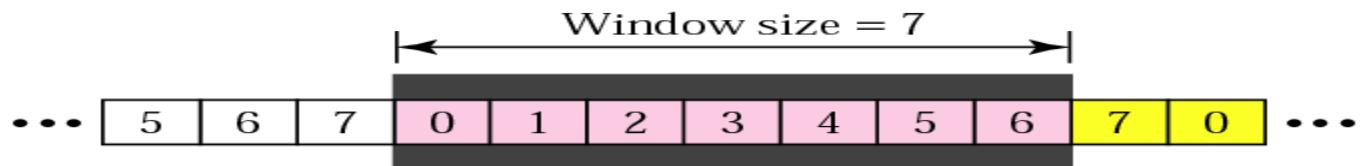


Go_Back_N ARQ

Sender sliding window

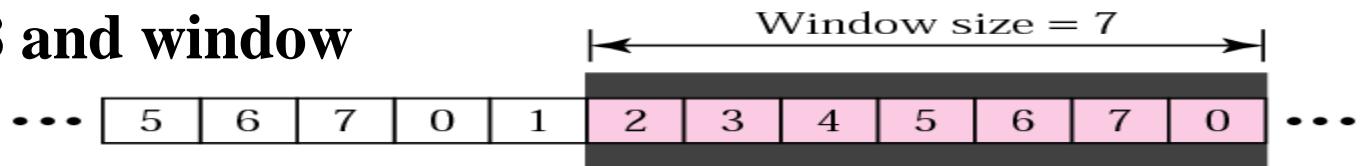
The sender window is an abstract concept defining an imaginary box of size $2^m - 1$ (sequence numbers -1)

The sender window can slide one or more slots when a valid acknowledgment arrives.



a. Before sliding

If $m = 3$; sequence
numbers = 8 and window
size = 7



b. After sliding two frames

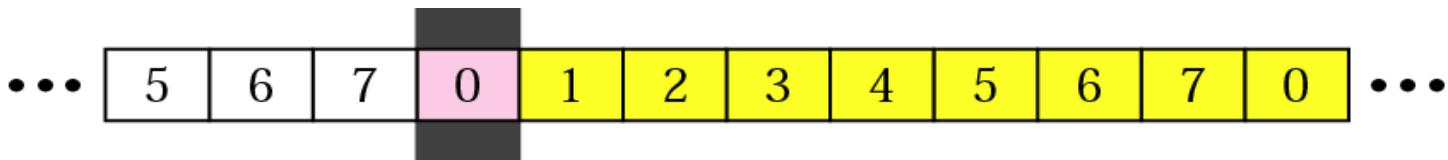
Acknowledged frames



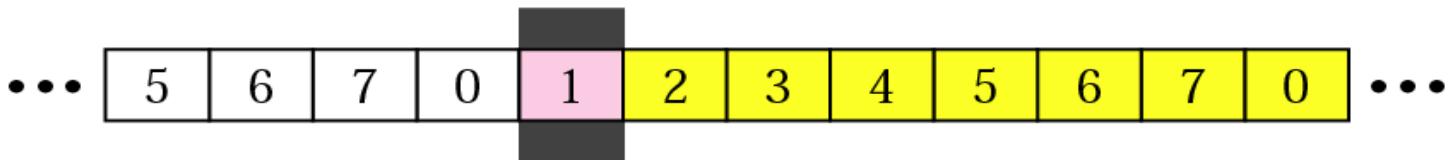
Go_Back_N ARQ

Receiver sliding window

- *The receive window is an abstract concept defining an **imaginary box of size 1** with one single variable R_n .*
- *The window slides when a correct frame has arrived; sliding occurs one slot at a time.*



a. Before sliding



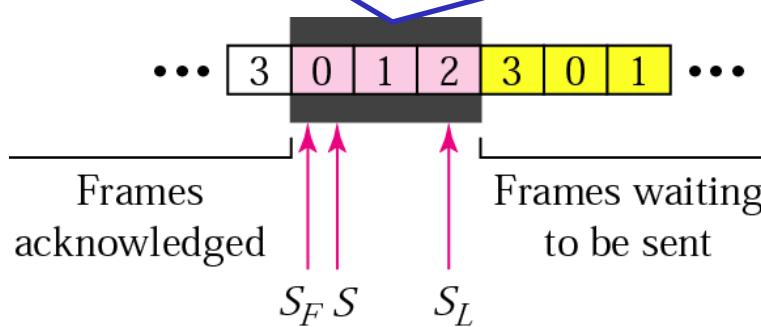
b. After sliding



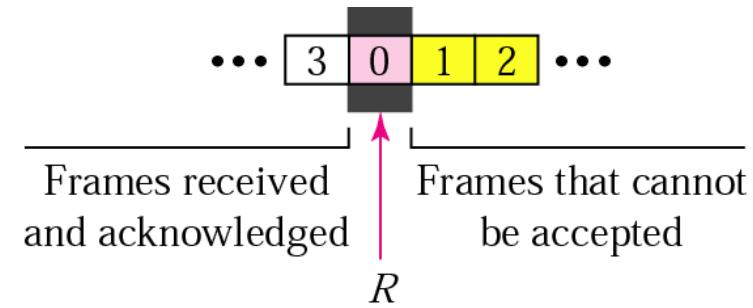
Go-Back-N ARQ

control variables

Outstanding frames: frames sent but not acknowledged



a. Sender window



b. Receiver window

S : hold the sequence number of the recently sent frame

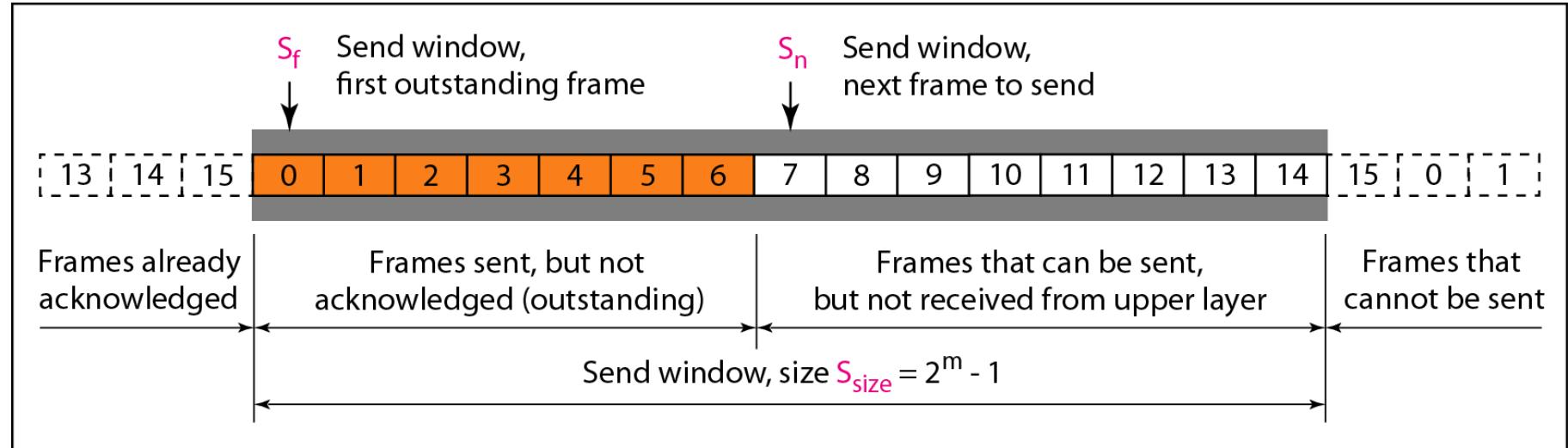
S_F : holds sequence number of the first frame in the window

S_L : holds the sequence number of the last frame

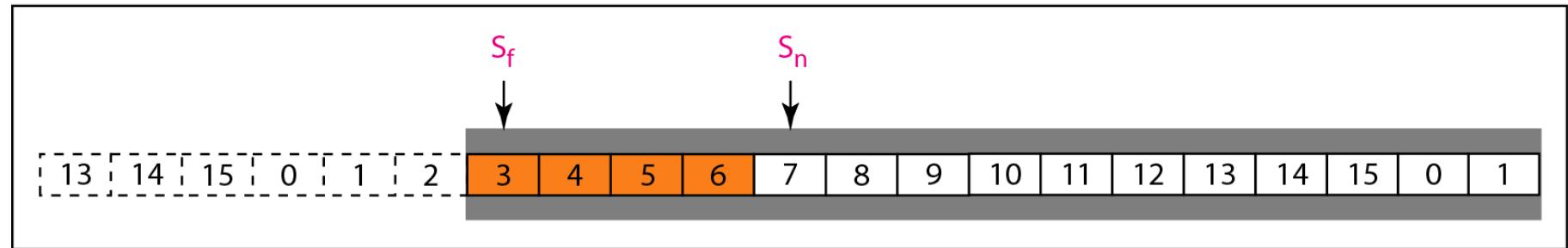
R : sequence number of the frame expected to received



Go-Back-N ARQ



a. Send window before sliding



b. Send window after sliding



Go-Back-N ARQ

In Go-Back-N ARQ we use one timer for the first outstanding frame

- *The receiver sends a positive ACK if a frame has arrived safe and in order.*
- *if a frame is damaged or out of order ,**the receiver is silent** and will discard all subsequent frames*
- *When the timer of an unacknowledged frame at the sender site is expired , the sender goes back and resend all frames, beginning with the one with expired timer.(that is why the protocol is called Go-Back-N ARQ)*
- *The receiver doesn't have to acknowledge each frame received . It can send **cumulative Ack** for several frame*



Go-Back-N ARQ

Example:

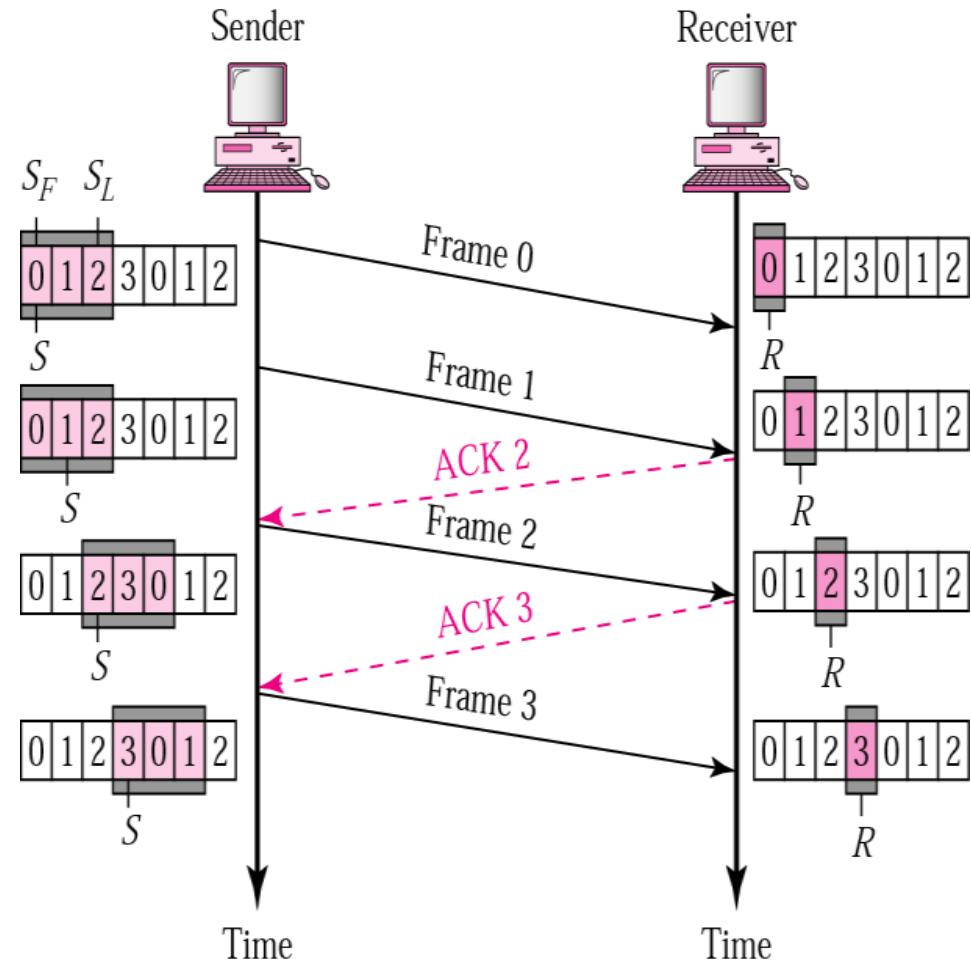
The sender has sent frame 6 , and timer expires for frame 3(frame 3 has not been acknowledge); the sender goes back and resends frames 3, 4,5 and 6



Go-Back-N ARQ

Normal operation

- How many frames can be transmitted Without acknowledgment?
- ACK1 is not necessary if ACK2 is sent: Cumulative ACK





Go-Back-N ARQ

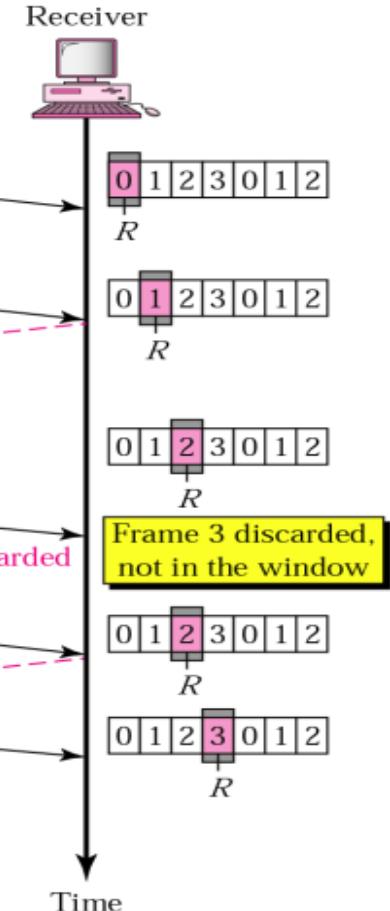
Damage or Lost Frame

*Correctly received out
of order packets are not
Buffered*

*What is the
disadvantage of this?*

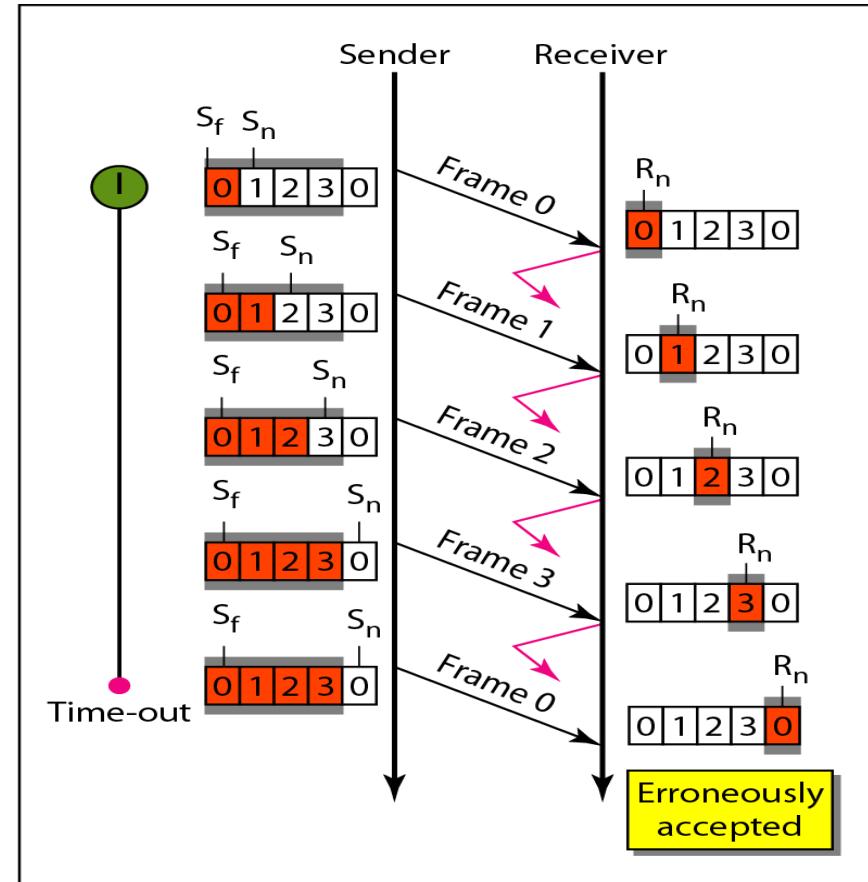
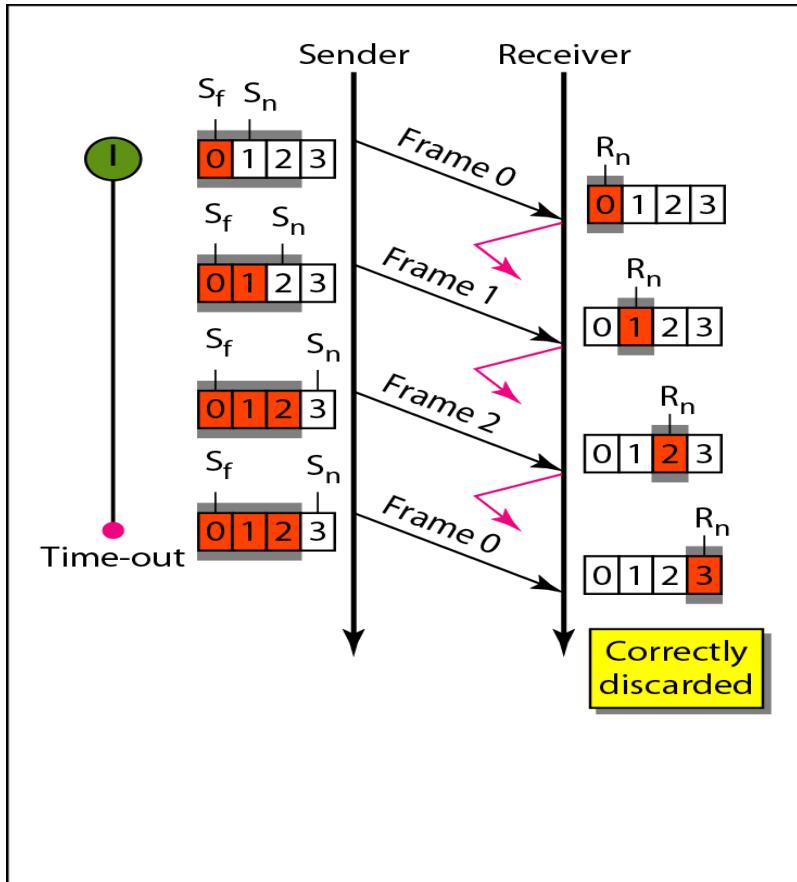
Time-out

Time





Go-Back-N ARQ





Go-Back-N ARQ

*In Go-Back-NARQ, the size of the **sender** window must be less than $2^m = (2^m - 1)$; the size of the **receiver** window is always 1..*

Bidirectional transmission : piggybacking

As Stop-and-Wait we can use piggybacking to improve the efficiency of bidirectional transmission . Each direction needs both a sender window and a receiver window.



Note

Stop-and-Wait ARQ is a special case of Go-Back-N ARQ in which the size of the send window is 1



Calculation of Window Size, Sequence number

- Total time = $T_t + 2 T_p$
- For 100% Efficiency \rightarrow Window size = $(T_t + 2T_p) / T_t$
- T_t : Transmission Time
- T_p : Propagation time
- $W_s = 1 + 2T_p / T_t$
- $\log(W_s) = \log_2(1 + 2 T_p / T_t) = \log_2(1) + \log_2(2 T_p / T_t)$
 - $\log_2(1) = 0$
- Example: $T_t = 1$ sec $T_p = 49.5$ sec
 - To get 100% efficiency : $W_s = (1 + 2 * 49.5) / 1 = 100$
 - Min no. of bits in seq for 100% efficiency = $\log_2(100) = 7$ bits
 - What if you use only no of bits is 6 , what is the max. efficiency you can get? You can use 2^6 seq numbers (64 seq numbers)
 - Window size = 64, so Efficiency is 64%



Go Back N algorithm

- Allow multiple outstanding frames at Sender
 - Outstanding frame: Frame sent but not yet acknowledged
- Sender cannot send more than MAX_SEQ to
 - enforce flow control
 - Avoid too much waste in case of packet loss/damage and large timeout
 - Certain incorrectness problems can occur if sender sends more than MAX_SEQ
- *Dropped* the assumption that network layer has *infinite* supply of packets
 - Network layer causes event ***network_layer_ready*** when it wants to send
- Need to enforce flow control of no more than MAX_SEQ outstanding buffers at sender
 - *enable_network_layer()* to allow network layer to send
 - *disable_network_layer()* to block network layer
- On timer expire, *all outstanding frames* are re-sent



Sliding Window Protocol Using Go Back N

- Always piggyback ACK with every data packet
- This means that one side may continue to get ACK even though it is not sending any traffic
- Hence, for this protocol, we cannot rely on duplicate ACK to infer that a packet is lost because the receiver may be sending reverse traffic at a very high rate and hence the reason the sender is receiving duplicate ACK is because the sent packets are still traveling on the way NOT that the sent packets were lost

- (Re-)Start a separate logical timer for every sent sequence number

/* Protocol 5 (pipelining) allows multiple outstanding frames. The sender may transmit up to MAX_SEQ frames without waiting for an ack. In addition, unlike 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);
}
```

- Window is between the sequence numbers **a** and **c**
- **a** is considered earlier than **c**
- Window is **circular**
- Checks if **b** is within the window

```
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 */
}
```

- **s.ack** contains the sequence number of the last frame received
- Think of **s.ack** as **circular(frame_expected - 1)**
- Remember that **circular(x-1) = (x>0) ? (x--) : MAX_SEQ**

Continued →



Sliding Window Protocol Using Go Back N

```
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;
nbuffed = 0;
```

- Receiver window is of **fixed size 1**
- Receiver window is between ***frame_expected*** and ***(frame_expected+1)***

```
/* 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 */
```

Sender window is between ***ack_expected***
and ***next_frame_to_send***

Continued →



Sliding Window Protocol Using Go Back N

```
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 */
            }
    }
}
```

- We try to send packet in every loop
- If there is no other event, we send packets
- We disable network layer when sender window is full
- Hence we will always attempt to transmit the entire sender window

- Advance upper end of **sender's** window
⇒ increase sender's window

- Advance Lower end of **receiver** window
- Remember receiver window has **fixed size 1**
⇒ decrease receiver's window

Continued →



Sliding Window Protocol Using Go Back N

e.g. if Ack 3
Then packets 2, 1, 0, ..., arrived
What is the benefit of this while loop?

```
/* 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;
```

- Outstanding packets are between `ack_expected` and `next_frame_to_send`

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

- Advance lower end of Sender's window until it hits `r.ack`
⇒ Reduce sender's window
⇒ Free more buffers

```
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 1 frame */
    inc(next_frame_to_send); /* prepare to send the next one */
}
```

- Assume timeout because of frame loss
- Retransmit all frames **starting** from the **last ACKed** frame because receiver has window size one

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

- Max value of nbuffered is (`MAX_SEQ`)
(1 more than maximum sequence number)
- Maximum number of outstanding packets is `MAX_SEQ NOT` (`MAX_SEQ+1`)
 - Because the network layer is enabled only if nbuffered is strictly less than `MAX_SEQ`
 - I.e. there are at most `MAX_SEQ+1` distinct sequence numbers



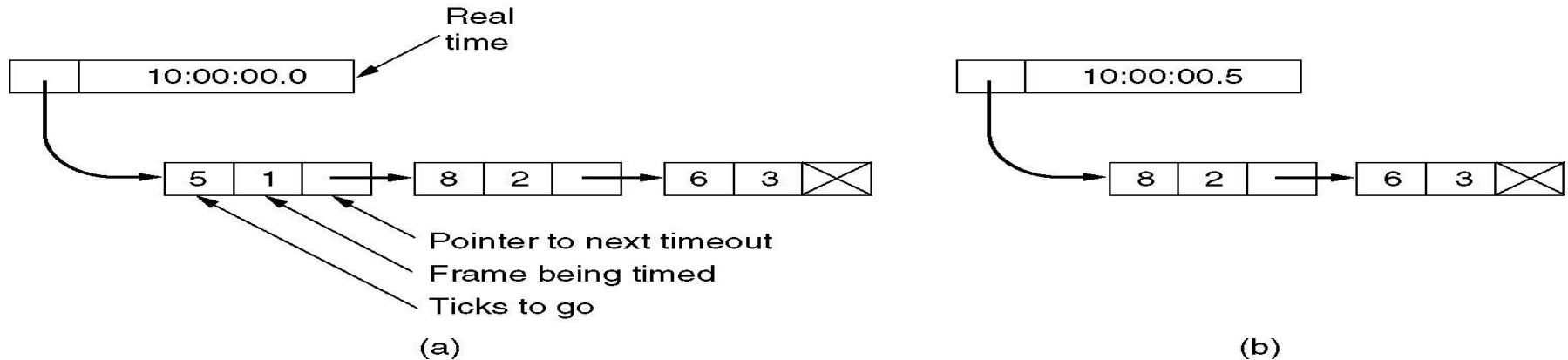
Sliding Window Protocol Using Go Back N

Discussion points

- Circular sequence number is MAX_SEQ
- ACK is *piggy backed* with every packet on reverse traffic
 - If the sender is not transmitting packets, sender receives duplicate ACK (harmless)
 - If there is **no reverse** traffic, protocol *fails*
 - sender will not receive ACK and not advance the window and hence will **block**
 - Because sender did not receive ACK, it will keep timing-out and retransmitting
 - Suppose sender sends 1-2 packets and there is no more traffic at the sender
 - It seems like there is no failure here because all sent packets are received by the receiver
 - However there is still a failure (*Why is that considered failure?*)
- Sender window size (maximum outstanding frames) **must be** MAX_SEQ and **not** MAX_SEQ+1 . I.e *one less than the maximum sequence* (*why*)
- Network layer is enabled only if nb buffered **strictly less** than MAX_SEQ
 - In the main loop, if there is no other event, the sender keeps sending up to the window size
 - Window size is MAX_SEQ **not** (MAX_SEQ+1)
- The receiver window size is 1 but we still need some buffering at the sender (*why*)
- We do **not** need buffering at the *receiver* (*why*)
- One ACK can be used for multiple buffers
 - ACK for frame n means that receiver received $(n-1), (n-2), \dots$, etc.
 - Good for lost or damaged ACKs
- Enable/disable network layer based on max outstanding buffers
- Need for *logically separate timer* per outstanding frame (*why*)
- Too many errors result in poor throughput because of retransmission



Sliding Window Protocol Using Go Back N Efficient Timer Implementation



- Sort timers by expiration time
- Put sorted timers in a queue (linked list)
- If timer T2 expires after timer T1, the “Ticks-to-go” field in timer T2 has the number of ticks that timer T2 expire after timer T1
- Every clock tick, decrement the timer at the head of the queue
- When the queue head expires, fire the timer and delete the timer from the queue
- Minimum processing per clock tick
- *Stop_timer* causes scan of the queue to find the timer that needs to be removed
- *Start_timer* causes scan of the queue to find where to insert the started timer and to update “Ticks-to-go” for timers *after* the inserted timers
- Argument of *start_timer* and *stop_timer* indicates which timer to start or stop



Selective Repeat ARQ

*Go-Back-N ARQ is inefficient in the case of a **noisy** link.*

- *In a noisy link frames have higher probability of damage , which means the resending of multiple frames.*
- *this resending consumes the bandwidth and slow down the transmission .*

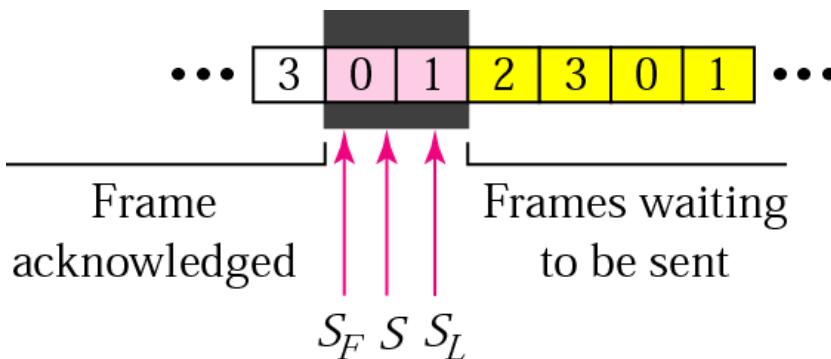
Solution:

- Selective Repeat ARQ protocol : resent only the damage frame
- It defines a **negative Acknolgment (NAK)** that report the sequence number of a damaged frame before the timer expires
- It is more efficient for noisy link, but the processing at the receiver is more complex

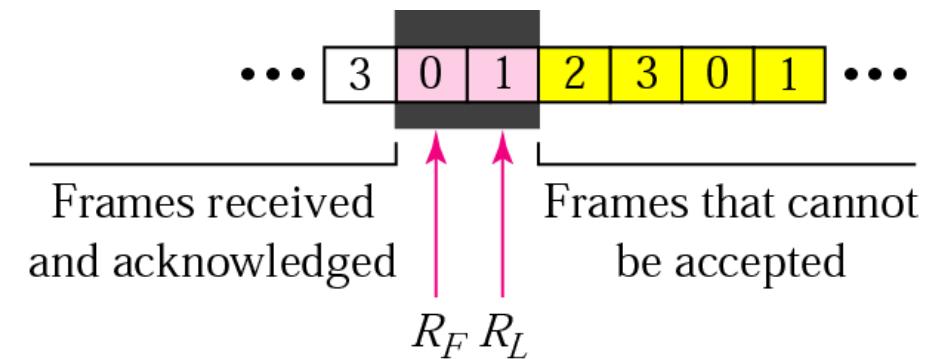


Selective Repeat ARQ

- The window size is reduced to one half of 2^m
- Sender window size = receiver window size = $2^m / 2$
- Window size = **(Max sequence number +1) / 2**
- If $m = 2$, Window size = $4/2=2$
- Sequence number = 0, 1, 2, 3



a. Sender window

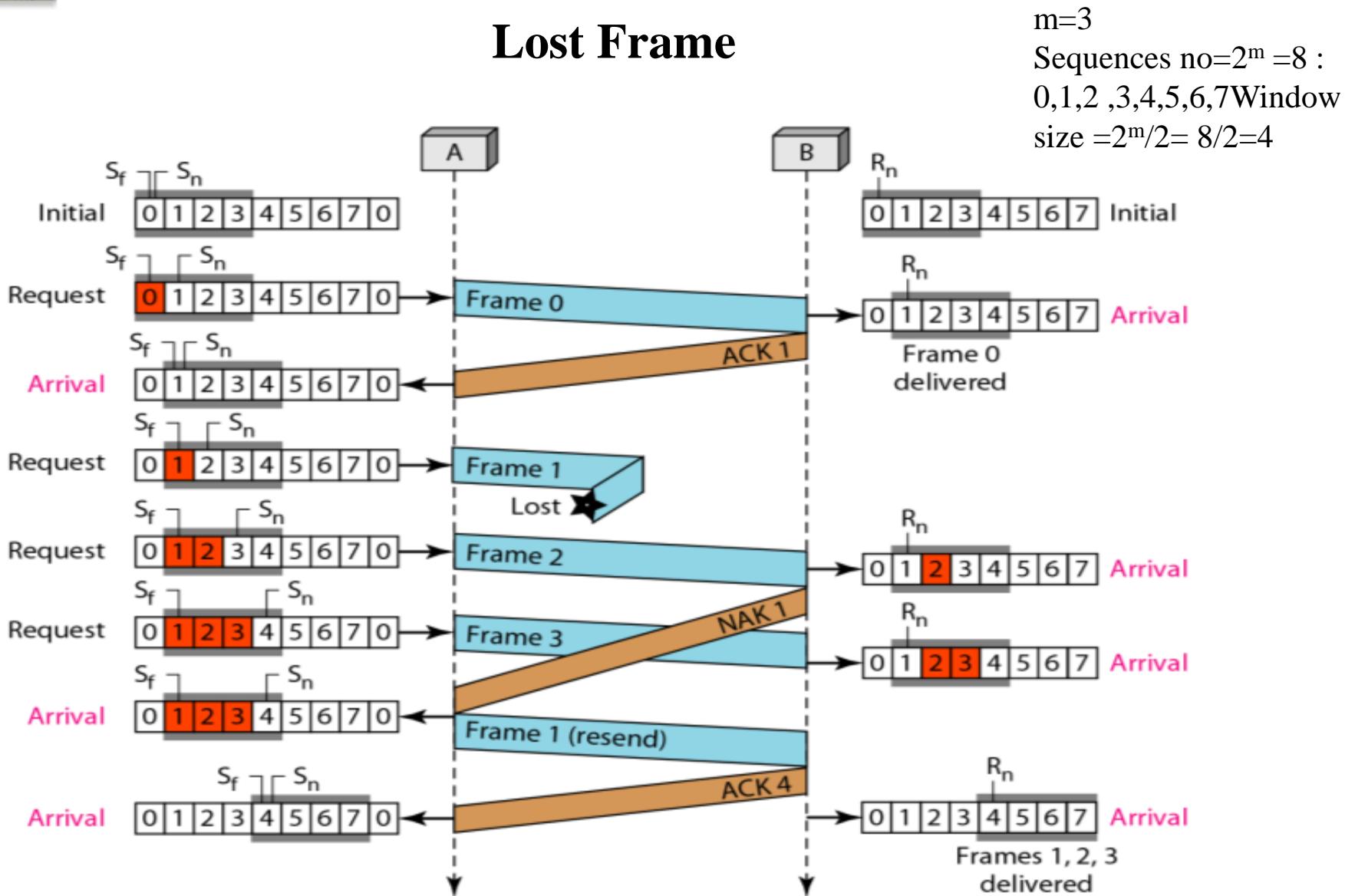


b. Receiver window



Selective Repeat ARQ

Lost Frame





Selective Repeat ARQ

- At the receiver site we need to distinguish between the acceptance of a frame and its delivery to the network layer.
- At the second arrival , frame 2 arrives and is stored and marked , but it can not be delivered because frame 1 is missing .
- At the next arrival , frame 3 arrives and is marked and stored , but still none of the frames can be delivered .
- Only at the last arrival , when finally a copy of frame 1 arrives , can frames 1 , 2 , and 3 be delivered to the network layer.
- There are two conditions for the delivery of frames to the network layer: First , a set of consecutive frames must have arrived. Second, the set starts from the beginning of the window .



Selective Repeat ARQ

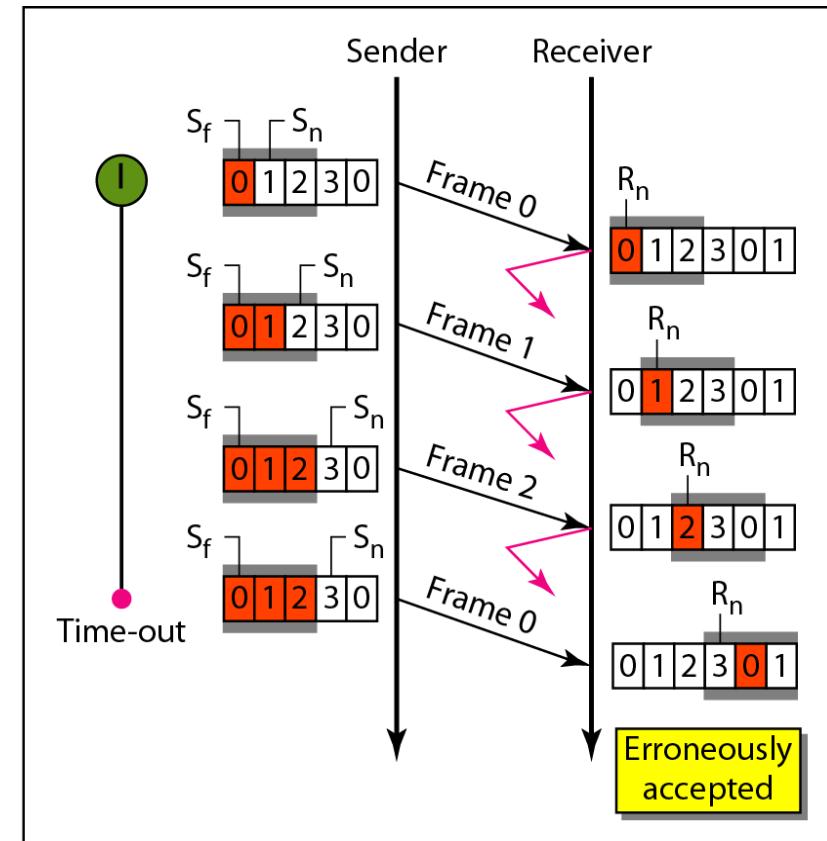
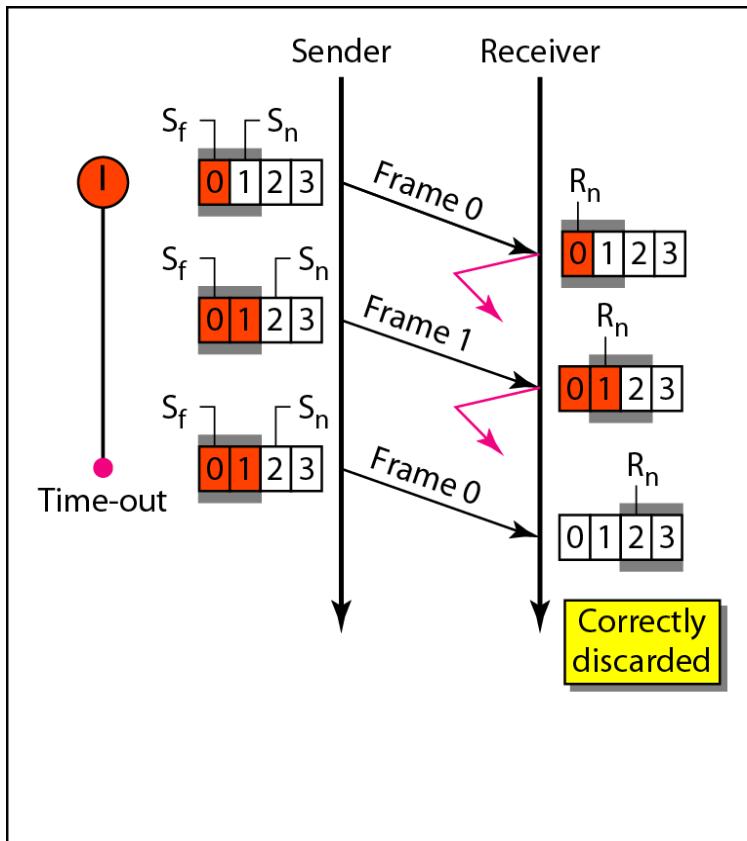
The next point is about the ACKs:

- *Notice that only two ACKs are sent here. The first one acknowledges only the first frame; the second one acknowledges three frames.*
- *In Selective Repeat, ACKs are sent when data are delivered to the network layer. If the data belonging to n frames are delivered in one shot , only one ACK is sent for all of them.*



Selective Repeat ARQ

$m=2$, Window size =2 , seq numbers is 4 (0,1,2,3)





Note

In Selective Repeat ARQ, the size of In the sender and receiver window must be at most one-half of 2^m .



SR_ARQ Algorithms



Selective Repeat Algorithm

- Accepts *out of order* frames
- **One timer per frame**
- On timer expire, only the frame associated with timer is re-sent \Rightarrow *selective repeat*
- Receiver window size is fixed at $(\text{MAX_SEQ}+1)/2$
- Sender window size starts at 0 and *grows* to $(\text{MAX_SEQ}+1)/2$
- We have timer for ACK \Rightarrow No need for reverse traffic to piggyback ACK
- For each sequence number within window, receiver has
 - a buffer
 - “arrived” bit. If set, means buffer is full
- When a packet arrives at receiver
 - Check to see if it falls within window of sequence numbers
 - Check to see if arrive bit is clear (i.e. buffer is empty)
- If both conditions are satisfied, store the arrived packet
- Receiver delivers packets to network layer in order and advances window
- Assume that the function `start_ack_timer()` **resets** the expiration time of the ACK timer to the current time.



A Sliding Window Protocol Using Selective Repeat

Sender & Receiver
window size is **half** of
MAX_SEQ

/* Protocol 6 (nonsequential receive) 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 */
```

If frame type is not data,
s.seq is ignored
⇒ We can put anything

- **s.ack** contains the sequence number of the last received frame in the contiguous sequence of frames
- you can think of **s.ack** as **circular(frame_expected-1, MAX_SEQ)**

If the packet that we are sending now is a NAK, then clear **no_nak**. This way if the next packet is NOT **frame_expected**, we will start the **ACK timer** instead of sending a NAK one more time.

Continued → 102



A Sliding Window Protocol Using Selective Repeat (2)

```
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();
    ack_expected = 0;
    next_frame_to_send = 0;
    frame_expected = 0;
    too_far = NR_BUFS;
    nbuffered = 0;
    for (i = 0; i < NR_BUFS; i++) arrived[i] = false;
```

/* lower edge of sender's window */
/* upper edge of sender's window + 1 */
/* lower edge of receiver's window */
/* upper edge of receiver's window + 1 */
/* 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 */

Need buffer at **both**
sender and receiver

Sender window is between **ack_expected**
and **next_frame_to_send**

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

/* initially no packets are buffered */

receiver window is **fixed** size NR_BUFS.
It is *initialized* between **0** and **NR_BUFS**

Continued →



A Sliding Window Protocol Using Selective Repeat (3)

```

out_buf[] is circular
while (true) {
    wait_for_event(&event);
    switch(event) {
        case network_layer_ready:
            nbuffered = nbuffered + 1;
            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:
            from_physical_layer(&r);
            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 */
                    }
                }
            }
    }
}

```

Because we are sending a NAK, this value is meaningless
⇒ Put anything

- Increment **both** lower and upper receiver window boundaries
⇒ Receiver window size always fixed at **NR_BUFS**

/* five possibilities: see event_type above */

/* accept, save, and transmit a new frame */
/* expand the window */

/* advance upper window edge */

/* a data or control frame has arrived */
/* fetch incoming frame from physical layer */

- We did NOT receive the lower end of receive window
⇒ Send NAK immediately
- Because **send_frame()** sets **s.ack** to **circular(frame_expected-1)** then the NAK frame contains the sequence number of the last received frame
- Thus when a sender receives a NAK, it should resend the frame with sequence number **circular(r.ack+1)**

Restart ACK timer every time we receive out of order packet (**See WHY later?**)

Deliver **contiguous** packet sequence to network layer starting from **bottom** of receiver window.

frame_expected is one more than the sequence number of the last received frame in **contiguous** sequence

Allow sending NAK because we send NAK for **frame_expected** and **frame_expected** will be incremented soon

Reset ACK timer to the current time

}



A Sliding Window Protocol Using Selective Repeat (4)

- When the other side sends a NAK, the other side sets the “**ack**” field to **circular(frame_expected - 1)**.
- Hence **r.ack** contains sequence number of the last received frame by the other side.
- Thus a sender should re-send the frame whose sequence number is **circular(r.ack+1)**
- Thus we have to test **between** for **circular(r.ack+1)**

- ACK means all frames in the **contiguous** sequence of frames **before and including** ACKed frame have been received. Do the following **between ack_expected and r.ack**
 - Free buffers
 - Stop all retransmit timers
 - Advance sender **lower** window

We assume that the timeout event causes the variable **oldest_frame** to be set according to the timeout that just expired

- On ACK timeout, we send ACK for the frame **before** bottom of the receiver window because **frame_expected** is one more than the sequence number of the last frame received in **contiguous** sequence
- Because **send_frame()** sets **s.ack** to **circular(frame_exptected-1)**, we will end up **re-ACKing** the last frame received in the **contiguous** sequence

Because we have ACK timeout
 ⇒ No need for reverse traffic
 ⇒ Solves the blocking problem of Go back N

```
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;
```

Re-send NAK for last frame received if we get a corrupted frame

```
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();
```

Window size is NR_BUF
 ⇒ half of MAX_SEQ



A Sliding Window Protocol Using Selective Repeat Discussion Points

- Why is NR_BUFS defined $(\text{MAX_SEQ}+1)/2$?
- How many buffers must receiver have?
- How many timers are needed at the receiver?
- How to get away without reverse traffic?
- How is NAK making protocol more efficient
- How to adjust timers
- *Why do we have to restart ACK timer every time we receive out of order packet?*



A Sliding Window Protocol Using Selective Repeat

Why $\text{NR_BUFS} = (\text{MAX_SEQ}+1)/2$

- Suppose we allow NR_BUFS to be $\text{MAX_SEQ}-1$ (just like Go Back N)
- Consider the following sequence of events
- Sender window is $0,1,2,3,4,5,6$
 - $\text{next_frame_to_send} = 7, \text{ack_expected} = 0$
- Receiver window is $0,1,2,3,4,5,6$
- Sender sends frames $0,1,2,3,4,5,6$
- Receiver receives all seven frames and sends ACK for all of them
 - All frames are valid frames because their sequence numbers lie within receiver window
 - Receiver delivers all 7 frames to network layer and sends ACK for $0,1,2,3,4,5,6$
 - Receiver advances its receive window to $7,0,1,2,3,4,5$
 - $\Rightarrow \text{Frame_expected} = 7, \text{too_far} = 6$
- Suppose all ACKs are lost
- Sender times out. Thus it **resends** frame 0 because frame 0 timer is the first timer started and hence it will be the first timer to expire
- Receiver receives **resent** data frame with $s.\text{seq} = 0$
 - $S.\text{ack} = 0$ is within the new receiver window
 - Receiver accepts frame 0 \Rightarrow **DUPLICATE** packet because this packet is already delivered to network layer
 - $\text{arrived}[0] = \text{TRUE}$
 - Does NOT advance frame_expected because frame_expected not received yet



A Sliding Window Protocol Using Selective Repeat

Why NR_BUFS (MAX_SEQ+1)/2

- Now receiver ACK timeout expires
 - Resends ACK with s.ack = $\text{circular}(\text{frame_expected} - 1) = 6$
- Sender receives ACK with s.ack = 6
 - Sender assumes that all frames 0,1,2,3,4,5,6 have been received
 - Sender advances its window to so that the sender window = 7,0,1,2,3,4,5
 - Sender sends frames 7,0,1,2,3,4,5
 - ⇒ $\text{ack_expected} = 7$, $\text{next_frame_to_send} = 6$
- Receiver receives frame 7,0,1,2,3,4,5
 - Receiver **accepts** frame 7 and puts it in buffer
 - Receiver **rejects** frame 0 because $\text{arrived}[0] = \text{TRUE} \Rightarrow$ The new frame 0 is **LOST**
 - Receiver **Accepts** 1,2,3,4,5 and puts them in buffer
 - Now receiver has a contiguous sequence of frames in the receive window so it delivers 7,0,1,2,3,4,5 to network layer
 - The delivered packets have the following problems
 - Frame 0 is **duplicate** and **out of sequence** because it belongs to the first batch
 - Frame 0 from the second batch is **lost**
- NOTE:
 - When Receiver receives frame 0 for the second time, it will send a NAK for frame_expected. Thus s.ack=6 in the NAK
 - The sender receives a NAK with r.ack = 6
 - The sender checks if **circular(r.ack+1)** lies between **ack_expected** and **next_frame_to_send** before resending the NAKed frame
 - $\text{circular}(r.ack+1) = 7$, $\text{ack_expected} = 0$, and $\text{next_frame_to_send} = 7$
 - Thus the check **Fails**
 - Hence the NAK will have **no effect**



A Sliding Window Protocol Using Selective Repeat

How many buffers and timers at receiver

- Receiver only accepts frames within the window size
- Window size is **half** the sequence number*
- Receiver needs buffers equal to window size **not MAX_SEQ**
- We need one timer **ONLY** at receiver: This is the ACK timer
- We need timers equal to window size, not MAX_SEQ at the sender



A Sliding Window Protocol Using Selective Repeat Auxiliary Timer and NAK

- Auxiliary ACK timer
- No need for reverse traffic
- Auxiliary ACK timer should be *shorter* than retransmit timer
- NAK to expedite retransmit (not needed for correctness)
- Send NAK on
 - Out of sequence: $r.seq \neq frame_expected$
 - Checksum error: possible damage
 - In both cases, we send NAK for **circular(frame_expected – 1)**
 - Remember that $circular(x-1) = (x>0) ? (x--) : MAX_SEQ$
- How to avoid multiple NAKs per packet
 - Variable `no_nak` is set only if receiver has **not** sent NAK for `frame_expected`



A Sliding Window Protocol Using Selective Repeat Adjusting timers

- Sender timeout at sender should be *slightly larger* than roundtrip time
- Problem if round trip time is variable
- If reverse traffic is sporadic, ACK will be irregular, making it hard for receiver to estimate roundtrip time

- Receiver auxiliary ACK timer should be appreciably shorter than sender retransmit timeout



Why Restart ACK timer For Out of Order packet?

- Consider the following sequence of events
 - Sender sends packets 0,1,2,3
 - Receiver receives packets 0,1,2,3
 - Receiver sends ACK for all of them and advances window to 4,5,6,7
 - All ACKs are lost
 - *How will the protocol recover?*



Go Back N vs. Selective Repeat

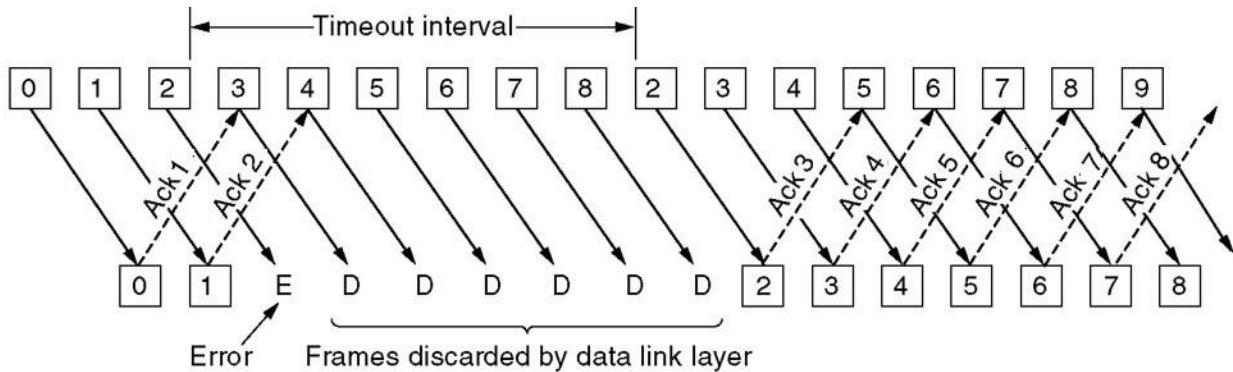
- Go Back N
 - Receiver discards all frames after lost or damaged frame
 - Receiver acknowledges received frame
 - Receiver does NOT send any ACK for frames received after lost or damaged frame
 - Relies on sender timeout
 - Equivalent to receiver window of size **1**
 - Wastes a lot of bandwidth in case of error
 - Receiver needs to *buffer 1 frame* only
- Selective Repeat
 - Receiver buffers all frames received within window
 - Receiver acknowledges *last received in sequence frame* for every out-of-sequence frame
 ⇒ **Cumulative ACK**
 - On timeout, sender only re-transmits *oldest unacknowledged* frame
 - Receiver can deliver all buffered frames, *in sequence*, to the network layer
 - Receiver often uses NAK* to stimulate retransmission before timeout
 - Receiver needs to *buffer multiple frames* up to window size
- *Tradeoff between buffer space and link bandwidth utilization*



Go Back N vs. Selective Repeat

Expected frame not last received frame

Go Back N

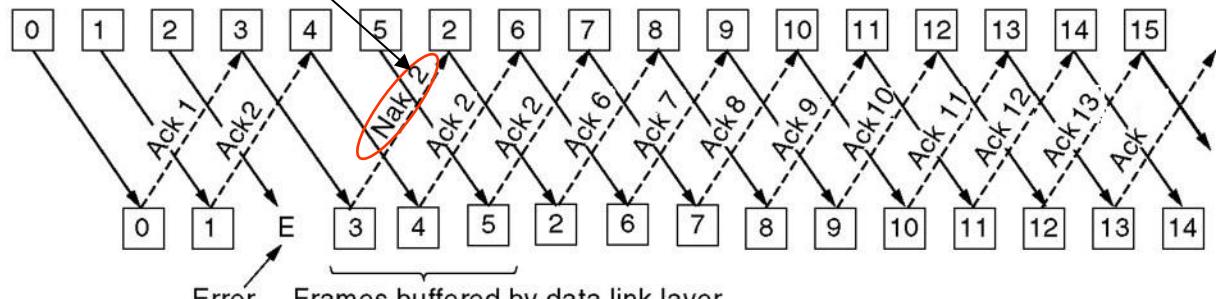


Time →

(a)

Selective Repeat
with NAK

Use NAK to
stimulate retransmit



(b)



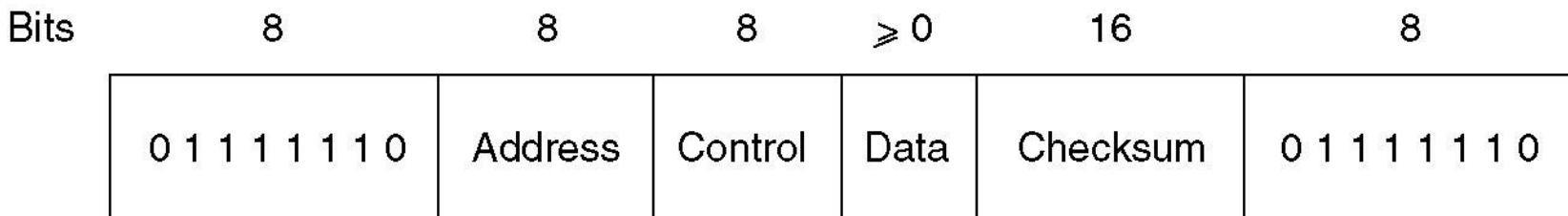
Example Data Link Protocols

- HDLC – High-Level Data Link Control
- PPP - The Data Link Layer in the Internet



High-Level Data Link Control

- Frame format for bit-oriented protocols.
- HDLC uses bit stuffing and allows non-integer frames of, say, 30.25 bytes
- HDLC provides reliable transmission with a sliding window





High-Level Data Link Control (2)

P/F Poll/Final bit

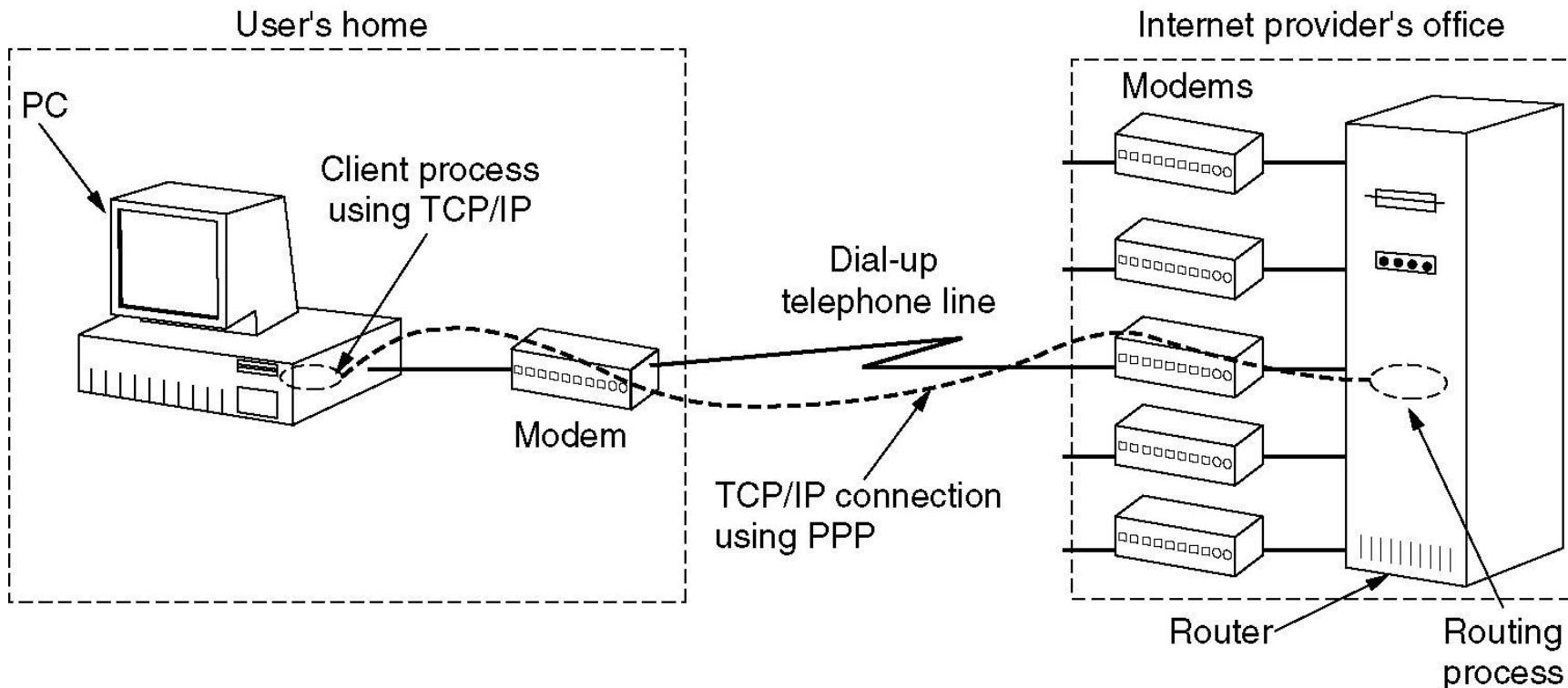
Bits	1	3	1	3
(a)	0	Seq	P/F	Next
(b)	1	0	Type	P/F
(c)	1	1	Type	P/F

- (a) An information frame starts with 0.
- (b) A supervisory frame 10: control functions such as acknowledgment of frames, requests for re-transmission, and requests for temporary suspension of frames being transmitted
- (c) An unnumbered frame 11: also used for control purposes. It is used to perform link initialization, link disconnection and other link control functions.



The Data Link Layer in the Internet

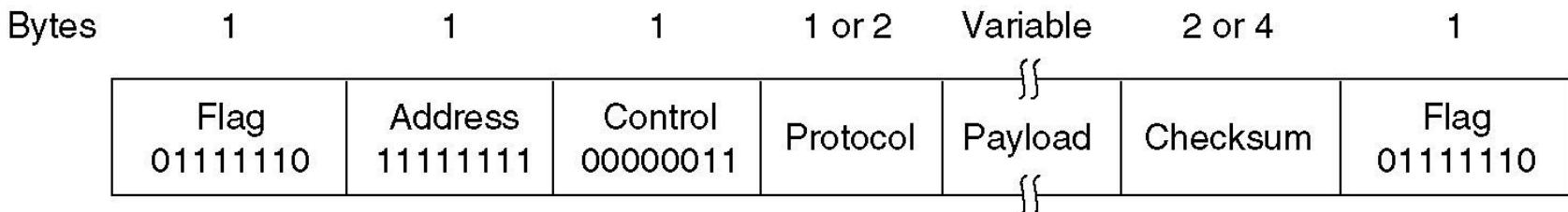
A home personal computer acting as an internet host.





PPP – Point to Point Protocol

- The PPP full frame format for unnumbered mode operation.
- PPP uses byte stuffing and all frames are an integral number of bytes



Address field: This field is always set to the binary value 11111111 to indicate that all stations are to accept the frame

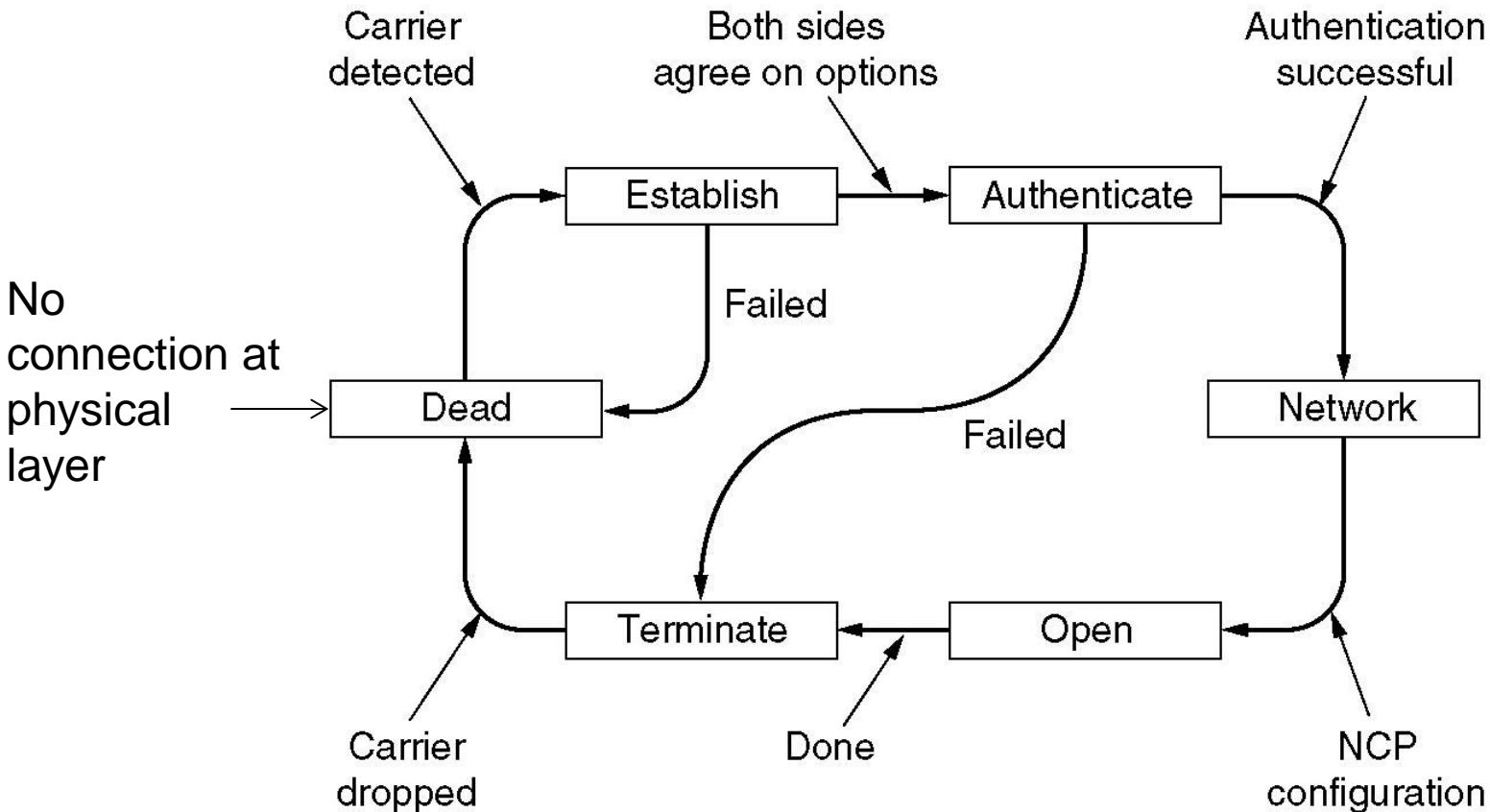
Control field: the default value of which is 00000011. This value indicates an unnumbered frame

Protocol field: To tell what kind of packet is in the Payload field

- Codes starting with 0 for information
- Codes starting with 1 are used for configurations (Link Control Protocol LCP, Network control Protocol NCP)



PPP – Point to Point Protocol (2)



A simplified phase diagram for bring a line up and down.



PPP – Point to Point Protocol (3)

The LCP frame types.

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)

