Simplex Stop and Wait Protocol

- Flow control deals with problem that sender transmits frames faster than receiver can accept, and solution is to limit sender into sending no faster than receiver can handle
- Consider the simplex case: data is transmitted in one direction (Note although data frames are transmitted in one direction, frames are going in both directions, i.e. link is duplex)
- **Stop and wait**: sender sends one **data frame**, waits for **acknowledgement** (ACK) from receiver before proceeding to transmit next frame
  - This simple flow control will break down if ACK gets lost or errors occur $\longrightarrow$ sender may wait for ACK that never arrives

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

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

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

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

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

Simplex Stop and Wait with ARQ

- For noisy link, pure stop and wait protocol will break down, and solution is to incorporate some error control mechanism
- **Stop and wait with ARQ**: Automatic Repeat reQuest (ARQ), an error control method, is incorporated with stop and wait flow control protocol
  - If error is detected by receiver, it discards the frame and send a negative ACK (NAK), causing sender to re-send the frame
  - In case a frame never got to receiver, sender has a **timer**: each time a frame is sent, timer is set $\longrightarrow$ If no ACK or NAK is received during timeout period, it re-sends the frame
  - Timer introduces a problem: Suppose timeout and sender retransmits a frame but receiver actually received the previous transmission $\longrightarrow$ receiver has **duplicated** copies
  - To avoid receiving and accepting two copies of same frame, frames and ACKs are alternatively **labeled** 0 or 1: ACK0 for frame 1, ACK1 for frame 0
- An important link parameter is defined by

$$a = \frac{\text{propagation time}}{\text{frame time}} = \frac{R\,d}{V\,L}$$

where R is data rate (bps), d is link distance (m), V is propagation velocity (m/s) and L frame length (bits)

Stop and Wait with ARQ (continue)

- In error-free case, **efficiency** or maximum **link utilisation** of stop and Wait with ARQ is:

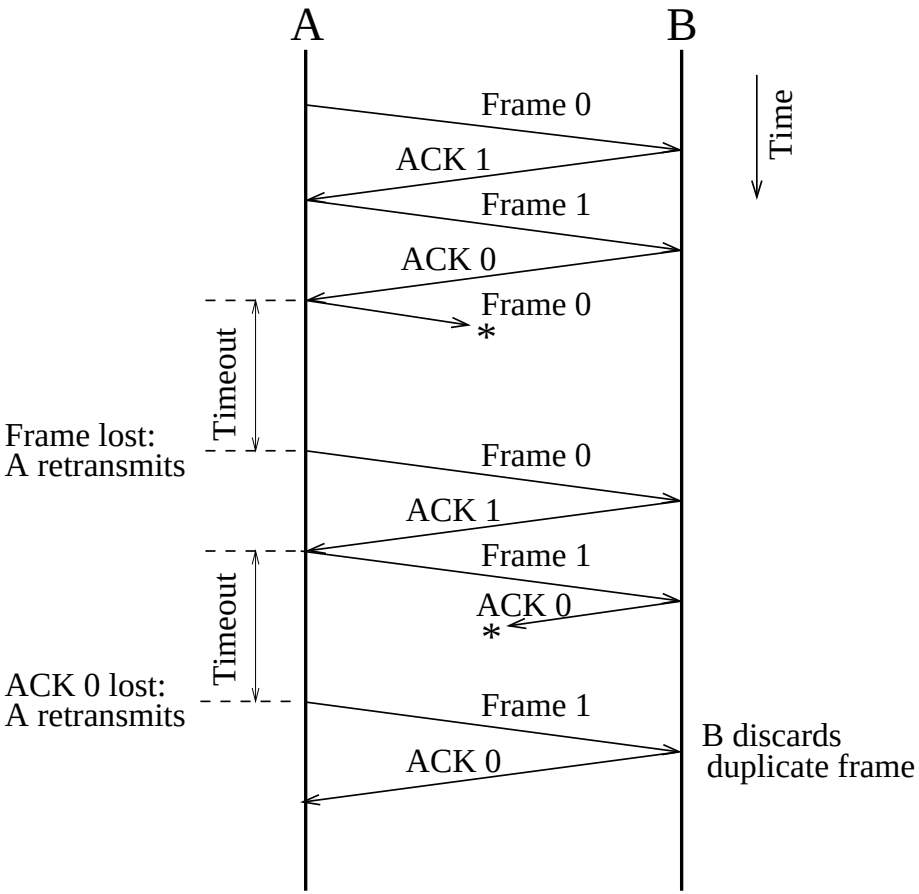
$$U = \frac{1}{1 + 2a}$$

- Illustration of how stop and wait with ARQ works:

  ACK0: frame 1 is received, waiting for next (frame 0)

  ACK1: frame 0 is received, waiting for next (frame 1)

  This is to have **1-bit sequence number**, and implies receiver have buffer for one frame



- For an LAN with $R = 10$ Mbps and $d = 1$ km, using $V = 2 \times 10^8$ m/s and $L = 500$ bits, $a = 0.1$ and stop-and-wait procedure has $U = 0.83$, which has adequate line utilisation

  But for a satellite link, link utilisation for stop-and-wait procedure may only be $U = 0.001$ or lower, which is clearly wasteful

Sliding Window Protocol

- For large link parameter a, stop and wait protocol is inefficient
- A universally accepted flow control procedure is the **sliding window protocol**
  - Frames and acknowledgements are numbered using **sequence numbers**
  - Sender maintains a list of sequence numbers (frames) it is allowed to transmit, called **sending window**
  - Receiver maintains a list of sequence numbers it is prepared to receive, called **receiving window**
  - A sending window of size N means that sender can send up to N frames without the need for an ACK
  - A window size of N implies buffer space for N frames
  - For n-bit sequence number, we have 2^n numbers: $0, 1, \cdots, 2^n - 1$, but the maximum window size $N = 2^n - 1$ (not 2^n)
  - ACK3 means that receiver has received frame 0 to frame 2 correctly, ready to receive frame 3 (and rest of N frames within window)
- In error-free case, efficiency or maximum **link utilisation** of sliding window protocol is:

$$U = \begin{cases} 1, & N > 2a + 1 \\ \frac{N}{1+2a}, & N < 2a + 1 \end{cases}$$

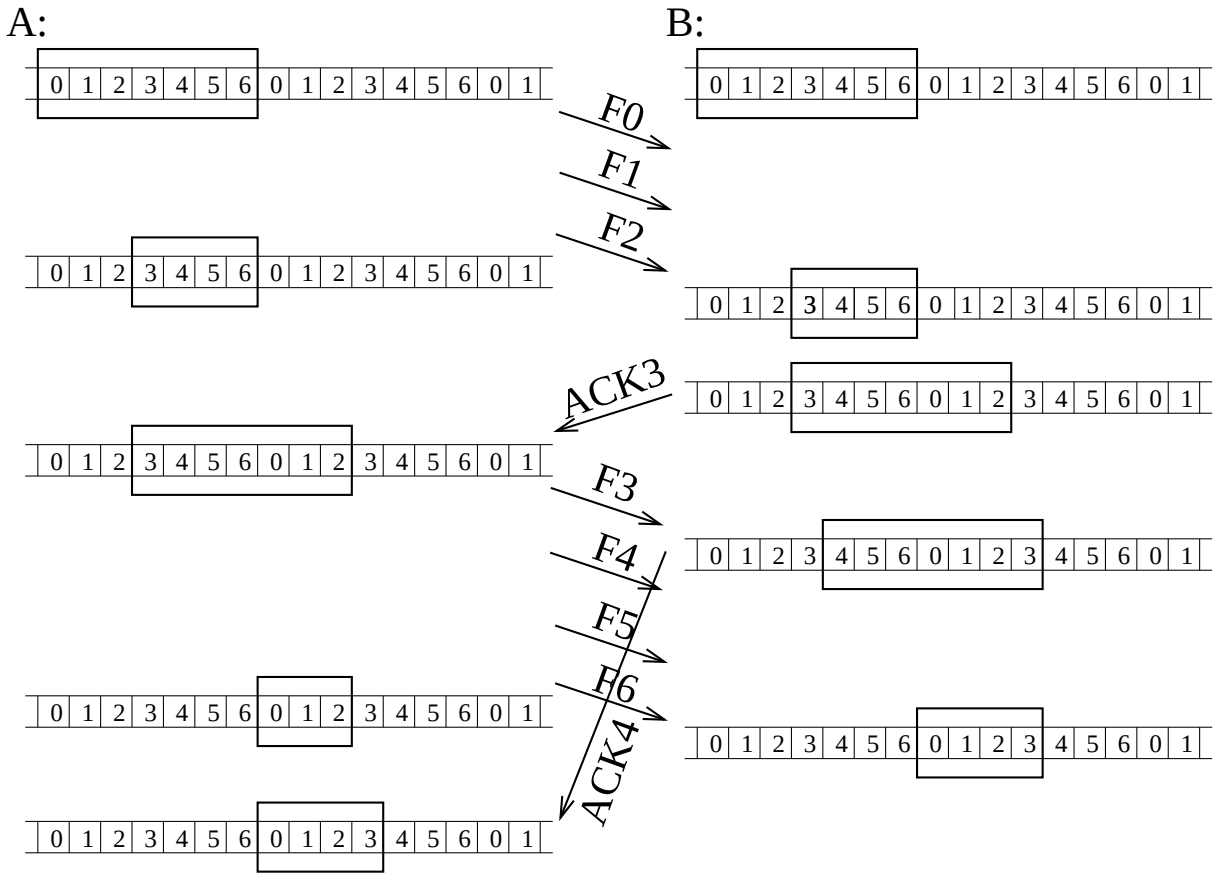
Thus it is able to maintain efficiency for large **link parameter** a: just use large widow size N

Sliding Window (continue)

- Note that $U = 1$ means that link has no idle time: there are always something in it, either data frames or ACKs
- Consider the case of 3-bit sequence number with maximum window size $N = 7$
- This illustration shows that

  Sending and receiving windows can shrink or grow during operation

  The receiver do not need to acknowledge every frames
- If both sending and receiving window sizes are $N = 1$, the sliding window protocol reduces to the stop-and-wait

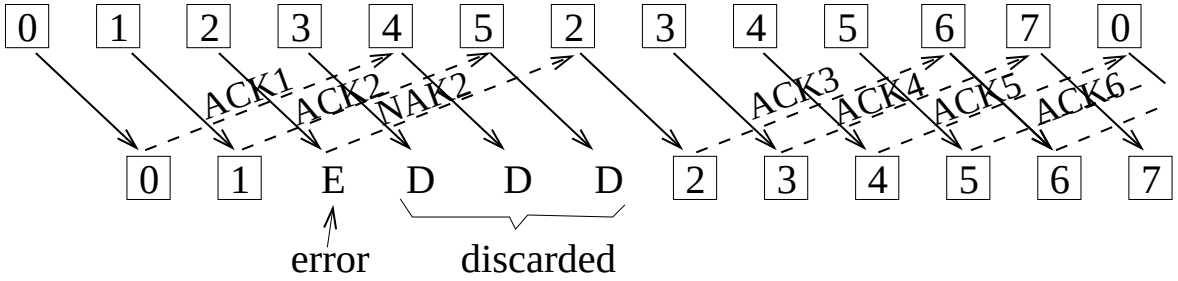


- In practice, error control must be incorporated with flow control, and we next discuss two common error control mechanisms

Go-back-n ARQ

- The basic idea of **go-back-n error control** is: If frame i is damaged, receiver requests retransmission of all frames starting from frame i

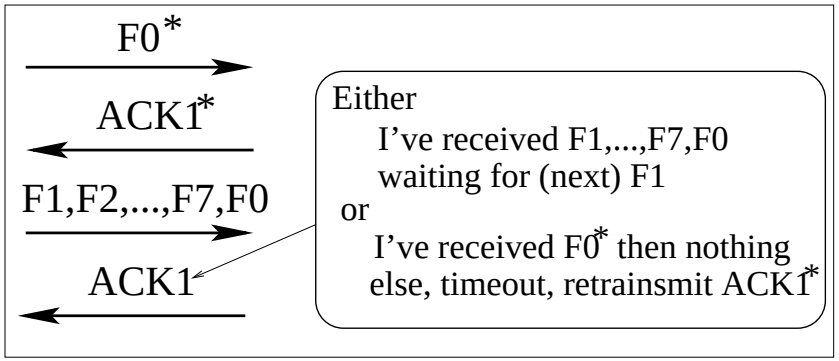
  An example:



- Notice that all possible cases of damaged frame and ACK / NAK must be taken into account

- For n-**bit sequence number**, **maximum window size** is $N = 2^n - 1$ not $N = 2^n \rightarrow$ with $N = 2^n$ confusion may occur

- Consider $n = 3$, if $N = 8$ what may happen:
  - Suppose that sender transmits frame 0 and gets an ACK1
  - It then transmits frames 1,2,3,4,5,6,7,0 (this is allowed, as they are within the sending window of size 8) and gets another ACK1

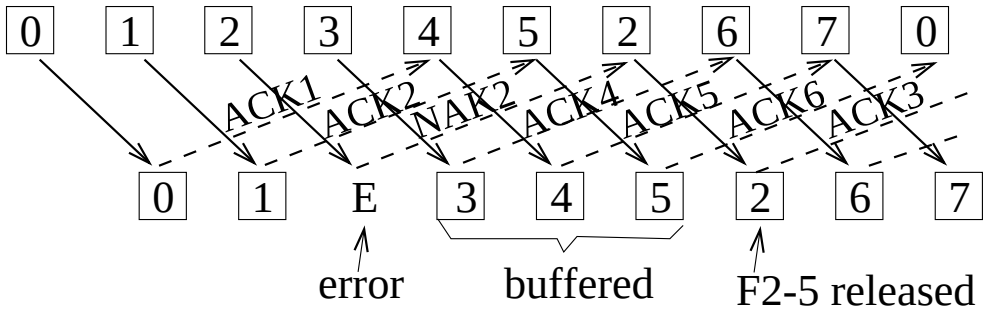


  - This could means that all eight frames were received correctly
  - It could also mean that all eight frames were lost, and receiver is repeating its previous ACK1
  - With $N = 7$, this confusing situation is avoided

Selective-Reject ARQ

- In **selective-reject** ARQ error control, the only frames retransmitted are those receive a NAK or which time out

  An illustrative example:



- Selective-reject would appear to be more efficient than go-back-n, but it is harder to implement and less used

- The window size is also more restrictive: for n-bit sequence number, the maximum window size is $N = \frac{2^n}{2}$ to avoid possible confusion

- Go-back-n and selective-reject can be seen as trade-offs between **link bandwidth** (data rate) and data link layer **buffer space**
  - If link bandwidth is large but buffer space is scarce, go-back-n is preferred
  - If link bandwidth is small but buffer space is pretty, selective-reject is preferred

From Simplex to Duplex

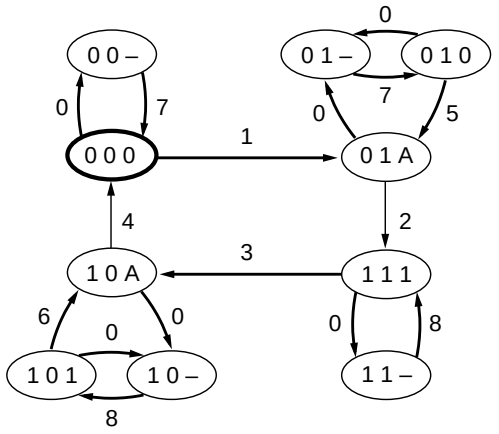
- So far, we consider data transmission in one direction (simplex), although the link is duplex
- If two sides exchange data (duplex), each needs to maintain two windows: one for transmitting and one for receiving
- In **duplex** communication, frames transmitted from either side can be data, ACKs and NAKs $\longrightarrow$ the need to distinguish them
- **Frame type**: Recall in frame header there is a control field, and part of it is typically used as frame type field to tell what type the frame is
- **Piggybacking**: In duplex situations, piggybacking is often used $\longrightarrow$ If one has data and an ACK to send, it sends both in one frame
- Discussion so far: data link layer is primarily concerned with making point-to-point link reliable
  - It is responsible for transmitting frames from sender to receiver (service to network layer), and can only uses physical layer to do the job
  - It has to take into account that transmission error may occur and sender/receiver may operate at different speeds $\longrightarrow$ error control/flow control (ACKs, NAKs, CRC, windows, sequence numbers)
  - Next lecture will see how all these fit into some data link layer protocols

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

#define MAX_SEQ 7                       /* should be 2^n – 1 */
typedef enum {frame_arrival, cksum_err, timeout, network_layer_ready} event_type;
#include "protocol.h"

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

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

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

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

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

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

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

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

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

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

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

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

   }

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

Sliding Window with Go-back-n C Codes

Protocol Verification

- How to know a protocol really works $\longrightarrow$ specify and verify protocol using, e.g. finite state machine
  - Each protocol machine (sender or receiver) is at a specific state at every time instant
  - Each state has zero or more possible transitions to other states
  - One particular state is initial state: from initial state, some or possibly all other states may be reachable by a sequence of transitions
- Simplex stop and wait ARQ protocol:
  - State SRC: $S = 0, 1 \longrightarrow$ which frame sender is sending; $R = 0, 1 \longrightarrow$ which frame receiver is expecting; $C = 0, 1, A$ (ACK), $-$ (empty) $\longrightarrow$ channel state, i.e. what is in channel
  - There are 9 transitions



(a)

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

(b)

  - Initial state (000): sender has just sent frame 0, receiver is expecting frame 0, and frame 0 is currently in channel
  - Transition 0 consists of channel losing its contents, transition 1 consists of channel correctly delivering frame 0 to receiver, and so on
  - During normal operation, transitions 1,2,3,4 are repeated in order over and over: in each cycle, two frames are delivered, bringing sender back to initial state

Summary

- Flow control and error control techniques for data link layer:

  Stop and wait ARQ, sliding window, go-back-n, selective-reject (repeat)

- Data link layer (part I) discussed so far:

  It is concerned with making a point-to-point link reliable, and is responsible for transmitting frames from sender to receiver, can only use physical layer to do job

- Error control and flow control (ACKs, NAKs, CRC, sliding windows, sequence numbers, go-back-n etc.):

  How these are included in a data link layer protocol will be discussed in next lecture