Reliable Transmission
Reliable Transmission

Hello!
My computer’s name is Alice.
Reliable Transmission

Hello! My Computer’s name is Alice.

Alice

Bob

Alice.

is

My

name
Reliable Transmission

- Suppose error protection identifies valid and invalid packets
  - How?

- Can we make the channel appear reliable?
  - Insure packet delivery
  - Maintain packet order
  - Provide reliability at full link capacity
Reliable Transmission Outline

- Fundamentals of Automatic Repeat reQuest (ARQ) algorithms
  - A family of algorithms that provide reliability through retransmission

- ARQ algorithms (simple to complex)
  - stop-and-wait
  - concurrent logical channels
  - sliding window
    - go-back-n
    - selective repeat

- Alternative: forward error correction (FEC)
Terminology

- **Acknowledgement (ACK)**
  - Receiver tells the sender when a frame is received

- **Selective acknowledgement (SACK)**
  - Specifies set of frames received

- **Cumulative acknowledgement (ACK)**
  - Have received specified frame and all previous

- **Negative acknowledgement (NAK)**
  - Receiver refuses to accept frame now, e.g., when out of buffer space
Terminology

- **Timeout (TO)**
  - Sender decides the frame (or ACK) was lost
  - Sender can try again

- **ARQ also called Positive Acknowledgement with Retransmission (PAR)**
Stop-and-Wait

Basic idea
1. Send a frame
2. Wait for an ACK or TO
3. If TO, go to 1
4. If ACK, get new frame, go to 1
Stop-and-Wait: Success

How long should the timeout be?

What can go wrong? How will it affect our protocol?
Stop-and-Wait: Lost Frame

Sender

Receiver

Frame

Frame

ACK

RTT

Time
Stop-and-Wait: Lost ACK

Sender

Timeout

Frame

Receiver

Timeout

ACK

RTT
Stop-and-Wait: Delayed Frame

How can receiver distinguish between two frames?

How many bits do you need for sequence numbers?
Stop-and-Wait

- **Goal**
  - Guaranteed, at-most-once delivery

- **Protocol Challenges**
  - Dropped frame/ACK
  - Duplicate frame/ACK

- **Requirements**
  - 1-bit sequence numbers (if physical network maintains order)
    - sender tracks frame ID to send
    - receiver tracks next frame ID expected
Stop-and-Wait State Diagram

- **Sender**
  - Send: 0
  - Expect: 0
- **Receiver**
  - Receive: 0

States:
- **Receive frame 0**
  - Send: 0
  - Expect: 0
  - Receive ACK 1
- **Receive frame 1**
  - Send: 1
  - Expect: 0
  - Receive ACK 0
- **Send: 1**
  - Expect: 1
  - Receive frame 1
- **Send: 0**
  - Expect: 1
  - Receive frame 0

Actions:
- Send: 1
- Expect: 0
- Receive: 0
- Receive ACK 1
- Receive frame 0
- Receive frame 1
- Receive ACK 0
Stop-and-Wait

- We have achieved
  - Frames delivered reliably and in order
  - Is that enough?

- Problem
  - Only allows one outstanding frame
    - Does not keep the pipe full
  - Example
    - 100ms RTT
    - One frame per RTT = 1KB
    - $1024 \times 8 \times 10 = 81920$ kbps
    - Regardless of link bandwidth!
Concurrent Logical Channels

- Used in ARPANET IMP-IMP protocol

Idea
- Multiplex logical channels over a physical link
  - Include channel ID in header
- Use stop-and-wait for each channel

Result
- Each channel is limited to stop-and-wait bandwidth
- Aggregate bandwidth uses full physical channel
- Supports multiple communicating processes
- Can use more than one channel per process
Concurrent Logical Channels

- **Problem**
  - **Bandwidth**
    - Use of a single channel per process may waste BW
  - **Ordering**
    - Use of multiple channel per process does not maintain packet ordering across channels!
    - If application has $n$ channels, and one needs a retransmission, it will always be one packet behind the other channels
ARQ: Where are We?

- **Goals for reliable transmission**
  - Make channel appear reliable
  - Maintain packet order (usually)
  - Impose low overhead/allow full use of link

- **Stop-and-Wait**
  - Provides reliable in-order delivery
  - Sacrifices performance

- **Concurrent Logical Channels**
  - Provides reliable delivery at full link bandwidth
  - Sacrifices packet ordering

- **Sliding Window Protocol**
  - Achieves all three!
Sliding Window Protocol

- Most important and general ARQ algorithm
- Used by TCP

Outline
- Concepts
- Terminology (from P&D)
- Details
- Code example
- Proof of eventual in-order delivery
- Classification scheme
  - (go-back-n, selective repeat)
Keeping the Pipe Full

Stop-and-Wait

Sender

Receiver

Frame

ACK

Frame

ACK

Frame

ACK

Goal

Sender

Receiver

Frame

Frame

Frame

ACK

Advantages:

- More frames in pipe
- Less time overall
- Piggybacked ACKs
Concepts

- Consider an ordered stream of data frames
- Stop-and-Wait
  - Window of one frame
  - Slides along stream over time
Concepts

- Sliding Window Protocol
  - Multiple-frame send window
  - Multiple frame receive window
Sliding Window

- **Send Window**
  - Fixed length
  - Starts at earliest unacknowledged frame
  - Only frames in window are active
Sliding Window

- **Receive Window**
  - Fixed length (unrelated to send window)
  - Starts at earliest frame not received
  - Only frames in window accepted

![Diagram showing different states of frames: Received and acknowledged, Received and not acknowledged, Received, outside receive window, Not yet received.](image-url)
Sliding Window Terminology

- Sender Parameters
  - Send Window Size (SWS)
  - Last Acknowledgement Received (LAR)
  - Last Frame Sent (LFS)

<table>
<thead>
<tr>
<th>Time</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWS</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LAR = 14      LFS = 18      Invariant: LFS – LAR ≤ SWS
Sliding Window Terminology

- Receiver Parameters
  - Receive Window Size (RWS)
  - Next Frame Expected (NFE)
  - Last Frame Acceptable (LFA)

RWS = 6
NFE = 4
LFA = 9
Invariant: LFA – NFE + 1 ≤ RWS
Sliding Window Details

Sender Tasks

- Assign sequence numbers
- On ACK Arrival
  - Advance LAR
  - Slide window

SWS = 4  SWS = 4
LAR = 14  LAR = 16
LFS = 18  FS = 20
Receive ACK 16
Sliding Window Details

- Receiver Tasks
  - On Frame Arrival (N)
    - Silently discard if outside of window
      - N < NFE (NACK possible, too)
      - N >= NFE + RWS
    - Send cumulative ACK if within window

\[
\begin{array}{cccccccccccc}
\text{Time} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \\
\end{array}
\]

- RWS = 6
- NFE = 4
- LFA = 9

Receive Frame 4
Send ACK 7
Sliding Window Details

- Receiver Tasks
  - On Frame Arrival (N)
    - Silently discard if outside of window
      - N < NFE (NACK possible, too)
      - N >= NFE + RWS
    - Send cumulative ACK if within window

- RWS = 6
- Time

- NFE = 8
- LFA = 13
Sliding Window Details

- **Sequence number space**
  - Finite number, so wrap around
  - Need space larger than SWS (outstanding frames)
  - In fact, need twice as large

- **Example**
  - 3-bit sequence numbers (0-7)
  - RWS = SWS = 7
Is $\log_2(SWS+1)$ bits enough?

- No. Example:
  - 3-bit sequence numbers (0-7)
  - $RWS = SWS = 7$
  - Why isn’t 3 bits enough (can you think of an example where it doesn’t work?)
Sliding Window Details

- Example of incorrect behavior
  - 3-bit sequence numbers 0-7
  - RWS = SWS = 7
  - Sender transmits 0-6
  - All arrive, but ACK’s lost
  - Sender retransmits
  - Receiver accepts as second incarnation of 0-6
Sliding Window Sequence Numbers

- How many sequence numbers are necessary?
  - Key questions
    - Where can the send window be?
    - What frame can be received next?
Sliding Window Sequence Numbers

- Assume $SWS = RWS$ (simplest, and typical)
- Sender transmits full SWS
- Two extreme cases:
  - None received (waiting for $0...SWS - 1$)
  - All received (waiting for $SWS...2 SWS - 1$)
- All possible packets must have unique sequence numbers
Sliding Window Sequence Numbers

- Extreme Locations for SWS
- Requirements
  - If a received packet is not in the receive window with no wrap, then it must not be in the receive window with wrap!
- Correctness condition:
  - Number of Sequence Numbers ≥ SWS + RWS
  - Alternates between two halves of the sequence number space

![Diagram of send and receive windows with sequence numbers ranging from 1 to 12]
Sliding Window Sequence Numbers

- Example
  - If SWS = RWS = 8
  - At least 16 sequence numbers are needed
  - A 4-bit sequence number space is enough

- Warning
  - P&D sometimes uses the variable Max_Seq_Num for the number of sequence numbers and sometimes for the maximum sequence number (these differ by one!)
  - Use Num_SEQ_Num for the number of sequence numbers: 0, 1, …, Num_SEQ_Num – 1
Window Sizes

- How big should we make SWS?
  - Compute from delay x bandwidth

- How big should we make RWS?
  - Depends on buffer capacity of receiver
Delay x Bandwidth Product - Revisited

- Amount of data in “pipe”
  - channel = pipe
  - delay = length
  - bandwidth = area of a cross section
  - bandwidth x delay product = volume
Delay x Bandwidth Product

- Pipe
  - Half of data that must be buffered before sender responds to slowdown request
Delay x Bandwidth Product

- Bandwidth x delay product
  - How many bits the sender must transmit before the first bit arrives at the receiver if the sender keeps the pipe full
  - Takes another one-way latency to receive a response from the receiver
Sliding Window Protocol Code Example

- Parameters
  - send/receive window size (SWS/RWS)
  - last acknowledgement received (LAR)
  - last frame sent (LFS)
  - next frame expected (NFE)
  - last frame acceptable (LFA)
Sliding Window Protocol Code Example

- Constants
  - Receive window size (RWS)
  - Maximum sequence number (MAX_SEQ_NO)
  - Frame size (FRAME_SIZE, constant for simplicity)
Sliding Window Protocol Code Example

- **Data structures**
  - Next frame expected (an integer)
  - One frame buffer for each entry in receive window
  - One presence bit for each entry

- **Receive window cycles through**
  - Sequence numbers
  - Data structures (thus RWS must divide MAX_SEQ_NO)
Sliding Window Protocol Code Example

#define RWS 8 /* receive window size */
#define MAX_SEQ_NO 16 /* max. sequence number+1 */
/* (must be multiple of */
/* RWS for this code) */
#define FRAME_SIZE 1000 /* constant for simplicity*/

char buf[RWS][FRAME_SIZE]; /* RWS frame buffers */
int present[RWS]; /* are frame buffers full?*/
/* (initialized to 0’s) */
int NFE = 0; /* next frame expected */
extern void send_ack (int seq_no);
extern void pass_to_app (char* data);
void recv_frame (char* data, int seq_no);
void recv_frame (char* data, int seq_no)
{
    int idx;    /* index into data structures */
    int i;      /* loop index */

    /* Map sequence numbers NFE...predecessor (NFE) into 0...MAX_SEQ_NO - 1, then see if seq_no falls within the receive window. */

    if (seq_no - NFE < RWS)
    {
        /* Frames outside the window */
        /* are ignored. (but an ACK */
        /* is sent; why?) */
    }
Sliding Window Protocol Code Example

/* Calculate index into data structures. */
idx = (seq_no % RWS);

if (!present[idx]) { /* frame is not dup */
present[idx] = 1; /* mark received */
memcpy (buf[idx], data, FRAME_SIZE);
 /* copy data into buf */
Sliding Window Protocol Code Example

/* Got a new frame; pass frames up to host? */
for (i = 0; i < RWS; i++) {
    idx = (i + NFE) % RWS;    /* Re-use idx. */
    /* first missing frame becomes NFE */
    /* after this loop terminates */
    if (!present[idx]) break;

    /* Frame is present—send it up! */
    pass_to_app (buf[idx]);
    present[idx] = 0; /* Mark buffer empty. */
}

/* Advance NFE to first missing frame. */
NFE = NFE + i;
Sliding Window Protocol Code Example

/* Frame handled (might have */
/* been duplicate). */
} /* (Send ACK for any frame received */

/* Now send acknowledgement for /*
/* predecessor (NFE). */
send_ack (NFE - 1);
}
Correctness

- **Claim**
  - A sliding window protocol leads to in-order delivery of all frames

- **Assumptions**
  - All sequence numbers are different
  - Frames can be lost
  - Frames can be delayed an arbitrarily finite amount of time
  - Frames are not reordered
  - Frames can arrive with detectable errors

- Are these assumptions adequate?
Sliding Window Protocol Correctness

- Need one more assumption
  - Any given frame is received without errors after a finite number of retransmissions

- Proof in two steps
  - Establish correctness assuming infinite sequence number space
  - Show that finite sequence number space does not affect result as long as it has \( \geq 2 \max(\text{SWS}, \text{RWS}) \) possible numbers
Sliding Window Protocol

Correctness

- Step 1: establish correctness assuming infinite sequence number space
  - Use induction on k with invariant “the k\textsuperscript{th} frame is eventually received”
- Step 2: show that finite sequence number space does not affect result as long as it has \( \geq 2 \max (\text{SWS}, \text{RWS}) \) possible numbers

![Diagram showing frames arrival over time with RWS = 6, NFE = 4, LFA = 9, and time from 2 to 13.]

What frame can arrive next?
ARQ Algorithm Classification

- Three Types:
  - Stop-and-Wait: $SWS = 1$ $RWS = 1$
  - Go-Back-N: $SWS = N$ $RWS = 1$
  - Selective Repeat: $SWS = N$ $RWS = M$
    - Usually $M = N$

![Diagram of ARQ Algorithm Classification]

Stop-And-Wait

Go-Back-N

Selective Repeat
Sliding Window Variations: Go-Back-N

- $SWS = N$, $RWS = 1$
- Receiver only buffers one frame
- If a frame is lost, the sender may need to retransmit up to $N$ frames
  - i.e., sender “goes back” $N$ frames
- Variations
  - How long is the frame timeout?
  - Does receiver send NACK for out-of-sequence frame?
Go-Back-N: Cumulative ACKs

Timeout for Packet 2

Packets 2, 3, 4, 5 are retransmitted

Packet 0

Packet 1

Packet 2

Packet 3

Packet 4

Packet 5

loss

ACK 0

ACK 1

ACK 1

ACK 1

ACK 3

ACK 4

ACK 5

ACK 6
Sliding Window Variations: Selective Repeat

- SWS = N, RWS = M
- Receiver buffer M frames
- If a frame is lost, sender must only resend
  - Frames lost within the receive window
- Variations
  - How long is the frame timeout?
  - Use cumulative or per-frame ACK?
  - Does protocol adapt timeouts?
  - Does protocol adapt SWS and/or RWS?
Selective Repeat

Packet 2 is retransmitted

Packet 0
Packet 1
Packet 2
Packet 3
Packet 4
Packet 5
Packet 2
Packet 6
Packet 7
Packet 8

A

B

ACK 0
ACK 1
ACK 3
ACK 4
ACK 5
ACK 2
ACK 9
ACK 7
ACK 8

loss
Roles of a Sliding Window Protocol

- Reliable delivery on an unreliable link
  - Core function
- Preserve delivery order
  - Controlled by the receiver
- Flow control
  - Allow receiver to throttle sender

- Separation of Concerns
  - Must be able to distinguish between different functions that are sometimes rolled into one mechanism
Forward Error Correction (FEC)

- Alternative to ARQ algorithms
- Idea
  - Error correction instead of error detection
  - Send extra information to avoid retransmission (i.e., fix errors first/forward rather than afterward/backward)
- Why
  - Very high latency connections
  - Difficult for retransmission