1. Description

The final protocol includes additional features of TCP – cumulative ACKs with pipelining, fast retransmit, and flow control (note that a single timer for the base of the window remains the same as in Part 2). To deal with high-loss scenarios below, set the maximum number of retransmits for all packets to 50.

1.1. Code (25 pts)

The input and output is the same as in Part 2, except now the window size can be above 1:

Main:   sender W = 5000, RTT 0.200 sec, loss 0.001 / 0.0001, link 1000 Mbps
Main:   initializing DWORD array with 2^25 elements... done in 15 ms
Main:   connected to s3.irl.cs.tamu.edu in 0.219 sec, pkt size 1472 bytes
  [ 2] B  184 ( 0.3 MB) N  368 T 0 F 1 W 184 S 1.077 Mbps RTT 0.219
  [ 4] B  2821 ( 4.2 MB) N  5642 T 1 F 5 W 2821 S 15.408 Mbps RTT 0.218
  [ 6] B  11492 (16.9 MB) N 16492 T 2 F 12 W 5000 S 50.741 Mbps RTT 0.218
  [ 8] B  18075 (26.6 MB) N 23075 T 5 F 18 W 5000 S 38.522 Mbps RTT 0.218
  [10] B  24680 (36.3 MB) N 29680 T 5 F 23 W 5000 S 38.651 Mbps RTT 0.218
  [12] B  32091 (44.6 MB) N 35291 T 7 F 28 W 5000 S 32.835 Mbps RTT 0.218
  [14] B  33904 (49.9 MB) N 38904 T 7 F 32 W 5000 S 21.142 Mbps RTT 0.218
  [16] B  37389 (55.0 MB) N 42389 T 8 F 37 W 5000 S 20.393 Mbps RTT 0.218
  [18] B  48062 (70.7 MB) N 51849 T 9 F 42 W 5000 S 62.459 Mbps RTT 0.248
  [20] B  52999 (78.0 MB) N 57999 T 11 F 50 W 5000 S 28.890 Mbps RTT 0.248
  [22] B  63145 (92.9 MB) N 68145 T 13 F 58 W 5000 S 59.371 Mbps RTT 0.216
  [24] B  75527 (111.2 MB) N 80206 T 14 F 67 W 5000 S 72.458 Mbps RTT 0.226
  [26] B  81802 (120.4 MB) N 86802 T 14 F 76 W 5000 S 36.683 Mbps RTT 0.226
[28] B  90697 (133.5 MB) N 91679 T 16 F 82 W 5000 S 52.051 Mbps RTT 0.226

[29.065] <-- FIN-ACK 91679 window FC6FB7CB
Main:   transfer finished in 28.626 sec, 37509.93 Kbps, checksum FC6FB7CB
Main:   estRTT 0.226, ideal rate 258854.99 Kbps

1.2. Report (25 pts)

All transfers that determine speed must have sufficient user buffer size to reach steady-state dynamics (i.e., the rate becomes stable). Once the transfer speed has stabilized, record this value for the analysis below. Several questions to address:

1. Set packet loss $p$ to zero in both directions, the RTT to 0.5 seconds, and bottleneck link speed to $S = 1$ Gbps. Examine how your goodput scales with window size $W$. This should be done by plotting the steady-state rate $r(W)$ for $W = 1, 2, 4, 8, \ldots, 2^{10}$ and keeping the $x$-axis on a log-scale. Your peak rate will be around 24 Mbps and, depending on your home bandwidth, usage of an on-campus server might be necessary. Using curve-fitting, generate a model for $r(W)$. Discuss whether it matches the theory discussed in class.

2. Expanding on the previous question, fix the window size at $W = 30$ packets and vary the RTT = 10, 20, 40, \ldots, 5120 ms. Plot stable rate $r$(RTT), again placing the $x$-axis on a log-scale. Perform curve-fitting to determine a model that describes this relationship. Due to queuing/transmission delays emulated by the server and various OS kernel overhead, the
actual RTT may deviate from the requested RTT. Thus, use the measured average in your plots and comment on whether the resulting curve matches theory.

3. Run the dummy receiver on your localhost and produce a trace using $W = 8K$ (the other parameters do not matter as the dummy receiver ignores them, although they should still be within valid ranges). Discuss your CPU configuration and whether you managed to exceed 1 Gbps. How about 10 Gbps using 9-KB packets (see dummy-receiver discussion in Part 1)?

4. Use buffer size $2^{23}$ DWORDs, RTT = 200 ms, window size $W = 300$ packets, link capacity $S = 10$ Mbps, and loss only in the reverse direction equal to $p = 0.1$. Show an entire trace of execution for this scenario and compare it to a similar case with no loss in either direction. Does your protocol keep the same rate in these two cases? Why or why not?

5. Determine the algorithm that the receiver uses to change its advertised window. What name does this technique have in TCP? *Hint:* the receiver window does not grow to infinity and you need provide its upper bound as part of the answer.

1.3. Extra Credit (20 pts)

Achieve the speed in section 1.12 using localhost (10 pts) or between ts2.cse.tamu.edu and s3.irl.cs.tamu.edu over the network (20 pts).

1.4. Program Structure

It is recommended to structure your program around the three threads in Figure 1. When `ss.Open()` succeeds with the connection, it spawns the worker and stats threads to run in the background and provide support for the remainder of the transfer. These threads can be signaled to quit in `ss.Close();` however, if the user deletes the socket class without calling `ss.Close()`, you may end up leaking memory or crashing. As a result, the destructor `~SenderSocket()` must check if these threads are still running and terminate them before deleting shared data objects inside the class (such as the queue of pending packets). The most common way of signaling termination is to set some shared event and then wait on both thread handles obtained from `CreateThread`. As a general rule, graceful termination of threads is the best method for avoiding unexpected crashes and various problems on exit.

![Figure 1. Organization of the program.](attachment:image.png)
Function \texttt{ss.Send()} interacts with the worker thread through a shared queue of pending packets. This nicely maps to the bounded producer-consumer (PC) problem, where the fixed queue size is \( W \) packets. The easiest way to implement this is to block \texttt{ss.Send()} on a semaphore that counts the number of empty slots in the buffer. For each received ACK that moves the base forward by \( k \) packets, this semaphore gets released by the same \( k \) slots (except when doing flow control, see below). The buffer is a circular array of packets (each with \texttt{MAX_PKT_SIZE} bytes). The following pseudocode should provide a starting idea:

```c
class Packet {
    int type;    // SYN, FIN, data
    int size;    // for the worker thread
    clock_t txTime;   // transmission time
    SenderDataHeader sdh;   // header
    char data[MAX_PACKET_SIZE];  // payload
};

int SenderSocket::Send (char *data, int size)
{    HANDLE arr[] = {eventQuit, empty};
    WaitForMultipleObjects (2, arr, false, INFINITE);
    // no need for mutex as no shared variables are modified
    slot = nextSeq % W;
    Packet *p = pending_pkts + slot;  // pointer to packet struct
    packet->sdh->seq = nextSeq;
    ...  // set up remaining fields in sdh and p
    memcpy (p->data, data, size);
    nextSeq ++;
    ReleaseSemaphore (full, 1);
}
```

To reduce the amount of code duplication, it is best to process both SYN and FIN packets inside \texttt{ss.Open()} and \texttt{ss.Close()} through the same shared buffer. You can use additional variables and logic as needed, building upon the architecture explained above.

Next, the worker thread requires response to three events – a timeout, a packet is ready in the socket, and a new packet is in the send buffer. To manage all three, we need ability to wait on socket events in \texttt{WaitForMultipleObjects}. As mentioned in hw1.pdf, this is accomplished using \texttt{WSAEventSelect}, which associates some event \texttt{socketReceiveReady} with the socket. Make sure to create this event using \texttt{CreateEvent} (instead of \texttt{WSACreateEvent}) and specify the auto-reset option. Pseudocode:

```c
void SenderSocket::WorkerRun (void)
{
    HANDLE events [] = {socketReceiveReady, full};
    while (true)
    {
        if (pending packets)
            timeout = timerExpire - cur_time;
        else
            timeout = INFINITE;

        int ret = WaitForMultipleObjects (2, events, false, timeout);
        switch (ret)
        {
            case timeout:  sendto(&pending_packets[senderBase % W].sdh, ...); // retx  break;
            case socket:   // move senderBase; update RTT; handle fast retx; do flow control
                            ReceiveACK ();
                            break;
            case sender:   sendto(&pending_packets[nextToSend % W].sdh, ...);
                            nextToSend ++;
        }
    }
}```
break;
    default: handle failed wait;
}

if ((first packet of window || just did a retx (timeout / 3-dup ACK)
    || senderBase moved forward)
    recompute timerExpire;
}

There are a few additional caveats. First, you need to ensure clean termination during timeouts. If
the worker thread encounters the maximum number of retx on the same packet, it must unblock
ss.Send() and somehow notify it that the connection has failed. Second, when ss.Close() is
called, the function must block until the worker thread has collected all outstanding acknowl-
edgments. Otherwise, the FIN packet may be rejected by the server and/or the transfer may be
incomplete. Third, upon receiving an ACK that moves the base from $x$ to $x + y$, an RTT sample is
computed only based on packet $x + y - 1$ and only if there were no prior retransmissions of base
$x$. Finally, when moving the window forward, reset the timer to current time plus the most-recent
RTO (retransmission timeout).

1.5. Winsock Issues

By default, the UDP sender/receiver buffer inside the Windows kernel is configured to support
only 8 KB of unprocessed data. You can achieve higher outbound performance and prevent
packet loss in the inbound direction by increasing both buffers, then setting your worker thread
to time-critical priority:

```c
int kernelBuffer = 20e6; // 20 meg
if (setsockopt (sock, SOL_SOCKET, SO_RCVBUF, &kernelBuffer, sizeof (int)) == SOCKET_ERROR)
    ...    // 20 meg
kernelBuffer = 20e6;
if (setsockopt (sock, SOL_SOCKET, SO_SNDBUF, &kernelBuffer, sizeof (int)) == SOCKET_ERROR)
    ...    SetThreadPriority (GetCurrentThread(), THREAD_PRIORITY_TIME_CRITICAL);
```

1.6. Flow Control

The semaphore shared between the main and worker threads can be reused to easily accomplish
flow control using this general architecture:

```c
HANDLE empty = CreateSemaphore (NULL, 0, W, NULL)
// after the SYN-ACK, inside ss.Open()
int lastReleased = min (W, synack->window);
ReleaseSemaphore (empty, lastReleased);

// in the worker thread
while (not end of transfer)
{
    get ACK with sequence y, receiver window R
    if (y > sndBase)
    {
        sndBase = y
        effectiveWin = min (W, ack->window)
        // how much we can advance the semaphore
        newReleased = sndBase + effectiveWin - lastReleased
        ReleaseSemaphore (empty, newReleased)
        lastReleased += newReleased
    }
}
```
To test that flow control works, set the RTT to 2 seconds and observe the effective window reported by your program. It should expand once per printout.

1.7. Small Window, No Loss

Main: sender W = 10, RTT 0.100 sec, loss 0 / 0, link 1000 Mbps
Main: initializing DWORD array with 2^20 elements... done in 0 ms
Main: connected to s3.irl.cs.tamu.edu in 0.115 sec, pkt size 1472 bytes
[  2] B 126 ( 0.2 MB) N 126 T 0 F 0 W 10 S 0.740 Mbps RTT 0.116
[  4] B 286 ( 0.4 MB) N 296 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[  6] B 446 ( 0.7 MB) N 456 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[  8] B 606 ( 0.9 MB) N 616 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[10] B 766 ( 1.1 MB) N 776 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[12] B 926 ( 1.4 MB) N 936 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[14] B 1086 ( 1.6 MB) N 1096 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[16] B 1246 ( 1.8 MB) N 1256 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[18] B 1406 ( 2.1 MB) N 1416 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[20] B 1566 ( 2.4 MB) N 1576 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[22] B 1726 ( 2.7 MB) N 1736 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[24] B 1886 ( 3.0 MB) N 1896 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[26] B 2046 ( 3.3 MB) N 2056 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[28] B 2206 ( 3.6 MB) N 2216 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[30] B 2366 ( 3.9 MB) N 2376 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[32] B 2456 ( 4.1 MB) N 2466 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[34] B 2616 ( 4.4 MB) N 2626 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[36] B 2776 ( 4.7 MB) N 2786 T 0 F 0 W 10 S 0.936 Mbps RTT 0.116
[37,837] <-- FIN-ACK 2865 window 5B0360D
Main: transfer finished in 37.594 sec, 892.54 Kbps, checksum 5B0360D
Main: estRTT 0.116, ideal rate 931.37 Kbps

1.8. Large Window, Low Loss

Main: sender W = 12000, RTT 0.100 sec, loss 0.0001 / 0, link 1000 Mbps
Main: initializing DWORD array with 2^28 elements... done in 811 ms
Main: connected to s3.irl.cs.tamu.edu in 0.123 sec, pkt size 1472 bytes
[  2] B 14559 (21.4 MB) N 22094 T 0 F 0 W 12000 S 85.553 Mbps RTT 0.130
[  4] B 85837 (126.4 MB) N 97837 T 0 F 6 W 12000 S 416.825 Mbps RTT 0.207
[  6] B 170753 (251.3 MB) N 182753 T 2 F 12 W 12000 S 496.914 Mbps RTT 0.187
[  8] B 249672 (367.5 MB) N 259675 T 3 F 19 W 12000 S 461.824 Mbps RTT 0.175
[10] B 325519 (479.2 MB) N 337519 T 5 F 29 W 12000 S 443.425 Mbps RTT 0.116
[12] B 394961 (581.4 MB) N 405233 T 7 F 40 W 12000 S 406.378 Mbps RTT 0.103
[14] B 472303 (695.2 MB) N 484303 T 7 F 47 W 12000 S 452.591 Mbps RTT 0.173
[16] B 545545 (803.0 MB) N 557545 T 7 F 55 W 12000 S 428.601 Mbps RTT 0.193
[18] B 628755 (925.5 MB) N 636984 T 8 F 61 W 12000 S 486.933 Mbps RTT 0.101
[20] B 694104 (1021.7 MB) N 706104 T 9 F 68 W 12000 S 382.410 Mbps RTT 0.161
[21,170] <-- FIN-ACK 733431 window E8F5B708
Main: transfer finished in 20.902 sec, 410954.64 Kbps, checksum E8F5B708
Main: estRTT 0.127, ideal rate 1110625.81 Kbps

1.9. Small Window, Moderate Loss

Main: sender W = 10, RTT 0.010 sec, loss 0.1 / 0, link 1000 Mbps
Main: initializing DWORD array with 2^20 elements... done in 0 ms
Main: connected to s3.irl.cs.tamu.edu in 0.022 sec, pkt size 1472 bytes
[  2] B 14559 ( 21.4 MB) N 22094 T 0 F 0 W 12000 S 85.553 Mbps RTT 0.130
[  4] B 85837 (126.4 MB) N 97837 T 0 F 6 W 12000 S 416.825 Mbps RTT 0.207
[  6] B 170753 (251.3 MB) N 182753 T 2 F 12 W 12000 S 496.914 Mbps RTT 0.187
[  8] B 249672 (367.5 MB) N 259675 T 3 F 19 W 12000 S 461.824 Mbps RTT 0.175
[10] B 325519 (479.2 MB) N 337519 T 5 F 29 W 12000 S 443.425 Mbps RTT 0.116
[12] B 394961 (581.4 MB) N 405233 T 7 F 40 W 12000 S 406.378 Mbps RTT 0.103
[14] B 472303 (695.2 MB) N 484303 T 7 F 47 W 12000 S 452.591 Mbps RTT 0.173
[16] B 545545 (803.0 MB) N 557545 T 7 F 55 W 12000 S 428.601 Mbps RTT 0.193
[18] B 628755 (925.5 MB) N 636984 T 8 F 61 W 12000 S 486.933 Mbps RTT 0.101
[20] B 694104 (1021.7 MB) N 706104 T 9 F 68 W 12000 S 382.410 Mbps RTT 0.161
[21,170] <-- FIN-ACK 733431 window E8F5B708
Main: transfer finished in 20.902 sec, 410954.64 Kbps, checksum E8F5B708
Main: estRTT 0.127, ideal rate 1110625.81 Kbps
Main: transfer finished in 26.675 sec, 1257.91 Kbps, checksum 5B0360D
Main: estRTT 0.028, ideal rate 4199.75 Kbps

1.10. Bottlenecked by Win/RTT

Main: sender W = 300, RTT 0.100 sec, loss 0.001 / 0, link 1000 Mbps
Main: initializing DWORD array with 2^24 elements... done in 15 ms
Main: connected to s3.irl.cs.tamu.edu in 0.118 sec, pkt size 1472 bytes
[ 2] B 984 ( 1.4 MB) N 1284 T 0 F 4 W 300 S 5.792 Mbps RTT 0.118
 [ 4] B 5008 ( 7.4 MB) N 5008 T 0 F 11 W 300 S 23.548 Mbps RTT 0.121
 [ 6] B 9384 (13.8 MB) N 9482 T 0 F 13 W 300 S 25.594 Mbps RTT 0.125
 [ 8] B 13847 (20.4 MB) N 14174 T 0 F 15 W 300 S 26.117 Mbps RTT 0.137
[10] B 17409 (25.6 MB) N 17709 T 0 F 21 W 300 S 20.844 Mbps RTT 0.137
[12] B 21438 (31.6 MB) N 21438 T 0 F 27 W 300 S 23.571 Mbps RTT 0.121
[14] B 25803 (38.0 MB) N 26092 T 0 F 30 W 300 S 25.524 Mbps RTT 0.118
[16] B 29561 (43.5 MB) N 29861 T 0 F 33 W 300 S 21.980 Mbps RTT 0.121
[18] B 33545 (49.4 MB) N 33655 T 0 F 38 W 300 S 23.313 Mbps RTT 0.123
[20] B 37275 (54.9 MB) N 37382 T 0 F 43 W 300 S 21.827 Mbps RTT 0.124
[22] B 41911 (61.7 MB) N 42139 T 0 F 45 W 300 S 27.129 Mbps RTT 0.118
[24] B 45604 (67.1 MB) N 45840 T 0 F 51 W 300 S 21.610 Mbps RTT 0.117
[24.680] <-- FIN-ACK 45840 window 85A854D4
Main: transfer finished in 24.430 sec, 21976.30 Kbps, checksum 85A854D4
Main: estRTT 0.117, ideal rate 29960.34 Kbps

1.11. Surviving Heavy Loss

Main: sender W = 10, RTT 0.010 sec, loss 0.5 / 0, link 14 Mbps
Main: initializing DWORD array with 2^15 elements... done in 0 ms
Main: connected to s3.irl.cs.tamu.edu in 0.023 sec, pkt size 1472 bytes
[ 2] B 20 ( 0.0 MB) N 30 T 19 F 1 W 10 S 0.117 Mbps RTT 0.025
 [ 4] B 44 ( 0.1 MB) N 54 T 40 F 1 W 10 S 0.140 Mbps RTT 0.025
 [ 6] B 69 ( 0.1 MB) N 79 T 59 F 3 W 10 S 0.146 Mbps RTT 0.025
[7.777] <-- FIN-ACK 90 window FC694CF3
Main: transfer finished in 7.721 sec, 135.81 Kbps, checksum FC694CF3
Main: estRTT 0.025, ideal rate 4591.14 Kbps

1.12. Extra Credit

Main: sender W = 3000, RTT 0.010 sec, loss 0 / 0, link 10000 Mbps
Main: initializing DWORD array with 2^30 elements... done in 3832 ms
Main: connected to s3.irl.cs.tamu.edu in 0.012 sec, pkt size 1472 bytes
[ 2] B 143717 (211.6 MB) N 145053 T 0 F 0 W 3000 S 846.312 Mbps RTT 0.013
 [ 4] B 306084 (450.6 MB) N 308365 T 0 F 0 W 3000 S 955.954 Mbps RTT 0.028
 [ 6] B 462012 (680.1 MB) N 464042 T 0 F 8 W 3000 S 918.050 Mbps RTT 0.024
 [ 8] B 610838 (899.2 MB) N 613515 T 0 F 16 W 3000 S 876.158 Mbps RTT 0.032
[10] B 766549 (1128.4 MB) N 768940 T 0 F 24 W 3000 S 916.671 Mbps RTT 0.030
[12] B 916665 (1349.3 MB) N 918596 T 0 F 32 W 3000 S 883.537 Mbps RTT 0.024
[14] B 1079442 (1567.5 MB) N 1081179 T 0 F 32 W 3000 S 952.486 Mbps RTT 0.032
[16] B 1234139 (1816.7 MB) N 1236689 T 0 F 40 W 3000 S 916.689 Mbps RTT 0.027
[18] B 1389514 (2045.4 MB) N 1392029 T 0 F 48 W 3000 S 914.757 Mbps RTT 0.027
[20] B 1544658 (2273.7 MB) N 1547081 T 0 F 56 W 3000 S 913.468 Mbps RTT 0.030
[22] B 1694635 (2494.5 MB) N 1696519 T 0 F 64 W 3000 S 882.628 Mbps RTT 0.023
[24] B 1850272 (2723.6 MB) N 1852081 T 0 F 72 W 3000 S 916.338 Mbps RTT 0.021
[26] B 2005076 (2951.5 MB) N 2006592 T 0 F 80 W 3000 S 911.432 Mbps RTT 0.017
[28] B 2167648 (3190.5 MB) N 2169668 T 0 F 80 W 3000 S 956.052 Mbps RTT 0.027
[30] B 2317339 (3411.1 MB) N 2320169 T 0 F 88 W 3000 S 882.086 Mbps RTT 0.030
[32] B 2472883 (3640.1 MB) N 2475262 T 0 F 96 W 3000 S 915.788 Mbps RTT 0.027
[34] B 2629129 (3870.1 MB) N 2631070 T 0 F 104 W 3000 S 919.922 Mbps RTT 0.023
[36] B 2785415 (4100.1 MB) N 2786436 T 0 F 112 W 3000 S 920.109 Mbps RTT 0.014
[37.870] <-- FIN-ACK 2933721 window 39F2A0E6
Main: transfer finished in 37.835 sec, 908153.36 Kbps, checksum 39F2A0E6
Main: estRTT 0.028, ideal rate 1275245.91 Kbps
### 463/612 Homework 3 Grade Sheet (Part 3)

Name: ______________________________

<table>
<thead>
<tr>
<th>Function</th>
<th>Points</th>
<th>Break down</th>
<th>Item</th>
<th>Deduction</th>
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<td>Model of ( r(W) )</td>
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<td>Dummy receiver trace</td>
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<td>Reverse packet loss trace</td>
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<td>Receiver window-resize algorithm</td>
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Total points: ________________