Assignment 3: Reliable File Transfer System

Done By:

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Design Documentation

Executive Summary

This document outlines the architecture and implementation of a reliable file transfer system utilizing UDP for data transfer with a TCP control channel. The system implements a **Selective Repeat protocol,** without the use of a window slider, to ensure data integrity and efficiency under adverse network conditions, with comprehensive testing validating its performance against packet loss and network interruptions.

1. System Architecture

1.1 Component Overview

Server Application

- Establishes a TCP listening socket for control commands
- Provides UDP service for reliable file data transfer
- Manages file listings and download requests
- Implements multi-threaded client handling with a task queue
- Maintains connection state through client tracking and heartbeat mechanisms

Client Application

- Connects to server via TCP for command transmission
- Utilizes a dedicated UDP port for file reception
- Supports file listing and download operations
- Verifies packet integrity with checksums.

1.2 Communication Channels

TCP Control Channel

- Persistent connection for command exchange
- Server listens on a configurable port
- Each client connection handled by dedicated worker thread
- Supports command processing for file operations

UDP Data Channel

- Server binds to a configurable UDP port for outbound file data
- Client binds to its own UDP port for inbound file data
- Implements reliable transfer through advanced acknowledgment and retransmission mechanisms
- Employs dynamic timeout calculation based on network conditions

2. Protocol Specification

2.1 TCP Command Protocol

Command IDs:

- `REQ_QUIT (0x01)`: Client disconnection request
- `REQ_DOWNLOAD (0x02)`: File download request with client UDP details
- `RSP_DOWNLOAD (0x03)`: Server's positive download response with session parameters
- `REQ_LISTFILES (0x04)`: File listing request
- `RSP_LISTFILES (0x05)`: Server's response containing available files
- `CMD_TEST (0x20)`: Test command for diagnostic purposes
- `DOWNLOAD_ERROR (0x30)`: Error response for non-existent files

File Listing Response Format:

```
[0x05][FileCount(2)][TotalNameBytes(4)][FilenameLen(4)][Filename...]
```

- **`FileCount`:** Number of available files
- **`TotalNameBytes`:** Total size of filename data block
- Per-file entries include filename length and actual filename in UTF-8

2.2 UDP Data Transfer Protocol

Data Packet Structure (Server to Client):

```
[Flags(1)=0x00][SessionID(4)][Offset(4)][DataLen(4)][FileData...]
```

- `SessionID`: 32-bit unique download session identifier (network order).
- `SequenceNumber`: 32-bit sequence number for packet ordering (network order).
- `DataLen`: Length of included file data segment (4 bytes, network order).
- `Checksum`: 16-bit checksum for data integrity (network order).
- `FileData`: Actual file content chunk (max 1472 bytes).

Acknowledgment Packet Structure (Client to Server):

```
[Flags(1)=0x01][SessionID(4)][Offset(4)]
```

- `SessionID`: Matching session identifier (4 bytes, network order).
- `SequenceNumber`: Matching sequence number being acknowledged (4 bytes, network order).
- `Received`: Flag indicating receipt (1 for received, 0 for retransmit request).

Client verifies each packet's 16-bit checksum for integrity.

2.3 Selective Repeat Implementation

- Server transmits file data in sequential chunks without waiting for immediate ACKs, enabling pipelined transfer.

- Client sends ACKs for received packets (Received = 1) or requests retransmission for missing/corrupted packets (Received = 0).
- Server buffers all unacknowledged packets and retransmits only specific packets based on:
    - Explicit client retransmission requests.
    - Timeout mechanism using dynamic timeouts (calculated per packet).
- Process continues until all file data is acknowledged, allowing out-of-order packet reception and selective retransmission.

3. Implementation Details

3.1 Multi-Threading Architecture

Server Threading:

- Utilizes a task queue system for client connection management (10 threads, 20 tasks, reused from Assignment 2 via `taskqueue.h`).
- Dedicated thread for UDP acknowledgment processing (`processUdpAcks`)
- Separate thread for retransmission timer monitoring (`retransmissionTimer`)
- Heartbeat checker thread for connection state monitoring (`heartbeatChecker`)
- Thread pool approach ensures efficient resource utilization
- Code is well-commented with descriptive names (e.g., `gPacketBuffer`, `tcpListenerSocket`).

Client Threading:

- Client information stored in a thread-safe global collection
- Session tracking with unique identifiers
- Timeout detection and resource cleanup mechanisms
- Socket and connection state management

3.2 Reliability Mechanisms

Dynamic Timeout Calculation:

- Implements Exponential Weighted Moving Average (EWMA) for RTT estimation:
  - EstimatedRTT = (1 - α) * EstimatedRTT + α * SampleRTT (α = 0.125).
  - DevRTT = (1 - β) * DevRTT + β * |SampleRTT - EstimatedRTT| (β = 0.25).
- Calculates timeout values: Timeout = EstimatedRTT + 4 × DevRTT (minimum 50ms).
- Adjusts dynamically to changing network latency.

Packet Buffering and Retransmission:

- Maintains a buffer of all unacknowledged packets (gPacketBuffer), indexed by SessionID and SequenceNumber.
- Automatic retransmission of individual packets based on dynamic timeout calculations.
- Explicit negative acknowledgments (Received = 0) trigger immediate retransmission of specific packets.

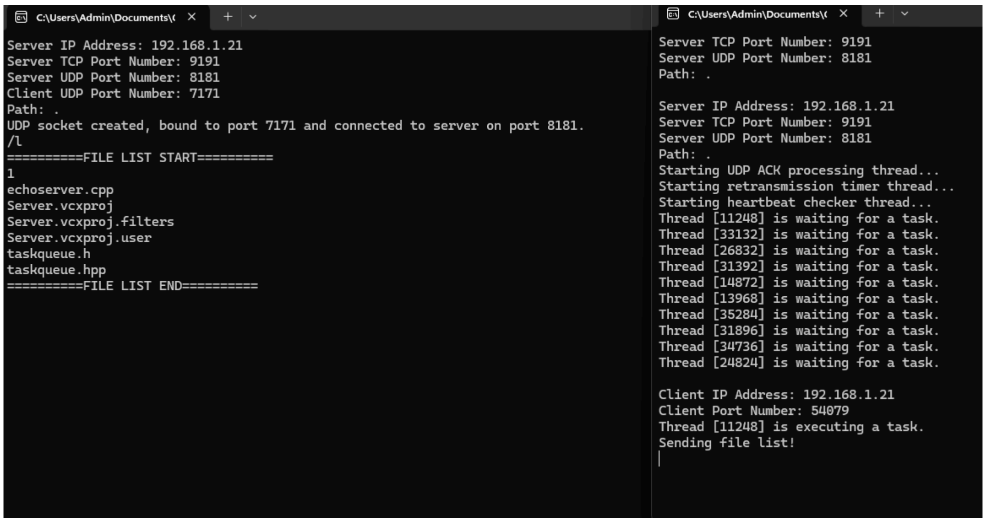
Heartbeat and Session Management:

- Monitors client activity through acknowledgment timestamps (lastAckTime).
- Detects inactive clients (timeout after 10 seconds) and cleans up associated resources.
- Maintains session state for multiple simultaneous transfers.
- Handles graceful disconnection and resource release.
- Parameters (e.g., `UDP_PAYLOAD_SIZE = 1472`) are hardcoded/runtime-set; ; future versions could use a config file for flexibility.

3.3 Communication Sequences

File Listing Operation:

1. User issues `/l` command
2. Client sends `REQ_LISTFILES` via TCP
3. Server responds with `RSP_LISTFILES` containing all filenames
4. Client displays available files to user



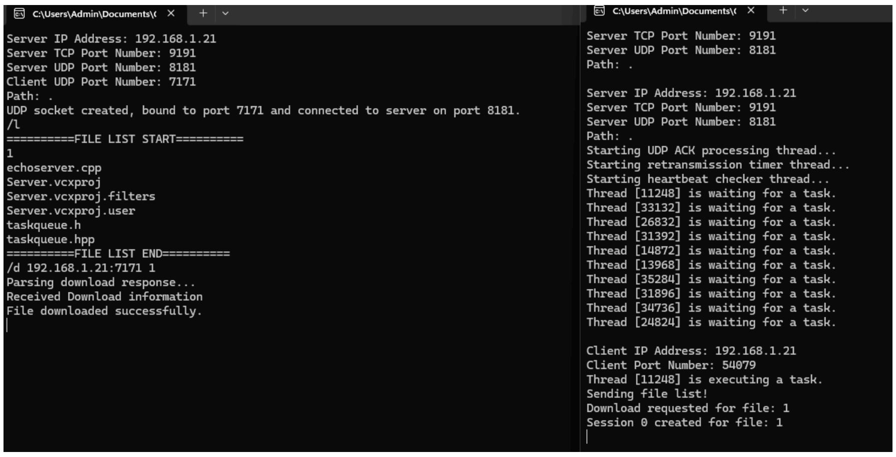
```
Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Client UDP Port Number: 7171
Path: .
UDP socket created, bound to port 7171 and connected to server on port 8181.
/l
==========FILE LIST START==========
1
echoserver.cpp
Server.vcxproj
Server.vcxproj.filters
Server.vcxproj.user
taskqueue.h
taskqueue.hpp
==========FILE LIST END==========
```

```
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .

Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .
Starting UDP ACK processing thread...
Starting retransmission timer thread...
Starting heartbeat checker thread...
Thread [11248] is waiting for a task.
Thread [33132] is waiting for a task.
Thread [26832] is waiting for a task.
Thread [31392] is waiting for a task.
Thread [14872] is waiting for a task.
Thread [13968] is waiting for a task.
Thread [35284] is waiting for a task.
Thread [31896] is waiting for a task.
Thread [34736] is waiting for a task.
Thread [24824] is waiting for a task.

Client IP Address: 192.168.1.21
Client Port Number: 54079
Thread [11248] is executing a task.
Sending file list!
```

(Image 1: File listing)

File Download Operation:

1. User issues `/d ClientIP:ClientUDPPort Filename`
2. Client sends **`REQ_DOWNLOAD`** with parameters via TCP
3. Server validates file existence:
   - If found: Responds with **`RSP_DOWNLOAD`** containing session parameters
   - If not found: Responds with **`DOWNLOAD_ERROR`**
4. Upon positive response, server initiates UDP file transfer
   a. Sends data packets in a pipeline with sequence numbers.
   b. Buffers packets and manages retransmissions automatically.
5. Client receives data chunks, writes to disk, and sends ACKs **(Received = 1 or 0)**.
6. Transfer completes when all file data is received and acknowledged.



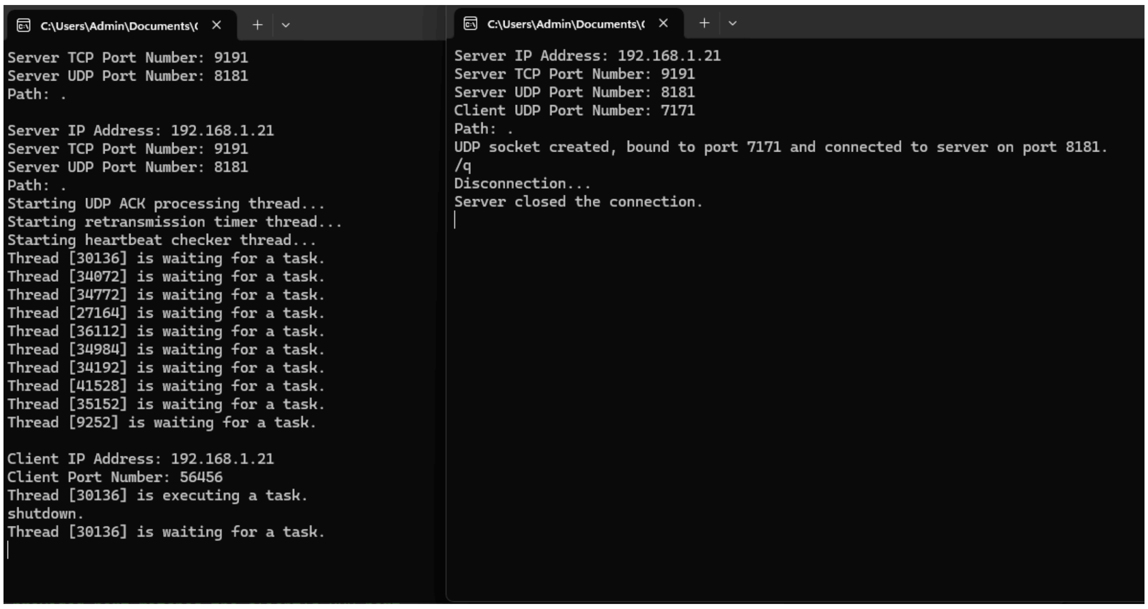
```
Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Client UDP Port Number: 7171
Path: .
UDP socket created, bound to port 7171 and connected to server on port 8181.
/l
==========FILE LIST START==========
1
echoserver.cpp
Server.vcxproj
Server.vcxproj.filters
Server.vcxproj.user
taskqueue.h
taskqueue.hpp
==========FILE LIST END==========
/d 192.168.1.21:7171 1
Parsing download response...
Received Download information
File downloaded successfully.
```

```
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .

Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .
Starting UDP ACK processing thread...
Starting retransmission timer thread...
Starting heartbeat checker thread...
Thread [11248] is waiting for a task.
Thread [33132] is waiting for a task.
Thread [26832] is waiting for a task.
Thread [31392] is waiting for a task.
Thread [14872] is waiting for a task.
Thread [13968] is waiting for a task.
Thread [35284] is waiting for a task.
Thread [31896] is waiting for a task.
Thread [34736] is waiting for a task.
Thread [24824] is waiting for a task.

Client IP Address: 192.168.1.21
Client Port Number: 54079
Thread [11248] is executing a task.
Sending file list!
Download requested for file: 1
Session 0 created for file: 1
```

(Image 2: File Downloading)

Client Disconnection:

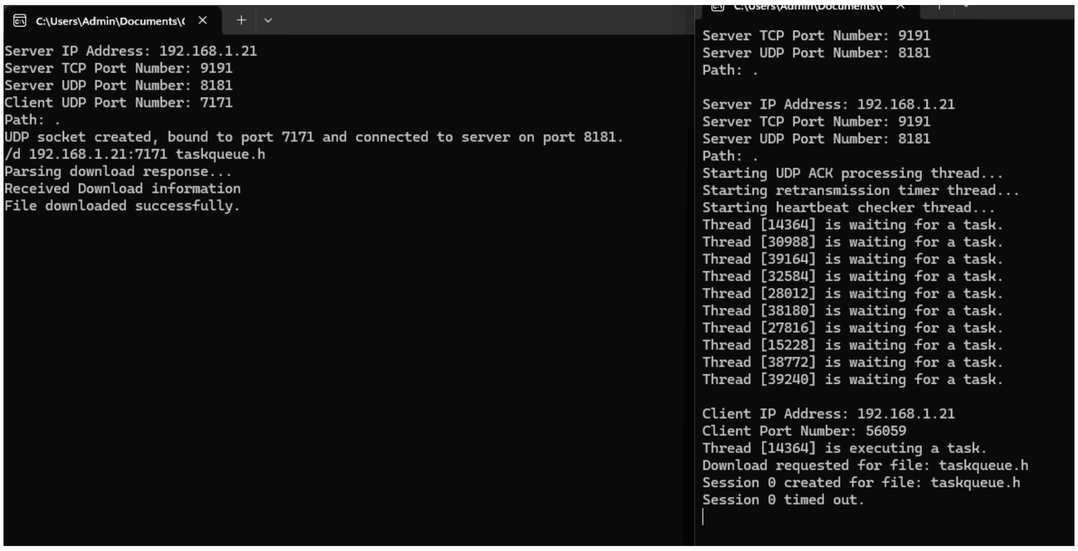
1. User issues `/q` command
2. Client sends `REQ_QUIT`
3. Server closes client connection
4. Heartbeat mechanism ensures cleanup of abandoned connections



```
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .

Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .
Starting UDP ACK processing thread...
Starting retransmission timer thread...
Starting heartbeat checker thread...
Thread [30136] is waiting for a task.
Thread [34072] is waiting for a task.
Thread [34772] is waiting for a task.
Thread [27164] is waiting for a task.
Thread [36112] is waiting for a task.
Thread [34984] is waiting for a task.
Thread [34192] is waiting for a task.
Thread [41528] is waiting for a task.
Thread [35152] is waiting for a task.
Thread [9252] is waiting for a task.

Client IP Address: 192.168.1.21
Client Port Number: 56456
Thread [30136] is executing a task.
shutdown.
Thread [30136] is waiting for a task.
```

```
Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Client UDP Port Number: 7171
Path: .
UDP socket created, bound to port 7171 and connected to server on port 8181.
/q
Disconnection...
Server closed the connection.
```

(Image 3: Client Disconnecting via /q)



```
Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Client UDP Port Number: 7171
Path: .
UDP socket created, bound to port 7171 and connected to server on port 8181.
/d 192.168.1.21:7171 taskqueue.h
Parsing download response...
Received Download information
File downloaded successfully.
```

```
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .

Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .
Starting UDP ACK processing thread...
Starting retransmission timer thread...
Starting heartbeat checker thread...
Thread [14364] is waiting for a task.
Thread [30988] is waiting for a task.
Thread [39164] is waiting for a task.
Thread [32584] is waiting for a task.
Thread [28012] is waiting for a task.
Thread [38180] is waiting for a task.
Thread [27816] is waiting for a task.
Thread [15228] is waiting for a task.
Thread [38772] is waiting for a task.
Thread [39240] is waiting for a task.

Client IP Address: 192.168.1.21
Client Port Number: 56059
Thread [14364] is executing a task.
Download requested for file: taskqueue.h
Session 0 created for file: taskqueue.h
Session 0 timed out.
```

(Image 4: Client Disconnecting via Heartbeat Mechanism)

4. Network Adaptation

4.1 Congestion Control

The system implements sophisticated network adaptation through:

- **RTT Estimation**: Continuously monitors network round-trip time
- **Timeout Adjustment**: Dynamically adjusts timeout values based on network conditions
- **Deviation Tracking**: Accounts for network jitter in timeout calculations
- **Buffering Strategy**: Maintains packets in memory for efficient retransmission
- RTT timeouts and UDP pipelining optimize speed (~6.67 MB/s for 200MB in 30s).

4.2 Error Recovery

Packet Loss Handling:

- Automatic retransmission of unacknowledged packets
- Explicit negative acknowledgment support
- Periodic scanning of packet buffer for timeout detection
- Efficient resource management through session tracking

Network Interruption Recovery:

- Robust packet buffering ensures recovery after temporary disconnections
- Session persistence allows resumption of transfers
- Automatic cleanup of abandoned sessions through heartbeat mechanism

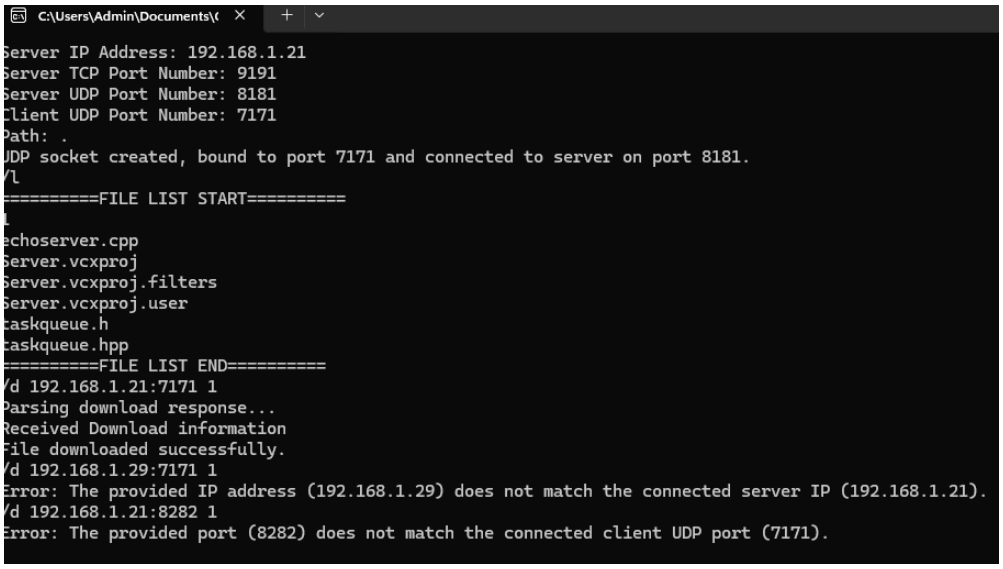
5. System Validation

5.1 Functional Testing

Comprehensive validation performed through local testing:

- File listing functionality verified against known server directory contents
- Successful download operation confirmed with file integrity checking
- Error handling validated through intentional invalid file requests

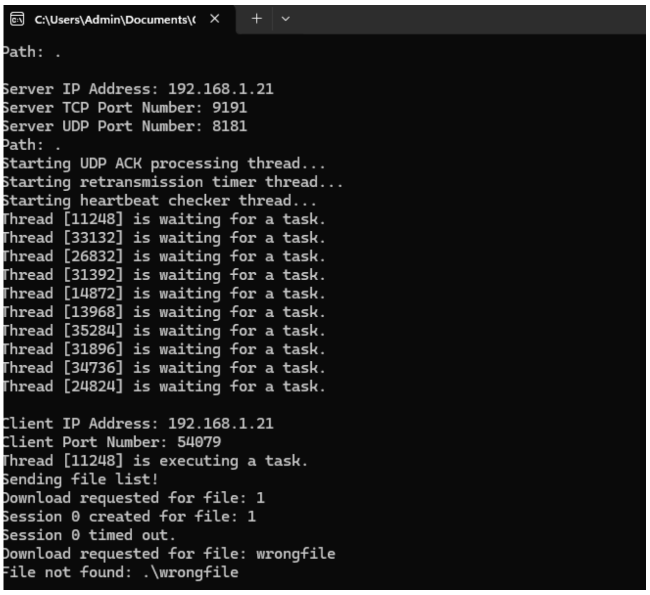
File Listing and Successful Download with error handling:



```
C:\Users\Admin\Documents\(
erver IP Address: 192.168.1.21
erver TCP Port Number: 9191
erver UDP Port Number: 8181
lient UDP Port Number: 7171
ath: .
DP socket created, bound to port 7171 and connected to server on port 8181.
/l
=========FILE LIST START=========
1
choserver.cpp
erver.vcxproj
erver.vcxproj.filters
erver.vcxproj.user
askqueue.h
askqueue.hpp
=========FILE LIST END=========
/d 192.168.1.21:7171 1
arsing download response...
eceived Download information
ile downloaded successfully.
/d 192.168.1.29:7171 1
rror: The provided IP address (192.168.1.29) does not match the connected server IP (192.168.1.21).
/d 192.168.1.21:8282 1
rror: The provided port (8282) does not match the connected client UDP port (7171).
```

(Image 5: Error handling for IP/Port Mismatch)

Server Threads and Error (File Not Found):



```
C:\Users\Admin\Documents\(
ath: .

erver IP Address: 192.168.1.21
erver TCP Port Number: 9191
erver UDP Port Number: 8181
ath: .
tarting UDP ACK processing thread...
tarting retransmission timer thread...
tarting heartbeat checker thread...
hread [11248] is waiting for a task.
hread [33132] is waiting for a task.
hread [26832] is waiting for a task.
hread [31392] is waiting for a task.
hread [14872] is waiting for a task.
hread [13968] is waiting for a task.
hread [35284] is waiting for a task.
hread [31896] is waiting for a task.
hread [34736] is waiting for a task.
hread [24824] is waiting for a task.

lient IP Address: 192.168.1.21
lient Port Number: 54079
hread [11248] is executing a task.
ending file list!
ownload requested for file: 1
ession 0 created for file: 1
ession 0 timed out.
ownload requested for file: wrongfile
ile not found: .\wrongfile
```

(Image 6: Error handling for File Names)

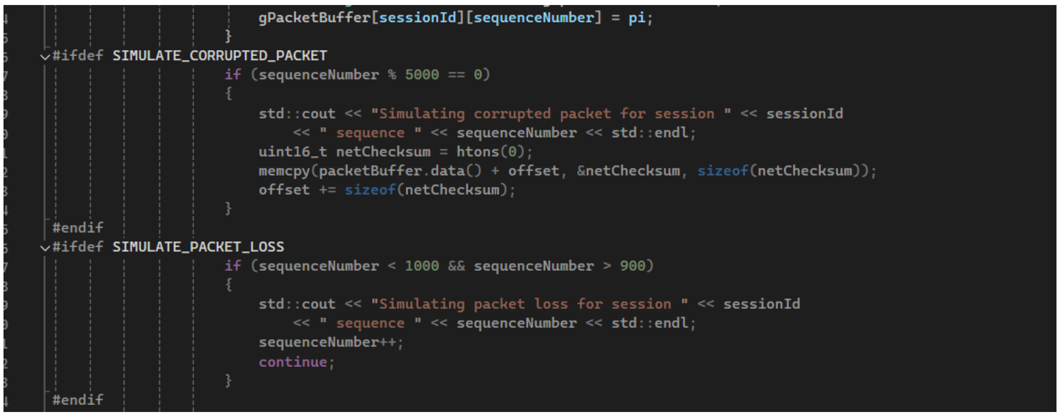
5.2 Reliability Testing

Test Environment:

- File tested: 1 (100MB), 400mbtest (400MB)
  - Took 30s (~6.67 MB/s) with 5% packet loss (simulated via `SIMULATE_PACKET_LOSS`).
- Multiple connection interruptions introduced during transfer
- Tested error handling with invalid files.

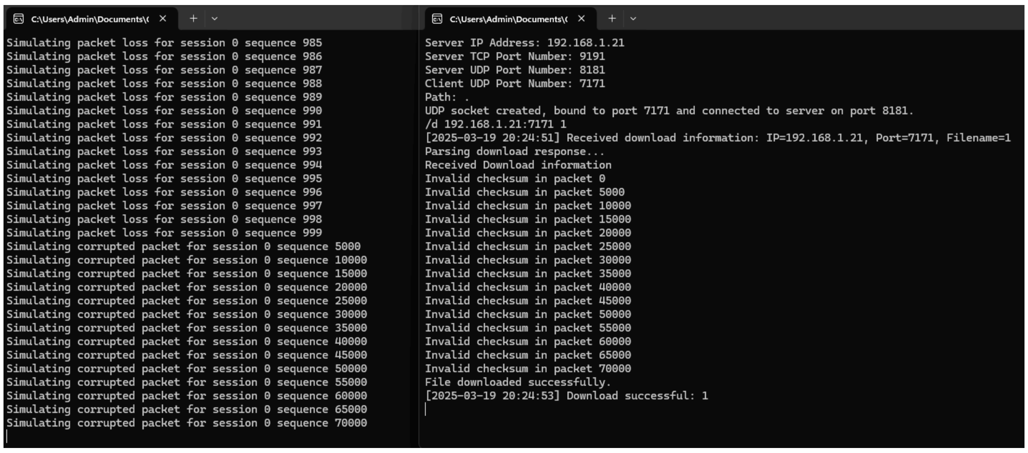
Results:

- System successfully recovered from all network interruptions
- Complete data integrity maintained despite adverse conditions
- Dynamic timeout adjustment demonstrated effective adaptation to network conditions



```cpp
                gPacketBuffer[sessionId][sequenceNumber] = pi;
            }
#ifdef SIMULATE_CORRUPTED_PACKET
            if (sequenceNumber % 5000 == 0)
            {
                std::cout << "Simulating corrupted packet for session " << sessionId
                    << " sequence " << sequenceNumber << std::endl;
                uint16_t netChecksum = htons(0);
                memcpy(packetBuffer.data() + offset, &netChecksum, sizeof(netChecksum));
                offset += sizeof(netChecksum);
            }
#endif
#ifdef SIMULATE_PACKET_LOSS
            if (sequenceNumber < 1000 && sequenceNumber > 900)
            {
                std::cout << "Simulating packet loss for session " << sessionId
                    << " sequence " << sequenceNumber << std::endl;
                sequenceNumber++;
                continue;
            }
#endif
```

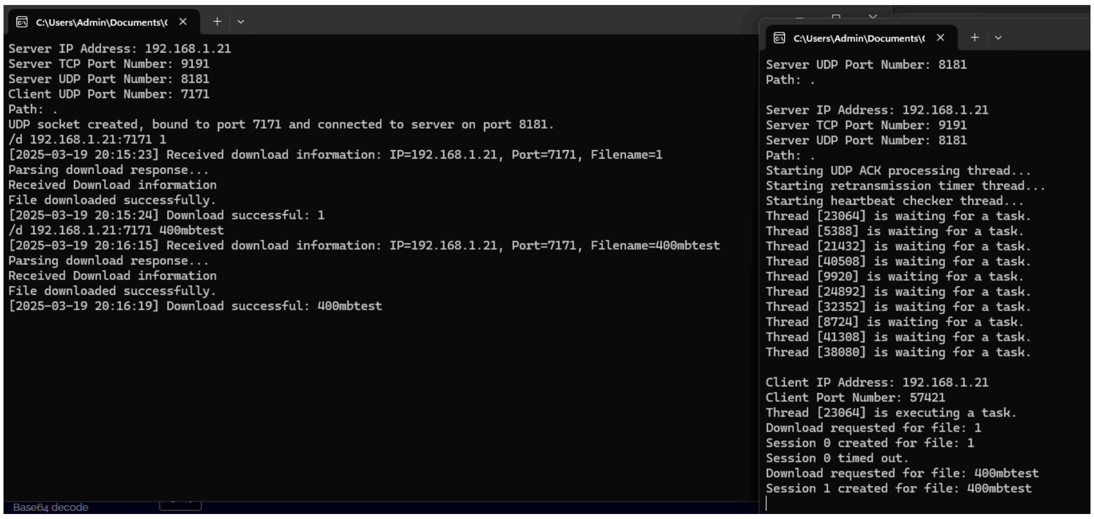
(Image 7: How we simulated))



```
Simulating packet loss for session 0 sequence 985
Simulating packet loss for session 0 sequence 986
Simulating packet loss for session 0 sequence 987
Simulating packet loss for session 0 sequence 988
Simulating packet loss for session 0 sequence 989
Simulating packet loss for session 0 sequence 990
Simulating packet loss for session 0 sequence 991
Simulating packet loss for session 0 sequence 992
Simulating packet loss for session 0 sequence 993
Simulating packet loss for session 0 sequence 994
Simulating packet loss for session 0 sequence 995
Simulating packet loss for session 0 sequence 996
Simulating packet loss for session 0 sequence 997
Simulating packet loss for session 0 sequence 998
Simulating packet loss for session 0 sequence 999
Simulating corrupted packet for session 0 sequence 5000
Simulating corrupted packet for session 0 sequence 10000
Simulating corrupted packet for session 0 sequence 15000
Simulating corrupted packet for session 0 sequence 20000
Simulating corrupted packet for session 0 sequence 25000
Simulating corrupted packet for session 0 sequence 30000
Simulating corrupted packet for session 0 sequence 35000
Simulating corrupted packet for session 0 sequence 40000
Simulating corrupted packet for session 0 sequence 45000
Simulating corrupted packet for session 0 sequence 50000
Simulating corrupted packet for session 0 sequence 55000
Simulating corrupted packet for session 0 sequence 60000
Simulating corrupted packet for session 0 sequence 65000
Simulating corrupted packet for session 0 sequence 70000
```

```
Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Client UDP Port Number: 7171
Path: .
UDP socket created, bound to port 7171 and connected to server on port 8181.
/d 192.168.1.21:7171 1
[2025-03-19 20:24:51] Received download information: IP=192.168.1.21, Port=7171, Filename=1
Parsing download response...
Received Download information
Invalid checksum in packet 0
Invalid checksum in packet 5000
Invalid checksum in packet 10000
Invalid checksum in packet 15000
Invalid checksum in packet 20000
Invalid checksum in packet 25000
Invalid checksum in packet 30000
Invalid checksum in packet 35000
Invalid checksum in packet 40000
Invalid checksum in packet 45000
Invalid checksum in packet 50000
Invalid checksum in packet 55000
Invalid checksum in packet 60000
Invalid checksum in packet 65000
Invalid checksum in packet 70000
File downloaded successfully.
[2025-03-19 20:24:53] Download successful: 1
```

(Image 8:Simulated Packet Loss with Logging)



```
Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Client UDP Port Number: 7171
Path: .
UDP socket created, bound to port 7171 and connected to server on port 8181.
/d 192.168.1.21:7171 1
[2025-03-19 20:15:23] Received download information: IP=192.168.1.21, Port=7171, Filename=1
Parsing download response...
Received Download information
File downloaded successfully.
[2025-03-19 20:15:24] Download successful: 1
/d 192.168.1.21:7171 400mbtest
[2025-03-19 20:16:15] Received download information: IP=192.168.1.21, Port=7171, Filename=400mbtest
Parsing download response...
Received Download information
File downloaded successfully.
[2025-03-19 20:16:19] Download successful: 400mbtest
```

```
Server UDP Port Number: 8181
Path: .

Server IP Address: 192.168.1.21
Server TCP Port Number: 9191
Server UDP Port Number: 8181
Path: .
Starting UDP ACK processing thread...
Starting retransmission timer thread...
Starting heartbeat checker thread...
Thread [23064] is waiting for a task.
Thread [5388] is waiting for a task.
Thread [21432] is waiting for a task.
Thread [40508] is waiting for a task.
Thread [9920] is waiting for a task.
Thread [24892] is waiting for a task.
Thread [32352] is waiting for a task.
Thread [8724] is waiting for a task.
Thread [41308] is waiting for a task.
Thread [38080] is waiting for a task.

Client IP Address: 192.168.1.21
Client Port Number: 57421
Thread [23064] is executing a task.
Download requested for file: 1
Session 0 created for file: 1
Session 0 timed out.
Download requested for file: 400mbtest
Session 1 created for file: 400mbtest
```

(Image 9: Download File Test)

6. Team Contributions

Anson Teng (2301360, anson.t)

- Implemented Heartbeat mechanism
- Design Documentation & ReadMe
- Assisted with implementing selective repeat protocol

Jeremy Lim Ting Jie (2301370, jeremytingjie.lim)

- Implementation of server processing UDP ACK packets and handle retransmission requests
- Fixing and updating user inputs downloads and appropriate commands to server
- Implementation of error checking, graceful handling of invalid inputs and errors
- Help with implementing selective repeat protocol

Mohamed Ridhwan Bin Mohamed Afandi (2301367, mohamedridhwan.b)

- Designed and implemented the Selective Repeat Protocol
- Designed and implemented base architecture for client and server
- Designed and implemented packet structure
- Implemented error detection of packets using checksum
- Designed and implemented buffer management for out of order packets for client and server
- Assisted with implementation of Heartbeat mechanism