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Online Gaming Performance Evaluation over Starlink Satellite Broadband

Bachelor's Thesis - Computer Science - May 2023

University
of Stavanger

I, **Jakob Bernhardt Danielsen, Endre Lund and Mats Husberg**, declare that this thesis titled, "Online Gaming Performance Evaluation over Starlink Satellite Broadband" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a bachelor's degree at the University of Stavanger.

- Where I have consulted the published work of others, this is always clearly attributed.

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- I have acknowledged all main sources of help.

Abstract

This thesis studies the performance and the Quality of Experience (QoE) of online gaming over the Starlink satellite network and compares it to terrestrial access technologies. Satellite broadband provides an opportunity to play games online from areas where traditional access networks are insufficient or not available. Modern games require certain standards of network performance, and games of different game genres have different requirements for certain metrics. Said metrics and how Starlink performs are investigated in this thesis. Our work provides results from experimental scenarios in two games from different game genres. The objective of this work is to evaluate the performance of online gaming through Starlink, and if the QoE meets the expectations of players.

Acknowledgements

Contents

Abbreviations

ACK	Acknowledgement
SYN	Synchronize
BBR	Bottleneck-Bandwidth and Round-Trip Time
CBR	Constant Bit Rate
CCA	Congestion Control Algorithm
CLI	Command Line Interface
CS:GO	Counter Strike: Global Offensive
CS model	Client-Server model
cwnd	Congestion Window
IP	Internet Protocol
ISP	Internet Service Provider
FPS	First Person Shooter
GEO	Geostationary Orbit
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MMOG	Massively Multiplayer Online Game
P2P	Peer-to-Peer
PEP	Performance Enhancing Proxy
QoE	Quality of Experience
QoS	Quality of Service
RTT	Round Trip Time
SSH	Secure Shell
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
VBR	Variable Bit Rate

Chapter 1

Introduction

1.1 Motivation

Broadband has become a requirement in most households and businesses around
the world. Generally, broadband is associated with high speeds and continu-
ous connectivity. Fiber-based networks are still recognized as the best option for
broadband today [9].

A challenge of fiber-based broadband and other terrestrial connections is cov-
erage. How can high-speed broadband be provided to even the most rural of ar-
eas? In an analysis carried out in 2018, [5], Briglauer and Gugler suggested that a
100% penetration of fiber-based broadband is unrealistic. In the paper, the cost-
benefit analysis estimated a 50% penetration to be most beneficial for growth in
GDP due to the increasingly high costs of rolling out fiber to rural areas.

The growth in demand for high-speed internet and the coverage restraints on
the terrestrial network have led to SpaceX developing Starlink, a satellite-based
broadband service. The service aims to provide high-speed internet access to its
users all around the world through a constellation of Low-Earth-Orbiting (LEO)
satellites. Starlink promises to deliver comparable internet speeds and latency
comparable to that of terrestrial connections, even to households and businesses
in rural areas where traditional broadband services are not available or reliable.
This technology can potentially revolutionize how we access and use the inter-
net, especially for gaming enthusiasts. Online gaming has established itself as a

mainstream form of entertainment, with millions of people playing online games every day.

The valued gaming market was at USD 203.2 billion in 2021 [38], and projects a market growth at a Compound Annual Growth Rate (CAGR) of 13.4% from 2023 to 2030. With the base of online game players projected to grow, so will the demand for high-speed connections with low latency and minimal packet loss. Starlink promises to provide gamers with a fast and reliable internet connection, even in "remote and rural locations across the globe" [41].

1.2 Problem Definition

Satellite performance for gaming often offers high latency, packet loss, and low bandwidth, which can cause poor performance and negatively impact the QoE for gaming users. Starlink's new solution for satellite networks should bring the latency, packet loss, and bandwidth to an adequate level for online gaming.

1.2.1 Research Questions

For this thesis, we will dive deeper with these research questions:

1. Does Starlink satisfy latency and bandwidth requirements for online gaming?

2. Does Starlink produce significant packet loss with regard to online gaming?

3. What are the differences in performance between terrestrial internet access and Starlink?

1.3 Objectives

The goal is to set up a Starlink antenna/dish on the roof of the University of Stavanger and create automated scripts to provide some results to analyze. Firstly performing a baseline measurement before investigating deeper into the gaming part.

After defining the research questions, more objectives of the work are:

1. Study how satellite performance is related to the metrics of gaming: Latency, jitter, packet loss, and bandwidth

2. Set up a testbed to run automated experiments simultaneously on both server and client

3. Create an automated testbed for baseline experiments of the Starlink connection

4. Obtain results of performance over the Starlink connection

5. Discuss the results obtained and reflect on the impact it has on the satellite gaming performance

1.4   Outline

This thesis has the following structure:

- Chapter 2 describes the differences in satellite solutions, and online gaming with insight into the games used in this thesis and key metrics for performance evaluation

- Chapter 3 shows the methodology of the work done, showing and describing the different tools used and the scenarios

- Chapter 4 is where the results are presented and how the results are achieved.

- Chapter 5 discusses the results given in Chapter 4 and how the results compare to the theory behind it.

- Chapter 6 is the conclusion, where we summarize and conclude our findings in this thesis and answer the research questions given in the introduction

Chapter 2

Background

The background aims to provide context for the work done in this thesis. It describes the foundation set by related works in the field, and it discusses its potential importance for the solution proposed for the problem statement.

This chapter starts with a section discussing satellite as a broadband service. It introduces three of the more common orbits: the Geostationary Orbit (GEO), the Medium Low Orbit (MEO), and the LEO. Then it describes their characteristics and the implications those have for coverage and network performance.

The section then introduces Starlink satellite broadband. Here, a brief overview of the constellation is given. Next, benchmarks of Starlinks network performance are provided, giving insight into whether the service has the potential to deliver what is necessary for online gaming. The section ends by introducing a possible problem for Starlink when online gaming is concerned; satellite handovers could induce spikes in the form of both packet loss and jitters. This could in turn affect player experience.

The next section in this chapter introduces online gaming. The start of this section explains what online gaming is and how it started, before introducing different online gaming architectures and genres. Next, the two games through which this thesis aims to test Starlink broadband are brought up. Related works on the games' demand for network performance are then presented.

Ending the chapter is a summary of related works. This section aims to organize the related works and present research gaps that our thesis potentially can fill.

2.1   Satellite Broadband Service

Satellites are generally categorized by which orbit they are traveling in. The three most common orbits are GEO, MEO, and LEO. Said categorizations are determined by altitude as seen in table 2.1.

Type of orbit	Altitude
GEO	35 786 km
MEO	Between GEO and LEO
LEO	<1000 km

Table 2.1: Types of orbits and their altitudes per The European Space Agency [3]

With the rise in demand for high-speed internet, broadband provided by modern communications satellites has emerged as a potential solution to the lack of coverage provided by terrestrial connections.

2.1.1   Satellite types

2.1.1.1   GEO satellites

Satellites in the geostationary orbit move at a speed of around 3 kilometers per second at an altitude of 35 786 kilometers [3]. An advantage to orbiting at such a high altitude is coverage, and it is estimated that three GEO satellites can provide close to global coverage. Some GEO satellites provide up to 100 Mbit/s on the downlink for the end user [11]. GEO satellite broadband is a good option for those in rural areas, though not for applications requiring a low propagation delay. In the best-case scenario, a propagation delay of at least 240ms is achieved [10], though together with other delays, a common Round Trip Time (RTT) for GEO satellites is roughly 600ms.

To mitigate the high delays, commercial satellite networks often use Performance Enhancing Proxies (PEPs) [11]. A characteristic of PEPs is the varying degree to which it is transparent to a network's end systems or to applications. It could turn out that Starlink Satellite Broadband does use PEPs, but not network-layer transparent PEPs [17]. This would mean that neither the Transmission Control Protocol (TCP)/Internet Protocol (IP) stack nor the applications would be aware of the PEP implementation.

2.1.1.2 LEO satellites

Satellites in the LEO circle the earth in different planes, normally at altitudes less than 1000 km but also as low as 160 km [3]. At such altitudes, LEO satellites cover small areas of the earth at once. They are typically launched in groups (i.e. a constellation), and thousands of them can provide global coverage.

For this to work, antennas need to be steerable and there need to be frequent satellite handovers [10]. On the other hand, LEO satellites provide propagation delays of only just a few milliseconds. Deutschmann et al. [11] propose that LEO mega-constellations have the potential to provide low latencies and high data rates for broadband internet.

2.1.1.3 MEO satellites

The MEO is a wide range of orbits anywhere between GEO and LEO [3]. Deutschmann et al. [11] suggest that an MEO satellite constellation at an altitude of about 8000 km provides a trade-off between the number of deployed satellites and acceptable latencies. MEO satellites are commonly used for navigation.

2.1.2 Starlink

Starlink is today the largest satellite constellation in the LEO. According to [42], 4165 satellites have been launched into space as of April 20th of this year. Of them, 3423 are active, 475 are inactive and 267 are burned. The Starlink satellites use an altitude of about 550 km [10]. Starlink [43] claims that their constellation can "deliver broadband internet capable of supporting streaming, online gaming, video calls and more".

2.1.2.1 Starlink Performance

Michel et al. [26] performed a benchmark on the Starlink service. It measured throughput for QUIC and TCP, packet loss, and latency. In addition, the study measured the QoE for Web browsing with Starlink. The latency was measured in two ways; with and without load on the link. They found the minimum latency of Starlink to be around 20ms for close destinations, rising to as high as a few hundred milliseconds under traffic load at sub-optimal destinations. For packet loss, they found that loss occurs more frequently under traffic load, but that it only affects a few consecutive packets. Without traffic load, the loss occurs less frequently but affects more consecutive packets and lasts longer.

The study then found that Starlink's download throughput ranges between 100 to 250 Mbit/s, with a median value of 178 Mbit/s. The upload throughput median value they found was 17 Mbit/s. Lastly, Michel et al. found that Starlink outperforms traditional Satellite Communication for Web browsing; comparable to that of regular wired access.

The same study [26] also analyzed the Starlink network for a potential presence of PEPs, middleboxes, and traffic discrimination (TD). They did not find any presence of any PEPs. The same was the outcome regarding traffic discrimination, as no TD policy was found.

"Starlinkstatus.space" [46] collects community Starlink performance data from different regions in the world. The site provides statistics on ICMP Ping and available bandwidth for the downlink (DL) and for the uplink (UL), as seen in table 2.2.

Region	Latency	DL throughput	UL throughput
Worldwide	47ms	157 Mbit/s	14 Mbit/s
USA	49ms	127 Mbit/s	11 Mbit/s
EU	45ms	206 Mbit/s	16 Mbit/s

Table 2.2: Average Starlink performance values rounded to the nearest whole number.

2.1.2.2 Satellite Handovers

A potential obstacle for Starlink satellite broadband for online gaming is a potential Quality of Service (QoS) degradation due to a satellite handover. When a current satellite goes out of sight, the satellite dish needs to switch the connection to another satellite. Kassem et al. [22] found significant rates of sudden User Datagram Protocol (UDP) packet loss in correlation with the satellites going out of the line of sight, strongly suggesting that the satellite switching causes severe packet loss. The study goes on to suggest that congestion control algorithms that are not loss-based could be an option to enhance Starlink's performance.

2.2 Online Gaming

Online gaming is video games being played by players in different locations connected together through the Internet. The players interact with a game world (state) that needs to be maintained by either a server or the personal computers of the players themselves.

The first online game was created when outside users connected to a text-based dungeon adventure game called MUD [34]. The game was developed by two undergraduate students at the University of Essex in the year 1980. This laid the foundation for expansion from other programmers, and it further led to the first wave of Massively Multiplayer Online Games (MMOG) introduced in the late 90s [34]. Together with the expansion of broadband internet connectivity in the early 2000s, online gaming became a popular form of entertainment for millions of people.

2.2.1 Online Gaming Architecture

When online gaming transitioned from being deployed in local area networks to wide-area networks, two main underlying online game architectures were and remain the favored alternatives. They are depicted in figure 2.1.
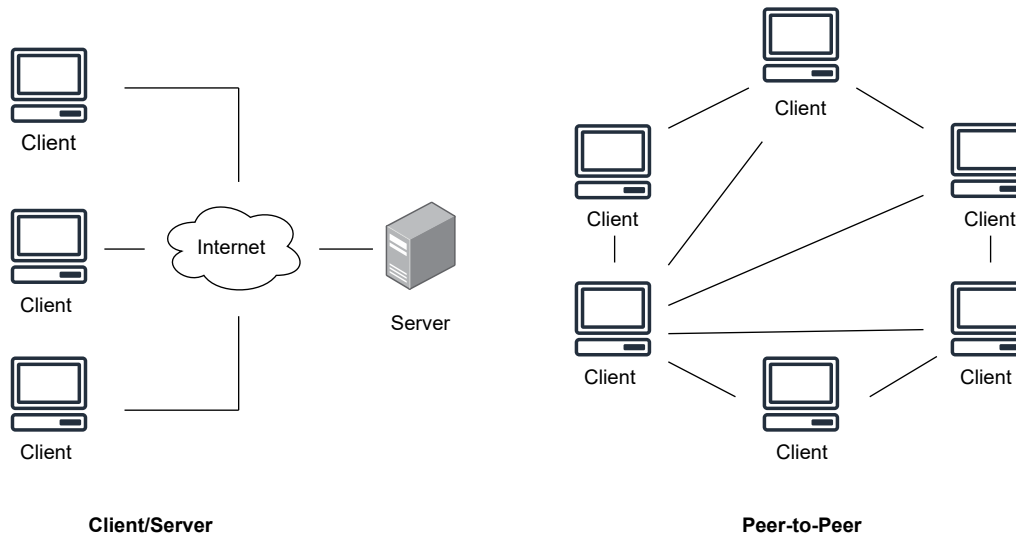
Figure 2.1: Client-Server model (CS model) vs Peer-to-Peer (P2P) comparison

2.2.1.1 Peer-to-Peer

P2P is a serverless online gaming architecture where game clients connect to each other's PCs in order to play in a multiplayer setting. Each client in-game has to maintain the state of the game, which leads to a greater demand for processing and memory on client PCs compared to server-based architectures.

Though P2P is not a popular choice among developers today, it is still a favorable choice for multiplayer indie games due to low costs [39]. Examples of popular P2P games are GTA Online [15] and Super Smash Bros. Ultimate [30].

2.2.1.2 The Client-Server Model

CS model is a centralized online gaming architecture where a dedicated server maintains the virtual environment and provides real-time world updates to its connected client PCs. It is by far the most popular choice for game developers as it is more secure and more scalable than any other architecture. The CS model is also the online gaming architecture that is used in both of the games that this thesis is evaluating gaming performance on.

2.2.2 Online Gaming Genres

There are many different genres online games fall into. Of them, only two are considered in this thesis.

2.2.2.1 Massively Multiplayer Online Games

MMOGs are games that are played by a huge amount of players at the same time. In MMOGs the virtual environment is persistent, meaning the game world cannot be stopped. If players disconnect from the game server, the game world continues without them. In networking terms, this means the server runs continuously and that clients can connect to the persistent game world at any time. Examples of widely popular MMOGs are Word of Warcraft [12] and Runescape [25].

2.2.2.2 First Person Shooter

First Person Shooters (FPS) are combat-oriented shooter games played from a first-person perspective. Except for Massively Multiplayer Online FPS, FPS games are not persistent but rather played in iterations of time-limited matches. The most common game type of these matches is deathmatches, a game mode where players gain points by killing other player characters. Call of Duty [1] and Valorant [14] are two examples of popular FPS games today.

2.2.3 Minecraft

The first game that was picked to evaluate the Starlink Broadband is the MMOG Sandbox game Minecraft [27]. Minecraft was released in 2009 and is a very popular adventure and construction-based game. The game has a CS model architecture.

2.2.3.1 Transport Protocol

From any active Minecraft server's details description, it says that all Minecraft game traffic uses TCP. Any client-to-server connections must first establish the connection, and they both keep track of all packets and their sequence of them. If a packet is lost in transmission, the packet will be re-sent as a TCP Retransmission. This essentially means that packet loss is not as relevant for TCP-based

games (as opposed to UDP-based games), but rather that packet loss induces more latency.

2.2.3.2 Metrics

Minecraft is in general much less sensitive to Quality of Service degradation compared to FPS games. Hohlfeld et al. [19] carried out an experiment where casual gamers played Minecraft with induced delays of 0ms, 170ms, and 1000ms respectively. The study did not find the effects of said latencies to be statistically significant, but rather barely visible. Another study [4] found that delay will impact gameplay from 250ms onwards.

2.2.4 Counter Strike: Global Offensive

The second game that was picked to evaluate the Starlink Broadband is the FPS game Counter Strike: Global Offensive (CS:GO) [8], a very popular shooter released in 2012. The game has a Client/Server architecture.

2.2.4.1 Transport Protocol

According to a study done in 2020 regarding CS:GO [18], the transport protocol for this game is UDP. A characteristic of CS:GO is high interactivity with low latency. This essentially means that the game is generating a large number of packets per second, also referred to as the tick rate. CS:GO's official servers run on 64 ticks, however, third-party services can host game servers with a tick rate of up to 128.

2.2.4.2 Metrics

CS:GO is an FPS game, and as mentioned in 3.1, it has the highest limits for latency for any game genre. Xu et al. [51] found latency in CS:GO to be significantly impacting player performance. Their results suggest an additional 100ms of delay reduces a player's shooting accuracy with an AK-47 assault rifle by about 15%. They also found a reduction of QoE of about 11% with a delay of 100ms. Quax et al. [33] concluded that an FPS player's QoE relies on the size of latency the network introduces, and found delay jitters below 100ms to be hampering the experience. The study did however show there are indications of performance degradation

from a delay of 60ms and onwards. Beigbeder et al. [6] found that shooting mechanics was "greatly affected" by latencies in a range of 75ms to 100ms and that shooting accuracy and the number of kills decrease up to 50% for such latency ranges. The study found that experiment subjects noticed latency as low as 100ms and that latency of 200ms is annoying.

A direct consequence of using UDP as the transport protocol is a higher degree of packet loss. The priority of CS:GO is high interactivity and low latency. Beigbeder et al. [6] did however find that packet loss did not have any measurable effect on player performance. The study then explained that users could barely even notice a packet loss of 5%.

2.3   Summary of Related Works

Below are related works summarized in two tables: Satellite Broadband 2.3 and Performance Demands of Online Gaming 2.4.

2.3.1 Satellite Broadband

Src	Traffic type(s)	Metric(s)	Findings	Research gap
[22]	TCP	Throughput, Loss	Throughput: high geographical difference. Highest median throughput: 147Mbit/s. Lowest: 34.3Mbit/s. Loss: Rare spikes of up to 50% loss. 12% of iPerf tests had a loss over 5%. Loss strongly correlates with satellite handovers.	Lacks RTT measurements. Does not evaluate UDP traffic. Does not test gaming over Starlink.
[10]	TCP	Goodput, Latency, Loss	Median goodput around 185Mbit/s. Latency "usually did not exceed 50ms". Packet loss of about 1.8%	Does not evaluate UDP traffic. Does not test gaming over Starlink.
[26]	QUIC, TCP	Throughput, Latency, Loss, QoE for Web browsing	Minimum delay 20ms. Maximum a few hundred ms under traffic load at sub-optimal locations. Median downlink throughput 178Mbit/s. Median uplink throughput 17Mbit/s. Starlink outperforms traditional SatCom for Web browsing. QUIC packet loss: 1.56% on the downlink and 1.96% on the uplink. Found no presence of PEPs.	Does test Web browsing over Starlink, but does not test gaming.
[11]	GEO, LEO	Bandwidth	Some GEO satellites provide up to 100Mbit/s. They usually use PEPs to mitigate high delays. The high latencies with GEO satellites are problematic for some applications. LEO mega-constellations have the potential for low delays and high data rates.	Does not conclude whether the LEO broadband solution is applicable for gaming.

Table 2.3: Table of related works on satellite broadband

Related works on satellite broadband have found that although GEO satellites provide enough bandwidth for online gaming, latencies are too high. Starlink latencies are found to be promising for the most part, except in certain edge cases.

Related works have found Starlink's performance regarding throughput to be sufficient for online gaming purposes. Packet loss is found to be strongly correlated with satellite handovers, which might pose a problem for online gaming.

Although works have been done on QoE for web browsing over Starlink, no previous works cover gaming over LEO satellite broadband. This thesis aims to cover this research gap.

2.3.2 Performance demands of Online Gaming

Src	Game (Genre)	Metric(s)	Findings	Research gap
[4]	Minecraft (MMOG)	Delay	Minecraft gameplay experience degrades with delays over 250ms	Does not test for experience degradation due to packet loss. It is not performed over Starlink.
[19]	Minecraft (MMOG)	Delay	Delays up to 1000ms in Minecraft does not degrade the player experience and is barely visible.	It is not performed over Starlink.
[35]	(MMOG)	Delay, Loss, Jitters	In MMOGs, increased latency negatively impacts subjective quality, more so than jitters. MMOGs were less reliant on delay than FPS games. Packet loss leads to a strong reduction in perceptual quality.	It is not performed over Starlink.
[33]	(FPS)	Latency, Jitters	Indications of performance degradation with delays over 60ms for FPS games. Jitters below 100ms are found to be hampering the experience.	It is not performed over Starlink.
[51]	CS:GO (FPS)	Delay, QoE	Additional 100ms of delay reduces a player's shooting accuracy with an AK-47 assault rifle by about 15%. QoE down 11% with 100ms delay.	It does not test player experience over Starlink.
[6]	(FPS)	Delay, Loss	Shooting mechanics was "greatly affected" by latencies in a range of 75ms to 100ms, and that shooting accuracy and the number of kills decrease up to 50% for such latency ranges. 100ms delay noticable, 200ms delay annoying. packet loss did not have any measurable effect on player performance. 5% was barely noticeable.	It does not test network performance playing FPS games over Starlink.
[29]	(FPS)	Delay	Found that the FPS genre has the tightest latency limits.	It does not test player experience over Starlink.

Table 2.4: Table of related works on network demands of online gaming

Related works on online gaming have found that the FPS game genre has the tightest latency limits, with MMOGs being less reliant on latency.

There are related works on QoS sensitivity for both Minecraft and CS:GO. There is no related work that evaluates to which degree the QoS for both games is satisfactory over the Starlink broadband. This thesis aims to cover this research gap.

Chapter 3

Methodology

This chapter describes the different testbed implementations, hardware equipment, various software and tools, post-processing, and other setup configurations.

3.1 Game Selection

Different online games have different network parameter demands. Thus, the choice of games to test in our work is important. First, we decided to pick an FPS, as this genre is considered to have the tightest latency limits [29].
Secondly, we picked an MMOG Sandbox game. The Sandbox game genre represents an open game world where the player can interact freely with the world. For MMOGs, a study [35] found that increased latency negatively impacts subjective quality, more so than jitters. Still, MMOGs are less reliant on latency than FPSs.

Most real-time interactive games use UDP as their transport protocol. We decided to pick two widely popular games to test with: one that uses UDP and one that uses TCP.

3.2 Testbed overview

The testbed used for this thesis is rewired in two different ways, each depending on which task to execute. The topology for the different testbed setups/networks that were used is shown in figure 3.1 and 3.2.
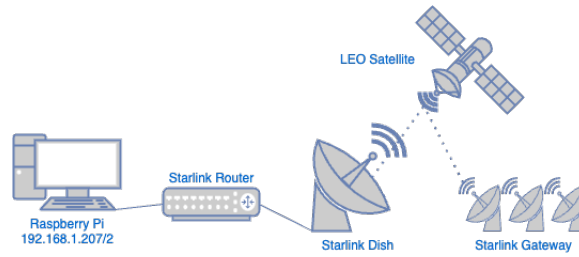
Figure 3.1: Topology describing the network used for latency measurements
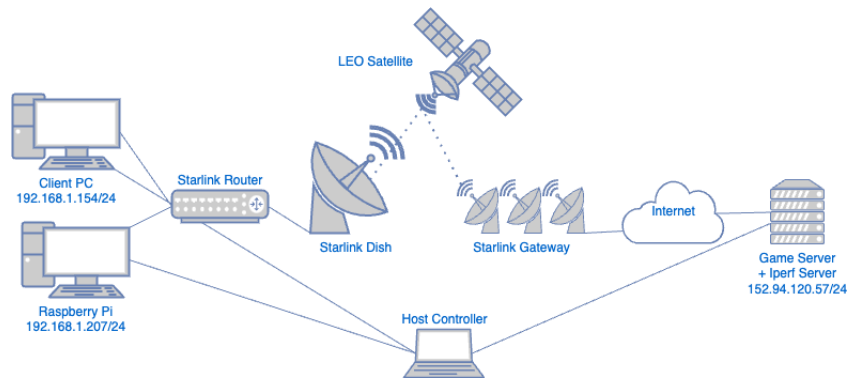
Figure 3.2: Topology describing the network used regarding iPerf3 measurements and for capturing game traffic

- The Host Controller takes care of remotely accessing the various nodes and executing commands or scripts on them

- The Host Controller uses Secure Shell (SSH) protocol to access the various machines

- The Raspberry Pi is used for more lightweight baseline measurements

3.3   Hardware Equipment

3.3.1   Server

To host games and other services, we used an HP Compaq 8200 Elite as a server with specifications listed in table 3.1.

CPU	4-core Intel i5-2400 3.40GHz
RAM	16GB DDR3
Storage	500GB
OS	Debian 11
Kernel-Version	3.38.5

Table 3.1: Server PC specifications

3.3.2 Client

The client PC is mainly used for playing online games, however, it is also used for some light-weight network measurements. Specifications listed in table 3.2.

CPU	Intel core i5-6600K 3.50 GHz
GPU	Geforce GTX 970 4GB
RAM	16GB DDR4 2133 MHz
Storage SSD(OS)	240GB
Storage HDD(Games)	1TB
OS	Windows 10
Kernel-Version	22H2

Table 3.2: Client PC specifications

3.3.3 Raspberry Pi

For some network measurements, we used a Raspberry Pi 4 Model B. This device has the specification listed in table 3.3.

CPU	4-core Arm Cortex A-72 1.50GHz
Ram	4GB DDR4
Storage	32GB
OS	Debian 11
Kernel-Version	3.38.5

Table 3.3: Raspberry Pi 4 model B specifications

3.3.4 Starlink Setup

The Starlink package ordered for this thesis is the baseline residential package [41]. The equipment inside is listed below:

1. One Dish/Antenna

2. One Router

3. One Starlink Cable

4. One AC Cable

The dish consists of an electronic phased array with a 100°field of view. It is placed on top of Kjølv Egelands hus at UiS approximately 63 meters above sea level, see figure 3.3. It weighs in under 3 kg and can handle winds up to 20m/s. The antenna is facing south (180°), with a clear view of ±50°. The antenna communicates with satellites that are visible on the horizon above an elevation angle of 25°.

Figure 3.3: Placement of the Starlink dish.

The antenna is facing south to connect to LEO satellites orbiting over central parts of Europe. Norway does not have a lot of satellite coverage as of the time of this thesis, as shown in figure 3.4.
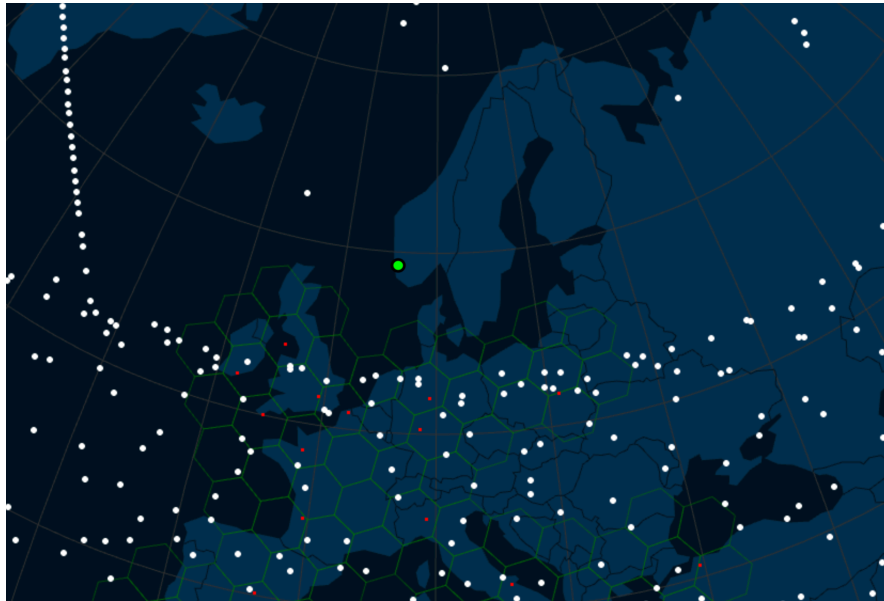
Figure 3.4: Screenshot of Starlink constellation map, green dot represents our position, white dots satellites, and red dots gateways [40]

3.4   Software

This section seeks to explain the various software and tools used for the thesis. Table 3.4 shows the software and tools used. To do this, the different sections are divided as shown in 3.4 to make experimenting easier.

Section	Title	Includes
3.4.1	Traffic Generators	iPerf, Ping, TCP ping, CS:GO, Minecraft
3.4.2	Loggers	Tshark, iPerf3 logs, Yr weather API, N2YO API
3.4.3	Experiment Automation	Python scripts, Libraries, Diagrams
3.4.4	Post Processing	Analysis, SPP, Visualization
3.4.5	Other Setup Configurations	Security, Difficulties

Table 3.4: Software and tools overview

3.4.1 Traffic Generators

3.4.1.1 iPerf3

iPerf3 is a tool for generating traffic and performing network measurements [21]. It is cross-platform, so it works with Windows, Linux, MacOS, FreeBSD, Android, and more. The default iPerf3 port is 5201.

It is based on IP networks and works with both IPv4 and Ipv6. iPerf uses TCP as the default protocol, however, UDP-specific tests can be instantiated. It can measure total available bandwidth through TCP. Through UDP the client can create streams with specified bandwidth, measure packet loss, and delay jitter.

For setup, iPerf uses a client host connection and needs to be installed on both ends, see figure 3.2. On the client side, the IP address needs to be specified along with other inputs that fit the needs of the measurement. See table 3.5 for some common parameters.

Parameter	Description
-p	Specify the port number to listen or connect to (client and host specific)
-s	Run iPerf in server mode (host-specific)
-c	Run iPerf in client mode, connecting to a host (client specific)
-u	Use UDP rather than TCP for tests (client specific)
-b	Set target bandwidth to n bit/s (client specific)
-R	Run in reverse mode, default is uplink client-to-server (client specific)
-t	The time in n seconds to transmit for (client specific)

Table 3.5: Table of common iPerf3 parameters [20]

3.4.1.2 Ping

Ping is a basic open-source internet application that allows users to test if a host is reachable. To reach the destination host users need to know the destination IP address (IPv4 or IPv6) or destination domain name. The way it works is that users send an Internet Control Message Protocol (ICMP) echo request and then wait for a reply. If the echo request reaches the destination host, it answers with an echo reply. By default a ping returns values like RTT, Time To Live (TTL), and

averages. If the request does not reach the destination, ping reports the packet as lost. See figure 3.5 for an example output.

```
Pinging google.com [2a00:1450:400f:801::200e] with 32 bytes of data:
Reply from 2a00:1450:400f:801::200e: time=15ms
Reply from 2a00:1450:400f:801::200e: time=14ms
Reply from 2a00:1450:400f:801::200e: time=14ms
Reply from 2a00:1450:400f:801::200e: time=15ms

Ping statistics for 2a00:1450:400f:801::200e:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
Approximate round trip times in milli-seconds:
    Minimum = 14ms, Maximum = 15ms, Average = 14ms
```

Figure 3.5: Example of an ICMP echo request to google.com

3.4.1.3 TCP ping

PsPing's [36] TCP ping uses a slightly different approach than the traditional ICMP echo request and echo reply, where TCP ping uses the TCP protocol to calculate RTT. Utilizing Synchronize (SYN), SYN-Acknowledgement (ACK), and retransmits it can measure the RTT of packets and if a packet has been dropped. So instead of opening a full TCP connection with a three-way handshake, it half-opens the connection and sends an ACK. Then it waits for the SYN-ACK so it can calculate the RTT and close the connection, as shown in figure 3.6. This method can be useful if ICMP packets are blocked by a firewall, and a client wants to measure RTT.
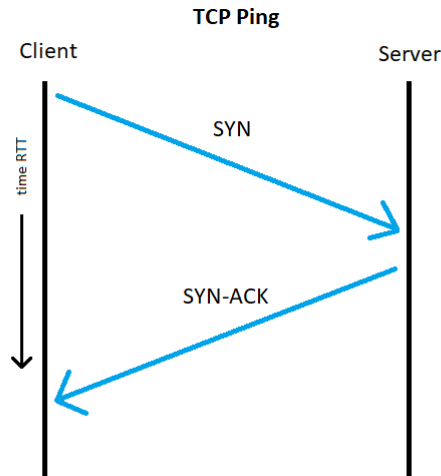
Figure 3.6: TCP ping

3.4.1.4 LinuxGSM

To host games on the Game server 3.1 we used a third-party application called LinuxGSM [24] V23.2.0, which integrates the use of SteamCMD [47] without the need to manage SteamCMD itself. The LinuxGSM software connects to Steam servers via SteamCMD to download game data, in our case CS:GO with appID 730. For Minecraft: Java Edition, LinuxGSM downloaded game data from the official Minecraft site [49].

LGSM is quickly downloaded using on the server using the command:

```
wget -O linuxgsm.sh https://linuxgsm.sh && chmod +x
linuxgsm.sh && bash linuxgsm.sh csgoserver
```

From the command, the CS:GO server is installed with:

```
./csgoserver install
```

Which installs the CS:GO server with appID 730 from Steam. To make the CS:GO server connect to the master server list in-game, we provided it with a valid Game server login token (GLST) from a valid account [44].

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The LinuxGSM uses the config files A.1 and A.2 to start up a CS:GO server. The same goes for Minecraft which the server uses the config files A.3 and A.4. These files contain information, parameters, and input that the server uses to start a specific game session.

3.4.1.5   CS:GO

CS:GO is one of the games generating network traffic for this thesis. The transport layer protocol for CS:GO game traffic is UDP. It is installed on the client's PC with default settings. The game version during the time of this thesis is 10905515. The CS:GO server is installed on the game server, see figure 3.1 and sub section 3.4.1.4.

3.4.1.6   Minecraft

Minecraft is the second game generating traffic for this thesis. The transport layer protocol for Minecraft game traffic is TCP. The game is installed on the client's PC with default settings. This includes graphical settings on high and a render distance of 12 chunks. The game version during the time of this thesis is 1.20 Java edition. The Minecraft server is installed on the Game Server, see figure 3.1 and sub section 3.4.1.4.

3.4.2   Loggers

The Raspberry Pi takes care of latency and iPerf3 measurements that run over a longer period. It also logs the results for later post-processing. The client PC and Game Server logs the game traffic and TCP ping measurements.

3.4.2.1   Tshark

Tshark [50] is a network protocol analyzer, which is used to capture data from a live network. The Tshark package is included in the standard Wireshark install. The output is either displayed in a command line interface or written to a file in PCAP format. Tshark works much like the tcpdump tool, however, with Tshark a duration parameter can be used. This makes the code easier and cleaner, which is the reason we chose Tshark and not tcpdump. It can also be used to estimate RTT on captured TCP traffic which needs to be in PCAP format. It is estimated

based on the timestamp when a packet is sent and the timestamp of the first ACK. Tshark (version 3.0.2 for Windows and version 2.6.8 for Linux) is installed on both the client PC and the server.

3.4.2.2 iPerf3 Logs

iPerf3-logs output some viable results. These are outputted in intervals that can be set by the host and client. The default interval is 1 second, however, intervals can be set as low as 0.1 seconds. The iPerf logs can be stored as normal text files and accessed later for post-processing.

3.4.2.3 Yr Weather API

To gather real-time weather data for the experiments, we used the API from MET Norway [31] with the parameters for longitude, latitude, and altitude in table 3.6:

Latitude	58.937
Longitude	5.698

Table 3.6: MET Api parameters

We got a JSON response from the API and selected the momentary forecast data to include in our experiments. Here are some of the values that can be extracted from the JSON:

1. Cloud coverage

2. Temperature

3. Wind

4. Precipitation

3.4.2.4 Available Satellites

To measure the distance of satellites relative to a position, an API from N2YO [28] returns what satellites are in view in JSON format as shown in figure 3.7.

The table 3.7 shows the input required for the API.

Parameter	Type	Required	Comments
Latitude	Float	Yes	Ground latitude(decimal degree format)
Longitude	Float	Yes	Ground longitude(decimal degree format)
Altitude	Integer	Yes	Ground altitude above sea level in meter
Search radius	Integer	Yes	Search radius(0-90)
Category ID	Integer	Yes	Id of satellite category

Table 3.7: Required input for the API. Category ID for Starlink is 52.

```
{
    "info": {
        "category": "Starlink",
        "transactionscount": 0,
        "satcount": 18
    },
    "above": [{
        "satid": 45682,
        "satname": "STARLINK-1397",
        "intDesignator": "2020-035AB",
        "launchDate": "2020-06-04",
        "satlat": 51.7785,
        "satlng": 1.8116,
        "satalt": 552.2623
    }, {
        "satid": 46081,
        "satname": "STARLINK-1571",
        "intDesignator": "2020-055BG",
        "launchDate": "2020-08-07",
        "satlat": 52.3349,
        "satlng": 9.2484,
        "satalt": 552.5664
    }, {
```

Figure 3.7: Snippet of results from API: *https://api.n2yo.com/rest/v1/satellite/ above/58.937/5.698/63.0/65/52apiKey=.* API key is needed to do this request.

From the response in figure 3.7 we can extract the *satlat*, *satlng*, and *satalt* from the satellites in view and calculate the distance from the dish. The *satid* can be used to identify which satellite is concerned. To calculate the distance from the satellites to a position on Earth we used Haversine formula [48]:

$$a = \sin^2(\Delta latitude/2) + \cos(earthLatitude)$$
$$* \cos(satelliteLatitude) * \sin^2(\Delta longtitude/2) \qquad \text{(i)}$$

$$c = 2 * a\tan 2(\sqrt{a}, \sqrt{1-a}) \qquad \text{(ii)}$$

$$Distance = EarthRadius * c \qquad \text{(iii)}$$

This equation takes in position in latitude, longitude, and same positions for the satellite. Then distance is calculated with the radius of the Earth. This formula is converted to Python code shown in the appendix A.11.

3.4.3 Experiment Automation

As the list of experiments gets longer, the need for automation increases. This can make the experiments much more efficient and time-saving. It also allows for repeatability, to make sure that experiments are always repeated under the same conditions.

3.4.3.1 Python Scripts

By using Python, automation of various tests can be done. The way this is set up for this thesis is through a Command Line Interface (CLI) script on the host controller from figure 3.2. When executing this script it first displays a set of options, these show the tests that are available. Then, depending on which option is chosen, it takes in some parameters that need to be set before the automated test can run. Operations like SSH, writing results to files, storing results in corresponding folders, executing tasks concurrently, logs to a log file, and so on. For lighter tests that run on the Raspberry Pi, single Python scripts on the device are executed.

3.4.3.2 Libraries

1. Pyshark

    Pyshark [23] is a wrapper for Tshark. It allows for packet parsing using Python. Pyshark was used to parse game capture PCAP files

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2. Scapy

> Scapy [37] is a Python library for packet manipulation. In our case, we used Scapy to alter IP addresses and ports of packets in PCAP files

3. Matplotlib

> Matplotlib [45] is a Python library for visualization

4. Fabric

> Fabric [13] is a Python library used to do shell commands over SSH

5. Scipy

> Scipy [7] is a library for mathematical algorithms and equations built on the Python library Numpy [32]

3.4.3.3 File structure

This section seeks to provide a summary of the different folders and files for the thesis including diagrams and tables. In the tables, the code is referenced from the appendix for a more convenient overview.
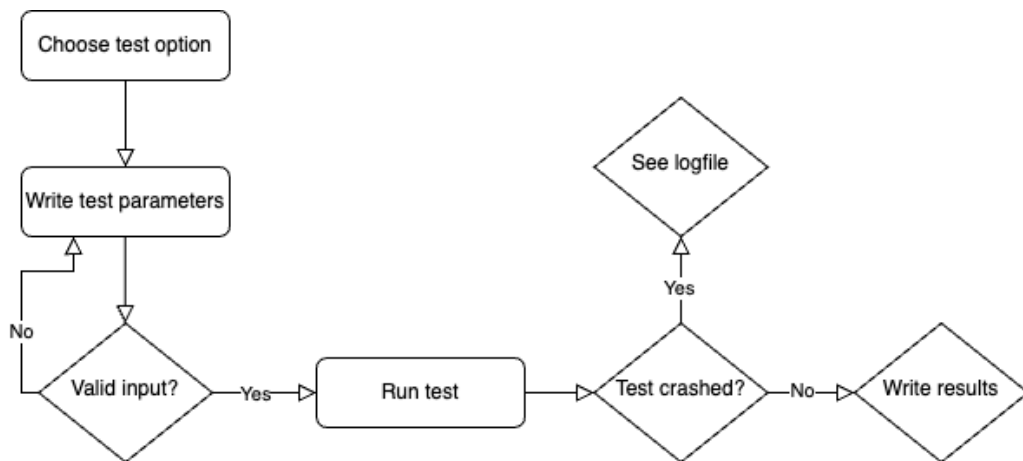
Figure 3.8: General flow of test automation
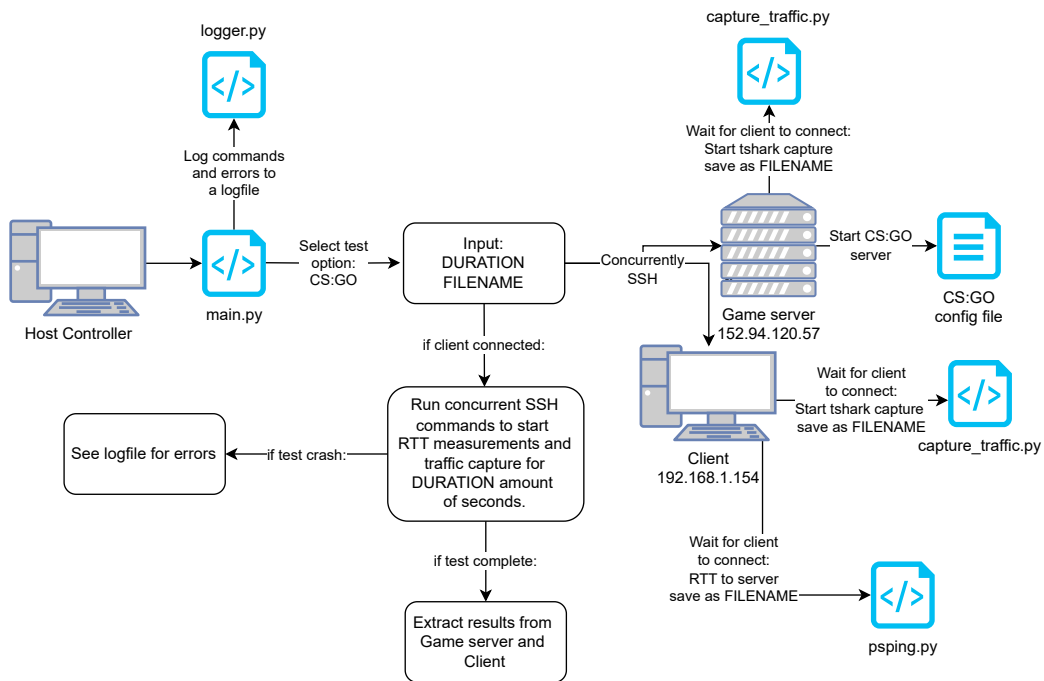
Figure 3.9: Flowchart of an automated test for a single CS:GO run

Figure 3.8 displays how the general flow of the test automation functions for the experiments. Figure 3.9 shows a more concrete example of how a run of CS:GO is tested. Figure 3.10 shows the file structure, containing folders with Python scripts and server configuration files.
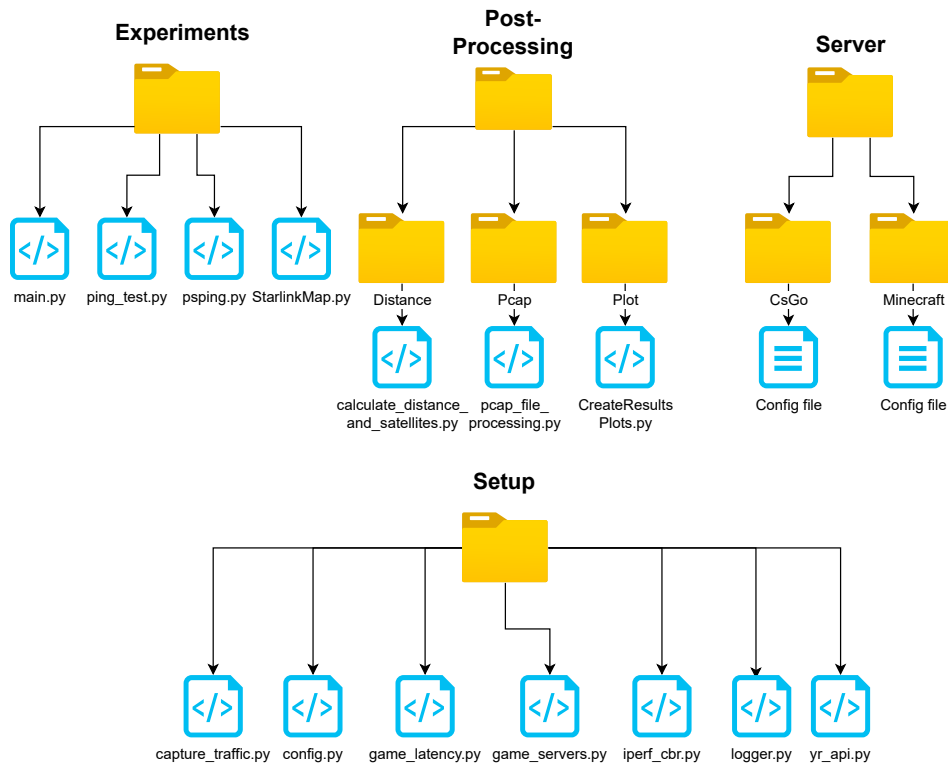
Figure 3.10: Diagram of the folders and files used in the thesis

Table 3.8 shows the files in the experiments folder 3.10, with a description of what the files do.

Reference	File name	Description
A.5	main.py	Where test automation code runs
A.6	ping_test.py	RTT measurement automation script
A.7	psping.py	RTT measurement using PsPing tool
A.8	StarlinkMap.py	Satellite API request

Table 3.8: Contents of the Experiment folder, files for running experiments

The table 3.9 shows the files used for post-processing located under the folder

post-processing 3.10.

Reference	File name	Description
A.9	pcap_file_processing.py	Extracting and accessing PCAP files
A.11	calculate_distance_and_satellites.py	Script for calculating satellite distance
A.10	CreateResultsPlots.py	All plots for results

Table 3.9: Contents of the Post-processing folder, files to do post-processing of data and plotting

The setup table 3.10 contains Python files for setup before an experiment run.

Reference	File name	Description
A.12	capture_traffic.py	Capture traffic
A.13	config.py	Config for experimental scripts
A.14	game_latency.py	Sets up Ping script over ssh
A.15	game_servers.py	Starting game server over ssh
A.16	Iperf_cbr.py	Setup for running iPerf experiment
A.17	logger.py	Setup for logger
A.18	yr_api.py	Setup for yr api

Table 3.10: Contents of the Setup folder, files to setup the experiments

Server config files are listed in table 3.11, which shows the config files for the CS:GO and Minecraft server.

Reference	File name	Description
A.1	CS:GO DefaultProperties	Default properties for CS:GO server
A.2	CS:GO ServerProperties	Server Properties for CS:GO server
A.3	Minecraft DefaultProperties	Default properties for Minecraft server
A.4	Minecraft ServerProperties	Server properties for Minecraft server

Table 3.11: Contents of the Server folder, files to configure the game server

3.4.4 Post Processing

After the experiment automation process, the results need to be processed. The results vary from PCAP files to normal text files, so, therefore, a set of functions in Python is created to handle the different results. These functions do everything from pattern matching to generating plots. Most of the post-processing happens on a host controller, however, some of the results are processed on other machines.

3.4.4.1 Game Capture

All game traffic was captured and stored in PCAP files. A Python script (see A.9) was then written to extract certain data from different packet fields. All fields that can be accessed are found in the Pyshark GitHub repository [23].

The script starts by importing the Pyshark library:

```
import pyshark
```

A method in Pyshark called "FileCapture" was then used to read the PCAP file and assign it to a variable. Next, there are two methods:

```
"get_tcp_data"
```

and

```
"get_udp_data"
```

that filters packets based on their transport layer field. The packets can then be filtered by source and destination IP addresses by using the method:

```
"get_pkts_by_ip"
```

The methods:

```
"list_of_pkts_per_second"
```

and

```
"list_of_bytes_per_second"
```

return lists of the number of packets and a number of bytes sent per second respectively. The main section of the script in A.9 is an example of processing a CS:GO game and generating lists of bytes per second sent between the server and the client.

3.4.4.2   Text files

Processed data was written into text files to make analysis and visualization easier. For RTT measurements and Constant Bit Rate (CBR) tests, RTT and throughput values were parsed and written to text files. As for packet and byte rate values, once calculated, were written to text files. All text files were structured in a way where there is one value for each line in the file.

3.4.4.3   Synthetic Packet Pairs

Synthetic Packet Pairs (SPP) is a CLI tool developed by the Centre for Advanced Internet Architecture [2] to measure RTT based on network data captured at the sender and receiver end, without the need for clock synchronization. It provides passive RTT measurement which means that it does not require running simultaneously to the network capture. This tool works on Linux and FreeBSD based and is installed on a separate machine running FreeBSD.

The way that it works: SPP uses two measurement points or MP's, MP_{ref} (reference) and MP_{mon} (monitor). Both MP's capture the network traffic of interest(sent and received), for example using Tshark. SPP takes in two PCAP files as input, one for each MP. It also needs the corresponding IP address for each of the MPs. For every recorded packet both MP_{ref} and MP_{mon} log a timestamp (ts) representing when the packet was captured, and a short 'Packet ID' (PID). The PID is calculated from a hash function (e.g. CRC32) over key bytes within the packet. SPP creates two lists for each of the MPs. One packet within the list consists of a PID and a timestamp. The two lists are then combined to identify packet pairs and calculate RTT.
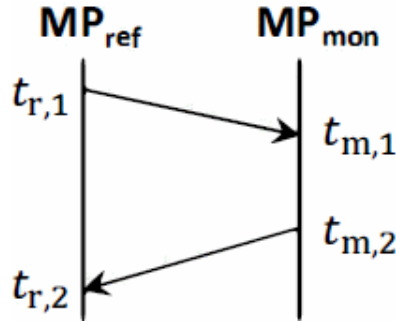
Figure 3.11: SPP packet pairing algorithm

To better explain the packet pair algorithm a short-hand notation needs to be defined. $t_{j,i}$ where t represents the timestamp, i represents MP_{ref} (r) or MP_{mon} (m), and j represents the first (1) or second (2) packet of a packet pair. In figure 3.11 we see an example of how the algorithm works. SPP assumes that a packet is used in at most one packet pair. It also searches for the closest packet pair where $t_{m,2} > t_{m,1}$. Once a packet pair has been discovered, the RTT calculation is straightforward, as shown in figure 3.12 [52].

$$RTT = (t_{r,2} - t_{r,1} - (t_{m,2} - t_{m,1}))$$

Figure 3.12: SPP RTT calculation equation

3.4.4.4 Visualization

To visualize the results gathered from the experiments the Matplotlib Python library was used as described in 3.4.3.2. We used Matplotlib to create quality plots from data collected after each experiment.

To begin using Matplotlib in Python, start by including this line in the Python file:

```
import Matplotlib.pyplot as plot
```

This command will import the pyplot library from Matplotlib and make it usable in the code.

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For some of the data collected, the need for smoothness was apparent. To smooth out data, we used a Python library called Scipy [7] 3.4.3.2 and imported it like this:

```
import Scipy.signal.savgol_filter as sc
```

This code line imports the Savitzky-Golay filter used to smooth out data. This filter takes in 3 important parameters: Data (array), window length, and poly order.

3.4.5   Other Setup Configurations

3.4.5.1   Security

Because the server hosts games, the network has to open ports to let traffic in and out. This leaves a vulnerability, the opened ports can be exploited if not handled correctly. Underneath is a list of security measures that are applied:

1. SSH keys are generated for the machines that use SSH to access the server

2. SSH as the root user is disabled

3. SHH using a password is disabled (only SSH keys accepted)

4. Default SSH port (22) is closed

5. Firewalld installed and blocks traffic from all ports except the ones used for the games

6. A Crowdsec bouncer is installed to block unwanted IP addresses that try to access through the opened ports

3.4.5.2   Difficulties

During this thesis, we encountered difficulties. Some related to one of the tools that were used, and others to the network. The difficulties and how they were solved are listed underneath:

1. The SPP tool was not compatible with Debian 11. To be able to use the SPP tool it was installed on another computer running FreeBSD (not the server

in figure 3.2 as initially intended). FreeBSD contrary to Debian 11 is compatible with SPP. This resulted in moving the files that needed to be processed by SPP to the FreeBSD computer, and then copying them back after they have been processed.

2. Another problem occurred when SPP for the first time processed the captured traffic and outputted nothing. Starlink is operating with Network Address Translation, which means that IP addresses and ports are logically changed between the endpoints. This results in SPP not recognizing the IP addresses and ports for the different endpoints in the two PCAP files, hence not returning any output.

   To solve this problem Scapy from 3.4.3.2 is used. With this library, we can manipulate IP addresses and ports in the PCAP files so that they match, this way SPP can successfully measure packet pairs.

3. ICMP packets are blocked into the UiS network where the game server is connected. This created some complications regarding RTT measurements for the server. To solve this issue TCP ping was used instead. This allowed for RTT measurement with TCP packets instead of ICMP.

4. We experienced difficulties with measuring packet loss in the Minecraft game data. With TCP as the transport protocol, the TCP agent will retransmit lost segments. TCP packet loss can thereby be interpreted as an increase in latency [35]. Given this and this project's time restraints, we decided to prioritize latency and throughput measurements of Minecraft game traffic.

Chapter 4

Experiments and Results

To conduct this research, a set of scenarios have been created. Most of the scenarios contain sub-scenarios for a more in-depth study. The results are mainly divided into two parts, one part for baseline measurements, and one for online gaming measurements. The table 4.1 shows a brief overview of the different sub-scenarios.

Scenarios	Description
4.1.1	Baseline latency
4.1.2	Available satellites
4.1.3	CBR measurements
4.1.4	VBR measurements
4.2.1	CS:GO single run
4.2.2	CS:GO all runs
4.2.3	Minecraft single run
4.2.4	Minecraft all runs

Table 4.1: Summary of sub scenarios

4.1 Scenario 1 - Baseline measurements

Scenario 1 will run baseline measurements of the Starlink broadband service. This includes RTT, constant bit rate tests, variable bit rate tests with different congestion control algorithms, and throughput. This will indicate how Starlink performs. For each of these experiments, the client device will always be at UiS

directly connected to the Starlink router.

4.1.1   Ping Starlink Gateway

Latency can play a huge part when it comes to online gaming. This experiment
seeks to find the RTT from a host to the first hop back on earth from the Starlink
satellites. See figure 3.1 for the topology. The host for this experiment will be a
Raspberry Pi. Traceroute will be used to find the Starlink gateway IP address, and
then the host uses ping to send an ICMP echo request to this IP. This way we get
an estimate of RTT over the Starlink satellites. The experiment runs for 24 hours
sending bursts of 1000 ICMP echo requests with one-second intervals, every 15
minutes. This process will be automated through a Python script.

4.1.2   Overview over available satellites

Distance to the satellite can play a big role in round trip time, and when hands-
on/off satellite switching is happening. To get a better understanding of what is
happening, this experiment investigates the correlation between the distance of
the closest satellites and RTT.

As per 4.1.1, we used Starlink gateway as the address used as the receiver for
Ping. This experiment runs for 500 seconds with an ICMP request every second.
Parallel to the Ping running, to get an overview of what satellites are available
each second, an API 3.4.2.4 request is sent. This API returns a JSON 3.7 of every
satellite in view, with information on latitude, longitude, and altitude. From this
information, the distance of the closest satellite is calculated in Python.

The Python script A.8 shows the process of running the API request and Ping
concurrently, and the Python script A.11 calculates the results afterward.

4.1.3   Constant Bit Rate

This experiment aims to measure the packet loss of the Starlink service when
there is constant traffic. This will be done through a 24-hour-long CBR test. By
utilizing iPerf, the server from figure 3.2 will send UDP traffic with a constant bit
rate of 10, 20, and 30 Mbps. Two times an hour, within the 24-hour window, a

5-minute run is carried out for each bit rate value. Therefore, each hour is represented with two runs of 5 minutes with a 30-minute interval in between, this counts for all bit rate values. See figure 4.1 for an example of a one-hour window. The cloud coverage, during the test, will also be recorded and displayed adjacent to the packet loss. This experiment gets automated through a Python script on the Raspberry Pi.
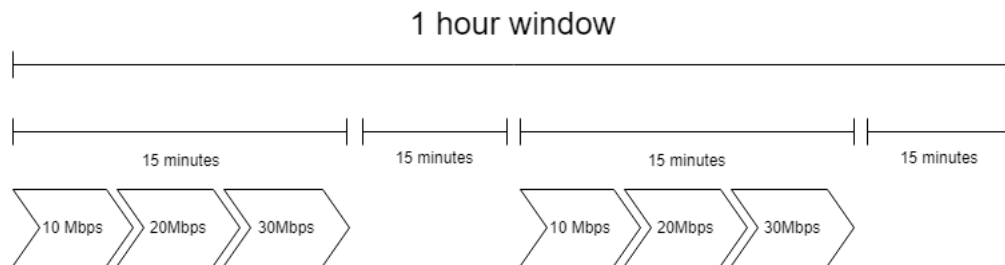
Figure 4.1: One hour window of how CBR experiments execute

4.1.4 Variable Bit Rate

Unlike the CBR test, this Variable Bit Rate (VBR) test aims to measure throughput over Starlink with different congestion control algorithms, see figure 4.8. The algorithms that will be used are Reno, Cubic, Bottleneck Bandwidth, and Round-trip propagation time (BBR). Again by utilizing iPerf the server from figure 3.2 will send traffic, but this time it is going to use the TCP protocol, not UDP. The experiments will run for 60 seconds for each congestion control algorithm.
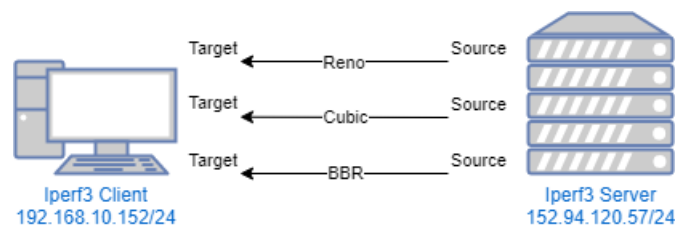
Figure 4.2: iPerf server sending TCP traffic using different congestion control algorithms

4.2   Scenario 2 - Gaming measurements

Scenario 2 aims to measure the gaming QoS on two different games. The games that will be played are CS:GO and Minecraft. Each game will have ten runs consisting of five minutes of game-play. This results in four sub-scenarios, two for a closer look at a single run for both games and two for a wider look at all the runs for both games. All the runs are going to be played on the client PC, and hosted on the game server in figure 3.2. Traffic will be captured along with latency measurements.

4.2.1   CS:GO Single Run

This sub-scenario will take a closer look at a single five-minute run of CS:GO over Starlink. Metrics such as RTT, throughput, and packet loss will be measured. To have some comparison, a similar five-minute run will be carried out over the terrestrial internet. Since the CS:GO game traffic is UDP, and to be able to measure RTT and packet loss, capturing of the packets needs to be done on both the client and server end. For this task, Tshark is going to be used. To ensure that the traffic capture starts and stops at the same time, this process will be automated using SSH from a host controller in a Python script, see figure 3.2. For RTT measurements two different tools will be utilized, TCP ping and SPP. These are also going to be automated using Python.

4.2.2   CS:GO All Runs

This experiment is similar to the CS:GO single-run scenario with regards to metrics and automation, however, it will look at all ten runs. It will look at averages over the different runs. This is to get a general understanding of how the traffic behaves over multiple runs and whether Starlink is stable enough or not.

4.2.3   Minecraft Single Run

Like CS:GO single run, this experiment will also look at a single five-minute run of Minecraft over Starlink. The metrics to be measured are RTT and throughput. TCP ping and Tshark will be used for measuring RTT, and Tshark for game traffic capture. This process will be automated using Python scripts along with SSH from

a host controller, see figure 3.2. A comparison between Starlink and terrestrial RTT will also be added.

4.2.4   Minecraft All Runs

This experiment will also look at all ten runs, only for Minecraft. it will look at averages over the different runs, and go through the same metrics as for Minecraft single run. This is to give an idea that Starlink is capable of playing Minecraft.

4.3   Results

This section presents the results for the different scenarios. They are represented as plots with some describing text on what we see.

4.3.1   Ping Starlink Gateway Results

Figure 4.3 is a single run gathered from all of the runs which are displayed in figure 4.4. One ICMP echo request is sent every second for 1000 seconds. The test started at 16:00 Monday 6. march 2023 and ended at 06:45 Tuesday 7. march 2023.
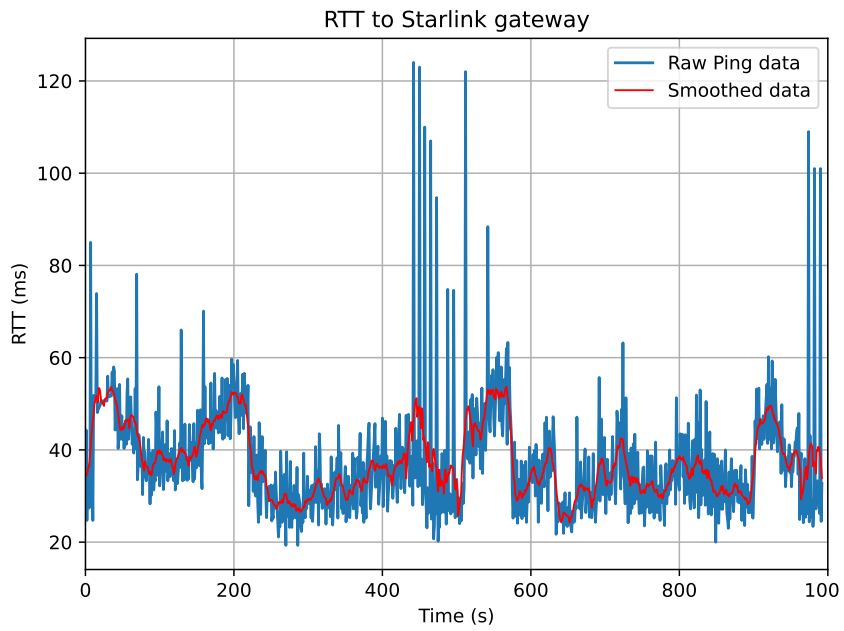
Figure 4.3: RTT measurement to Starlink gateway with one echo request each second for 1000 seconds. The smoothing filter used is Scipy´s Savgol filter with a window length of 21
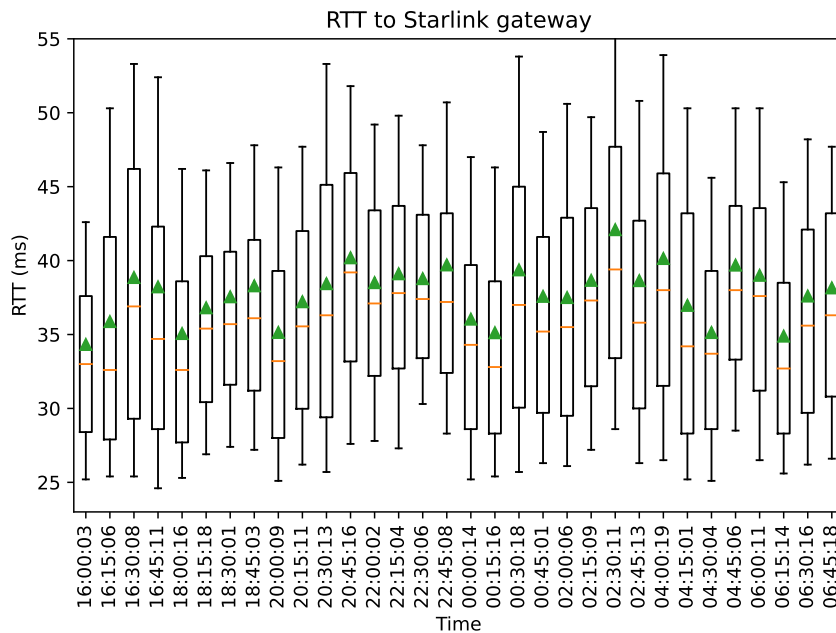
Figure 4.4: Ping test to Starlink gateway. The boxes are configured with 10th and 90th percentiles. Each box contains a measurement of one ICMP request every second for 1000 seconds

From the collective data 4.4 we see the trends of the orange line (median) and green arrowhead (mean) is contained in a relatively small window of around 10ms. The data was captured from Monday 6. to Tuesday 7. March 2023. The weather on this run was stable, with no clouds and no precipitation.

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4.3.2 Overview over available satellites results
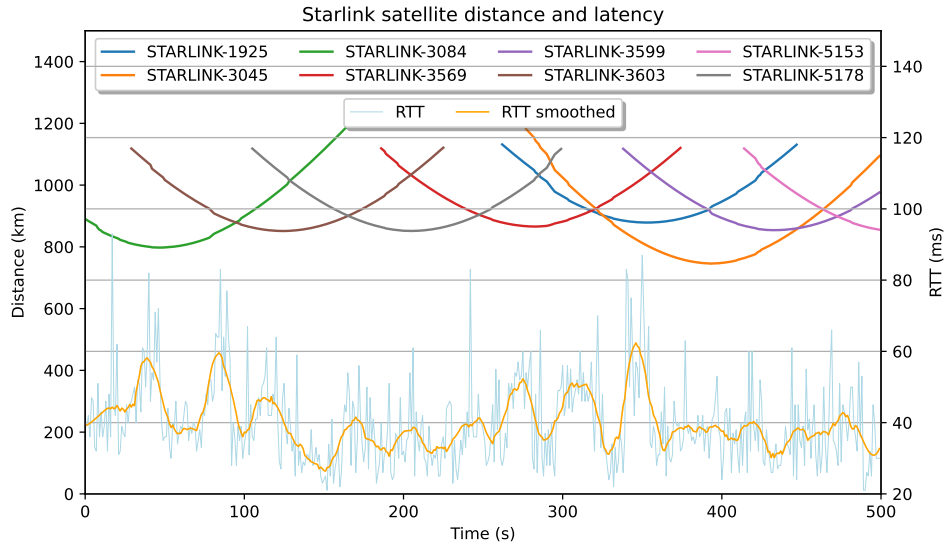
Figure 4.5: Satellite distance from Starlink dish location 3.3.4, together with result from ping to Starlink gateway (100.64.0.1). The smoothing filter used is Scipy´s Savgol filter with a window length of 30 on the RTT

Figure 4.5 shows the satellites in view at the same time as the latency experiment. This is a 500 seconds run of RTT measurements to a Starlink gateway and API request to gather satellite positional data. For the RTT graph, a smoothed line is added with a filter 3.4.4.4 to aid visualization. The figure shows satellites coming in/out of view at given times, with overlapping distances from the ground. The satellites stay in view up to a distance of around 1200 km. In the time interval of 500 seconds, we see eight different satellites in view.

4.3.3 Constant Bit Rate Results

In figure 4.6 and 4.7 the packet loss median stays consistently at zero percent, however, the mean varies a bit around one percent. The runs were measured at 05.April 2023.
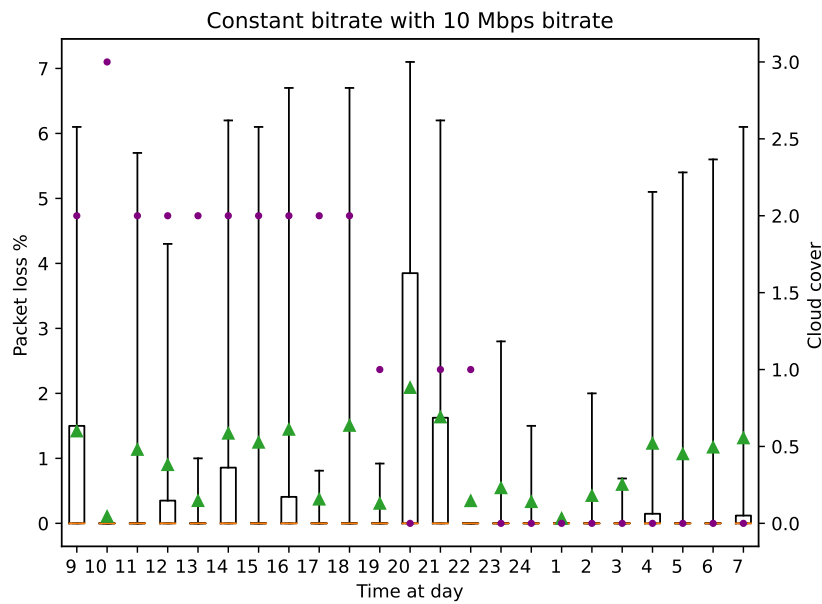
(a) CBR 10 Mbps
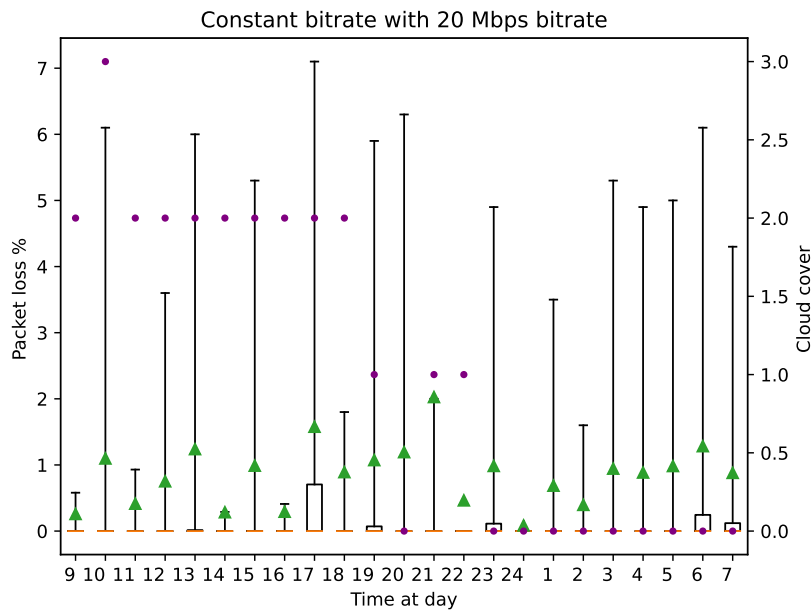
(b) CBR 20 Mbps

Figure 4.6: Constant bitrate baseline run with 10 Mbit/s and 20 Mbit/s, 2nd y-axis shows the cloud cover value from each run. Each run is a 5-minute test and started at 09.00 05.04.2023. The boxes are configured with 10th and 90th percentiles. The purple dot is the cloud cover value, and the green is the average measurement

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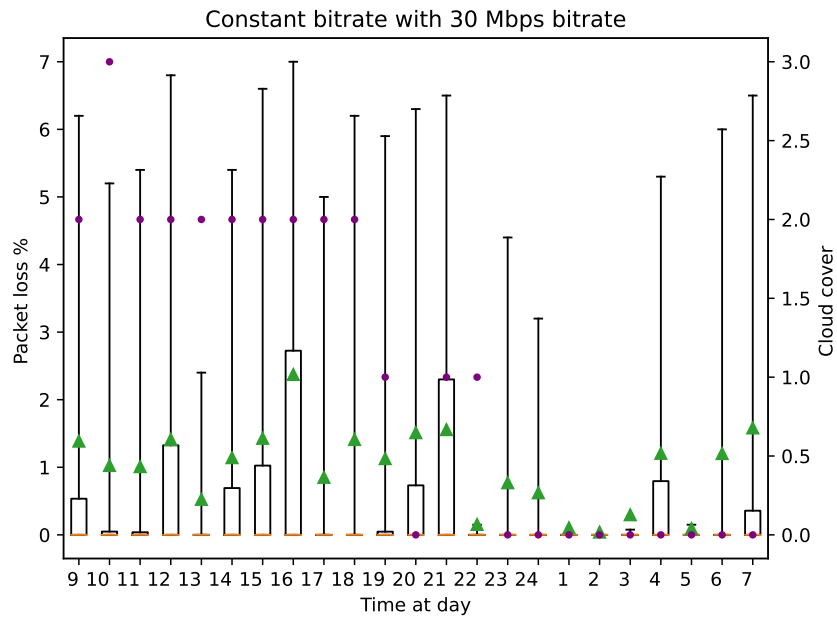
Figure 4.7: Constant bitrate baseline run with 30 Mbit/s, 2nd y-axis shows the cloud cover value from each run. Each run is a 5-minute test and started at 09.00 05.04.2023. The boxes are configured with 10th and 90th percentiles. The purple dot is the cloud cover value, and the green is the average measurement

The figures 4.6and 4.7 shows experiments described in scenario 4.1.3. These figures display a constant bit rate test with fixed bandwidth, packet loss in percent, and cloud coverage on the y-axis.

4.3.4 Variable Bit Rate Results
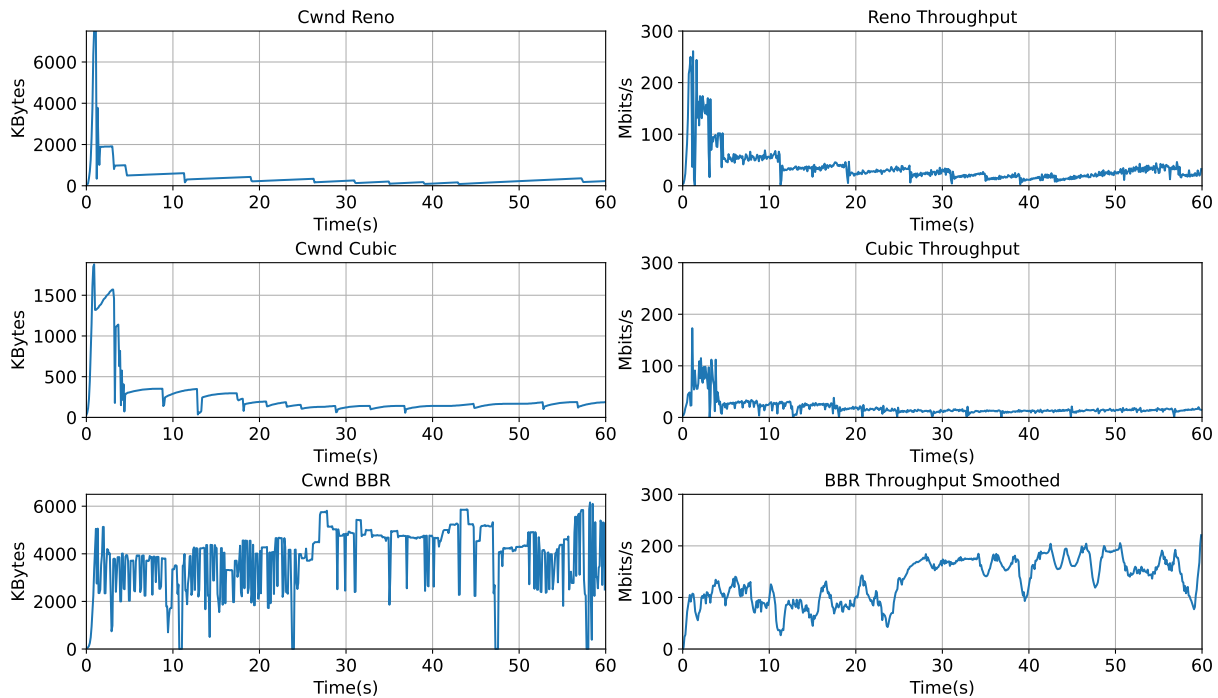
Figure 4.8: VBR downlink test with Reno, Cubic, and BBR, for 60 seconds each with 0.1-second interval. BBR throughput is smoothed with a window length of 18. The Congestion Window (cwnd) is on the server endpoint, and the throughput is measured on the receiving end

Figure 4.8 shows the results of experiment 4.1.4 with a variable bit rate. The figure displays the usage of three different congestion controls: Reno, Cubic, and BBR. Cwnd and throughput results of each Congestion Control Algorithm (CCA) are plotted against each other. Reno's throughput gradually steps down until it stabilizes at around 35 Mbit/s. The same can be observed for Cubic until it reaches a throughput of approximately 20 Mbits/s. BBR, however, achieves an average throughput of 131 Mbit/s.

4.3.5 CS:GO Single Run Results

The results for this run are taken from run number 9. See figure 4.14.
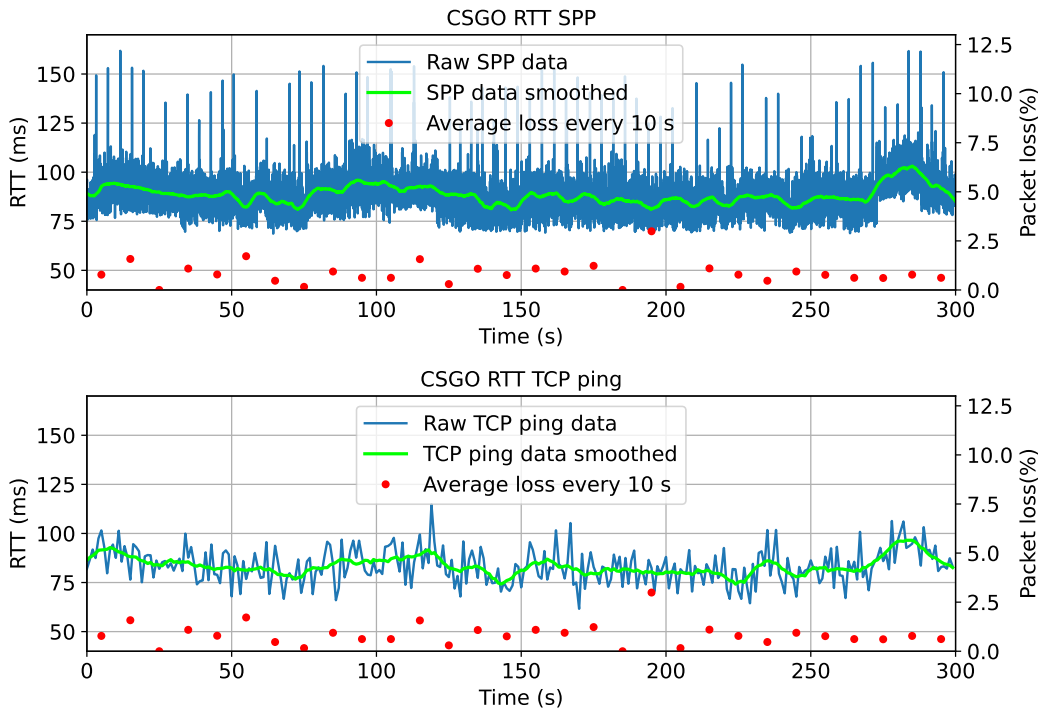
Figure 4.9: RTT measurements over Starlink during a CS:GO run using SPP and PsPing (TCP ping). Smoothed using Scipy's Savgol filter with a window length of respectively 1000 and 22. This gives a window length factor of around 15

In figure 4.9 and 4.10 we observe that RTT measurements for SPP has more data points (around 15 000) than that of TCP ping. TCP ping measures RTT once every second which equals 300 data points in both figures. The RTT over Starlink with SPP ranges between 70-120ms with spikes up to 150ms, and the RTT with TCP ping ranges between 70-110ms.

For the terrestrial run in figure 4.10 the RTT with SPP ranges between 3-6ms with spikes up to 15ms, whereas the RTT with TCP ping ranges between 4-7ms.
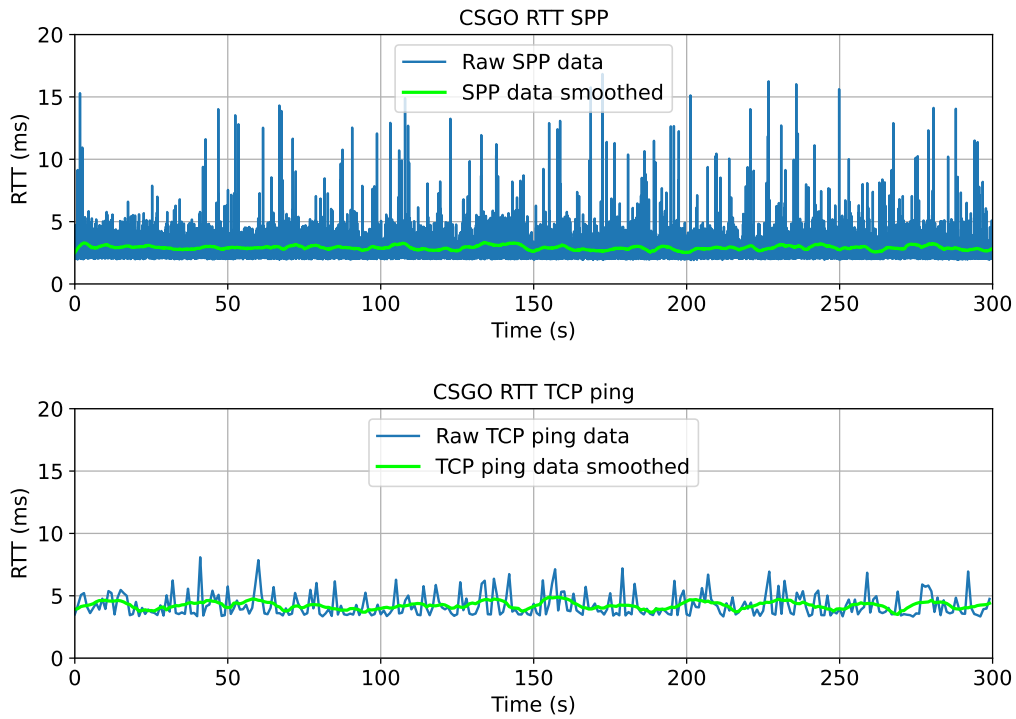
Figure 4.10: RTT measurements over terrestrial internet during a CS:GO run using SPP and PsPing (TCP ping). Same smoothing method and window lengths as in figure 4.9
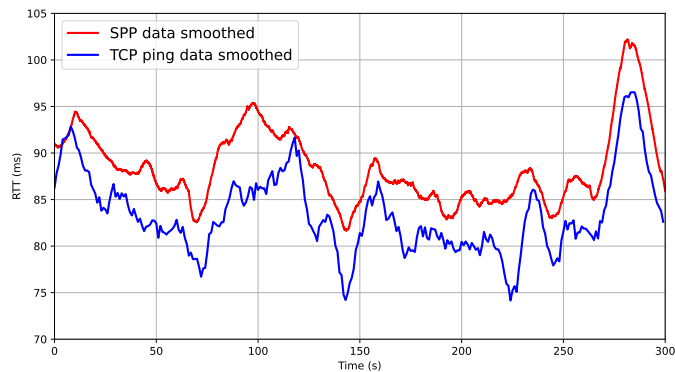
Figure 4.11: Smoothed RTT data from SPP and TCP ping in figure 4.9

In figure 4.11 we see that the smoothed results from TCP ping and SPP follow a similar trend, however, the TCP ping data averages a bit lower than the SPP data. Note that SPP is measuring RTT on the actual game traffic (passive measurement), whereas TCP ping is an active measurement that sits on top of the game traffic.
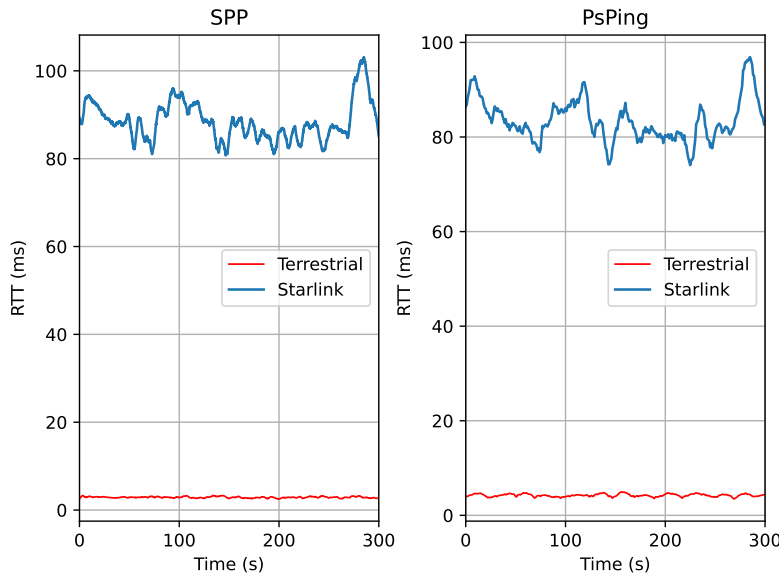
Figure 4.12: Comparison of RTT (measured with PsPing (TCP ping) and SPP) in CS:GO between Starlink and terrestrial

Figure 4.12 is showing a comparison of RTT in terrestrial and Starlink networks, on a CS:GO gaming run. The terrestrial RTT is much more stable and consistent than the Starlink network. The difference in RTT on this run is in general around 70ms.

In figure 4.13 we see a five-minute run of CS:GO on Starlink and over terrestrial internet. The throughput on the two runs differs with 61 Kbit/s. On the terrestrial link, there is virtually no packet loss compared to Starlink that have around 1% on average. The RTT (measured with TCP ping) on Starlink stays regularly between 70-100ms, and for the terrestrial run, it stays between 4-6ms.
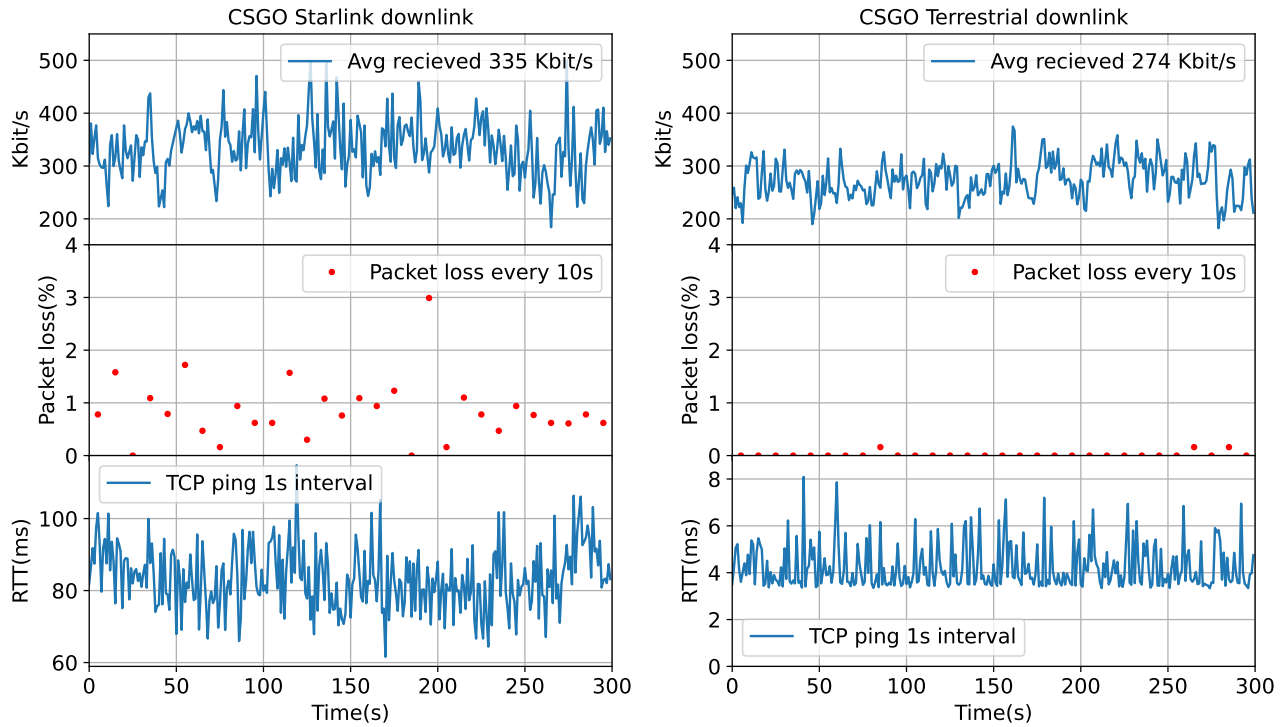
Figure 4.13: Downlink throughput, packet loss, and RTT in a single CS:GO run for Starlink and terrestrial internet. PsPing (TCP ping) is used to measure RTT

4.3.6 CS:GO All Runs Results

The CS:GO game data was captured on March 27th, consisting of ten five-minute captures. The mean is represented as arrowheads and the median is a line.
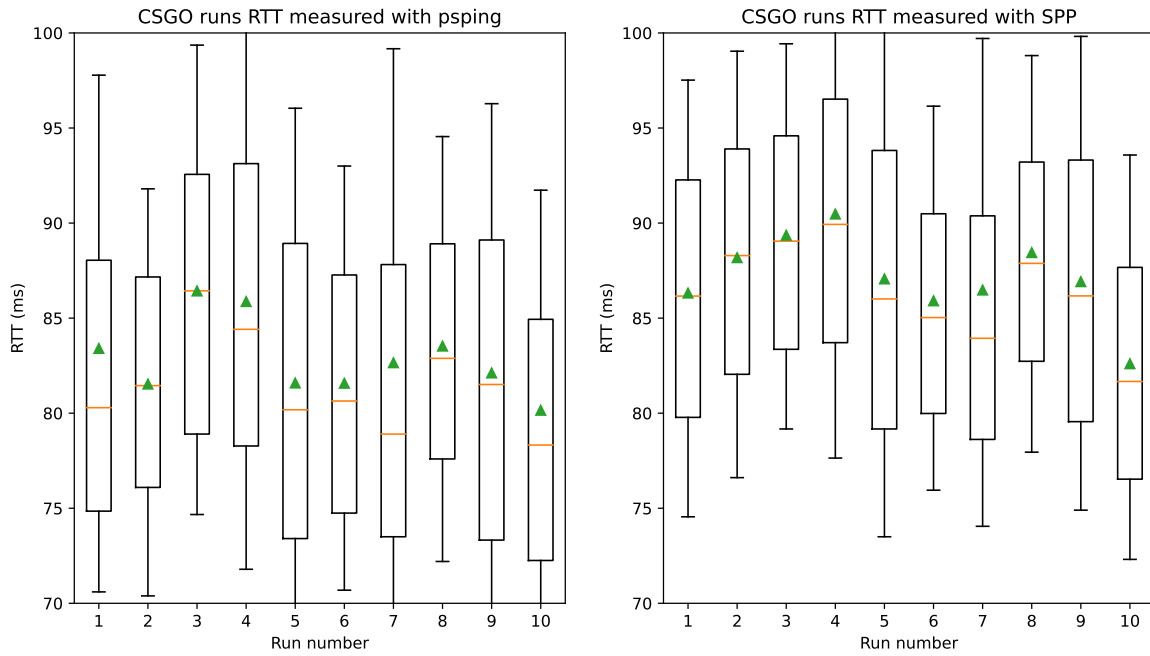
Figure 4.14: PsPing (TCP ping) and SPP is used to measure RTT for all CS:GO runs. Distribution edges are set to 10 and 90 percentile

In figure 4.14 it is evident that the two box plots share a similar pattern. Here we also notice that the RTT data from SPP is slightly higher than that of TCP ping. SPP results in a median of around 83ms, and for TCP ping it is slightly lower with a median of around 80ms.
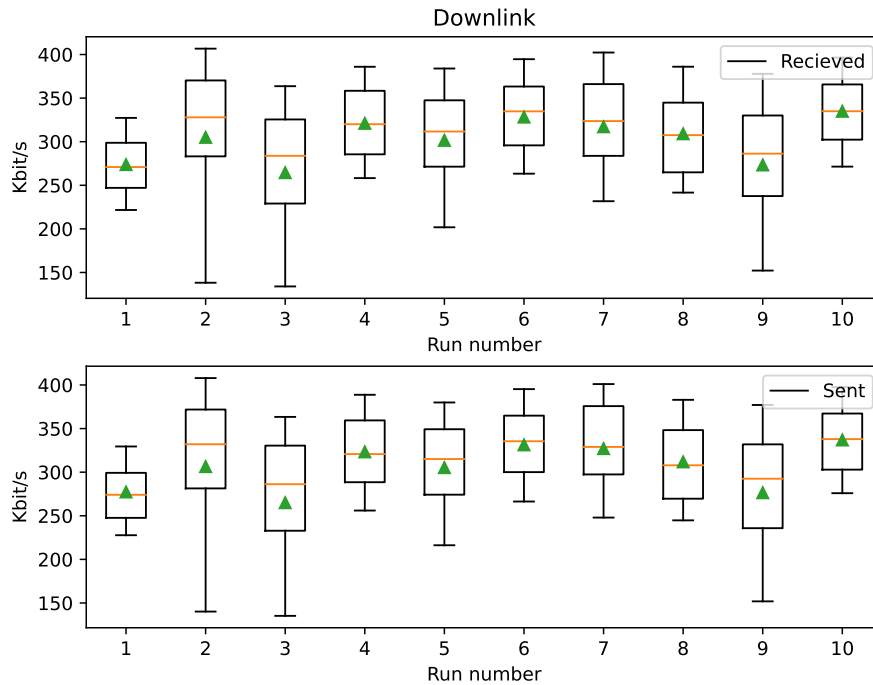
Figure 4.15: CS:GO downlink Bitrate for ten runs with five minutes each, the boxes are configured with 10th and 90th percentiles

Figure 4.15 shows the traffic sent and received on the downlink. We see only a negligible difference between the sent and the received traffic. This coincides with our findings for packet loss in 4.13 a single run, where the loss average is about 1%. The difference between the sent and received traffic seems to be consistent for all the respective runs.

4.4 Minecraft Single Run Results

The results for the Minecraft data are from run number six in figure 4.20. All smoothing methods of graphs use Scipy's Savgol filter from the Scipy library [7].
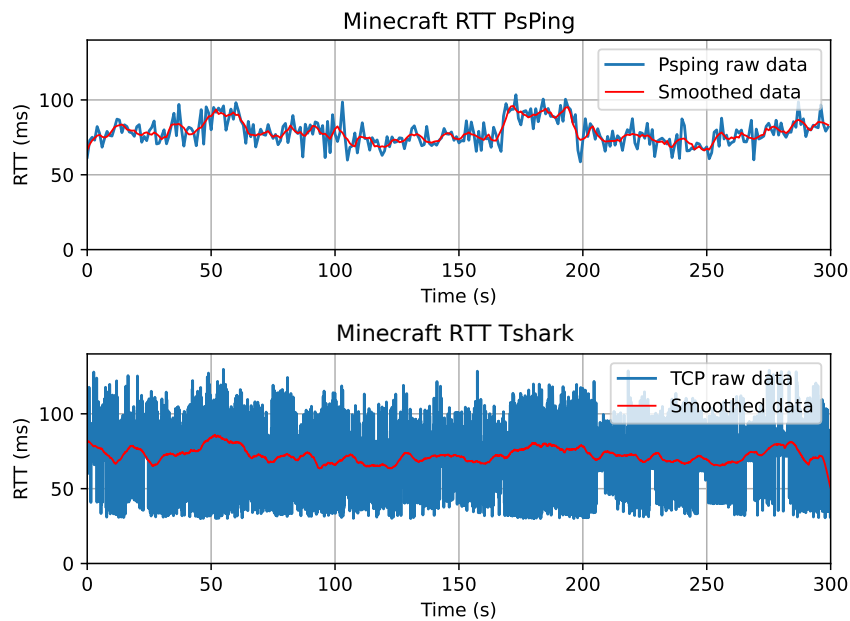
Figure 4.16: RTT measured with PsPing (TCP ping) and with Tshark from the TCP packets. Grapsh are smoothed using Scipy's Savgol filter with a window length of 20 and 1000

From figure 4.16 note that TCP ping measures the RTT once every second meanwhile the RTT of the TCP packets is measured for every packet sent in the game capture (in this case containing 13436 data points). TCP ping measurements show RTTs in a range of about 55ms on the lower end up to about 100ms on the higher end. In the second graph, RTTs vary greater, with latency somewhere between about 30ms and about 125ms. The median RTT is 75.55ms for the TCP packets.
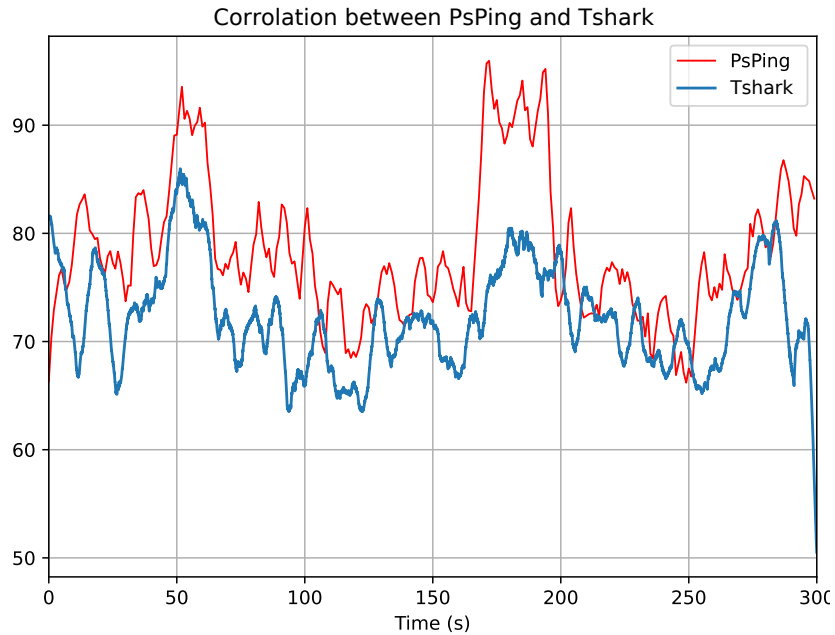
Figure 4.17: Corrolation plot between smoothed RTT measurement with PsPing (TCP ping) and Tshark from TCP packets. Graphs are smoothed using Scipy's Savgol filter with a window length of respectively 20 and 1000.

Figure 4.17 is showing smoothed RTT from TCP packets and PsPing (TCP ping) together. The graphs seem to have the same trends, although the TCP ping data averages a slightly higher latency, the two share similar sudden ups and downs in latency over the five minutes.
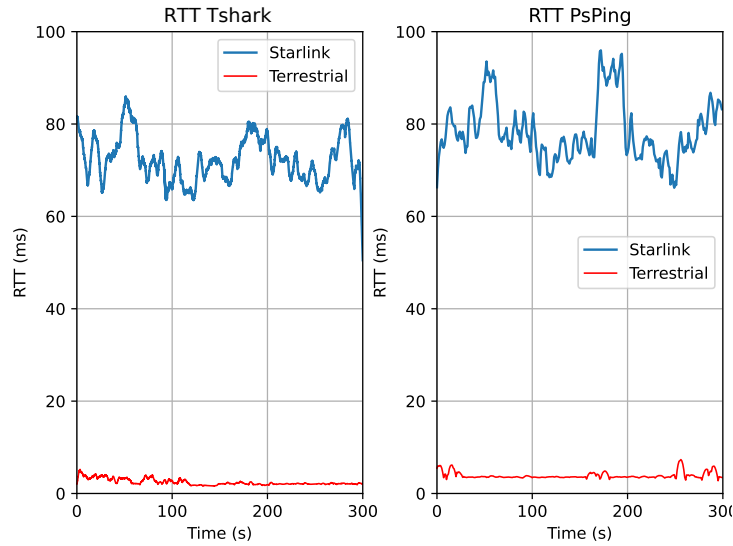
Figure 4.18: Comparison of RTT in Minecraft between Starlink and terrestrial internet with measurement tools: Tshark and PsPing (TCP ping)

Figure 4.18 is showing a comparison of RTT in terrestrial and Starlink networks, on a Minecraft gaming run. The terrestrial RTT is much more stable and consistent than the Starlink network. The difference in RTT on this run is in general around 70ms.
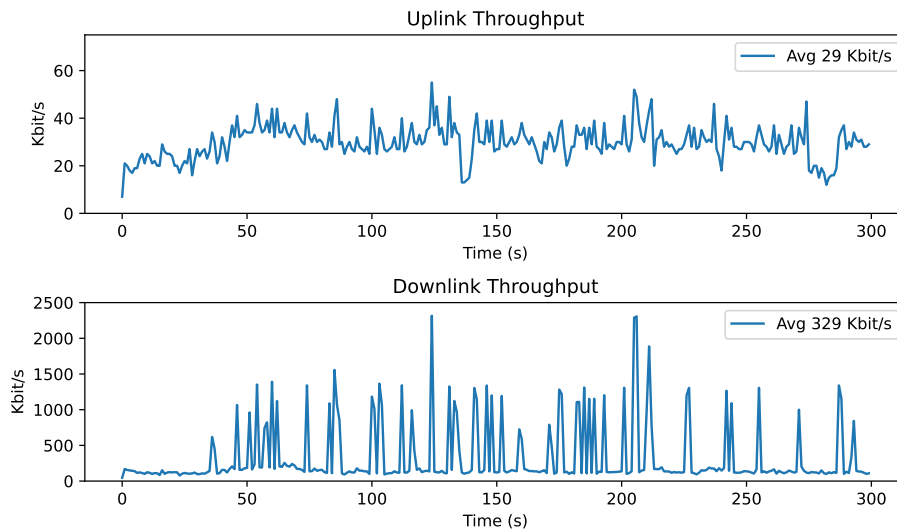
Figure 4.19: Minecraft uplink and downlink on run number 6 of Minecraft gaming

The throughput on the links in figure 4.19 are asymmetrical. On the uplink, the throughput lies mostly between 25 Kbit/s per second and 50 Kbit/s per second with some exceptions. As for the downlink, the throughput is mostly in the range of 10 Kbit/s per second to 20 Kbit/s, but it experiences significant traffic bursts of up to about 2300 Kbit/s per second. Why this could be the case will be addressed in the discussion section.

4.4.1 Minecraft All Runs Results

The Minecraft game data was captured on March 28th, consisting of ten five-minute captures. In this section, our findings are represented in box plots. For the plots, the distribution edges are set to 10 and 90, the mean is represented as arrowheads and the median is displayed as a line.

Figure 4.20 shows RTT values using TCP ping and TCP packet measurements for all the Minecraft game captures.
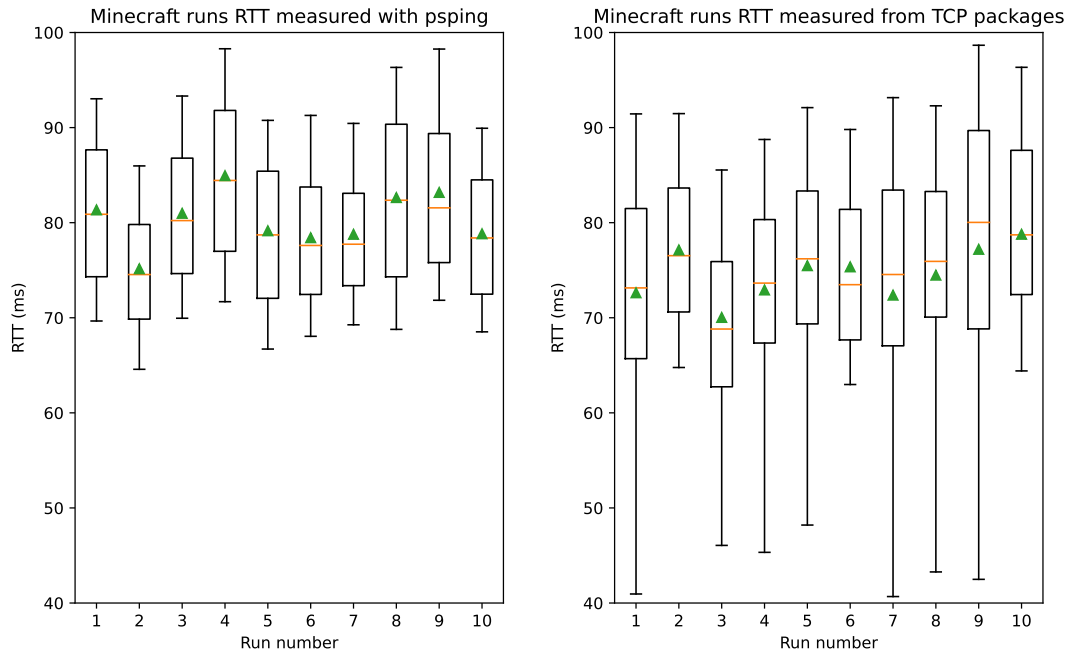
Figure 4.20: RTT data from 10 Minecraft gaming runs, measured with PsPing (TCP ping) and on TCP packets with Tshark. The boxes are configured with 10th and 90th percentiles

Results show consistent RTT distributions with TCP ping measurements and with TCP measurements but to a lesser extent. Overall, neither of the plots appears to be skewed in any direction. With TCP ping the median RTT ranges from 75ms to 85ms. As for the captured TCP data, median RTTs are slightly lower in a range from 68ms to 79ms. Given the significantly larger data set, the second box plot indicates a greater variance in RTT. Each box in the first plot consists of 300 RTT values, whereas in the second plot, the boxes consist of about 13 thousand to 14 thousand RTT values.

Figures 4.21 and 4.22 show Kbits per second for all runs on the uplink and the downlink respectively.
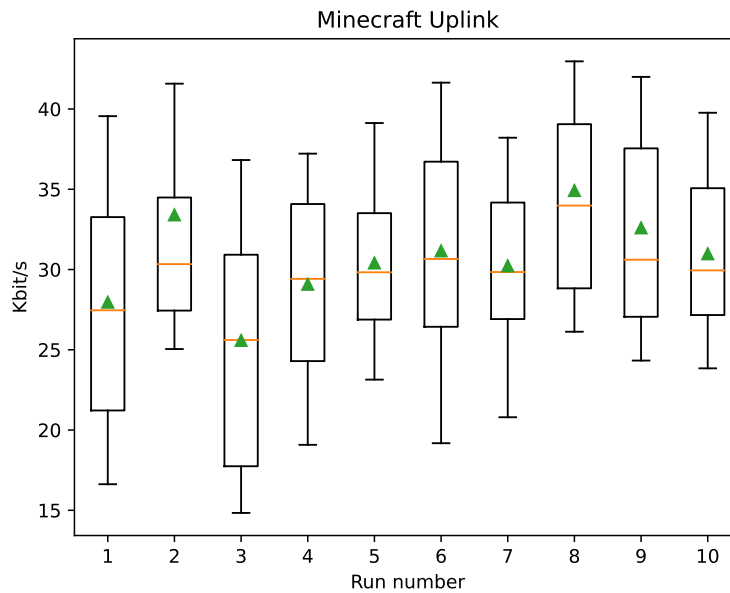
Figure 4.21: Boxplot with Kbit/s on the Uplink for 10 runs of gaming in Minecraft. The boxes are configured with 10th and 90th percentiles

We see that throughput varies on the uplink. For instance, the difference in average Kbit per second between the second and the third run is close to 8 Kbit/s. The median figure is in a range between 26 Kbit/s and 34 Kbit/s. It appears that in half of the test runs the box plots are skewed upwards.
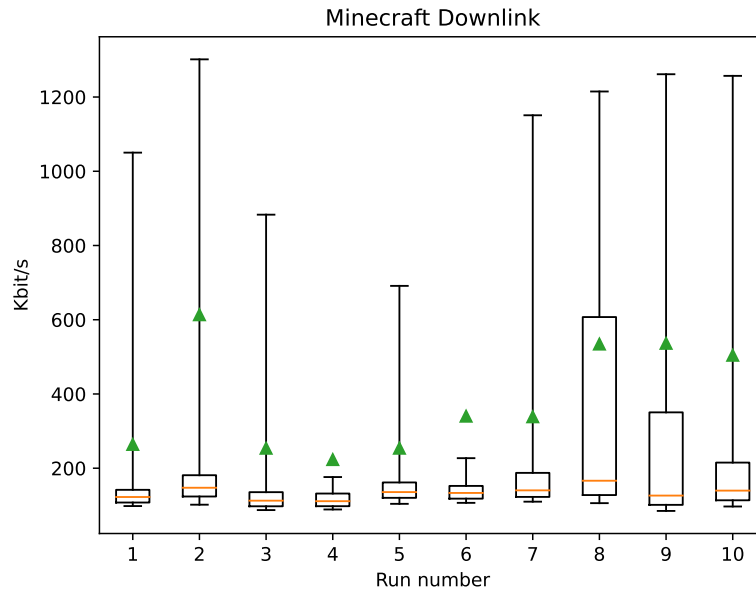
Figure 4.22: Boxplot with Kbit/s on the Downlink with 10 runs of gaming in Minecraft. The boxes are configured with 10th and 90th percentiles

The throughput on the downlink is affected by the extreme deviations in traffic as mentioned in subsection 4.4 covering a single Minecraft game capture. We see that the median value on the downlink is between 100 Kbit/s to 160 Kbit/s. The averages are skewed by the extreme server loads and vary from 200 Kbit/s up to slightly above 600 Kbit/s.

Chapter 5

Discussion

5.1 Scenario 1 - Baseline measurements

5.1.1 Ping Starlink Gateway

The results from scenario 4.3.1 give a solid indication of the RTT over the Starlink network which sits around 40ms most of the time. However, as seen in figure 4.3 it is coherent that the RTT is ramping up and down. A reason for this could be the variation in the satellite distance. Since the satellite is moving at great speeds, the latency probably gets a little higher or lower depending on if the satellite is moving closer, or further away. It is also evident from figure 4.3 that there are some high spikes up to 120ms, this could be because of the satellite hand-offs. Weather data is not measured during this experiment due to clouds and rain not having any impact on the speed of light, and therefore no impact on latency.

5.1.2 Overview over available satellites

From the results in figure 4.5 we see some spikes in the RTT. This happens when the closest satellite is overtaken by another closer satellite which could indicate a hand-off (switching). The study [22] finds packet loss when an overtaking satellite comes closer than the previous closest satellite. A similar tendency could occur when we have spikes in the RTT.

As the satellites travel closer to our position at UiS, we can see a trend in lower RTT, which can indicate a correlation between satellite distance and RTT. The op-

posite is the case when satellites travel further away from us, which can be seen in figure 4.5 at around 300 seconds.

5.1.3 Constant Bit Rate

We can see from the results in figures 4.6 and 4.7 that the Starlink Satellite broadband service is more than capable of delivering a stable connection with sufficient bandwidth for online gaming. This experiment shows the combination of satellite and terrestrial connection since the server receiving the CBR is located in the UiS.

Included in the plots is the cloud coverage for each run, which tells us that the cloudiness does little to nothing for the packet loss in our case. The median shows us that the packet loss stays mostly at the fixed rate of the selected bandwidth for the experiment, but the average packet loss is above 1% across all runs and bandwidths. From other studies [10], it has been found packet loss is around 0.1% for GEO satellites and LEO (Starlink) around 1.8%. This tells us that our connection with Starlink is on the better side, compared to this study.

5.1.4 Variable Bit Rate

From figure 4.8 it is apparent that BBR outperforms both Reno and Cubic in terms of throughput. The study in [16] about cellular networks informs that it has been tested that BBR outperforms Cubic and NewReno in terms of throughput and latency trade-off. Another paper [22] shows that BBR achieves much higher throughput over Starlink than other CCAs such as Cubic, Reno, Veno, and Vegas. BBR, in this study, achieves a throughput of 55% of the capacity compared to Cubic and Reno which achieve respectively 37% and 30%. The same paper [22] reports that Starlink's satellite hand-offs introduce packet loss. This could explain why there is such a drop in throughput in both Reno and Cubic.

By the nature of how those two (Reno and Cubic) algorithms work, they drop the sending rate of packets based on loss detection. The way Cubic and Reno lower the sending rate is by adjusting the cwnd, when the loss is detected the cwnd is reduced by half. They also have a slow start followed by increasing the sending rate rapidly. Although the two share similar patterns, the way the cwnd is incremented differs. For Reno, this results in a linear recovery state, which means that

the cwnd is incremented linearly. For Cubic the recovery state resembles more that of a cubic function, hence the name Cubic. These characteristics for Reno and Cubic can be seen in figure 4.8.

BBR, however, factors in latency rather than packet loss, and attempts to utilize as much bandwidth as possible. If the latency increases significantly it indicates that buffer queues are full and the sending rate of packets needs to be paused until the queues are emptied. This is also referred to as "draining" the queues. This results in sudden drops in the cwnd which also can be seen in figure 4.8.

5.2   Scenario 2 - Gaming measurements

5.2.1   CS:GO

Based on the results from scenario 4.2.1 it is noticeable that CS:GO does not require much bandwidth. On average for a five-minute run of a classic Deathmatch, the download throughput sits around 300 Kbit/s which translates to 0.3 Mbit/s. From the results in scenario 4.3.3 there is barely any packet loss at 10, 20, and 30 Mbit/s on the downlink. In figure 4.13 we see an average packet loss per ten seconds mostly around one percent. This study [33] says that the limit for acceptable packet loss for FPS games is five percent, which makes Starlink a suitable Internet Service Provider (ISP) for playing CS:GO in terms of packet loss.

The throughput for Starlink compared to terrestrial internet is roughly the same, but there is slightly less on terrestrial as can be seen in figure 4.13. This is probably because the in-game maps that was played were different. The terrestrial test was done only ten km away from UiS, which explains the RRT of around 4ms.

Before investigating further into the RTT, it is worth mentioning that the game server the client connects to is located at University in Stavanger. This means that the traffic travels from UiS through the Starlink satellite network, back to Earth (probably somewhere in Germany based on the angle of the dish), and finally back to UiS through terrestrial internet. The average RTT from UiS to the closest hops near the Starlink gateways in Germany is about 30ms.

In figure 4.9 the RTT results from SPP shows some significant spikes. They seem to appear quite regularly and can be caused by satellite hand-offs as shown in figure 4.5. However, some spikes in SPP data can also be seen in the terrestrial run.

5.2.2   Minecraft

In figure 4.17, Tshark and PsPing data are shown together to illustrate that their trends in RTT values are correlated, thus validating our measurements. Figure 4.16 shows that RTT changes frequently, with highs up to about 125ms and lows at about 30ms. We speculate these changes in RTT may be caused by satellite switching or Starlink gateway switching.

Figure 4.20 shows us the RTT with PsPing and Tshark for all of the Minecraft runs. Here the boxplots display a trend in RTT with values mostly in the region of 65-95ms. With 30ms of deviation between the 10th and the 90th percentile of latency, the distribution of RTT measurements appear promising in regards to Starlink. As seen in a relevant study [19], latency up to 1000ms does not impact gaming QoE, and another study [4] states that a latency of 250ms does start to degrade the performance of the game. Measured against related works, our results prove that Starlink is capable of delivering adequate RTT for Minecraft.

We did compare gaming in Minecraft on both Starlink and terrestrial networks, as can be seen in figure 4.18. This experiment shows us how big of a gap there is in RTT between satellite and terrestrial connection, which is approximately 60-70ms more on the satellite connection. When gaming on the satellite network, we did not feel and noticed the high latency compared to the terrestrial connection. The connection on Starlink did feel as seamless when gaming in Minecraft, as it did on the terrestrial network.

Figure 4.19 shows the throughput Minecraft requires as displayed in the graph of a single experiment run. We see that the average throughput on the downlink stays at around 330 kbit/s which Starlink is more than capable of delivering. This is still the case when the game traffic spikes to almost 2500 kbit/s which occurs when players are exploring and rendering new world data in the game.

Minecraft utilizes an asymmetric downlink/uplink pattern which can be seen in the figure displaying downlink and uplink 4.19 on the same single run. Here we can see that the uplink is far lower than the downlink, which is comparable to the asymmetrical links of the Starlink broadband.

5.2.3 Criteria

Table 5.1 shows a brief overview of the different metrics and their corresponding criteria for CS:GO and Minecraft. It also shows our findings to check if the criteria are satisfied.

Criteria	Related work	Our results	Criteria met?
RTT CS:GO: < 60ms	[33]	83ms	No
RTT Minecraft: < 250ms	[4]	80ms	Yes
Throughput CS:GO: > 400 Kbit/s	4.15	150 Mbit/s	Yes
Throughput Minecraft: > 2400 Kbit/s	4.19	150 Mbit/s	Yes
Packet loss CS:GO: < 5%	[6]	1%	Yes

Table 5.1: QoS metric criteria for CS:GO and Minecraft

Chapter 6

Conclusions

This thesis has evaluated the Starlink broadband service for the following metrics: latency, throughput, and packet loss. These metrics were evaluated in baseline experiments, and through online gaming experiments. This is to establish if Starlink as an ISP meets the QoS criteria for CS:GO and Minecraft, this is shown in table 5.1. Some online gaming experiments over the terrestrial internet have also been done for comparison reasons. Additionally, we did an experiment to figure out how the satellites move in/out of our Starlink dish view. This result showed us the distance of satellites in correlation with a latency experiment in parallel. The testbed used was rewired depending on the different scenarios, and all of the experiments ran over some variation of automated Python scripts.

The results from this thesis offer some answers to the different research questions that were given in the introduction part. They also open up for some more research regarding Starlink as an ISP for online gaming.

6.1 Answering the Research Questions

- RQ1: Does Starlink satisfy latency and bandwidth requirements for online gaming?

Yes. Our results show that for both CS:GO and Minecraft the throughput Starlink provides, is more than enough for playing these games. One paper about Minecraft [4] points out that it tolerates RTTs up to

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250ms. Our results show that Minecraft gameplay has on average a RTT of around 80ms over Starlink. A study on CS:GO QoE [33] found that for RRT higher than 60ms, performance is degrading. The results for this thesis show that RTTs for CS:GO over Starlink are averaging around 85ms. However, as mentioned in the discussion section, the game server is located at UiS which adds an additional 30ms. When connecting to official game servers hosted by Valve, CS:GO automatically tries to find a server with the lowest possible latency. This means that the RTT would be substantially lower (probably in the 50-60ms range) when connecting to an official game server, rather than connecting to the private hosted server at UiS.

- RQ2: Does Starlink produce significant packet loss with regard to online gaming?

For CS:GO, yes. In table 5.1 we see that the packet loss criteria for CS:GO is under 5%. Our results have proven that packet loss over Starlink while playing CS:GO is roughly 1%, as shown in figure 4.13.

- RQ3: What are the differences in performance between terrestrial internet access and Starlink?

The clear difference between Starlink and our terrestrial connection is in the latency. Compared to the fiber-based terrestrial connection, Starlink achieves delays that are 60 to 70ms higher. Regarding bandwidth, both connections provide more than enough capacity for online gaming. Lastly, the packet loss on the terrestrial network was close to none while Starlink averaged at about 1%.

6.2   Future directions

To further discover the online gaming performance on Starlink, we propose conducting thorough QoE surveys on online games. Further, we suggest testing the Starlink broadband through a wider selection of online games and game genres.

Appendix A

Instructions to Compile and Run System

Write your Appendix content here.

A.1   Server config files

A.1.1   CS:GO

```
1  ###################################
2  ######## Default Settings ########
3  ###################################
4  # DO NOT EDIT, ANY CHANGES WILL BE OVERWRITTEN!
5  # Copy settings from here and use them in either:
6  # common.cfg - applies settings to every instance.
7  # [instance].cfg - applies settings to a specific instance.
8
9  #### Game Server Settings ####
10
11 ## Predefined Parameters | https://docs.linuxgsm.com/configuration/
      start-parameters
12 # https://docs.linuxgsm.com/game-servers/counter-strike-global-
      offensive
13 gametype="0"
14 gamemode="0"
15 gamemodeflags="0"
16 skirmishid="0"
17 mapgroup="mg_active"
```

```
18 ip="0.0.0.0"
19 port="27015"
20 clientport="27005"
21 sourcetvport="27020"
22 steamport="26901"
23 defaultmap="de_mirage"
24 maxplayers="16"
25 tickrate="64"
26
27 ## Game Server Login Token (GSLT): Required
28 # GSLT is required for running a public server.
29 # More info: https://docs.linuxgsm.com/steamcmd/gslt
30 gslt=""
31
32 ## Workshop Parameters | https://developer.valvesoftware.com/wiki/
      CSGO_Workshop_For_Server_Operators
33 # To get an API key visit - https://steamcommunity.com/dev/apikey
34 wsapikey=""
35 wscollectionid=""
36 wsstartmap=""
37
38 ## Server Parameters | https://docs.linuxgsm.com/configuration
39 /start-parameters#additional-parameters
40 startparameters="-game csgo -usercon -strictportbind -ip ${ip}
41 -port ${port} +clientport ${clientport}
42 +tv_port ${sourcetvport} +sv_setsteamaccount ${gslt}
43 -tickrate ${tickrate} +map ${defaultmap}
44 +servercfgfile ${servercfg} -maxplayers_override
45 ${maxplayers} +mapgroup ${mapgroup} +game_type
46 ${gametype} +game_mode ${gamemode} +sv_game_mode_flags
47 ${gamemodeflags} +sv_skirmish_id ${skirmishid}
48 +host_workshop_collection ${wscollectionid}
49 +workshop_start_map ${wsstartmap} -authkey ${wsapikey} -nobreakpad"
50
51 #### LinuxGSM Settings ####
52
53 ## LinuxGSM Stats
54 # Send useful stats to LinuxGSM developers.
55 # https://docs.linuxgsm.com/configuration/linuxgsm-stats
56 # (on|off)
57 stats="off"
58
59 ## Notification Alerts
```

```
60  # (on|off)
61
62  # Display IP | https://docs.linuxgsm.com/alerts#display-ip
63  displayip=""
64
65  # More info | https://docs.linuxgsm.com/alerts#more-info
66  postalert="off"
67
68  # Discord Alerts | https://docs.linuxgsm.com/alerts/discord
69  discordalert="off"
70  discordwebhook="webhook"
71
72  # Email Alerts | https://docs.linuxgsm.com/alerts/email
73  emailalert="off"
74  email="email@example.com"
75  emailfrom=""
76
77  # Gotify Alerts | https://docs.linuxgsm.com/alerts/gotify
78  gotifyalert="off"
79  gotifytoken="token"
80  gotifywebhook="webhook"
81
82  # IFTTT Alerts | https://docs.linuxgsm.com/alerts/ifttt
83  iftttalert="off"
84  iftttoken="accesstoken"
85  iftttevent="linuxgsm_alert"
86
87  # Mailgun Email Alerts | https://docs.linuxgsm.com/alerts/mailgun
88  mailgunalert="off"
89  mailgunapiregion="us"
90  mailguntoken="accesstoken"
91  mailgundomain="example.com"
92  mailgunemailfrom="alert@example.com"
93  mailgunemail="email@myemail.com"
94
95  # Pushbullet Alerts | https://docs.linuxgsm.com/alerts/pushbullet
96  pushbulletalert="off"
97  pushbullettoken="accesstoken"
98  channeltag=""
99
100 # Pushover Alerts | https://docs.linuxgsm.com/alerts/pushover
101 pushoveralert="off"
102 pushovertoken="accesstoken"
```

```
103 pushoveruserkey="userkey"
104
105 # Rocket.Chat Alerts | https://docs.linuxgsm.com/alerts/rocket.chat
106 rocketchatalert="off"
107 rocketchatwebhook="webhook"
108 rocketchattoken=""
109
110 # Slack Alerts | https://docs.linuxgsm.com/alerts/slack
111 slackalert="off"
112 slackwebhook="webhook"
113
114 # Telegram Alerts | https://docs.linuxgsm.com/alerts/telegram
115 # You can add a custom cURL string eg proxy (useful in Russia) in "
       curlcustomstring".
116 # For example "--socks5 ipaddr:port" for socks5 proxy see more in "curl
        --help".
117 telegramapi="api.telegram.org"
118 telegramalert="off"
119 telegramtoken="accesstoken"
120 telegramchatid=""
121 curlcustomstring=""
122
123 ## Updating | https://docs.linuxgsm.com/commands/update
124 updateonstart="off"
125
126 ## Backup | https://docs.linuxgsm.com/commands/backup
127 maxbackups="4"
128 maxbackupdays="30"
129 stoponbackup="on"
130
131 ## Logging | https://docs.linuxgsm.com/features/logging
132 consolelogging="on"
133 logdays="7"
134
135 ## Monitor | https://docs.linuxgsm.com/commands/monitor
136 # Query delay time
137 querydelay="1"
138
139 ## ANSI Colors | https://docs.linuxgsm.com/features/ansi-colors
140 ansi="on"
141
142 #### Advanced Settings ####
143
```

```
144  ## Message Display Time | https://docs.linuxgsm.com/features/message-
         display-time
145  sleeptime="0.5"
146
147  ## SteamCMD Settings | https://docs.linuxgsm.com/steamcmd
148  # Server appid
149  appid="740"
150  steamcmdforcewindows="no"
151  # SteamCMD Branch | https://docs.linuxgsm.com/steamcmd/branch
152  branch=""
153  betapassword=""
154  # Master Server | https://docs.linuxgsm.com/steamcmd/steam-master-
         server
155  steammaster="true"
156
157  ## Stop Mode | https://docs.linuxgsm.com/features/stop-mode
158  # 1: tmux kill
159  # 2: CTRL+c
160  # 3: quit
161  # 4: quit 120s
162  # 5: stop
163  # 6: q
164  # 7: exit
165  # 8: 7 Days to Die
166  # 9: GoldSrc
167  # 10: Avorion
168  # 11: end
169  stopmode="9"
170
171  ## Query mode
172  # 1: session only
173  # 2: gamedig (gsquery fallback)
174  # 3: gamedig
175  # 4: gsquery
176  # 5: tcp
177  querymode="2"
178  querytype="protocol-valve"
179
180  ## Console type
181  consoleverbose="yes"
182  consoleinteract="yes"
183
184  ## Game Server Details
```

```
185 # Do not edit
186 gamename="Counter-Strike: Global Offensive"
187 engine="source"
188 glibc="2.15"
189
190 #### Directories ####
191 # Edit with care
192
193 ## Game Server Directories
194 systemdir="${serverfiles}/csgo"
195 executabledir="${serverfiles}"
196 executable="./srcds_run"
197 servercfgdir="${systemdir}/cfg"
198 servercfg="${selfname}.cfg"
199 servercfgdefault="server.cfg"
200 servercfgfullpath="${servercfgdir}/${servercfg}"
201
202 ## Backup Directory
203 backupdir="${lgsmdir}/backup"
204
205 ## Logging Directories
206 logdir="${rootdir}/log"
207 gamelogdir="${systemdir}/logs"
208 lgsmlogdir="${logdir}/script"
209 consolelogdir="${logdir}/console"
210 lgsmlog="${lgsmlogdir}/${selfname}-script.log"
211 consolelog="${consolelogdir}/${selfname}-console.log"
212 alertlog="${lgsmlogdir}/${selfname}-alert.log"
213 postdetailslog="${lgsmlogdir}/${selfname}-postdetails.log"
214
215 ## Logs Naming
216 lgsmlogdate="${lgsmlogdir}/${selfname}-script-$(date '+%Y-%m-%d-%H:%M:%
        S').log"
217 consolelogdate="${consolelogdir}/${selfname}-console-$(date '+%Y-%m-%d
        -%H:%M:%S').log"
```

Listing A.1: default properties for csgo server

```
1 ##################################
2 ####### Instance Settings ########
3 ##################################
```

```
 4 # PLACE INSTANCE SETTINGS HERE
 5 ## These settings will apply to a specific instance.
 6 defaultmap="de_dust2"
 7 gslt="7A5801E75278DB8BD7B6D1AFB9BD3883"
 8 gametype="1"
 9 gamemode="2"
10 gamemodeflags="32"
11 maxplayers="32"
```

Listing A.2: server properties for csgo server

A.1.2   Minecraft

```
 1 ####################################
 2 ######## Default Settings ########
 3 ####################################
 4 # DO NOT EDIT, ANY CHANGES WILL BE OVERWRITTEN!
 5 # Copy settings from here and use them in either:
 6 # common.cfg - applies settings to every instance.
 7 # [instance].cfg - applies settings to a specific instance.
 8
 9 #### Game Server Settings ####
10
11 ## Predefined Parameters | https://docs.linuxgsm.com/configuration
12 /start-parameters
13 javaram="1024" # -Xmx$1024M
14
15 ## Server Parameters | https://docs.linuxgsm.com/configuration
16 /start-parameters#additional-parameters
17 startparameters="nogui"
18
19 ## Release Settings | https://docs.linuxgsm.com/game-servers
20 /minecraft#release-settings
21 # Branch (release|snapshot)
22 branch="release"
23 # Version (latest|1.16)
24 mcversion="latest"
25
26 #### LinuxGSM Settings ####
27
28 ## LinuxGSM Stats
```

```
29 # Send useful stats to LinuxGSM developers.
30 # https://docs.linuxgsm.com/configuration/linuxgsm-stats
31 # (on|off)
32 stats="off"

33
34 ## Notification Alerts
35 # (on|off)

36
37 # Display IP | https://docs.linuxgsm.com/alerts#display-ip
38 displayip=""

39
40 # More info | https://docs.linuxgsm.com/alerts#more-info
41 postalert="off"

42
43 # Discord Alerts | https://docs.linuxgsm.com/alerts/discord
44 discordalert="off"
45 discordwebhook="webhook"

46
47 # Email Alerts | https://docs.linuxgsm.com/alerts/email
48 emailalert="off"
49 email="email@example.com"
50 emailfrom=""

51
52 # Gotify Alerts | https://docs.linuxgsm.com/alerts/gotify
53 gotifyalert="off"
54 gotifytoken="token"
55 gotifywebhook="webhook"

56
57 # IFTTT Alerts | https://docs.linuxgsm.com/alerts/ifttt
58 iftttalert="off"
59 iftttoken="accesstoken"
60 iftttevent="linuxgsm_alert"

61
62 # Mailgun Email Alerts | https://docs.linuxgsm.com/alerts/mailgun
63 mailgunalert="off"
64 mailgunapiregion="us"
65 mailguntoken="accesstoken"
66 mailgundomain="example.com"
67 mailgunemailfrom="alert@example.com"
68 mailgunemail="email@myemail.com"

69
70 # Pushbullet Alerts | https://docs.linuxgsm.com/alerts/pushbullet
71 pushbulletalert="off"
```

```
72 pushbullettoken="accesstoken"
73 channeltag=""
74
75 # Pushover Alerts | https://docs.linuxgsm.com/alerts/pushover
76 pushoveralert="off"
77 pushovertoken="accesstoken"
78 pushoveruserkey="userkey"
79
80 # Rocket.Chat Alerts | https://docs.linuxgsm.com/alerts/rocket.chat
81 rocketchatalert="off"
82 rocketchatwebhook="webhook"
83 rocketchattoken=""
84
85 # Slack Alerts | https://docs.linuxgsm.com/alerts/slack
86 slackalert="off"
87 slackwebhook="webhook"
88
89 # Telegram Alerts | https://docs.linuxgsm.com/alerts/telegram
90 # You can add a custom cURL string eg proxy (useful in Russia) in "
        curlcustomstring".
91 # For example "--socks5 ipaddr:port" for socks5 proxy see more in "curl
         --help".
92 telegramapi="api.telegram.org"
93 telegramalert="off"
94 telegramtoken="accesstoken"
95 telegramchatid=""
96 curlcustomstring=""
97
98 ## Updating | https://docs.linuxgsm.com/commands/update
99 updateonstart="off"
100
101 ## Backup | https://docs.linuxgsm.com/commands/backup
102 maxbackups="4"
103 maxbackupdays="30"
104 stoponbackup="on"
105
106 ## Logging | https://docs.linuxgsm.com/features/logging
107 consolelogging="on"
108 logdays="7"
109
110 ## Monitor | https://docs.linuxgsm.com/commands/monitor
111 # Query delay time
112 querydelay="1"
```

```
113
114 ## ANSI Colors | https://docs.linuxgsm.com/features/ansi-colors
115 ansi="on"
116
117 #### Advanced Settings ####
118
119 ## Message Display Time | https://docs.linuxgsm.com/features/message-
         display-time
120 sleeptime="0.5"
121
122 ## Stop Mode | https://docs.linuxgsm.com/features/stop-mode
123 # 1: tmux kill
124 # 2: CTRL+c
125 # 3: quit
126 # 4: quit 120s
127 # 5: stop
128 # 6: q
129 # 7: exit
130 # 8: 7 Days to Die
131 # 9: GoldSrc
132 # 10: Avorion
133 # 11: end
134 stopmode="5"
135
136 ## Query mode
137 # 1: session only
138 # 2: gamedig (gsquery fallback)
139 # 3: gamedig
140 # 4: gsquery
141 # 5: tcp
142 querymode="2"
143 querytype="minecraft"
144
145 ## Console type
146 consoleverbose="yes"
147 consoleinteract="yes"
148
149 ## Game Server Details
150 # Do not edit
151 gamename="Minecraft"
152 engine="lwjgl2"
153 glibc="null"
154
```

```
155  #### Directories ####
156  # Edit with care
157
158  ## Game Server Directories
159  systemdir="${serverfiles}"
160  executabledir="${serverfiles}"
161  preexecutable="java -Xmx${javaram}M -jar"
162  executable="./minecraft_server.jar"
163  servercfgdir="${systemdir}"
164  servercfg="server.properties"
165  servercfgdefault="server.properties"
166  servercfgfullpath="${servercfgdir}/${servercfg}"
167
168  ## Backup Directory
169  backupdir="${lgsmdir}/backup"
170
171  ## Logging Directories
172  logdir="${rootdir}/log"
173  gamelogdir="${systemdir}/logs"
174  lgsmlogdir="${logdir}/script"
175  consolelogdir="${logdir}/console"
176  lgsmlog="${lgsmlogdir}/${selfname}-script.log"
177  consolelog="${consolelogdir}/${selfname}-console.log"
178  alertlog="${lgsmlogdir}/${selfname}-alert.log"
179  postdetailslog="${lgsmlogdir}/${selfname}-postdetails.log"
180
181  ## Logs Naming
182  lgsmlogdate="${lgsmlogdir}/${selfname}-script-$(date '+%Y-%m-%d-%H:%M:%
         S').log"
183  consolelogdate="${consolelogdir}/${selfname}-console-$(date '+%Y-%m-%d
         -%H:%M:%S').log"
```

Listing A.3: default properties for minecraft server

```
1  #Minecraft server properties
2  #Wed Apr 19 09:49:20 CEST 2023
3  enable-jmx-monitoring=false
4  level-seed=
5  rcon.port=27016
6  enable-command-block=false
7  gamemode=survival
```

```
 8 enable-query=true
 9 generator-settings={}
10 enforce-secure-profile=true
11 level-name=world
12 motd=LinuxGSM
13 query.port=27017
14 pvp=true
15 generate-structures=true
16 max-chained-neighbor-updates=1000000
17 difficulty=easy
18 network-compression-threshold=256
19 max-tick-time=60000
20 require-resource-pack=false
21 max-players=20
22 use-native-transport=true
23 online-mode=true
24 enable-status=true
25 allow-flight=false
26 initial-disabled-packs=
27 broadcast-rcon-to-ops=true
28 view-distance=10
29 max-build-height=256
30 server-ip=152.94.120.57
31 resource-pack-prompt=
32 allow-nether=true
33 server-port=27015
34 enable-rcon=false
35 sync-chunk-writes=true
36 op-permission-level=4
37 prevent-proxy-connections=false
38 hide-online-players=false
39 resource-pack=
40 entity-broadcast-range-percentage=100
41 simulation-distance=10
42 player-idle-timeout=0
43 rcon.password=adminvpuplYWH
44 force-gamemode=false
45 rate-limit=0
46 hardcore=false
47 white-list=false
48 broadcast-console-to-ops=true
49 spawn-npcs=true
50 spawn-animals=true
```

```
51 snooper-enabled=true
52 function-permission-level=2
53 initial-enabled-packs=vanilla
54 level-type=default
55 text-filtering-config=
56 spawn-monsters=true
57 enforce-whitelist=false
58 resource-pack-sha1=
59 spawn-protection=16
60 max-world-size=29999984
```

Listing A.4: server properties for minecraft server

A.2 Code

A.2.1 Experiments

```python
1 from setup.game_servers import CSGOServer, MinecraftServer
2 from setup.iperf_cbr import run_iperf_cbr_udp, filter_iperf_cbr_udp
3 from setup.yr_api import yr
4 from setup.config import SERVER_IP, CS_PORT, MINECRAFT_PORT
5 from setup.loggers import clear_log, log
6 from setup.capture_traffic import CSGOClientCapture, CSGOServerCapture,
       MinecraftCapture
7 from setup.game_latency import ping_client_server
8 from colorama import Fore, Style
9 from multiprocessing import Process
10
11 import time
12 import sys
13
14
15 if __name__ == "__main__":
16
17     tests = ["iperf_cbr", "iperf_tcp", "csgo_capture", "mc_capture"]
18     print("")
19
20     clear_log()
21
22     for i in tests:
23         print(Fore.GREEN + i)
```

```python
    print(Fore.WHITE + "")

    while True:
        test_option = input(Fore.WHITE + "Choose one of the test
    options above: ").lower().strip()

        if test_option not in tests:
            print(Fore.RED + "Invalid option: " + test_option)
            continue
        log(f"Test option: {test_option}")
        break

    print("")

    while True:
        test_duration = input(Fore.WHITE + "Enter test duration in
    seconds: ")

        try:
            test_duration = int(test_duration.strip())
        except ValueError:
            print(Fore.RED + "Invalid duration, not an interger: " +
    test_duration)
            continue
        log(f"Test duration: {test_duration}")
        break

    print("")

    while True:
        test_iterations = input(Fore.WHITE + "Enter test iterations: ")

        try:
            test_iterations = int(test_iterations.strip())
        except ValueError:
            print(Fore.RED + "Invalid iteration, not an interger: " +
    test_iterations)
            continue
        log(f"Test iterations: {test_iterations}")
        break

    print("")
```

```python
 63
 64     while True:
 65         if test_option == "iperf_cbr":
 66
 67             test_iperf_stream = input("Upload or download test(up/down)
     ?: ").lower()
 68             if test_iperf_stream == "up":
 69                 revert = True
 70             elif test_iperf_stream == "down":
 71                 revert = False
 72             else:
 73                 revert = False
 74
 75             test_bandwidth = input(Fore.WHITE + "Enter test bandwidth
     in Mbps: ")
 76             try:
 77                 test_bandwidth = int(test_bandwidth)
 78             except ValueError:
 79                 print(Fore.RED + "Invalid bandwidth, not an interger: "
      + test_iterations)
 80                 continue
 81             log(f"Test bandwidth: {test_bandwidth}")
 82
 83         break
 84
 85
 86     if test_option == "csgo_capture":
 87
 88         cs_server = CSGOServer("2", "de_dust2")
 89
 90         log("Starting CSGO-server")
 91
 92         try:
 93             cs_server.start_csgo_server()
 94         except TimeoutError:
 95             log("FATAL ERROR: Failed to start CSGO-server, check ssh
     connection")
 96             sys.exit(0)
 97         except:
 98             log("CSGO-server already running")
 99
100         input("Press 'Enter' when client is connected to the server: ")
101
```

```python
102         log("Client is connected")
103
104         cs_server_capture = CSGOServerCapture(test_duration)
105         cs_client_capture = CSGOClientCapture(test_duration)
106
107         time_now_string = f"{time.localtime().tm_mday}-{time.localtime
    ().tm_mon}-{time.localtime().tm_hour}-{time.localtime().tm_min}"
108
109         for i in range(test_iterations):
110
111             if i > 0:
112                 input("Press 'Enter' when client is connected to the
    server: ")
113
114             filename = str(time.localtime().tm_mday)+"-"+str(time.
    localtime().tm_mon)+"-"+str(time.localtime().tm_hour)+"-"+str(time.
    localtime().tm_min)+"_"+str(i+1)
115
116             try:
117                 yr(f"csgo_capture_{time_now_string}", i+1)
118             except:
119                 log("FATAL ERROR: Failed to fetch yr weather statistics
    ")
120
121             log(f"Yr api weather measure complete run: {i+1}")
122
123             log(f"Starting CSGO capture on server and client run: {i+1}
    ")
124
125             try:
126                 cs_server_capture_process = Process(target=
    cs_server_capture.start_csgo_capture, args=[filename])
127                 cs_server_capture_process.start()
128
129                 cs_client_capture_process = Process(target=
    cs_client_capture.start_csgo_capture, args=[filename])
130                 cs_client_capture_process.start()
131
132                 ping_process = Process(target=ping_client_server, args
    =(SERVER_IP, test_duration, filename, CS_PORT))
133                 ping_process.start()
134
135                 cs_server_capture_process.join()
```

```python
136                     cs_client_capture_process.join()
137                     ping_process.join()
138
139             except TimeoutError:
140                 log("FATAL ERROR: Failed to capture CSGO-traffic, check
     ssh connection")
141                 sys.exit(0)
142
143         log(f"Capture run complete: {i+1}")
144
145     log("FINISHED! CSGO-capture complete")
146
147
148
149     if test_option == "iperf_cbr":
150         for i in range(test_iterations):
151             filename = str(time.localtime().tm_mday)+"-"+str(time.
     localtime().tm_mon)+"-"+str(time.localtime().tm_hour)+"-"+str(time.
     localtime().tm_min)+"_"+str(i+1)
152             run_iperf_cbr_udp(test_bandwidth, test_duration, filename,
     revert)
153
154
155
156     if test_option == "mc_capture":
157
158         mc_server = MinecraftServer()
159
160         log("Starting Minecraft-server")
161
162         try:
163             mc_server.start_mc_server()
164         except TimeoutError:
165             log("FATAL ERROR: Failed to start Minecraft-server, check
     ssh connection")
166             sys.exit(0)
167         except:
168             log("Minecraft-server already running")
169
170         input("Press 'Enter' when client is connected to the server: ")
171
172         mc_capture = MinecraftCapture(test_duration)
173
```

```python
        time_now_string = f"{time.localtime().tm_mday}-{time.localtime
().tm_mon}-{time.localtime().tm_hour}-{time.localtime().tm_min}"

        for i in range (test_iterations):

            if i > 0:
                input("Press 'Enter' when client is connected to the
server: ")

            try:
                yr(f"minecraft_capture_{time_now_string}", i+1)
            except:
                log("FATAL ERROR: Failed to fetch yr weather statistics
")

            log(f"Yr api weather measure complete run: {i+1}")

            log(f"Starting Minecraft run: {i+1}")
            filename = str(time.localtime().tm_mday)+"-"+str(time.
localtime().tm_mon)+"-"+str(time.localtime().tm_hour)+"-"+str(time.
localtime().tm_min)+"_"+str(i+1)
            mc_filename = "mc_ping_"+filename

            try:
                mc_capture_porcess = Process(target=mc_capture.
start_mc_capture, args=[filename])
                mc_capture_porcess.start()

                ping_process = Process(target=ping_client_server, args
=(SERVER_IP, test_duration, mc_filename, MINECRAFT_PORT))
                ping_process.start()

                mc_capture_porcess.join()
                ping_process.join()

            except TimeoutError:
                log("FATAL ERROR: Failed to start Minecraft capture,
check ssh connection")
                sys.exit(0)



    if test_option == "iperf_tcp":
```

```
209             pass
```

Listing A.5: Main script

```python
1  import subprocess
2  import time
3  import re
4  import matplotlib.pyplot as _plot
5  from setup.yr_api import yr
6
7  def ping(target, interval, burst_size):
8
9      command = "ping -i %s -c %s %s" % (interval, burst_size, target)
10     print(command)
11
12     dict = {}
13     errorList = []
14     connection = True
15     timeOfPing = time.asctime()
16     timeOut = 0
17
18     #If connection drops, it retries the ping
19     while connection:
20         try:
21             ping = subprocess.check_output(command, shell=True, stderr=
    subprocess.STDOUT).decode("utf-8")
22             connection = False
23         except subprocess.CalledProcessError as e:
24             errorList.append(["error",e.stdout,time.asctime()])
25             print("error")
26             time.sleep(10)
27             timeOut += 1
28             if timeOut == 4:
29                 connection = False
30
31     #Split ping data to list
32     try:
33         splitPingToList = re.split("\s", ping)
34     except:
35         splitPingToList = []
36
```

```python
37     #Add time of ping and errors
38     dict["time"] = timeOfPing
39     dict["error"] = errorList
40
41     #Add pings to dict
42     dict["ping"] = []
43     for i in splitPingToList:
44         if re.search("^time=", i):
45             float_ping = round(float(i[5:]), 1)
46             dict["ping"].append(float_ping)
47         if re.search("^packet",i):
48             dict["loss"] = splitPingToList[splitPingToList.index(i)-1]
49
50     #Get weather information
51     try:
52         weather = yr()
53         dict["cloud"] = str(weather["shortIntervals"][0]["symbol"]["
    clouds"])
54         dict["uv"] = str(weather["shortIntervals"][0]["uvIndex"]["value
    "])
55     except:
56         dict["cloud"] = "No data"
57         dict["uv"] = "No data"
58     return dict
59
60
61 def dayRun(stopdate, stophour):
62     nowDate = time.localtime().tm_mday
63     nowHour = time.localtime().tm_hour
64     counter = 0
65
66     while nowDate < stopdate or nowHour < stophour:
67         if time.localtime().tm_hour % 2 == 0:
68             if time.localtime().tm_min % 15 == 0:
69                 #Get dictionary with pings and data
70                 dict = ping("100.64.0.1", 0.5, 1000)
71
72                 file = open(f'{counter}','w')
73                 file.write(dict["time"] + "\t" + "cloud:" + dict["cloud
    "] + "\t" + "uv:" + dict["uv"] + "\t" + "loss:" + dict["loss"] + "\
    n")
74
75                 for index in range(len(dict["ping"])):
```

```
76                    file.write(str(dict["ping"][index])+ "\n")
77                file.close()
78
79                if len(dict["error"]) > 0:
80                    file = open(f'error_{dict["time"]}','w')
81                    for i in range(len(dict["error"])):
82                        file.write(str(dict["error"][i]))
83                    file.close()
84
85                counter += 1
86                nowDate = time.localtime().tm_mday
87                nowHour = time.localtime().tm_hour
88            else:
89                print("15 min sleep")
90                nowDate = time.localtime().tm_mday
91                nowHour = time.localtime().tm_hour
92                time.sleep(20)
93        else:
94            print("hour sleep")
95            nowDate = time.localtime().tm_mday
96            nowHour = time.localtime().tm_hour
97            time.sleep(20)
```

Listing A.6: Python script to run ping script

```
1  import subprocess
2  import sys
3
4  args = sys.argv[1:]
5
6  def psping(target, duration, filename):
7
8      pingList = subprocess.run(f"psping -n {duration}s {target} ",stdout=
         subprocess.PIPE, shell=True).stdout.decode("utf-8")
9
10     file = open(f"psping{filename}.txt","w")
11
12     line = pingList.splitlines()
13     for i in line[8:-4]:
14         splittedLine = i.split(" ")
15         file.write(str(splittedLine[5][:-2]) + "\n")
```

```
16
17     file.close()
18
19  psping(args[0], args[1], args[2])
20  #psping("152.94.120.57:27015","5","3")
```

Listing A.7: Main script

```
1  from multiprocessing import Process
2  import subprocess
3  import time
4  from urllib import request
5  from setup.config import LATITUDE, LONGTIDUDE, ALTITUDE, DEG,
       N2YO_API_URL, STARLINK_CATEGORY
6
7  def closest_sat():
8      key ="xxxxx"
9      index = 0
10     file = open("satellitesMap.txt", "w")
11     while index < 500:
12         if time.localtime().tm_sec % 2 == 0:
13             index += 1
14             response = request.get(f"{N2YO_API_URL}above/{LATITUDE}/{
       LONGTIDUDE}/{ALTITUDE}/{DEG}/{STARLINK_CATEGORY}&apiKey={key}").
       json()
15             file.write(str(response)+"\n")
16     file.close()
17
18  def ping():
19
20     file = open("satellitePing.txt", "w")
21     runPing =  subprocess.run(f"ping -n 500s 100.64.0.1",stdout=
       subprocess.PIPE, shell=True).stdout.decode("utf-8")
22     file.write(runPing)
23     file.close()
24
25  def main():
26
27     satellite_map = Process(target=closest_sat)
28     satellite_map.start()
29
```

```
30    ping_map = Process(target=ping)
31    ping_map.start()
32
33    satellite_map.join()
34    ping_map.join()
```

Listing A.8: Python script to run API for satellite distance measurment

A.2.2   Post processing

A.2.2.1   PCAP files

```python
1  import pyshark
2  from datetime import datetime
3  import matplotlib.pyplot as plt
4
5  pathToFileTcp = "" # Path to tcp pcap file
6
7  # Specified path to Pcap-file
8  pathToFileClient = ""
9  pathToFileServer = ""
10 iteration = 10
11
12 # Returns a list of packets filtered by provided source and dst IP
       addresses
13 def get_pkts_by_ip(list, ipSrc, ipDst):
14     listPackets = []
15
16     # Assigns source and destination IPs for every packet in a list to
       two variables.
17     for packet in list:
18         try:
19             ipExists = packet.ip.src
20         except:
21             pass
22         try:
23             ipExist = packet.ip.dst
24         except:
25             pass
26         # Checks if packet IPs matches IPs we are filtering for
27         if ipExists == ipSrc and ipExist == ipDst:
```

```python
28              listPackets.append(packet)

29

30     return listPackets

31

32

33 # Returns Pcap-file from specified path
34 def capture(path):
35     cap = pyshark.FileCapture(path)
36     return cap

37

38 # Returns Pcap-file of only TCP retransmission packets
39 def capture_file_tcp_retransmit(path):
40     cap = pyshark.FileCapture(path, display_filter='tcp.analysis.
       retransmission')
41     return cap

42

43 # Returns a list of all captured UDP data
44 def get_udp_data(capFile):
45     udpData = []
46     for packet in capFile:
47         if packet.transport_layer == "UDP":
48             udpData.append(packet)
49         #might need try/except
50     return udpData

51

52 # Returns a list of all captured TCP data
53 def get_tcp_data(capFile):
54     tcpData = []
55     for packet in capFile:
56         if packet.transport_layer == "TCP":
57             tcpData.append(packet)
58         #might need try/except
59     return tcpData

60

61 # Writes a single value to the end of a txt file.
62 # You need to specify your path and fileNum represents the iteration
       number
63 def write_single_variable_to_txt(path, variable, fileNum):
64     f = open(f"{path}_{fileNum}.txt",  "a+")
65     f.write(f"{variable}"+ "\n")
66     f.close()

67

68
```

```python
69  # Returns a list of lists where each list contains the amount of
        packets sent in a single second
70  def list_of_pkts_per_second(someList):
71      megaList = []
72      newList = []
73      nextSeconds = 0
74      currSeconds = 0
75
76      newList.append(someList[0])
77
78      for i in range(len(someList) - 1):
79          # Parses the time field of the packet to seconds and compares
        it to the seconds of the next packet
80          currSeconds = int(someList[i].sniff_time.second)
81          nextSeconds = int(someList[i+1].sniff_time.second)
82          if nextSeconds != currSeconds:
83              # Appends the list if they are inequal, empties the
        concurrent list and appends the next packet to it.
84              megaList.append(newList)
85              newList = []
86              newList.append(someList[i+1])
87          else:
88              # The packets are in the same second and appends the packet
        .
89              newList.append(someList[i+1])
90
91      return megaList
92
93  # Returns a list of lists where each list contains the sum of bytes in
        a single second
94  def list_of_bytes_per_second(someList):
95      megaList = []
96      newList = []
97      nextSeconds = 0
98      currSeconds = 0
99
100     newList.append(int(someList[0].length))
101
102     for i in range(len(someList) - 1):
103         # Parses the time field of the packet to seconds and compares
        it to the seconds of the next packet
104         currSeconds = int(someList[i].sniff_time.second)
105         nextSeconds = int(someList[i+1].sniff_time.second)
```

```python
106          if nextSeconds != currSeconds:
107              # If inequal, sums bytelengths of packets in the concurrent
       list and appends it, empties the concurrent list and appends the
      next packet to it.
108              sum = 0
109              for i in newList:
110                  sum += i
111              megaList.append(sum)
112              newList = []
113              sum = 0
114              newList.append(int(someList[i+1].length))
115          else:
116              # If equal, appends packet to concurrent list.
117              newList.append(int(someList[i+1].length))
118
119      return megaList
120
121 # How to process a CSGO run with pcap files from both the client and
      the server
122 # It writes bytes per second to txt files of specified paths
123
124 if __name__ == "__main__":
125     print("Analyzing packets...")
126
127     # IP addresses of the client and of the server. Used to filter out
      game data
128     clientIp = ""
129     serverIp = ""
130
131     # Specify paths to write to
132     pathServerDataFromServer = ""
133     pathServerDataFromClient = ""
134     pathClientDataFromServer = ""
135     pathClientDataFromClient = ""
136
137     # Read server pcap file and extract UDP data
138     csgoDataServer = capture(pathToFileServer)
139     csgoUdpDataServer = get_udp_data(csgoDataServer)
140
141     # Read client pcap file and extract UDP data
142     csgoDataClient = capture(pathToFileServer)
143     csgoUdpDataClient = get_udp_data(csgoDataClient)
144
```

```
145    # Extract packets by specified client and server IPs.
146    serverDataFromServer = get_pkts_by_ip(csgoUdpDataServer,serverIp,
       clientIp)
147    serverDataFromClient = get_pkts_by_ip(csgoUdpDataServer,clientIp,
       serverIp)
148    clientDataFromServer = get_pkts_by_ip(csgoUdpDataClient,serverIp,
       clientIp)
149    clientDataFromClient = get_pkts_by_ip(csgoUdpDataClient,clientIp,
       serverIp)
150
151    # Get a list of lists of bytes per second for the game data
152    serverDataFromServerBytesPerSecond = list_of_bytes_per_second(
       serverDataFromServer)
153    serverDataFromClientBytesPerSecond = list_of_bytes_per_second(
       serverDataFromClient)
154    clientDataFromServerBytesPerSecond = list_of_bytes_per_second(
       clientDataFromServer)
155    clientDataFromClientBytesPerSecond = list_of_bytes_per_second(
       clientDataFromClient)
156
157
158    # Lastly, loop through the list of lists to get the number of bytes
        each second and write it to a txt file.
159    # The txt file will be written to the specified path with the run
       number in the end of it.
160    for listOfBytes in serverDataFromServerBytesPerSecond:
161        write_single_variable_to_txt(pathServerDataFromServer,
       listOfBytes, iteration)
162
163    for listOfBytes in serverDataFromClientBytesPerSecond:
164        write_single_variable_to_txt(pathServerDataFromClient,
       listOfBytes, iteration)
165
166    for listOfBytes in clientDataFromServerBytesPerSecond:
167        write_single_variable_to_txt(pathClientDataFromServer,
       listOfBytes, iteration)
168
169    for listOfBytes in clientDataFromClientBytesPerSecond:
170        write_single_variable_to_txt(pathClientDataFromClient,
       listOfBytes, iteration)
```

Listing A.9: Processing pcap files

A.2.2.2 Plot

```python
import json
import os
import signal
import statistics
import matplotlib.pyplot as _plot
import numpy as np
import scipy.signal as sc
import pandas as pd
import statistics


#############################
#######Helper functions######
#############################
def return_minecraft_psping_measurment_list(path):
    file = open(path, "r")
    list = []
    for i in file:
        value = i.strip("\n")
        if(float(value) < 250): # filter out outliers
            list.append(float(value))
    return list


def return_minecraft_tshark_measurmentlist(path):
    file = open(path, "r")
    list = []
    lines = file.readlines()
    for i in lines:
        if float(i.strip("\n")) < 130:
            list.append(float(i.strip("\n")))
        else:
            list.append(float(80))
    return list


def psping_terrestrial_minecraft(path):
    file = open(path, "r")
    lines = file.readlines()
    list = []
    for line in lines:
        list.append(float(line.strip("\n")))
    file.close()
```

```python
41
42      return list
43
44  def tshark_terrestiral_minecraft(path):
45      file = open(path, "r")
46      lines = file.readlines()
47      list = []
48      for line in lines:
49          list.append(float(line.strip("\n")))
50      file.close()
51
52      return list
53
54  def return_psping_measurment_list_from_minecraft_runs(path):
55      arr = os.listdir(path)
56      tcpping_list = []
57      for i in arr:
58          file = open(f"{path}/{i}", "r")
59          list = []
60          for i in file:
61              value = i.strip("\n")
62              if(float(value) < 250):
63                  list.append(float(value))
64          tcpping_list.append(list)
65      return tcpping_list
66
67
68  def return_spp_measurment_list_from_minecraft_runs(path):
69      arr = os.listdir(path)
70      list = []
71      for i in arr[7:]:
72          file = open(f"{path}/{i}", "r")
73          lines = file.readlines()
74          list = []
75          for line in lines:
76              list.append(float(line.strip("\n")))
77
78          list.append(list)
79      return list
80
81  def return_csgo_psping_measurment_list(path):
82      arr = os.listdir(path)
83      tcpping_list = []
```

```python
84      for i in arr:
85          file = open(f"{path}/{i}", "r")
86          list = []
87          for i in file:
88              value = i.strip("\n")
89              if(float(value) < 250):
90                  list.append(float(value))
91          tcpping_list.append(list)
92      return tcpping_list
93
94
95  def return_csgo_spp_measurment_list(path):
96      arr = os.listdir(path)
97      tcpping_list = []
98      for i in arr:
99          file = open(f"{path}/{i}", "r")
100         list = []
101         for i in file:
102             value = i.strip("\n")
103             if round(float(value[-9:-1])*1000, 2) < 250:
104                 list.append(round(float(value[-9:-1])*1000, 2))
105         tcpping_list.append(list)
106     return tcpping_list
107
108 def get_weather_from_cbr_run(path):
109     file = open(path, "r")
110     line = file.readlines()
111     list = []
112     counter = 1
113     for i in line:
114         if counter % 2 == 0:
115             a = i.split("\t")
116             list.append(int(a[0]))
117         counter += 1
118     return list
119
120 def box_plot(data, edge_color, fill_color):
121     bp = _plot.boxplot(data, whis=[10,90],patch_artist=True, showfliers
        =False,showmeans=True)
122
123     for element in ['boxes', 'whiskers', 'fliers', 'means', 'medians',
        'caps']:
124         _plot.setp(bp[element], color=edge_color)
```

```python
125
126     for patch in bp['boxes']:
127         patch.set(facecolor=fill_color)
128
129     return bp
130
131 def CSGO_TCPping_list(path):
132     file = open(path, "r")
133     tcpping_list = []
134     for i in file:
135         value = i.strip("\n")
136         if(float(value) < 250):
137             tcpping_list.append(float(value))
138
139     y = np.array(tcpping_list)
140     return y
141
142 def get_packet_loss_percent(clientfile, serverfile):
143     clientFile_downlink = open(clientfile, "r")
144     serverFile_uplink = open(serverfile, "r")
145
146     server_lines = serverFile_uplink.readlines()
147     client_lines = clientFile_downlink.readlines()
148
149     client_list = []
150     server_list = []
151
152     for i in client_lines:
153         i.strip("\n")
154         if int(i) > 50:
155             client_list.append(int(i))
156         else:
157             client_list.append(64)
158
159     for i in server_lines:
160         i.strip("\n")
161         if int(i) > 50:
162             server_list.append(int(i))
163         else:
164             server_list.append(64)
165
166     packet_loss_list = []
167     counter = 0
```

```
168    num_of_packets_sent = 0
169    packet_loss = 0
170
171    while counter < 299:
172        for i in range(10): ## Adjust this range to set window length.
173            packet_loss += client_list[counter] - server_list[counter]
174            num_of_packets_sent += server_list[counter]
175            counter += 1
176        pl_percent = round(float(packet_loss/num_of_packets_sent*100),
    2)
177        if pl_percent < 0:
178            packet_loss_list.append(0.0)
179        else:
180            packet_loss_list.append(pl_percent)
181        num_of_packets_sent = 0
182        packet_loss = 0
183
184    return(packet_loss_list)
185
186
187 ############################
188 ######Plot functions#######
189 ############################
190
191 ####### Baseline
    ################################################################################

192
193 def baseline_single_run_to_starlink_gateWay(path): # Create RTT plots
    for a single run with baseline measurment to starlink gateway
194    runNumber = "20"
195    file = open(path, "r")
196    tcpping_list = []
197    for i in file.readlines()[1:]:
198        value = i.strip("\n")
199        if(float(value) < 250):
200
201            tcpping_list.append(round(float(value),2))
202
203    smoothendGraph = sc.savgol_filter(tcpping_list, window_length=21,
    polyorder=3, mode="nearest")
204
205    _plot.plot(tcpping_list)
```

```python
206         _plot.plot(smoothendGraph,"r-",lw=1 )
207         _plot.legend(["Raw Ping data", "Smoothed data"])
208         _plot.ylabel("RTT (ms)")
209         _plot.xlabel("Time (s)")
210         _plot.title("RTT to Starlink gateway")
211         _plot.xlim(0, 1000)
212         _plot.grid()
213         _plot.show()
214
215 def baseline_all_runs_to_starlink_gateway_box_plot(path): #Create RTT
        plots for all baseline runs to starlink gateway
216         pingsTotalList = []
217         dateList = []
218         count = 0
219         TotalCount = 0
220
221         for i in range(0,32):
222             file = open(f"{path}/{i}", "r") # open files
223             lines = file.readlines()
224             pings = []
225
226             for line in lines[1:]:
227                 TotalCount += 1
228                 splittedLine = line.strip("\n")
229                 if float(splittedLine) < 250:
230                     pings.append(float(splittedLine))
231
232                 if float(splittedLine) > 100:
233                     count += 1
234
235             pingsTotalList.append(pings)
236
237             for data in lines[0:1]:
238                 splittedData = data.split("\t")
239                 date = splittedData[0]
240                 dateList.append(date[11:19])
241             file.close()
242         print(f"Count: {count}, TotalCount = {TotalCount}")
243         print(dateList)
244         _plot.boxplot(pingsTotalList,whis=[10,90],showfliers=False,
        showmeans=True)
245         _plot.xticks(np.arange(1, len(dateList)+1), dateList, rotation=90)
246         _plot.xlabel("Time")
```

```python
247    _plot.ylabel("RTT (ms)")
248    _plot.ylim(23,55)
249    _plot.title("RTT to Starlink gateway")
250    _plot.show()
251
252
253 ##### CsGo
       ##########################################################################
254 def combine_psping_and_spp_all_csgo_runs():  # Combine RTT measurments
       from CSGO runs
255    pspingList = return_csgo_psping_measurment_list("Ping")
256    sppList = return_csgo_spp_measurment_list()
257
258    fig, (ax1, ax2) = _plot.subplots(1, 2)
259
260    ax1.boxplot(pspingList, whis=[10,90], showfliers=False, showmeans=
       True)
261    ax1.set_title("CSGO runs RTT measured with psping")
262    ax1.set_ylim(70,100)
263    ax1.set_xlabel("Run number")
264    ax1.set_ylabel("RTT (ms)")
265
266    ax2.boxplot(sppList, whis=[10,90], showfliers=False, showmeans=
       True)
267    ax2.set_title("CSGO runs RTT measured with SPP")
268    ax2.set_ylim(70,100)
269    ax2.set_xlabel("Run number")
270    ax2.set_ylabel("RTT (ms)")
271
272    _plot.show()
273
274 def CSGo_starlink_spp_tcpping_loss_plot(path, path2,path3):
275
276    spp_ping_list = []
277
278    file = open(path, "r")
279
280    lines = file.readlines()
281    for line in lines:
282        spp_ping_list.append(round(float(line[-9:-1])*1000, 2))
283
284    _plot.rcParams['font.size'] = 13
```

```
285
286    y1 = np.array(spp_ping_list)
287    x1 = np.arange(0, 300, 50/2527)
288    yhat = signal.savgol_filter(y1, window_length=501, polyorder=3,
       mode="nearest")
289
290    fig, (ax1, ax2) = _plot.subplots(2, 1)
291
292    y3 = packet_loss_percent(path2,
293                             path3)
294    x3 = np.arange(5, 305, 10)
295
296    ax3 = ax1.twinx()
297    ax3.plot(x3, y3, "o", markersize="4", color="red", )
298    ax3.set_ylim(0, 13)
299    ax3.set_ylabel("Packet loss(%)")
300
301    ax1.plot(x1, y1, "-", markersize="5", label="SPP")
302    ax1.plot(x1, yhat, "-", lw=2, color="lime")
303    ax1.plot(x3, y3, "o", markersize="4", color="red", )
304    ax1.set_ylabel("RTT (ms)", fontsize=13)
305    ax1.grid()
306    ax1.set_xlim(0, 300)
307    ax1.set_ylim(40, 170)
308    ax1.legend(["Raw SPP data", "SPP data smoothed", "Average loss
       every 10 s"], loc="upper center", fontsize=13)
309    ax1.set_xlabel("Time (s)", fontsize=13)
310    ax1.set_title("CSGO RTT SPP", fontsize=13)
311
312    y2 = CSGO_TCPping_list("psping27-3-16-11_9.txt")
313    x2 = np.arange(0, len(y2))
314    yhat2 = signal.savgol_filter(y2, window_length=22, polyorder=3,
       mode="nearest")
315
316    ax3 = ax2.twinx()
317    ax3.plot(x3, y3, "o", markersize="4", color="red")
318    ax3.set_ylim(0, 13)
319    ax3.set_ylabel("Packet loss(%)")
320
321    ax2.plot(x2, y2, "-", markersize=5)
322    ax2.plot(x2, yhat2, "-",lw=2, color="lime")
323    ax2.plot(x3, y3, "o", markersize="4", color="red")
324    ax2.set_ylabel("RTT (ms)", fontsize=13)
```

```python
325     ax2.set_ylim(40,170)
326     ax2.set_xlim(0, 300)
327     ax2.grid()
328     ax2.legend(["Raw TCP ping data", "TCP ping data smoothed", "Average
         loss every 10 s"], loc="upper center", fontsize=13)
329     ax2.set_xlabel("Time (s)", fontsize=13)
330     ax2.set_title("CSGO RTT TCP ping", fontsize=13)
331
332     _plot.subplots_adjust(hspace=0.5)
333     _plot.show()
334
335 def CSGO_terrestrial_spp_tcpping_plot(path):
336     tcpping_list = []
337
338     file = open(path, "r")
339
340     lines = file.readlines()
341     for line in lines:
342         tcpping_list.append(round(float(line[-9:-1])*1000, 2))
343
344     _plot.rcParams['font.size'] = 13
345
346     y1 = np.array(tcpping_list)
347     x1 = np.arange(0, 300, 100/6353)
348     yhat = signal.savgol_filter(y1, window_length=501, polyorder=3,
         mode="nearest")
349
350     fig, (ax1, ax2) = _plot.subplots(2, 1)
351
352     ax1.plot(x1, y1, "-", markersize="5", label="SPP")
353     ax1.plot(x1, yhat, "-", lw=2, color="lime")
354     ax1.set_ylabel("RTT (ms)", fontsize=13)
355     ax1.grid()
356     ax1.set_xlim(0, 300)
357     ax1.set_ylim(0, 20)
358     ax1.legend(["Raw SPP data", "SPP data smoothed", "Average loss
         every 10 s"], loc="upper center", fontsize=13)
359     ax1.set_xlabel("Time (s)", fontsize=13)
360     ax1.set_title("CSGO RTT SPP", fontsize=13)
361
362     y2 = CSGO_TCPping_list("psping1CSGOClient.txt")
363     x2 = np.arange(0, len(y2))
364     yhat2 = signal.savgol_filter(y2, window_length=22, polyorder=3,
```

```python
          mode="nearest")

      ax2.plot(x2, y2, "-", markersize=5)
      ax2.plot(x2, yhat2, "-",lw=2, color="lime")
      ax2.set_ylabel("RTT (ms)", fontsize=13)
      ax2.set_ylim(0,20)
      ax2.set_xlim(0, 300)
      ax2.grid()
      ax2.legend(["Raw TCP ping data", "TCP ping data smoothed", "Average
       loss every 10 s"], loc="upper center", fontsize=13)
      ax2.set_xlabel("Time (s)", fontsize=13)
      ax2.set_title("CSGO RTT TCP ping", fontsize=13)

      _plot.subplots_adjust(hspace=0.5)
      _plot.show()

def CSGO_downlink_starlink_terrestrial_rtt_packetloss_plot(client_path,
       server_path, terr_path, terr_ping_path, sl_ping_path,
      client_downlink_path, server_uplink_path, terr_downlink_path,
      terr_uplink_path):
      clientFile = open(client_path, "r")
      serverFile = open(server_path, "r")

      terr_client = open(terr_path, "r")
      terr_ping = open(terr_ping_path, "r")
      sl_ping = open(sl_ping_path,"r")

      lines_client = clientFile.readlines()
      lines_server = serverFile.readlines()
      lines_terr = terr_client.readlines()
      lines_terr_ping = terr_ping.readlines()
      lines_sl_ping = sl_ping.readlines()

      nyList1 = []
      nyList2 = []
      terr_list = []
      terr_ping_list = []
      sl_ping_list = []

      for i in lines_client:
          i.strip("\n")
          if int(i) > 50:
              nyList1.append(float(i)/1000*8)
```

```python
        else:
            nyList1.append(64)

    x1 = np.arange(0, len(nyList1), 1)
    y1 = np.array(nyList1)

    for i in lines_server:
        i.strip("\n")
        if int(i) > 50:
            nyList2.append(float(i)/1000*8)
        else:
            nyList2.append(64)

    mean_client = round(statistics.mean(nyList1))

    for i in lines_terr:
        i.strip("\n")
        terr_list.append(float(i)/1000*8)

    for i in lines_terr_ping:
        i.strip("\n")
        terr_ping_list.append(float(i))

    for i in lines_sl_ping:
        i.strip("\n")
        sl_ping_list.append(float(i))

    _plot.rcParams['font.size'] = 13

    fig, ((ax1, ax4),(ax2, ax3),(ax6, ax5)) = _plot.subplots(3, 2,
    sharex=True)
    mean_terr = round(statistics.mean(terr_list))

    ax1.plot(x1, y1)

    ax2.set_xlabel("Time(s)", fontsize=13)
    ax1.set_ylabel("Kbit/s", fontsize=13)

    ax1.legend([f"Avg recieved {mean_client} Kbit/s"], fontsize=13, loc
    ='upper right')
    ax1.set_title("CSGO Starlink downlink", fontsize=13)
    ax1.set_ylim(151, 550)
    ax1.grid()
```

```python
444
445     y2 = packet_loss_percent(client_downlink_path,
446                              server_uplink_path)
447     x2 = np.arange(5, 305, 10)
448
449     ax2.plot(x2, y2, "ro", markersize="3")
450     ax2.legend(["Packet loss every 10s"], fontsize=13, loc='upper right
        ')
451     ax2.set_ylim(0, 4)
452     ax2.set_xlim(0, 300)
453     ax2.set_ylabel("Packet loss(%)", fontsize=13)
454     ax2.grid()
455
456     y3 = packet_loss_percent(terr_downlink_path,
457                              terr_uplink_path)
458     x3 = np.arange(5, 305, 10)
459
460     y4 = np.array(terr_list)
461     x4 = np.arange(0, 300)
462
463     ax3.plot(x3, y3, "ro", markersize="3")
464     ax3.set_ylim(0, 4)
465     ax3.set_ylabel("Packet loss(%)", fontsize=13)
466     ax3.legend(["Packet loss every 10s"], fontsize=13, loc='upper right
        ')
467     ax3.grid()
468     ax3.set_xlabel("Time(s)", fontsize=13)
469
470     ax4.set_title("CSGO Terrestrial downlink", fontsize=13)
471     ax4.set_ylabel("Kbit/s", fontsize=13)
472     ax4.plot(x4, y4)
473     ax4.legend([f"Avg recieved {mean_terr} Kbit/s"], fontsize=13, loc='
        upper right')
474     ax4.set_ylim(151,550)
475     ax4.set_xlim(0,300)
476     ax4.grid()
477
478     y5 = np.array(terr_ping_list)
479     x5 = np.arange(0, 300)
480
481     ax5.plot(x5, y5)
482     ax5.set_ylabel("RTT(ms)", fontsize=13)
483     ax5.set_xlabel("Time(s)", fontsize=13)
```

```python
484      ax5.legend(["TCP ping 1s interval"])
485      ax5.set_ylim(0, 9)
486      ax5.grid()
487
488      y6 = np.array(sl_ping_list)
489      x6 = np.arange(0, 300)
490
491      ax6.plot(x6, y6)
492      ax6.set_ylabel("RTT(ms)", fontsize=13)
493      ax6.set_xlabel("Time(s)", fontsize=13)
494      ax6.legend(["TCP ping 1s interval"])
495      ax6.grid()
496
497      _plot.subplots_adjust(hspace=0)
498      _plot.show()
499
500  def CSGO_compare_spp_tcpping(sppPath, tcppingPath):
501
502      spp_ping_list = []
503      spp_file = open(sppPath, "r")
504
505      lines = spp_file.readlines()
506      for line in lines:
507          spp_ping_list.append(round(float(line[-9:-1])*1000, 2))
508
509      tcpping_file = open(tcppingPath, "r")
510
511      tcpping_list = []
512      for i in tcpping_file:
513          value = i.strip("\n")
514          if(float(value) < 250):
515              tcpping_list.append(float(value))
516
517      y1 = np.array(spp_ping_list)
518      x1 = np.arange(0, 300, 50/2527)
519      yhat1 = signal.savgol_filter(y1, window_length=1000, polyorder=3,
         mode="nearest")
520
521      x2 = np.arange(0, len(tcpping_list))
522      y2 = np.array(tcpping_list)
523      yhat2 = signal.savgol_filter(y2, window_length=22, polyorder=3,
         mode="nearest")
524
```

```
525    _plot.plot(x1, yhat1, "r-", lw=2)
526    _plot.plot(x2, yhat2, "b-", lw=2)
527    _plot.legend(["SPP data smoothed", "TCP ping data smoothed"], loc="
       upper left", fontsize=14)
528    _plot.xlabel("Time (s)")
529    _plot.ylabel("RTT (ms)")
530    _plot.xlim(0,300)
531    _plot.ylim(70, 105)
532
533    _plot.grid()
534    _plot.show()
535
536
537 ##### Minecraft runs
       ################################################################################
538
539 def combine_minecraft_single_run_rtt_plots(psPingPath, TsharkPath): #
       Create RTT plots for a single run with minecraft measurments with
       different RTT measurment tools
540    psPingList = return_minecraft_psping_measurment_list(psPingPath)
541    tsharkList = return_minecraft_tshark_measurmentlist(TsharkPath)
542
543    ## Uncomment if wanting terrestrial data
544    #tsharkList = RTTTerrestiralMinecraft()
545    #tsharkList = pspingTerrestrialMinecraft()
546
547    filteredPsPing = sc.savgol_filter(psPingList, window_length=11,
       polyorder=3, mode="nearest")
548
549    filteredTshark = sc.savgol_filter(tsharkList, window_length=451,
       polyorder=3, mode="nearest")
550
551    x2 = np.arange(0,300,300/len(tsharkList))
552
553    medianTCP = statistics.median(tsharkList)
554    print(medianTCP)
555
556    # create subplots with the two lists
557    fig, (ax1, ax2) = _plot.subplots(2)
558
559    ax1.plot(psPingList)
560    ax1.plot(filteredPsPing,"r-",lw=1 )
```

```python
561      ax1.set_title("Minecraft RTT PsPing")
562      ax1.legend(["Psping raw data ","Smoothed data"],loc ="upper right")
563      ax1.set_ylim(0,140)
564      ax1.set_xlabel("Time (s)")
565      ax1.set_ylabel("RTT (ms)")
566      ax1.grid(True)
567      ax1.set_xlim(0,300)
568
569      ax2.plot(x2,tsharkList)
570      ax2.plot(x2,filteredTshark,"r-",lw=1 )
571
572      ax2.set_title("Minecraft RTT TcpPing")
573      ax2.set_ylim(0,140)
574      ax2.legend(["TCP raw data","Smoothed data"],loc ="upper right")
575      ax2.set_xlabel("Time (s)")
576      ax2.set_ylabel("RTT (ms)")
577      ax2.grid(True)
578      ax2.set_xlim(0,300)
579      _plot.show()
580
581
582  def combine_spp_and_psping_minecraft_runs(psPingPath, TsharkPath):  #
         Combine RTT measurments from Minecraft runs
583      pspingList = return_psping_measurment_list_from_minecraft_runs(
         psPingPath)
584      sppList = return_spp_measurment_list_from_minecraft_runs(TsharkPath
         )
585
586      fig, (ax1, ax2) = _plot.subplots(1, 2)
587
588      ax1.boxplot(pspingList, whis=[10,90], showfliers=False, showmeans=
         True)
589      ax1.set_title("Minecraft runs RTT measured with psping")
590      ax1.set_ylim(40,100)
591      ax1.set_xlabel("Run number")
592      ax1.set_ylabel("RTT (ms)")
593
594      ax2.boxplot(sppList, whis=[10,90], showfliers=False, showmeans=
         True)
595      ax2.set_title("Minecraft runs RTT measured from TCP packages")
596      ax2.set_ylim(40,100)
597      ax2.set_xlabel("Run number")
598      ax2.set_ylabel("RTT (ms)")
```

```python
599
600      _plot.show()
601
602  def combine_tcpping_and_psping_minecraft_starlink_and_terrestrial():#
         Combine Terrestrial and Starlink RTT measurments when gaming on
         Minecraft
603      pspingListStarlink = return_minecraft_psping_measurment_list()
604      pspingListTerrestrial = psping_terrestrial_minecraft()
605
606      tcpPingStarlink = return_minecraft_tshark_measurmentlist()
607      tcpPingTerrestrial = tshark_terrestiral_minecraft()
608
609      smoothendPsPingStarlink = sc.savgol_filter(pspingListStarlink,
         window_length=11, polyorder=3, mode="nearest")
610
611      smoothendPsPingTerrestrial = sc.savgol_filter(pspingListTerrestrial
         , window_length=11, polyorder=3, mode="nearest")
612
613      smoothendTcpPingStarlink = sc.savgol_filter(tcpPingStarlink,
         window_length=451, polyorder=3, mode="nearest")
614
615      smoothendTcpPingTerrestrial = sc.savgol_filter(tcpPingTerrestrial,
         window_length=451, polyorder=3, mode="nearest")
616
617      x1 = np.arange(0,300,300/len(smoothendTcpPingStarlink))
618      x2 = np.arange(0,300,300/len(smoothendTcpPingTerrestrial))
619
620      fig, (ax1, ax2) = _plot.subplots(1, 2)
621
622      ax1.plot(x1,smoothendTcpPingStarlink)
623      ax1.plot(x2,smoothendTcpPingTerrestrial,"r-",lw=1 )
624      ax1.legend(["Starlink", "Terrestrial"])
625      ax1.set_title("RTT TcpPing")
626      ax1.set_ylim(0,100)
627      ax1.set_xlabel("Time (s)")
628      ax1.set_ylabel("RTT (ms)")
629      ax1.grid(True)
630      ax1.set_xlim(0,300)
631
632      ax2.plot(smoothendPsPingStarlink)
633      ax2.plot(smoothendPsPingTerrestrial,"r-",lw=1 )
634      ax2.legend(["Starlink", "Terrestrial"])
635      ax2.set_title("RTT PsPing")
```

```python
636    ax2.set_ylim(0,100)
637    ax2.set_xlabel("Time (s)")
638    ax2.set_ylabel("RTT (ms)")
639    ax2.grid(True)
640    ax2.set_xlim(0,300)
641
642    _plot.show()
643
644
645 #### Iperf CBR
    ###########################################################################################

646
647 def create_cbr_box_plot_with_clod_coverage(path):  # Create CBR box
    plot with cloud coverage
648    file = open(path, "r")
649
650    line = file.readlines()
651
652    totalList = []
653    counter = 0
654    intList = []
655    intss = 1
656
657    for i in line:
658        if counter % 2 == 0:
659            intList.append(intss)
660            intss += 1
661            a = i.strip("\n")
662            nylist = json.loads(a)
663            totalList.append(nylist)
664        counter += 1
665
666    yrList = get_weather_from_cbr_run()
667
668    x = np.arange(1, len(totalList)+1, 1)
669
670    fig, ax1 = _plot.subplots()
671
672    dateList = []
673    for i in range(len(totalList)):
674
675        if i > 15:
```

```python
676              dateList.append(int(09.00 + i - 24))

677

678          else:

679              dateList.append(int(09.00 + i))

680

681      ax2 = ax1.twinx()

682      ax1.boxplot(totalList ,whis=[10,90],showfliers=False, showmeans=
         True)

683      ax1.set_title("Constant bitrate with 30 Mbps bitrate")

684

685      ax2.plot(x,yrList,".", color='purple')

686      ax2.set_ylabel("Cloud cover")

687      ax1.set_xticklabels(dateList, ha="right")

688

689      ax1.set_ylabel("Packet loss % ")

690      ax1.set_xlabel("Time at day")

691      _plot.show()

692

693  ##### Uplink & Downlink
     ###############################################################################

694

695  def byte_rate_all_runs_minecraft(serverUplinkPath, serverDownlinkPath):
          # Create box plot of byte rate for all runs of Minecraft

696      serverUplink = os.listdir(serverUplinkPath)

697      serverDownlink = os.listdir(serverDownlinkPath)

698

699      serverUploadTotalList = []

700      serverDownloadTotalList = []

701

702      for i in range(len(serverUplink)):

703

704          serverUplinkFile = open(f"{serverUplinkPath}\{serverUplink[i]}"
         , "r")

705          serverDownlinkFile = open(f"{serverDownlinkPath}\\{
         serverDownlink[i]}", "r")

706

707          serverUplinkLines = serverUplinkFile.readlines()

708          serverDownlinkLines = serverDownlinkFile.readlines()

709          serverUplinkList = []

710          serverDownlinkList = []

711

712          for i in serverUplinkLines:
```

```
713                i.strip("\n")
714                serverUplinkList.append(8*(int(i)/1000))
715
716
717        for i in serverDownlinkLines:
718                i.strip("\n")
719
720                serverDownlinkList.append(8*(int(i)/1024))
721
722        serverUploadTotalList.append(serverUplinkList)
723        serverDownloadTotalList.append(serverDownlinkList)
724
725    _plot.boxplot(serverUploadTotalList,whis=[10,90],showfliers=False,
       showmeans=True)
726
727    _plot.title("Minecraft Downlink")
728    _plot.xlabel("Run number")
729    _plot.ylabel("Kbit/s")
730    _plot.show()
731
732
733 def packet_rate_all_runs_minecraft(serverUplinkPath, serverDownlinkPath
       ):
734    serverUplink = os.listdir(serverUplinkPath)
735    serverDownlink = os.listdir(serverDownlinkPath)
736
737    serverUploadTotalList = []
738    serverDownloadTotalList = []
739
740    for i in range(len(serverUplink)):
741        serverUplinkFile = open(f"{serverUplinkPath}\\{serverUplink[i]}
       ", "r")
742        serverDownlinkFile = open(f"{serverDownlinkPath}\\{
       serverDownlink[i]}", "r")
743
744        serverUplinkLines = serverUplinkFile.readlines()
745        serverDownlinkLines = serverDownlinkFile.readlines()
746        serverUplinkList = []
747        serverDownlinkList = []
748
749        for i in serverUplinkLines:
750                i.strip("\n")
751                serverUplinkList.append(int(i))
```

115

```
752
753        for i in serverDownlinkLines :
754            i.strip("\n")
755            serverDownlinkList.append(int(i))
756
757        serverUploadTotalList.append(serverUplinkList)
758        serverDownloadTotalList.append(serverDownlinkList)
759
760    fig, ax = _plot.subplots()
761
762    bp1 = box_plot(serverUploadTotalList, 'black', 'lightgreen')
763    bp2 = box_plot(serverDownloadTotalList, 'black', 'lightblue')
764
765    ax.legend([bp1["boxes"][0], bp2["boxes"][0]], ['Downlink', 'Uplink'
       ],loc='upper right')
766
767    ax.set_title('Minecraft Packet rate')
768    ax.set_ylim(20,370)
769    ax.set_xlabel('Run number')
770    ax.set_ylabel('Packets/s')
771    _plot.show()
```

Listing A.10: Script for making plots

A.2.2.3 Satellite distance calculation

```
1  import ast
2  import math
3  from setup.config import LATITUDE, LONGTIDUDE, ALTITUDE
4
5  def calculate_distance(satellite_latitude, satellite_longtitude,
       satellite_altitude):
6
7      # convert longitude and latitude to radians
8      converted_latitude = math.radians(LATITUDE)
9      converted_longitude = math.radians(LONGTIDUDE)
10     converted_satellite_latitude = math.radians(satellite_latitude)
11     converted_satellite_longtitude = math.radians(satellite_longtitude)
12
13     # Using Haversine formula to calculate the great circle distance
14     line_1 = math.sin((converted_satellite_latitude -
```

```python
      converted_latitude) / 2) ** 2 + math.cos(converted_latitude) * math
      .cos(converted_satellite_latitude) * math.sin((
      converted_satellite_longtitude - converted_longitude) / 2) ** 2

      line_2 = 2 * math.atan2(math.sqrt(line_1), math.sqrt(1 - line_1))

      radius_earth = 6371  # Radius of earth in km
      distance_earth = radius_earth * line_2


      # Calculate distance from earth to satellite
      radius_earth = 6371 + ALTITUDE  # Radius of the Earth plus altitude
       of first point
      radius_satellite = radius_earth + satellite_altitude  # Radius of
      the satellite plus altitude of second point
      distance_space = math.sqrt(radius_earth ** 2 + radius_satellite **
      2 - 2 * radius_earth * radius_satellite * math.cos(distance_earth))

      return distance_space

def get_sat(path): # get overview over all satellites in the file that
    is closest

      file = open(path, "r")

      lines = file.readlines()



      distanseList = []
      nameList = []
      listOverSatelliteNames = []

      for index in range(len(lines)):
          findAboveIndex = lines[index].find("above")

          satelliteList = lines[index][findAboveIndex+8:-2]
          res = ast.literal_eval(satelliteList)

          if float(res[i]["satlat"]) < LATITUDE:
              distanse = calculate_distance(res[i]["satlat"], res[i]["
    satlng"], res[i]["satalt"])
              distanseList.append(distanse)
              nameList.append(res[i]["satname"])
```

```
50            if distanse < lowestDistanse:
51                lowestDistanse = distanse
52                lowestSatname = res[i]["satname"]
53                listOverSatelliteNames.append(f"{res[i]['satname']} +{
     index} ")
54            distanseList.sort()
55
56        distanseRef = 1000000
57        satname = ""
58
59        for i in range(len(distanseList)):
60            if distanseList[i] < distanseRef:
61                distanseRef = distanseList[i]
62                satname = nameList[i]
63
64        listOverSatelliteNames.append(f"{satname} is {distanseRef} km
     away at time: + {index}  ")
65
66        fila = open("satellitesCalculated.txt", "w")
67
68        for i in range(len(listOverSatelliteNames)):
69            print(listOverSatelliteNames[i])
70            fila.write(listOverSatelliteNames[i] + "\n")
71
72            fila.close()
```

Listing A.11: Script for calculating satellite distance

A.2.3 Setup

```
1  from fabric import Connection
2
3  class CSGOServerCapture:
4
5      def __init__(self, duration):
6          self.duration = duration
7          self.test_option = "csgo_server_capture"
8
9
10     def server_connection(self,user,host,port,key_path):
11         with Connection(host=host, user=user, port=port, connect_kwargs
```

```python
            ={'key_filename': {key_path}}) as connection:
12              return connection


14
15      def start_csgo_capture(self, filename):
16          with self.server_connection() as sl_server:
17              sl_server.run(f'tshark -i eno1 -w /home/ss/server/TCPDUMP/
        CSGOoutput/{self.test_option}_{filename}.pcap -f "udp or tcp
        portrange 27005-27015" -a duration:{self.duration}')

18
19  class CSGOClientCapture:

20
21      def __init__(self, duration):
22          self.duration = duration
23          self.test_option = "csgo_client_capture"


25
26      def client_connection(self,host,user,port,key_path):
27          with Connection(host=host, user=user, port=port, connect_kwargs
        ={'key_filename': {key_path}}) as connection:
28              return connection


30
31      def start_csgo_capture(self, filename):
32          with self.client_connection() as sl_client:
33              sl_client.run(f'tshark -i 4 -w C:/Users/masth/Desktop/{self
        .test_option}_{filename}.pcap -f "udp or tcp portrange 27005-27015"
         -a duration:{self.duration}')

34
35  class MinecraftCapture:

36
37      def __init__(self, duration):
38          self.duration = duration
39          self.test_option = "mc_capture"

40

41
42      def server_connection(self,host,user,port,key_path):
43          with Connection(host=host, user=user, port=port, connect_kwargs
        ={'key_filename': {key_path}}) as connection:
44              return connection

45

46
47      def start_mc_capture(self, filename):
```

```
48          with self.server_connection() as sl_server:
49              sl_server.run(f'tshark -i eno1 -w /home/ss/server/TCPDUMP/
      output/{self.test_option}_{filename}.pcap -f "tcp port 27015" -a
      duration:{self.duration}')
```

Listing A.12: Python script to capture network traffic

```
1  IPERF3_PORT = 27050
2  IPERF_HOST_IP = '152.94.120.57'
3  IPERF_CBR_PATH = 'ENTER PATH TO IPERF CBR LOGS HERE'
4
5  YR_PATH = 'ENTER PATH FOR YR CAPTURE FILE HERE'
6  YR_API_URL = "https://yr.no/api/v0/locations/10-991227/forecast?"
7
8  LOG_PATH = 'ENTER PATH TO LOGS HERE'
9
10 SERVER_IP = '152.94.120.57'
11 CLIENT_IP = '192.168.1.154'
12
13 CS_PORT = '27015'
14 MINECRAFT_PORT = '27015'
15
16 LONGTIDUDE = 5.733107
17 LATITUDE = 58.969975
18 ALTITUDE = 63.0
19 DEG = 65
20 N2YO_API_URL = 'https://api.n2yo.com/rest/v1/satellite/'
21 STARLINK_CATEGORY = 52
```

Listing A.13: Python config

```
1  from fabric import Connection
2  from config import CLIENT_IP
3
4  def ping_client_server(target,user, duration, filename, port):
5      with Connection(host=CLIENT_IP, user=user, port=port,
      connect_kwargs={'key_filename': 'ENTER KEY PATH'}) as connection:
6          connection.run(f"python3 psping.py {target}:{port} {duration} {
```

```
     filename}")
```

Listing A.14: Python script to ssh to client

```
1  from fabric import Connection
2
3  class CSGOServer:
4
5      def __init__(self, game_mode, map, tick_rate=64):
6          self.game_mode = game_mode
7          self.map = map
8          self.tick_rate = tick_rate
9
10     def server_connection(self,host,user,port,key_path):
11         with Connection(host=host, user=user, port=port, connect_kwargs
    ={'key_filename': {key_path}}) as connection:
12             return connection
13
14
15     def start_csgo_server(self):
16         with self.server_connection() as sl_server:
17             with sl_server.cd("server"):
18                 sl_server.run(f"bash csgostart.bash {self.map}")
19
20
21     def stop_csgo_server(self):
22          pass
23
24  class MinecraftServer:
25
26      def __init__(self) -> None:
27          pass
28
29      def server_connection(self,host,user,port,key_path):
30          with Connection(host=host, user=user, port=port, connect_kwargs
    ={'key_filename': {key_path}}) as connection:
31              return connection
32
33
34      def start_mc_server(self):
35          with self.server_connection() as sl_server:
```

```
36          with sl_server.cd("mcjaca"):
37              sl_server.run("./mcserver start")
```

Listing A.15: Python script to connect and start game server

```
1 from config import IPERF3_PORT, IPERF_HOST_IP, IPERF_CBR_PATH
2 from loggers import log
3 import os
4
5
6 def run_iperf_cbr_udp(bandwidth, duration, filename, revert=False):
7
8     if revert:
9         log(f"Running Iperf CBR command download: iperf3 -c {
    IPERF_HOST_IP} -p {IPERF3_PORT} -b {bandwidth} -t {duration} -u -R
    --logfile {IPERF_CBR_PATH}{filename}")
10        iperf_run = os.system(f"iperf3 -c {IPERF_HOST_IP} -p {
    IPERF3_PORT} -b {bandwidth} -t {duration} -u -R --logfile {
    IPERF_CBR_PATH}{filename}")
11    else:
12        log(f"Running Iperf CBR command upload: iperf3 -c {
    IPERF_HOST_IP} -p {IPERF3_PORT} -b {bandwidth} -t {duration} -u --
    logfile {IPERF_CBR_PATH}{filename}")
13        iperf_run = os.system(f"iperf3 -c {IPERF_HOST_IP} -p {
    IPERF3_PORT} -b {bandwidth} -t {duration} -u --logfile {
    IPERF_CBR_PATH}{filename}")
```

Listing A.16: Python script to do iPerf

```
1 from os.path import exists
2 from config import LOG_PATH
3
4 import os
5
6 def log(log_string):
7     if log_string == "":
8         return
9
10    log_file = open(LOG_PATH+"logfile.log", "a+")
```

```
11    log_file.write(log_string+"\n")
12    log_file.close()
13
14
15 def clear_log():
16    if exists(LOG_PATH+"logfile.log"):
17        os.remove(LOG_PATH+"logfile.log")
```

Listing A.17: Python script to start loggers

```
1 from config import YR_PATH, YR_API_URL
2 import requests
3
4 def yr(filename, iteration):
5
6     response = requests.get(YR_API_URL).json()
7
8     cloud_value = response["shortIntervals"][0]["symbol"]["clouds"]
9     uv_value = response["shortIntervals"][0]["uvIndex"]["value"]
10    precip = response["shortIntervals"][0]["symbol"]["precip"]
11
12    file = open(YR_PATH+filename, "a+")
13
14    file.write(str(cloud_value)+"\t")
15    file.write(str(uv_value)+"\t")
16    file.write(str(precip)+"\t")
17    file.write(str(iteration)+"\n")
18    file.close()
19
20    return
```

Listing A.18: Python script for weather API request

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