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Throughput Analysis of Starlink Satellite Internet:

A Study on the Effects of Precipitation and Hourly Variability with UDP and TCP

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Abstract

Starlink is a company that provides satellite internet to customers all over the world. Starlink uses Low Earth Orbit (LEO)-satellites to connect to ground stations and antennas. This is a relatively new technology with many unexplored areas. This bachelor thesis studies how the throughput is affected in the Starlink network by precipitation (rainfall), hour-by-day, and different transport protocols. The study was conducted in Stockholm, Sweden, which has a sparse amount of satellites compared to Central Europe and the United States of America. Studies performed at this location could therefore be different from those in other parts of the world. The experiments consist of throughput measurements of the two different transport protocols Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) using the tool *iPerf3*, as well as precipitation measurements. The results of the study show how there is a notable performance hit when rainfall is present, possibly due to rain attenuation affecting the signal. The data also shows that the throughput varies during different hours of the day, and the best bitrate is received at night. It is assumed that the active user count is presumably low during the night, which results in less traffic on the network. It can also be seen that TCP is more susceptible to a low throughput due to traffic compared to UDP. This could be due to an interrupt that occurs every 15 seconds when the antennas and ground stations re-configure their route, something that the TCP is unable to handle well. The findings provide further knowledge about Starlink's performance in general but specifically in Sweden.

Keywords

Starlink, LEO-antennas, Network, TCP, UDP, Weather, Precipitation, iPerf3, Ping, Throughput, Latency, Internet Measurements.

Sammanfattning

Starlink är ett företag som tillhandahåller satellit-internet till kunder över hela världen. Starlink använder sig av satelliter i en lägre atmosfär/bana runt jorden vid namnet Low Earth Orbit-satelliter för att skicka och ta emot information från markstationer och antenner. Det är en relativt ny teknologi med många outforskade områden. Den här studien studerar hur Starlinksystemets prestanda påverkas av nederbörd (regn), tid på dygnet, samt olika transportprotokoll. Studien är genomförd i Stockholm, Sverige, som inte tillhandahåller en lika stor mängd satelliter över sig jämfört med till exempel centrala Europa eller USA. Därför kan resultatet variera mellan dessa platser. Experimentet gick ut på att mäta genomströmmningen mellan de två transportprotokollen Transmission Control Protocol (TCP) och User Datagram Protocol (UDP) med hjälp av verktyget *iPerf3*, samt att mäta nederbörden med hjälp av en regnkollektor. Resultaten visar att det finns en stor påverkan på hastighet i Starlinkens nät vid regn, där anledningen kan vara att regnet försvagar signalen. Datan visar också att genomströmmningen varierar beroende på tid på dygnet, där den bästa hastigheten uppnås på natten. Det antas att det är låg användaraktivitet på natten, vilket resulterar i lägre tryck på nätverkstrafiken. Det syns även att TCP är mer benägen att få en lägre genomströmmning än UDP. Det har förmodligen att göra med ett avbrott som sker var 15:e sekund när antennerna och markstationerna om-konfigurerar sin rutt. något som TCP kan ha svårt att hantera. Fynden ger en bättre kunskap om Starlinks prestanda allmänt, men framför allt i Sverige.

Nyckelord

Starlink, LEO-antenner, Nätverk, TCP, UDP, Väder, Nederbörd, iPerf3, Ping, Prestanda, Fördröjning, Internetmätningar.

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Céline Careau and Emil Fredriksson

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List of acronyms and abbreviations

BBR Bottleneck Bandwidth and Round-trip propagation time

FCC Federal Communications Commission

GEO Geostationary earth orbit

ICMP Internet Control Message Protocol

IP Internet Protocol

ISL Intersatellite Link

KDE Kernel density estimation

KTH Royal Institute of Technology

LEO Low Earth Orbit

MEO Medium Earth Orbit

MIMO Multiple Input and Multiple Output

NASA National Aeronautics and Space Administration

NTIA National Telecommunications and Information Administration

PoP Point of Presence

RTT Round-trip time

SMHI The Swedish Meteorological and Hydrological Institute

TCP Transmission Control Protocol

TTL Time to live

UDP User Datagram Protocol

WMO World Meteorological Organization

Chapter 1

Introduction

Starlink is a network created by SpaceX that offers internet to customers via Low Earth Orbit (LEO) satellite communication. LEO satellites are much closer to the atmosphere compared to other satellites. Sending satellites to a lower orbit is cheaper and easier, however, it limits the satellites' coverage. Starlink aims to combat the coverage limitations with the use of big satellite constellations to form a network of satellites, working together to achieve stable coverage. Over 4500 Starlink satellites can be found in the LEO as of now. OneWeb is another company that aims to provide satellite Internet as well. OneWeb makes use of GEO and LEO satellites. However, OneWeb has a limited amount of active satellites compared to Starlink. OneWeb is working with an aim towards enterprises, while Starlink is open to the public. As previously stated, the Starlink system is new territory and research is lacking in a lot of areas.

1.1 Research problem

There is a limited amount of information released from SpaceX regarding how Starlink works. The effect that the weather has on the Starlink system in Sweden remains unexplored. Previous papers have provided data on Starlink's performance through the use of TCP and UDP. However, no study has been found comparing the two protocols over the Starlink network.

This thesis will examine throughput performance on the Starlink network, how it is affected by rainfall, and how the throughput varies by hour-of-day, using two different transport protocols.

1.2 Purpose

Internet is essential in today's society because it provides economic growth, lowers the cost of health and improves the quality of education [1]. Satellite Internet systems like Starlink can reach out to the outliers in modern society with no Internet access to give them the same conditions to communicate and learn via the Internet. The purpose of this bachelor thesis is to give a broad understanding of the Starlink system by doing a performance analysis and to give some insight into what affects the throughput.

1.3 Goals

The goal of this project is to measure the Starlink network performance and analyse the results. This has been divided into the following three sub-goals:

1. Examine how Starlink throughput differs when using the two Internet transport protocols (TCP and UDP).
2. Examine how Starlink throughput is affected by precipitation (rainfall).
3. Examine how Starlink throughput varies by hour of the day.

1.4 Research Methodology

This study is based on a positivist paradigm, which means that the study is quantitative and objective[2]. This paradigm steers the study towards an experimental path where large data sets are required. The experimental research will examine different variables within- and around the Starlink system and their relationship with each other. A deductive approach will be used to conclude the research, which means that large data sets will be collected. The large data sets will, together with analysing the different variables, verify if the hypothesis is true or false.

1.5 Delimitations

The experiments conducted in the bachelor thesis are made with *iPerf3*, and validated with *Ping* and *Traceroute*, for testing network performance. Other methods have been taken into consideration, but no experiments using these methods have been conducted. An analysis of different measurement tools is an interesting idea but will not be examined in this thesis.

The study also has a delimitation that the weather data is collected from the Davis 6464 rain collector [3] only. Different ways of measuring the weather could give different results. Data from more advanced weather stations can be provided by institutions such as The Swedish Meteorological and Hydrological Institute (SMHI). Data from SMHI is only used to validate that the rain collector gives correct results. The weather data collected is only precipitation from rainfall. Snow, hail and other weather phenomena are not a part of this study and will not be taken into consideration.

1.6 Structure of the thesis

The thesis starts with an introduction in Chapter 1 which presents the topic, problem, and goals. It follows with relevant theory and a background in Chapter 2. The method in Chapter 3 describes the approach and details of the experiment. Chapter 4 presents and analyses the results obtained from the experiment. A discussion of the findings follows in Chapter 5. The final chapter is Chapter 6 concludes the thesis and proposes potential future work.

Chapter 2

Background and theory

This chapter will in detail describe relevant information that needs to be known before presenting the study. The chapter starts with Section 2.1 which describes the specifications of Starlink satellites and technology. The section is followed by Section 2.2 which brings up internet performance, and latency and presents information about the transport protocols Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). In the next section, which is Section 2.3, information is presented regarding how satellites in general work during rainfall. Section 2.4 provides facts about different measurement tools relevant to this study. After the information about the different tools has been presented, Section 2.5 follows with related work conducting similar research.

2.1 Starlink

Starlink is a network that is founded by the company SpaceX. Starlink provides internet via satellites. SpaceX proposed its first internet solution back in 2015. By 2019, the first Starlink satellites group was sent up into space, containing 60 satellites[4]. As of June 2024, the Starlink satellite network contained circa 5000 active satellites [5].

The Starlink network is the first public satellite internet service using technology unknown to many. This section covers the technology of Starlink, starting with Subsection 2.1.1 which contains information about the orbit in which Starlink satellites are located, continuing with Subsection 2.1.2 which delves into the Starlink satellite communication, followed by Sub-section 2.1.3 that presents how the Starlink connects users to the regular Internet.

Figure 2.1: The first 60 Starlink satellites placed in orbit and photographed from Earth. Photo by Marco Langbroek [6].

2.1.1 Low earth orbit satellites

At less than 1000 kilometres above the Earth, there exists an orbit called Low Earth Orbit (LEO), in which many man-made objects can be found. Other orbits such as the Medium Earth Orbit (MEO) and the Geostationary earth orbit (GEO) are positioned at a higher altitude compared to the LEO orbit. The GEO satellites give signals to a fixed position on earth since they travel around the earth at approximately 24 hours, which means that the satellites travel as fast as the earth rotates around its own axis, making their position fixed relative to earth. The GEO travels in line with the equator. Thanks to the fixed position relative to Earth, the GEO satellites offer a good and well-used method for telecommunication. Since they are far from Earth, GEO satellites also offer a large radius with coverage, but it is also difficult and expensive to send up and access these satellites [7].

Low Earth Orbit is often the preferred orbit when launching into space since it is easily accessible and does not require to be launched anywhere specific like the GEO satellites do. In the LEO, the International Space Station ISS can be found along with satellites such as the Starlink satellite constellation[7].

A satellite constellation is a net of multiple satellites out of the same or similar units that all share the same task[8]. Starlink offers satellite Internet to consumers via a LEO satellite constellation positioned at a height less than 600 km above earth[9]. The Starlink constellation works together to create internet coverage on Earth. With a short distance to Earth, there is a narrow coverage radius per satellite. This means that a Low Earth Orbit satellite constellations require more satellites to get coverage than a Geostationary earth orbit constellation does. The LEO satellite completes one lap around the earth in 90 minutes, travelling at a speed of 7.8 km per second[7].

2.1.2 Starlink communication

The satellites connect to the ground via antennas on the client side, and ground stations on the server side. A Starlink satellite has a coverage area of $379\,\mathrm{km}^2$ [10]. Due to the LEO satellites' limited coverage and high travelling speed, the satellites quickly move out of range for antennas on the ground. To connect to a satellite within range, the Starlink system performs a network reconfiguration every $15\,\mathrm{seconds}$ [11]. The user antennas and Starlink ground stations will connect to the optimal satellite for data transfer. This process introduces a short interruption. This is however a necessary procedure to utilise the satellite constellation in the best way possible.

The Starlink makes use of three different radio frequencies for communication. The National Telecommunications and Information Administration (NTIA) states that Starlink is authorised to use the Ku-band ($10.7\,\mathrm{GHz}$-$14.5\,\mathrm{GHz}$), the Ka-band (17.3-$30.0\,\mathrm{GHz}$) as well as the E-band (37.5-$51.4\,\mathrm{GHz}$) [12]. The Ku-band is used for uplink and downlink between the user antenna and the satellite. Whilst the Ka-band is used for uplink and downlink between satellite and ground station [13]. In a public note published by the Federal Communications Commission (FCC), Starlink makes use of the E-band for both earth-to-space and space-to-earth communication. It is assumed that the E-band is used between the Starlink satellite and the ground station, as this connection has a higher bandwidth requirement. The configuration of the different radio frequency bands is illustrated in Figure 2.2.

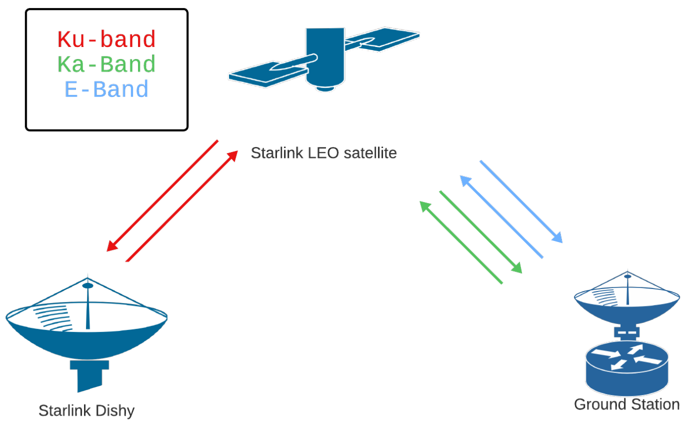


Figure 2.2: The frequency bands that Starlink use between their satellites and their ground stations/antennas.

Communication between satellites within the constellation is also possible via “Optical inter-satellite links” or Intersatellite Links (ISLs) [9]. The ISL technology enables the Starlink system to reach global coverage with less infrastructure on Earth. If no ground station is within reach of a Starlink satellite, the data will be sent via ISL to another satellite that has better connectivity to Earth. Different versions of Starlink satellites have been launched. According to National Aeronautics and Space Administration (NASA)'s records [14] the first 60 Starlink satellites called Block v0.9 lacked the hardware for Ka-band communication and ISL which the latest versions of Starlink satellites have. However, according to the Starlink website, the ISL technology has not left the testing phase [9].

Figure 2.3 shows a screenshot captured of the Starlink satellites' positions at a point in time. The density of satellites varies at different latitudes. As can be seen in the figure, there is a sparse amount of satellites over Sweden and the northern part of the globe.

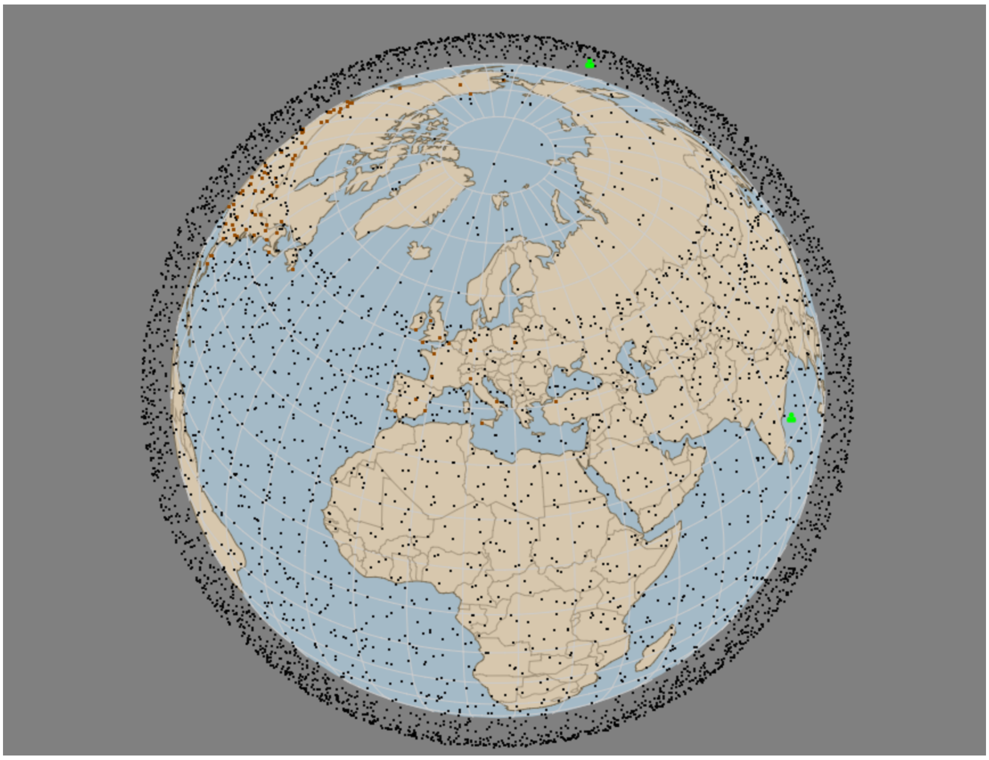


Figure 2.3: Screenshot from `https://satellitemap.space`, a satellite tracker [15] displaying Starlink satellites and their positions at a point in time. The black dots represent a Starlink satellite. The red dots represent approximate locations for Starlink ground stations. The green dots are locations for space stations

2.1.3 Starlink Connectivity

The Starlink satellites are not directly connected to the Internet. The data path visualised in Figure 2.4 contains both a ground station and a Point of Presence (PoP). The PoP acts as a bridge between the Starlink network and the rest of the Internet. The Starlink system makes use of ground stations scattered around the world to be able to connect to the satellites. The ground stations are connected via leased fibre to the closest PoP [13]. Aggregated data is then able to travel from the ground station to the PoP where the data enters the Internet as regular traffic[16]. SpaceX has not revealed where Starlink's PoPs and ground stations are located.

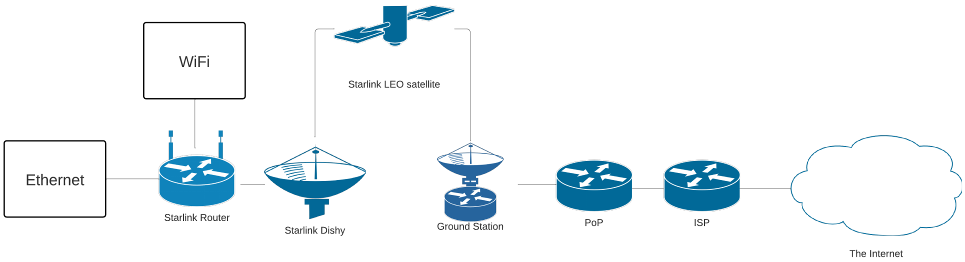


Figure 2.4: The data path for Starlink.

2.2 Internet performance

An article by CNET includes recommended internet speeds for different internet services[17], where the recommended internet speed for video calls sits around 10-20Mbit/s. Services such as video calls have become a part of internet users' daily lives, making a quality internet connection essential. The Internet Performance section includes an explanation of the two Internet quality metrics throughput and latency, as well as a comparison between the two transport protocols UDP and TCP.

2.2.1 Network Performance Metrics

Bandwidth, network speed, and throughput all measure the bitrate within a network. Because they all share the same unit (bits per second), it is easy to assume that they are the same. However, there are distinct differences between the different metrics. The network speed represents the maximum data transfer rate. No outside factors are considered when determining the speed. The bandwidth is the network channel's maximum capacity in terms of carrying data. The bandwidth, unlike the network speed, determines the bitrate based on factors such as the width of the communication channel. The bitrate for bandwidth can for example be affected depending on the amount of users that use the same network. Throughput is the real-world experience of network performance and takes network traffic and limitations into consideration when measuring the bitrate. Delays, slow data transfers, and network performance issues are examples of factors that could lower the bitrate

2.2.2 Latency

Latency is an important internet performance metric. In the context of Networking, latency is the time for data to go from point A to B. Latency is often referred to as RTT, which is the time it takes for data to be received and then returned between two nodes. Latency in the world of the Internet can vary quite a bit. Many factors may impact the latency between nodes on the Internet. Internet routing is what determines which path data is sent between two nodes. The path is dynamic and is chosen by the use of different routing algorithms. There are different tools to measure latency as well as show the routing path of the data. This will be future discussed in section 2.4.

2.2.3 Transport protocols

The two major Internet transport protocols are UDP and TCP. The two transport protocols have different approaches to sending data, which will be discussed in this section.

2.2.3.1 TCP

Transmission Control Protocol (TCP) is a connection-oriented Internet transport protocol. This implies that before data is sent, the connection between the sender and receiver has to be confirmed. The acknowledgement between the two points is referred to as a TCP handshake. The acknowledgement solves the problem of data being sent to a receiver that is not capable of receiving it. The TCP protocol re-transmits data if an error occurs. An error could for example occur due to data loss, corrupt data or data being transmitted in the wrong order. The re-transmission process can increase the total transmission time, reducing throughput. The TCP protocol has built-in flow- and congestion control services. These services are implemented to control the transfer rate between a sender and receiver and can affect the throughput. Flow control is a service allowing the transfer speed of the sender to be matched with the receiver, eliminating the possibility for the sender to overflow the data buffer of the receiver[18]. Congestion control will throttle the transmission speed when the network used between the sender and receiver experiences congestion. Congestion control can reduce transfer speed. However, without accommodating congestion when transferring data, the Internet would become overloaded with traffic [18]. Parallel *TCP* connections can be used to achieve high bandwidth utilisation. The number of parallel connections for maximum bandwidth utilisation depends on the size of the network bandwidth. If the number of TCP connections is too much for the network bandwidth, the bandwidth utilisation will be unaffected, and an increase in packet loss will instead occur [19].

2.2.3.2 UDP

User Datagram Protocol (UDP) is a transport protocol that, unlike TCP, does not require a connection to transmit data. The transmission rate when using the UDP protocol is decided by the sender. This allows high transfer speed but can cause packet loss if the receiver is incapable of receiving data at the same rate as it is sent [18].

2.3 Satellites and weather

The connection between satellites and the ground antenna is often affected by rain, and the LEO satellites are no exception [20]. The Swedish climate can vary between really warm- and cold temperatures depending on the season, but during all seasons, rain can be expected. During a year the average precipitation can reach 700 millimetres (or $700kg/m^2$ in the preferred unit of the World Meteorological Organization (WMO)), and that number is expected to rise in the future due to the higher vaporisation that comes with the warmer climate [21].

To calculate signal interference from rainfall, the ITU-R P.838-3 model [22] is often used. The ITU R model calculates the rain attenuation and contains tables of pre-calculated values to use in their formulas combined with the rain rates. How the rain affects the antenna on the ground depends on the polarisation. A horizontal polarisation occurs when an antenna is placed horizontally and causes the electromagnetic field to orient in a horizontal direction over the ground, and vice versa with the vertical polarisation [23]. The rain attenuation is lesser when the polarisation is vertical rather than horizontal. This is because the rain droplets fall wider in the horizontal direction with an oblate-spheroid shape, which can disrupt the entire horizontal signal rather than just a small piece of the vertical signal [24]. Figure 2.5 demonstrates how the drop will fall on the vertical- and horizontal signal.

How much the satellite connection is affected by rainfall can also be dependent on which frequency band is used. A higher frequency band is much more affected by the rain droplets than a lower frequency band [25]. This is because the wavelength of the high-frequency bands is smaller, which means that the droplet covers more signal compared with the low-frequency bands. An example of a band that could be affected by rain is the Ka-band, which operates from 26 GHz to 40 GHz. This band, among others, is considered a high-frequency band. Rain attenuation starts at 10 GHz [26]. This means that the Ku-band, which operates at 12-18 GHz, also is affected by the rain.

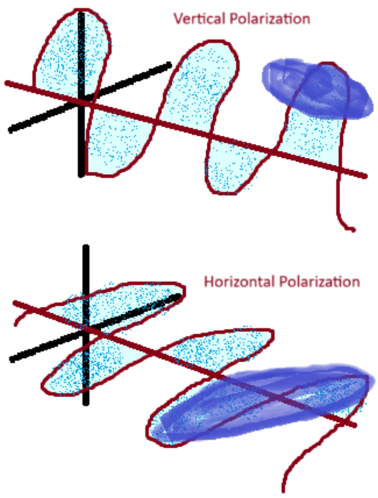


Figure 2.5: Horizontal- and vertical signal, where the blue dot represents a fallen rain droplet.

2.4 Measurement tools

This section discusses different measurement tools used to measure internet performance and weather.

2.4.1 Internet measurements

The number of different websites and software available for measuring internet performance is vast. The small differences between them make it hard to pick and choose. Accuracy behind these tools is a big question amongst internet performance enthusiasts. Internet measurement websites such as *Speedtest* by Ookla [27], *Fast* [28] and *Bredbandskollen* [29] are some bigger names, with *Bredbanskollen* being a major site specifically for Sweden. These websites run or rent dedicated servers around the world, to which users can send data to take measurements of their internet performance. Software such as *iPerf3* lets the user instead send to a user-hosted server, or set up a *iPerf3* server themselves.

2.4.1.1 Throughput

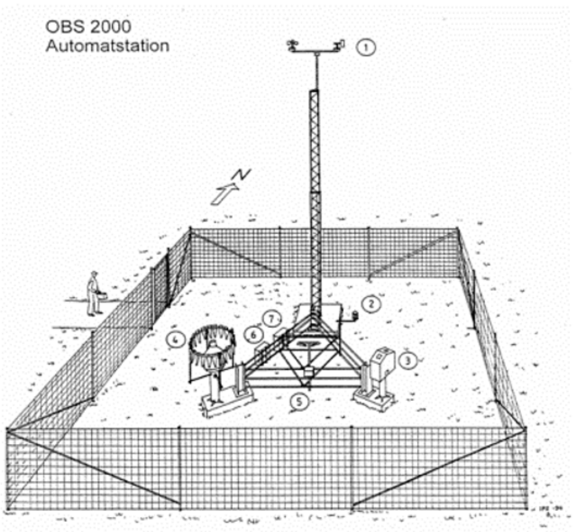
As stated in chapter 2.2, two main transport protocols are used on the Internet, TCP and UDP. The tools *Fast* and *Speedtest* use several TCP connections for their measurements. The number of TCP connections used during the measurements is dynamic for both of the measurement sites and dependent on the network's available bandwidth [30] [31]. As discussed in 2.2 the number of TCP connections make a difference in performance. To measure reliably, dynamic variables should be avoided. The results of *Speedtest* are also manipulated before giving the results to the user. According to *Speedtest*, the two best measurements are removed followed by a removal of the bottom quarter of the measurements. The result of this is what is averaged and shown to the user [31]. *iPerf3* gives the user raw data and the ability to customise the measurements. With TCP the number of parallel TCP connections and congestion control algorithm can be changed by the user. *iPerf3* also supports UDP with the possibility of changing transfer speed and packet size.

2.4.1.2 Latency

Ping is a software that measures latency by sending a Internet Control Message Protocol (ICMP) package to a remote host to tell if the receiver is active as well as the Round-trip time (RTT) for the data. The *Ping* tool can be used on almost all IP addresses and is a very lightweight and simple tool [32]. As discussed in section 2.2.2, routing is a big factor to take into consideration when looking at variations in the latency. *Traceroute* [33] is a *UNIX* tool which takes advantage of Time to live (TTL) to be able to measure latency throughout the routing path taken by the data.

2.4.2 Weather measurements

Weather is measured to produce weather forecasts, as well as to keep a history of weather data. SMHI is a Swedish expert authority under the Ministry of Climate and Enterprise. This expert authority focuses on weather data collection for weather forecasting and research. SMHI use manual and automatic weather stations to collect meteorological data. Figure 2.6a shows an illustration of an automatic SMHI meteorological data collection station [34]. Wind speed, humidity, temperature, and precipitation are some measurements collected at the station. To be able to measure precipitation,



(a) Map of the automatic station [34]. The precipitation measuring station is marked with (4) on the map.

(b) Picture of the precipitation measuring station [34].

Figure 2.6: The Swedish Meteorological and Hydrological Institute (SMHI) weather station.

rain has to be collected. There are a few different methods of collecting the rain. SMHI makes use of a bucket hung up by strings. The weight of the bucket is measured to be able to calculate how much water has been collected [34]. Another way of measuring precipitation is by using a tipping bucket. An example of this is the Davis 6464 tipping bucket. The bowl will tip after 0.2 mm of rain has been collected. Every tipping is counted. From the amount of tippings, the precipitation is calculated. The tipping bucket is a cheaper option between the two precipitation data collection methods [34].

2.5 Related work area

This chapter includes two different research papers on the subject of Starlink's performance, with different measurements and results.

2.5.1 Previous data using UDP

Laniewski et al. conducted experiments resulting in one of, if not the largest, data set of Starlink performance measurements as well as a comparison to weather data. The purpose of the research is similar to the one stated in this degree project. The researchers aimed to provide a large data set which is free to use to be able to conduct further analysis on the Starlink system. In the paper, UDP is used to measure the throughput of Starlink during different weather conditions, which has some advantages and disadvantages. The major advantage of using UDP is being able to see the non-throttled throughput of Starlink. The UDP has no flow control, meaning that the sender will not throttle the transfer speed when data is lost during transmission. However, the majority of internet traffic is sent via TCP [35]. High levels of packet loss, such as interrupts in the satellite connection, could negatively affect the TCP throughput, something that has to be taken into consideration when looking at the user perspective of the Starlink system. The paper by Laniewski et al. includes measurements from two different locations (Netherlands and Germany) which gives a broader view of Starlink's performance. This degree project will on the other hand give researchers a measurement database from a location with far fewer Starlink satellites nearby orbits, giving another perspective. The paper includes an analysis of how performance differs for specific hours of the day. The time-of-day analysis can contribute to a better understanding of how the Starlink network is affected by user traffic. The paper concludes that the UDP performance varies by $\pm 10\%$ between specific hours during a day [36].

2.5.2 Previous data using TCP

Michel et al. wrote a paper with an early insight into the Starlink service to show the user-perceived performance. In the paper, TCP is tested via Speedtest by Ookla[27]. Another transport protocol, the QUIC protocol [37] is used for measurement as well. According to the authors of the research paper, QUIC is used to measure latency instead of TCP to avoid being affected by the use of proxies and middleboxes which according to the paper is not implemented on the QUIC protocol. However, this degree project aims to give a more realistic view of the Starlink system. The QUIC protocol is used on about $7.9\,\%$ of internet websites [38]. This degree project will focus mainly on TCP measurements which, as discussed in 2.5.1, is the most used Internet protocol at the time of writing. To be able to get a good interpretation from the user's perspective there will be no attempts to avoid proxies or middleboxes as they are a part of the Internet of today [39].

Chapter 3

Method

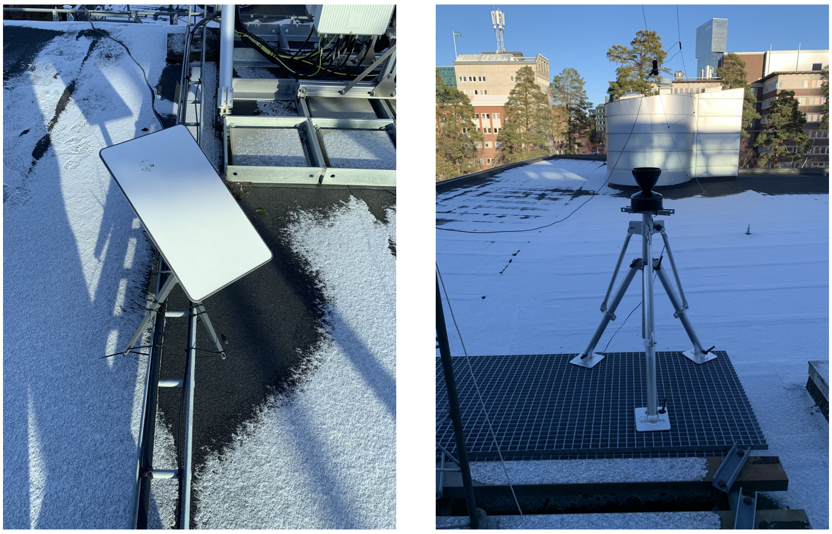
The execution of this degree project consists of measurements from a Starlink dishy located on the roof of the Royal Institute of Technology (KTH) Electrum in Kista, Stockholm. The Starlink router is directly connected to a terminal, from which all measurements are performed. The weather data collected during the degree project comes from equipment located next to the dishy containing a rain collector as well as humidity and temperature sensors. The measurements in the degree project were designed to get the same results as a regular Starlink user to give a real-life estimate of the system. The degree project is written to provide data to be used as an example of the performance to be expected from LEO satellite Internet connectivity.

3.1 Test bed/Data Collection

The experiment tests the throughput for TCP and UDP via *iPerf3*, the latency via *Ping*, and the route via *Traceroute*. The precipitation data is collected with equipment located on the roof at KTH Electrum in Kista.

3.1.1 Data path

The data throughput is measured between a client- and a server terminal with *iPerf3*. Both terminals are located at KTH Kista. Figure 3.2 visualises the data path. The client/measurement terminal is connected directly to the Starlink wireless router via Ethernet, whilst the KTH server is connected directly to the network at KTH Kista with a gigabit Ethernet connection. The server has been configured as an *iPerf3* server. *iPerf3* gives the possibility to send or retrieve data from the server to be able to measure both the down- and



(a) The Starlink user antenna called *Dishy*.

(b) The Davis 6464 rain collector.

Figure 3.1: The hardware used in the study, installed on top of the roof at KTH.

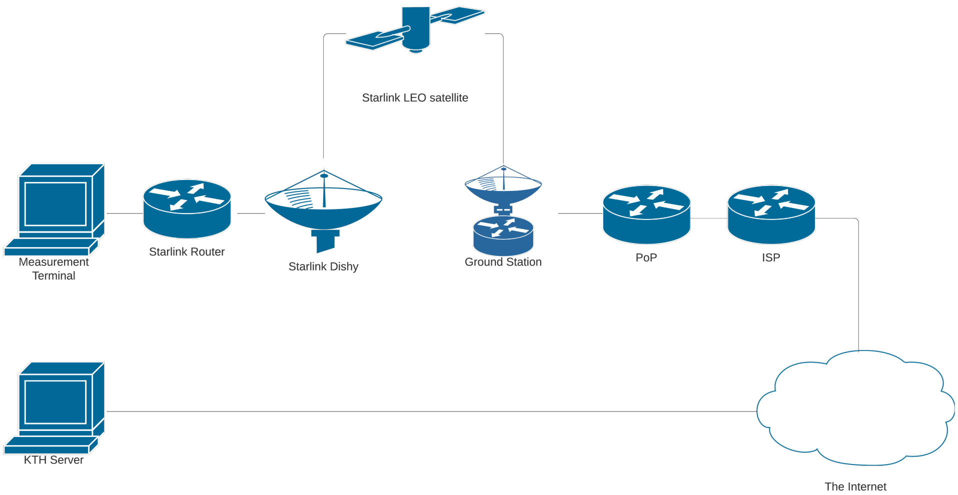


Figure 3.2: The data path that the measurements take, starting at the client, which is marked as *Measurement Terminal*.

uplink of the Starlink system. Data collected by the precipitation equipment is retrieved by the measurement terminal. The latency data is the result of a *Ping* measurement sent between the client and the PoP to showcase the latency within the Starlink network. The data path between the server and the client is tracked with the use of *Traceroute*.

The weather is measured every minute, and the throughput downlink and uplink are measured every five minutes for TCP and UDP. To avoid the throughput tests from interfering with one another, they are all run separately. The latency is measured in parallel with all the other data measurements. The small ICMP packets the *Ping* tool uses in its measurements make it possible to run in parallel with other measurements, without *Ping* affecting the results of the throughput measurements. The route is measured every five minutes to ensure that the same path is taken each time. This way, if some pattern breaks, it will be possible to see if another route has been taken or if the problem lies elsewhere.

3.1.2 Specifications

This chapter includes hardware and software used during the experiment phase of this bachelor thesis. To replicate the results of this thesis, the following equipment should be used.

3.1.2.1 Hardware

The hardware used to collect the internet performance measurements consists of two terminals seen in Table 3.1; as well as the *Starlink Standard Actuated kit*[40]. To collect weather data, a *DAVIS 6464* rain collector[3] is used, as well as temperature and humidity sensors.

Specifications *iPerf3* Throughput Tests		
	Client	Server
Product	HP EliteDesk 800 G1 SFF	HP Compaq Elite 8300 CMT
CPU	i7-4770 CPU @ 3.40GHz	i7-3770 CPU @ 3.40GHz
GPU	Intel Xeon E3-1200 v3/4th Gen	Intel Xeon E3-1200 v3/4th Gen
RAM	8GB @ 1600 MHz	16GB @ 1600MHz
OS	Ubuntu 22.04.3 LTS	Ubuntu 22.04.2 LTS
Kernel	Linux 6.5.0-28-generic	Linux 5.15.0-76-generic

Table 3.1: Measurement hardware specifications for the client and server.

Specifications Davis 6464 Rain Collector[3]	
Sensor Type	Tipping spoon with magnetic switch
Collection Area	214 square cm
Range Daily Rainfall	0.0 mm to 999.8 mm
Range Total Rainfall	0.0 mm to 6553 mm
Accuracy	For rain rates up to 50 mm/hr ±4% of total or +0.2mm (one tip of the spoon) whichever is greater
Update interval	20–24 seconds

Table 3.2: Measurement hardware specifications for Davis 6464 Rain Collector[3].

Specifications Starlink	
Antenna	Electronic Phased Array
Orientation	Motorised Self Orienting
Environmental Rating	IP54
Snow Melt Capability	Up to 40 mm/hour
Operating Temperature	-30°C to 50°C
Field of vision	110°
Average power consumption	50–75 W

Table 3.3: Measurement hardware specifications for the Starlink Dishy[40].

Specifications Starlink WIFI-Router	
Wi-Fi technique	IEEE 802.11a/b/g/n/ac standard
Generation	Motorised Self Orienting
Radio	Double band – 3x3 MIMO
Security	WPA2
Environmental Rating	IP54, configured for indoor use
Range	Up to 185 square meters
Operating Temperature	-30°C to 50°C
Mesh Compatibility	Compatible with up to 3 Starlink Mesh-nodes

Table 3.4: Measurement hardware specifications for the Starlink Wi-Fi router[3].

3.1.2.2 Software

iPerf3 is an active measurement tool that can measure throughput, latency, etc. over IP networks [41]. *Ping* is a latency measurement tool which is included in *UNIX* [42]. *Traceroute* is a *UNIX* tool that measures the routing to a specified target along with the latency of each routing-point[33]. The specifications of these tests can be found in Table 3.5 and 3.6.

Specifications *iPerf3* Throughput Tests						
No.	Protocol	Direction	Bitrate	Streams	Time	Buffer length
1	TCP	Downlink	Dynamic	8	40 s	128 kB
2	TCP	Uplink	Dynamic	8	40 s	128 kB
3	UDP	Downlink	250Mbit/s	1	40 s	1.4 kB
4	UDP	Uplink	250Mbit/s	1	40 s	1.4 kB

Table 3.5: Specifications for the throughput tests via the tool *iPerf3*, that runs one after another every 5 minutes.

Specifications Other Tests					
No.	Measurement	Tool	Target-address	Time	Frequency
5	Route	*Traceroute*	KTH-server	-	Every 5 min
6	Latency	*Ping*	PoP	40 s	Every min
7	Precipitation (Rainfall)	*Davis 6464* Rain Collector	-	-	Every min

Table 3.6: Specifications for route-, latency- and precipitation tests.

3.1.3 Framework for Analysis and Evaluation

By manipulating the data, a broader interpretation can be achieved, which is necessary to show how the Starlink system performance varies over longer periods. The captured data is analysed and evaluated with statistical methods which follows the path of quantitative studies. To remove outliers, the 1st and 99th percentile are not included in the plots for all data except the precipitation data. That is because the precipitation data does not vary in the same manner as the other data collected.

3.2 Reliability and validity

With a quantitative path within a study, there are 4 aspects to evaluate to ensure that the study is of high quality. These are validity, reliability, replicability, and ethics. This means that the project assures high quality if the test methods measure correct data with good stability, but also that the same results as presented within this report will be achieved if another researcher performs this research again. Lastly, to achieve a high quality, ethics need to be taken into consideration. This means that the project needs to respect privacy and confidentiality within systems, but also with participants to which it is relevant [2].

This quantitative study of Starlink's performance requires experimental methods with large sets of data to get reliable data. This is because the large data set will give the full perspective of how Starlink works and how different variables play a role in the received data. If only a small set of data is used, or without the relationship between the variables, false conclusions can be drawn.

The first step to having valid data is to make sure that the data is reliable. It is also important to ensure that the data is measured correctly. To help validate the results, the route and latency are measured. Depending on deviations or changes in the route or latency from the Point of Presence, any odd results in the throughput measurements can be authenticated or discarded as valuable data. If an error occurs in the measurements, it is also easier to trace by doing these measurements. The data is also validated by having a measuring phase span over several days, which gives the ability to compare different data sets to check consistency. The data is compared to other papers in relevant work, as well as other sources of information that produce the same types of data.

During this study, the data is collected using common tools for Internet measurements. The test-bed on which these experiments are conducted is easily replicated. However, the results are only expected to be identical if they are run in the same location. The measurements are geographically dependent, which may lead to some distinctions in the results. The data is ethically presented whereas security and confidentiality are taken into consideration regarding KTH, to ensure there is no leak of information. That means that no KTH IP-addresses are presented in this report, or other information that could jeopardise the security of the institute.

Chapter 4

Results and Analysis

This chapter presents and analyses the results of three topics; Starlink's performance regarding precipitation, hour-of-day and an analysis of TCP and UDP throughput. It also presents a validity- and reliability analysis of the findings. All the results presented in this chapter present the throughput for the downlink data. The throughput for uplink data has also been examined but is not a focus for this study. The plots for uplink data in all three examining points are found in the Appendix.

4.1 Precipitation

The first examination point was to see if precipitation could affect Starlink's performance. It can be seen that there is a difference in the performance during the rainy hours compared to the dry days.

A day with significant rainfall was inspected further to get a better sense of the performance during days with precipitation, which was made by zooming into the specific period with the rain. The day with precipitation can be seen in Figure 4.1. Starlink performance measurements are also included in the graph to show how it is affected by the precipitation.

It is hard to distinguish exactly how much the performance is affected by the precipitation as the throughput varies quite a bit, however when comparing the period between 15:00-16:00 the UDP measurements seem a bit more stable.

To get a better interpretation of the effect caused by precipitation, the data is compared to a day with clear weather. The data from the specific day was extracted and compared to days without precipitation and can be seen in Figure 4.2a and Figure 4.2b. When looking at the data in this format, it is apparent that the dips are lower on the precipitation date and the highs are higher on the clear day, but the average is hard to determine.

For a better presentation of the results, a rolling average with a window of ten is performed on the throughput measurements seen in Figure 4.3a and Figure 4.3b, which contains one day with rainfall and two clear days. The plot includes two clear days for validation that throughput is lower on the day with rainfall. In other words, it is not a coincidence that the throughput is higher during days without rainfall. The same three days are also illustrated as Kernel density estimation (KDE)-distributions of the precipitation date in Figure 4.4. KDE is a non-parametric probability function calculation method. The average throughput is lower on the day with precipitation, according to the graphs. The distribution of measurements for UDP in Figure 4.4b is more compact in the days without rainfall compared to the day with rainfall. During the day containing precipitation, the whole distribution is shifted to the left for both transport protocols, meaning that the bitrate is lower during rainfall.

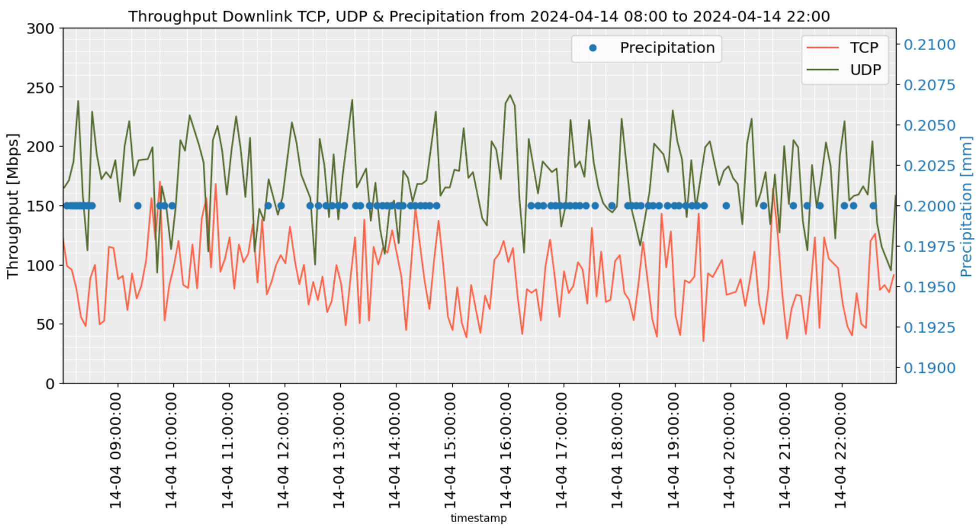
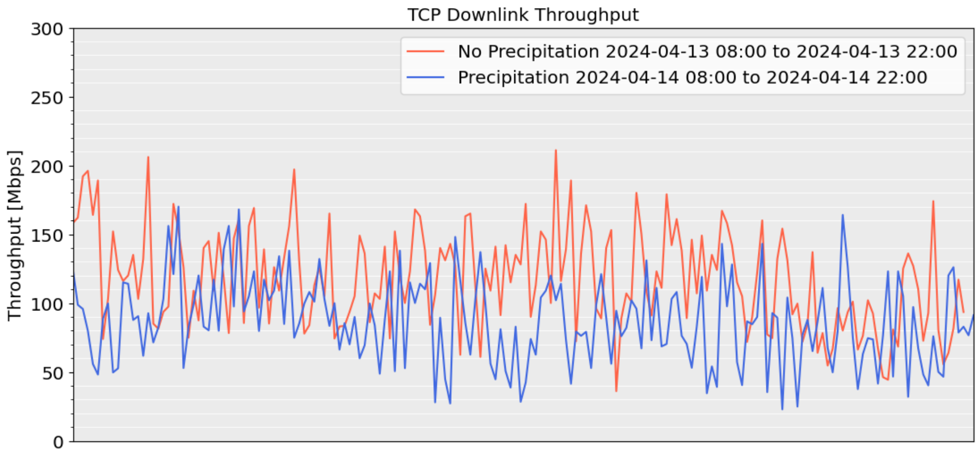
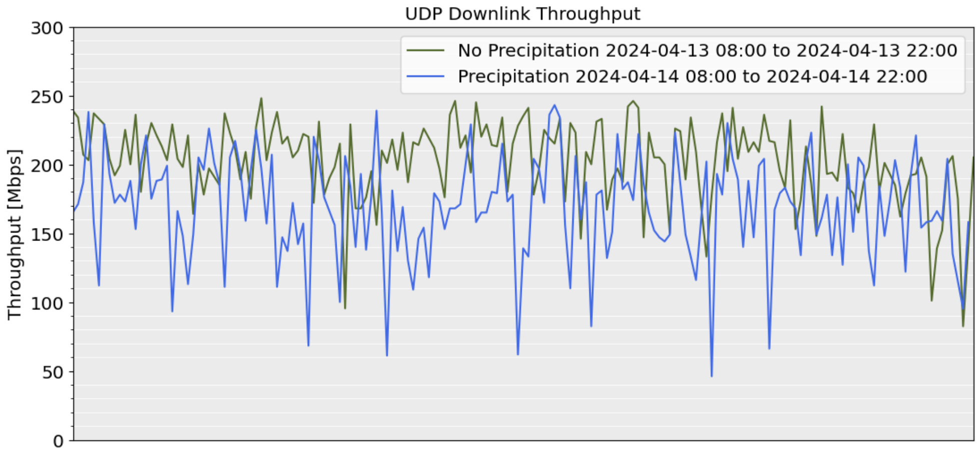


Figure 4.1: A rainy day presenting throughput data from TCP (Red) and UDP (Green) in downlink. One blue dot represents the amount of collected rain under a minute.

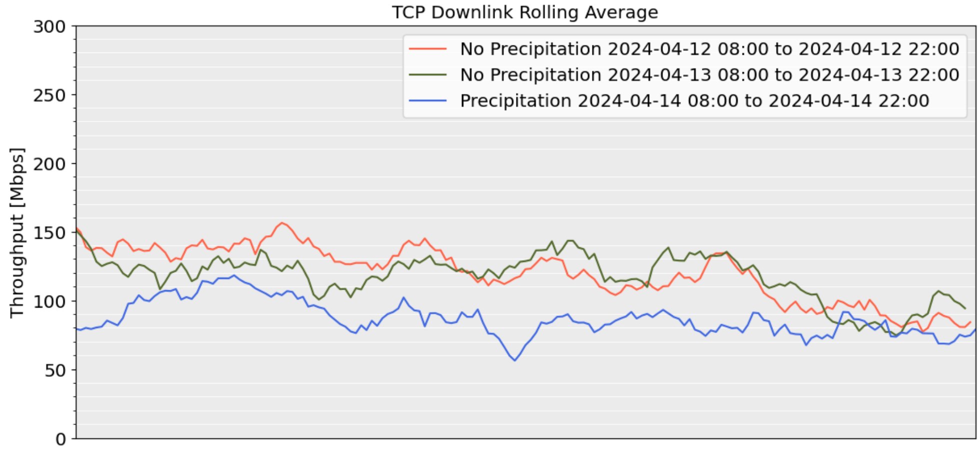


(a) TCP

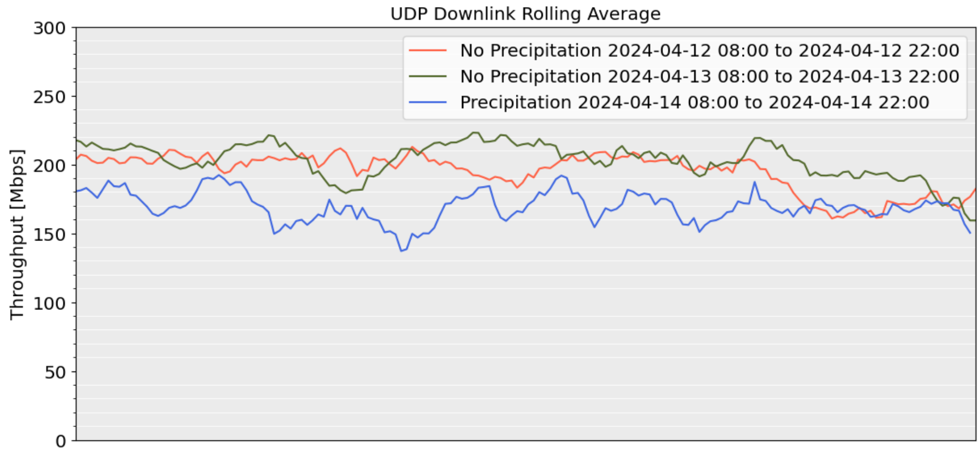


(b) UDP

Figure 4.2: Comparison of throughput on a day with precipitation (Blue) vs a day without precipitation (Red and Green).

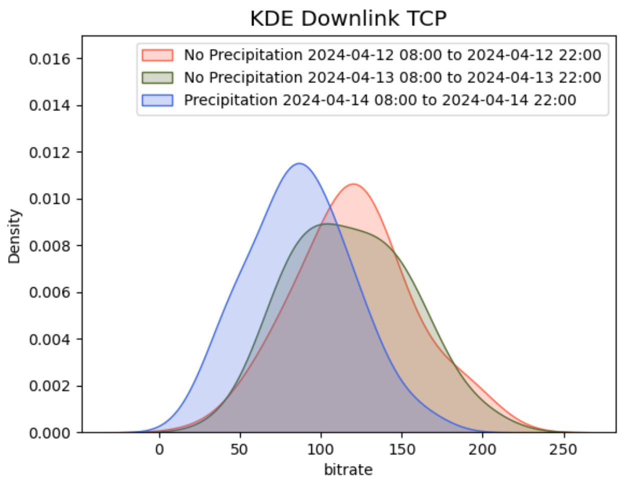


(a) TCP

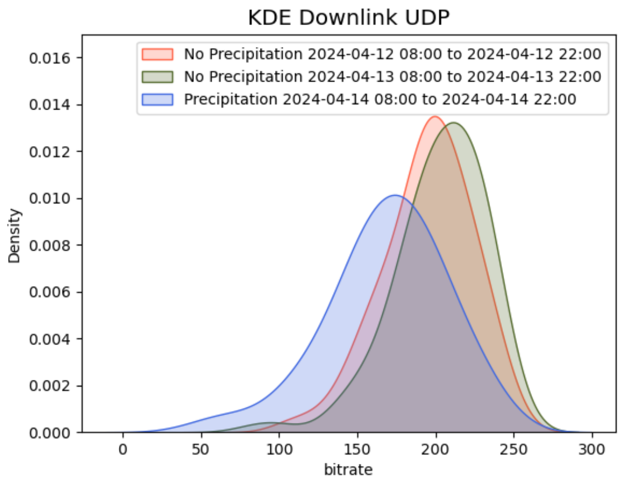


(b) UDP

Figure 4.3: Comparison of throughput on a day with precipitation (Blue) vs a day without precipitation (Red and Green) using a rolling average on every 10th measurement.



(a) TCP



(b) UDP

Figure 4.4: Comparison of throughput for a day with precipitation (Blue) vs a day without precipitation (Red and Green), using *Seaborn* KDE-plots, with a bandwidth of 0.5 [43].

4.2 Hour of day

When importing the throughput data into a graph, there was a distinct pattern shown in the presentation. In the region where the experiment was conducted, there was a clear dip in Starlink performance during the day compared to the night, as can be seen in Figure 4.5. The most visible dip occurred for TCP, but it can be seen in UDP as well. The plot shows a timeline of three days, all containing the same dips. The best throughput was measured during the night and early mornings for each of these days, and the worst throughput was measured past noon and during the evenings.

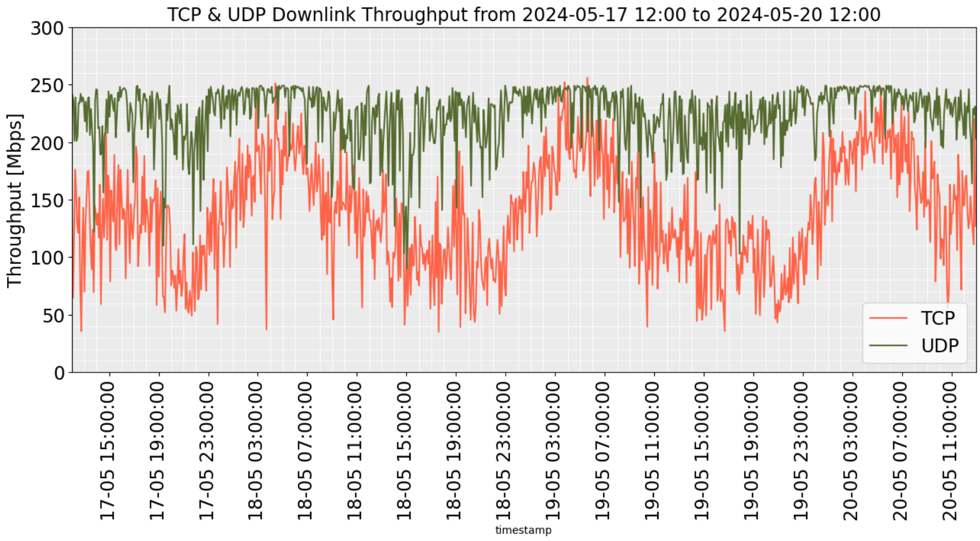
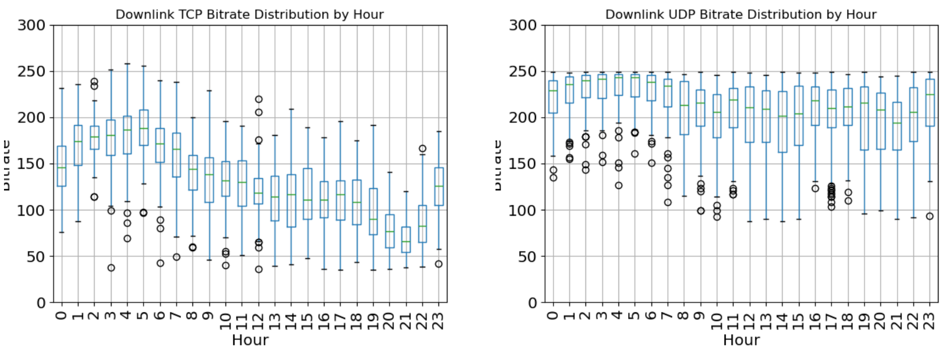


Figure 4.5: Throughput data from TCP (Red) and UDP (Green) for three rain-free days.

4.3 Internet protocol

All the throughput tests were made in both TCP and UDP. These results show how the throughput varies when using the two different transport protocols on the Starlink network. The results, which are presented in Figure 4.6 show a more stable throughput in UDP which is in Figure 4.6b, but also a higher one. The distribution in TCP, which is presented in Figure 4.6a often varies by around $150\,\mathrm{Mbps}$ in bitrate in just one hour. The TCP bitrate has a very low average value compared to the UDP measurement. The bitrate in UDP varies, but the peak is always close to $250\,\mathrm{Mbps}$.

In Figure 4.6b the median throughput for UDP at 00:00 is approximately $230\,\mathrm{Mbit/s}$ while the median at 21:00 sits at around $180\,\mathrm{Mbit/s}$. Resulting in a day cycle with an approximate fluctuation of $\pm 11\%$ in throughput. However, when looking at the TCP measurements in Figure 4.6a the median throughput is much lower than the UDP results. The peak median is at around 06:00 with an approximate median of $180\,\mathrm{Mbit/s}$, whilst the lowest median is found at around 21:00 with a value of $70\,\mathrm{Mbit/s}$. This result gives us a daily fluctuation for TCP of around $\pm 30\%$.



(a) TCP

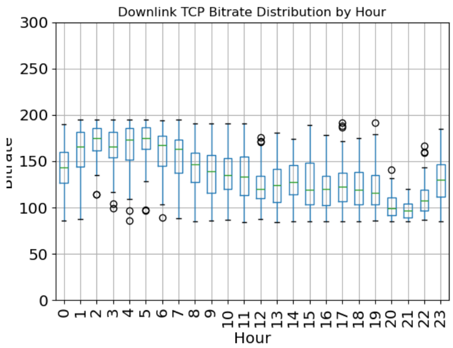
(b) UDP

Figure 4.6: Bitrate distribution by the hour using box plots. The data is taken from 6 days without rain.

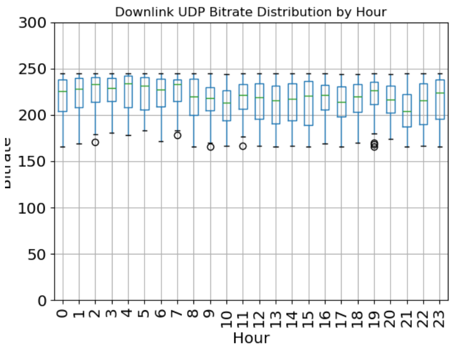
4.4 Reliability and Validity Analysis

To ensure that the data is reliable, the experiment has been measuring data over multiple days. When all data gets analysed, there are patterns to search for to confirm that the data is reliable. An example of this is graph 4.5 which shows similar patterns over multiple days, which confirms that the data is consistent and reliable.

Another form of validation is that the methods used during this degree project share similarities with the related work discussed in Chapter 2.5.1. The Starlink performance of the related works is similar in results to the findings of this study. The paper used $500\,\mathrm{Mbit/s}$ for UDP transfer rate, whilst the UDP-measurements in this bachelor thesis are limited to $250\,\mathrm{Mbits/s}$. However, when looking at the overall results such as the hour variance, they are comparable to the results as the related work calculated an hour of day variance of $\pm 10\%$ whilst this thesis found the variance to be $\pm 11\%$. To further validate data, the downlink-throughput data was examined. The results varied a lot within the throughput data, which could raise some questions. However, the achieved throughput is expected according to Starlink's website. Speeds between $111\,\mathrm{Mbps}$ and $212\,\mathrm{Mbps}$ is the expected throughput at KTH Kista[44]. The expected speed provided by Starlink is in the 20th to the 80th percentile of throughput measurements. Figure 4.7 shows the bitrate



(a) TCP



(b) UDP

Figure 4.7: Bitrate distribution by the hour for the 20th- to 80th Percentile, using box plots. The data is taken from 6 days without rain.

distribution within the 20th- to 80th percentile of the results from this study during 8 days. With the TCP protocol, the distribution is similar to the numbers given by Starlink. As for the UDP protocol, the results show better numbers. The protocol used to which Starlink is referring their numbers is never specified, and the given bitrate spectra are not guaranteed, but this gap gives some validation in the high varying in numbers given mostly by TCP but also UDP.

To validate the rain collector, the data was compared to SMHI. Figure 4.8 presents data from SMHI, which shows that there was precipitation over Kista, Stockholm, during the same date as in the measurements in Section 4.1 [45]. It also shows the two days with no rainfall, which confirms that the measurements from the rain collector are accurate.

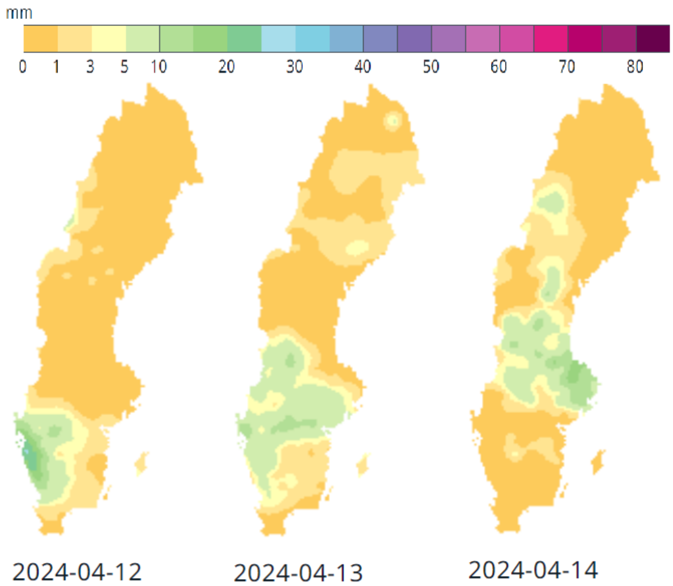


Figure 4.8: Data of precipitation (rainfall) from The Swedish Meteorological and Hydrological Institute (SMHI)[45] during the testing dates.

Chapter 5

Discussion

The results have presented valuable data for the experiment. The results show that the downlink throughput is affected by rain when using the Starlink network. This discovery is not surprising, since satellites in general have a hard time transmitting and receiving signals during precipitation. The higher frequency bands are more prone to be affected by rain attenuation. Starlink uses three bands over $10\,\mathrm{GHz}$, where the rain attenuation limit lies. These bands are the Ku-, Ka- and E-band. If it had rained by the ground stations (which use the Ka- and E-band), the result might have been more obvious, since these bands operate at higher frequencies than the Ku-band. The rain was never measured at the ground stations and was only measured in the area where the user antenna was located. The Ku-band was the frequency band used for both up- and downlink for user antennas, or *Dishys*. The Ku-band is also affected by rain when transmitting signals, even though it is not as strongly affected as the other two bands. This could be an explanation for the lowered throughput during rain.

The Starlink also shows a distinct change in bitrate depending on the time of day. During the night and early mornings, the bitrate is higher than in the day and evenings. The reason for this pattern could be that the data traffic is high during the day and therefore there could be a high load on the network. Ares with a low number of Starlink satellites may be more affected by network traffic since more users need to share the same satellites. There is a strong possibility that the throughput variation on the time of day will flatten with the rising popularity of the Starlink system. Especially if more enterprises adopt the Starlink technology within the region of Sweden. With a bigger number of businesses on Starlink's network, the throughput during the day could match the performance now seen at noon. This conclusion is drawn from the fact that the data shown in Figure 4.5 show that in Sweden, private users make up the majority of Starlink users, by how throughput decreases during non-office hours.

The paper discussed in Section 2.5.1 concluded that the throughput for UDP varies by $\pm 10\%$ during the day. This is similar to the results shown in Section 4.3. The data shows how TCP varies by $\pm 30\%$. The variation is expected, since the two transport protocols transmit the data differently. As discussed in Section 2.2.3, the TCP protocol includes flow- and congestion control, affecting the throughput. The UDP protocol does not adapt bitrate to congestion, making the difference in variation for throughput between the two protocols expected. The Starlink system's TCP variation can be compared to 4G cellular to give perspective to the results. Garcia et al. conducted a study that included a comparison of network throughput, depending on hour-of-day. The study used TCP over different 4G cellular network operators [46]. The operator with the most fluctuation in throughput during the day varied between approximately $35\text{-}45\,\mathrm{Mbit/s}$, resulting in a daily variation of $\pm 12.5\%$. The throughput for 4G shows a significantly lower fluctuation than Starlink measurements do, even though they both use the TCP protocol. This verifies that the TCP protocol can have a more stable bitrate within a network under the right circumstances. Since TCP is a connection-oriented protocol, latency also impacts the bitrate [47]. The performance impact due to latency depends on the congestion control algorithm used.

There are different types of congestion control algorithms. When data is sent with a high transfer rate and/or high latency, congestion control will have a larger impact on the throughput. Congestion control algorithms are designed for different network environments[48], with the LEO satellite network creating a new kind of network environment there is no specialised algorithm for the network's congestion. The Starlink network environment includes a re-configuration of the entire network every 15 seconds, which no congestion control algorithm is adapted to as of today. Barbosa et al. published a comparison of congestion control algorithms on a simulated LEO satellite network. The results of the papers show that there is a latency and throughput difference when using different algorithms, with Bottleneck Bandwidth and Round-trip propagation time (BBR) being able to adapt to the LEO network the best. According to the authors [49], BBR adopted the best to the simulated LEO satellite network. This bachelor thesis did not consider congestion control algorithms when constructing the test bed. According to the paper by Barbosa et al., Linux uses the *CUBIC* congestion control as a standard, and therefore it is assumed to be the congestion control algorithm used in the experiments conducted in this thesis. This thesis did not have a latency and congestion control algorithm analysis in scope. However, it would be a good topic for future studies. Expanding on the testing done by Barbosa et al., is also an area of exploration. By doing a similar test on a real-world LEO satellite constellation as the Starlink, a better understanding of how different TCP congestion control algorithms affect the satellite internet throughput and latency.

As the user base of Starlink expands, the system network load increases. In the U.S., Starlink charges different rates depending on the user's location. Users located in areas with high traffic will have a higher monthly fee compared to those in low-traffic areas. To be able to handle an increasing number of users, Starlink is required to expand its satellite network. It remains to be seen if Starlink can expand the LEO satellite constellations at the same rate as its user base.

Chapter 6

Conclusions

This bachelor thesis examined how Starlink's performance is affected by weather, time of day, and Internet protocol. The study showed results whereas Starlink's throughput was impacted on all three topics. This study was conducted in Stockholm, Sweden, and since the Satellite constellation is sparse in this location, the results could vary if the test is conducted in a different country. The three main goals were met by doing the following:

1. With the collection of precipitation data, a comparison between clear- and rainy days gave an insight into how throughput via Starlink's network is affected by rainfall.

2. By conducting throughput measurements on Starlink's system via TCP and UDP, a statistical analysis of throughput difference between the two transport protocols gave a better understanding of the Starlink network's strengths and weaknesses.

3. By plotting the data over a longer period, the time of day was illustrated. By doing a statistical analysis of an hourly average of throughput, a clear picture of the variation in the hour-of-day was made.

With the little knowledge the authors had about Starlink and other systems when starting this project, the start could not have gone differently. There were some setbacks, such as a change in routing which destroyed the measurements for a few days. Most of these setbacks could have been avoided if the authors retained the same knowledge as of today.

The positives from this project were that this was a great way of learning a lot more about Starlink itself, and also about the different measurement- and data analysis tools used.

For future Starlink researchers, it is important to know that there is limited information out there. The information out there can be outdated quickly since Starlink is a new system that is constantly being updated and changed. Therefore, there needs to be a lot of time spent on keeping updated about this topic, and a lot of reliance on other researchers' studies as well. Even though this is the case, it is a very interesting topic. The authors recommend diving deep into it since the research never gets dull.

6.1 Limitations

Time was a limitation in this study. Since a bachelor thesis is around two months, there was not enough time to perform more- and longer tests. In the beginning, a lot of time was spent researching different methods, and also doing literature study. Another limitation was the weather. Since the experiment lies in the hands of something uncontrollable, the results will be affected. There is also a risk with the weather that it might not even present data on, for example, precipitation. This study was fortunately conducted during a period where there were both rainy- and sunny days, but most of the rain occurred during the literature study- and test setup phase, where lots of relevant data could have been captured. The weather situation was also affected by time since this study could have been able to collect more weather data if the study had started earlier.

6.2 Future work

There are a lot of things that can be examined within Starlink, and since there is limited information out there about it, it is of high interest that this research gets done. Possible future work could be:

- Testing different methods of examining throughput.
- Testing throughput and other parameters with a Starlink API [50].
- Examining the Starlink's satellite alignment.
- Examining how throughput via Starlink network is affected by rain at the ground station.

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Appendix A

GitHub

Link to GitHub, including scripts and data:
https://github.com/starlink-celine-emil/starlink_KTH_VT2024

Appendix B

Uplink data

B.1 Precipitation

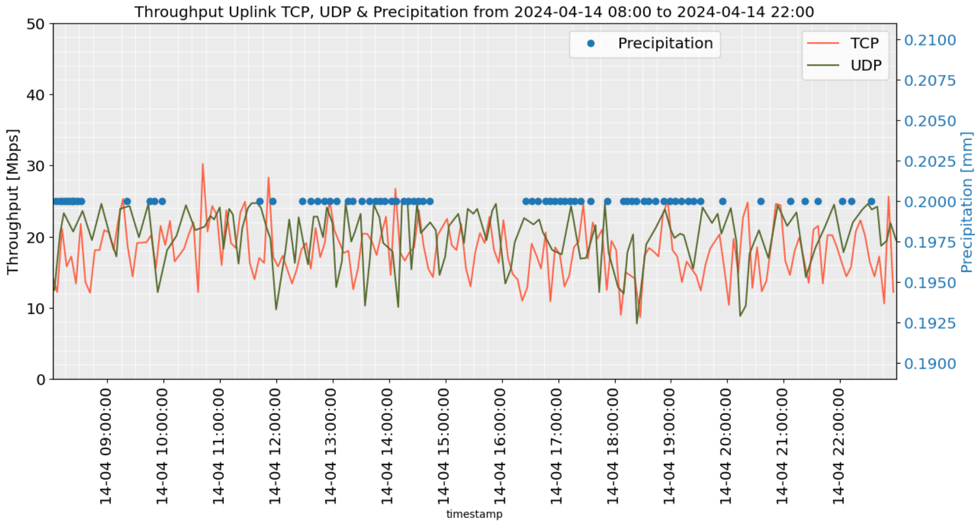
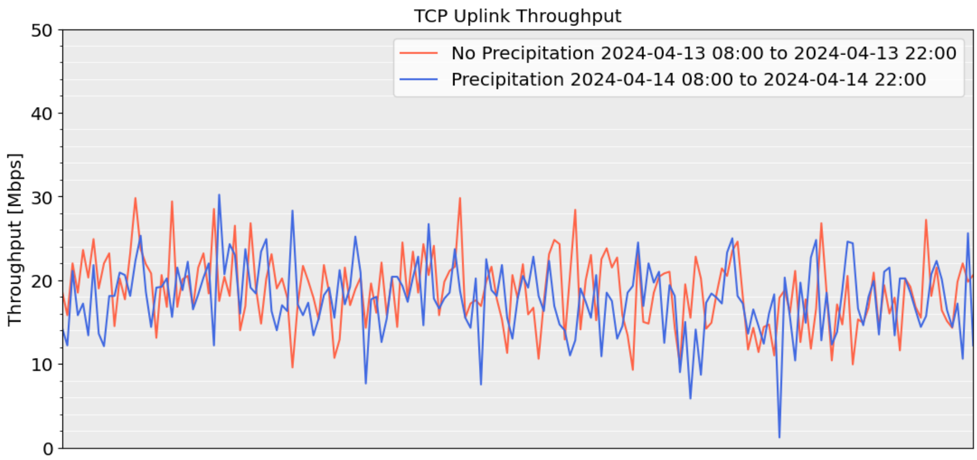
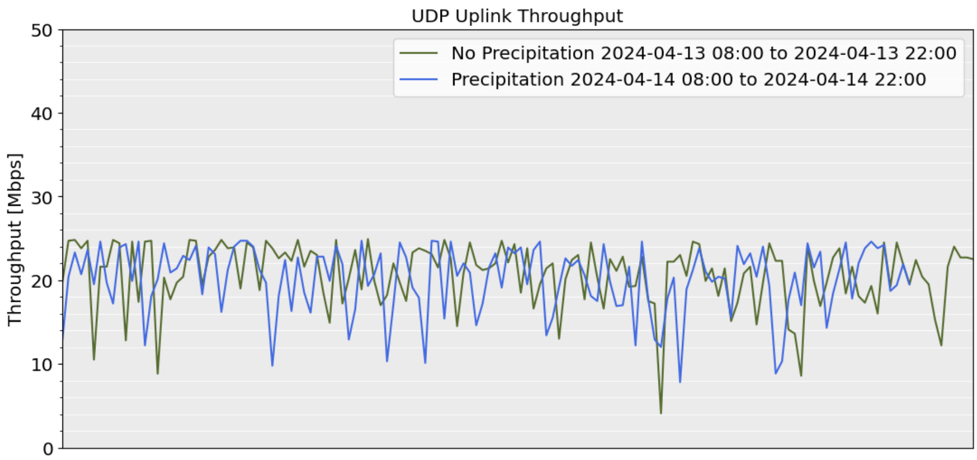


Figure B.1: Uplink: A rainy day presenting throughput data from TCP (Red) and UDP (Green) in downlink. One blue dot represents the amount of collected rain under a minute.

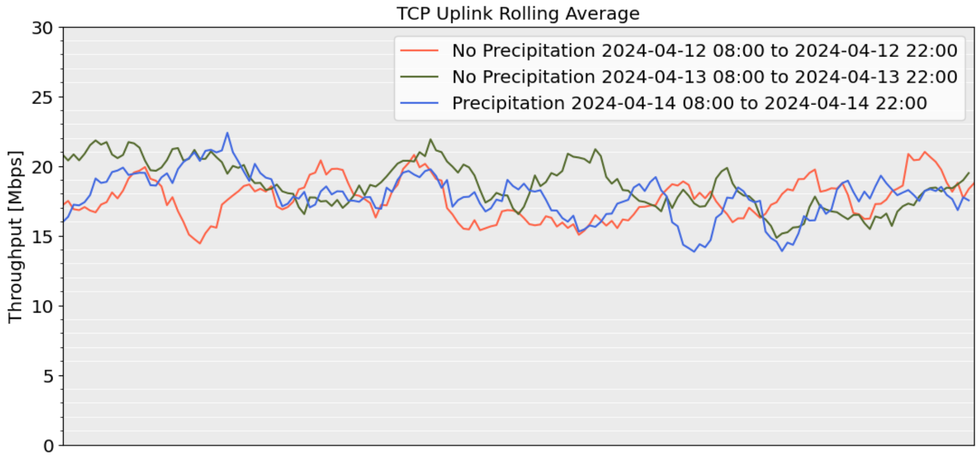


(a) TCP

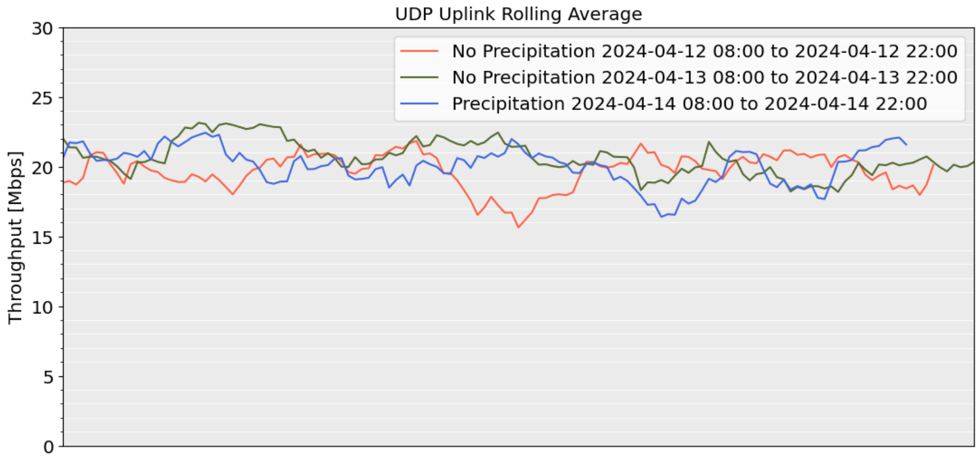


(b) UDP

Figure B.2: Uplink: Comparison of throughput on a day with precipitation (Blue) vs a day without precipitation (Red and Green).

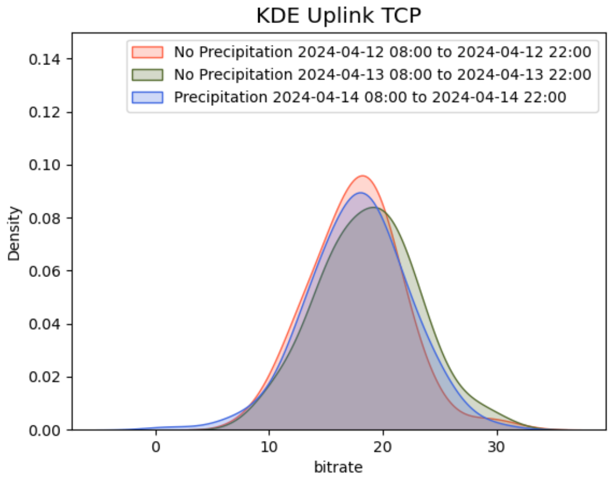


(a) TCP

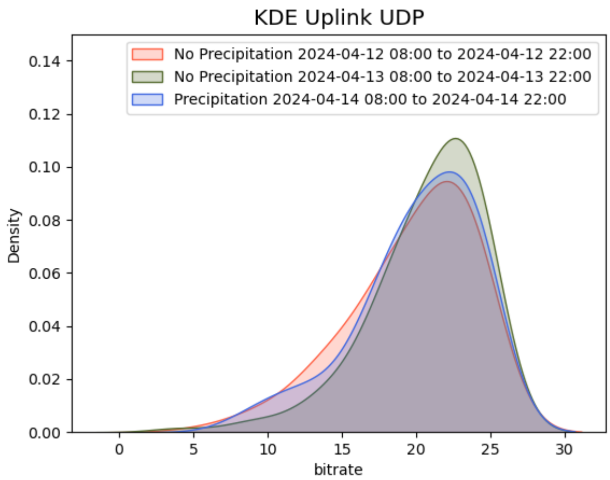


(b) UDP

Figure B.3: Uplink: Comparison of throughput on a day with precipitation (Blue) vs a day without precipitation (Red and Green) using a rolling average on every 10th measurement.



(a) TCP



(b) UDP

Figure B.4: Uplink: Comparison of throughput for a day with precipitation (Blue) vs a day without precipitation (Red and Green), using *Seaborn* KDE-plots, with a bandwidth of 0.5 [43].

B.2 Hour of day

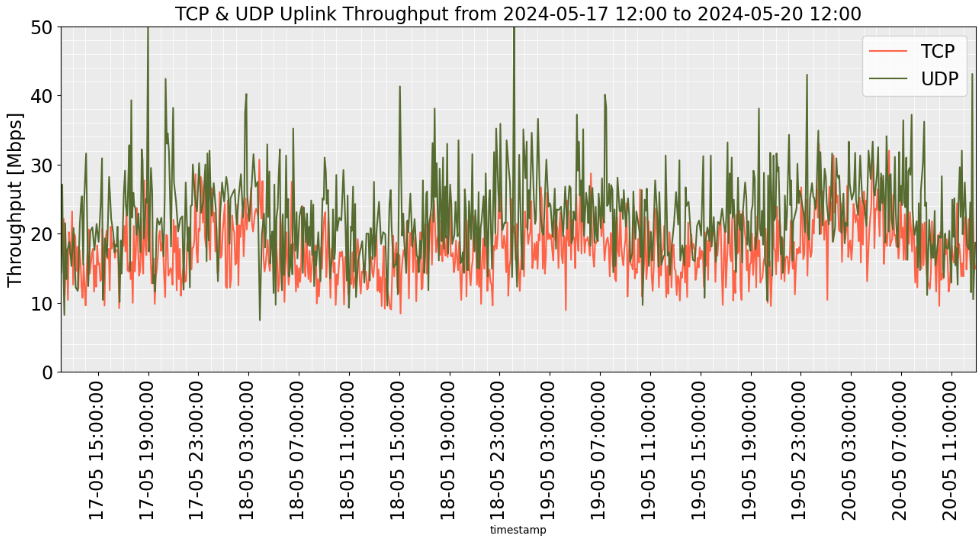
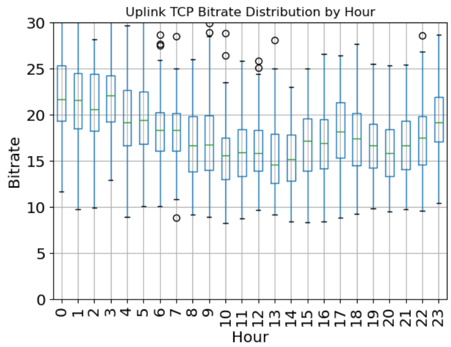
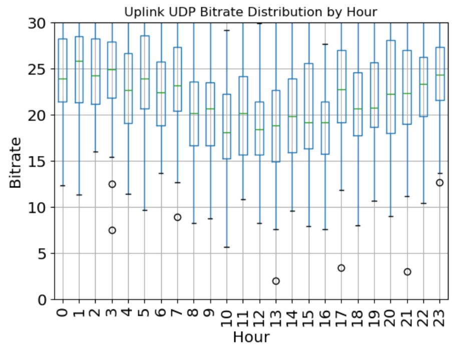


Figure B.5: Uplink: Throughput data from TCP (Red) and UDP (Green) for three rain-free days.

B.3 Transport protocol



(a) TCP



(b) UDP

Figure B.6: Uplink: Bitrate distribution by the hour using box plots. The data is taken from 6 days without rain.

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