Hourly and Weather-Based Variability in Starlink Internet Performance: A TCP and UDP Throughput Study

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***Abstract*—Starlink provides satellite internet connectivity to customers worldwide using Low Earth Orbit (LEO) satellites connecting to ground stations and user equipment. Precipitation, hourly variability, and the use of different transport protocols, all have impact on throughput. The study was conducted in Stockholm, Sweden, at a latitude of 59.3 degrees north, which is well north of the main coverage area of Starlink. Higher latitudes are covered by fewer satellites compared to Central Europe and the main regions of the United States. The study consists of throughput measurements with the network performance measurement tool iPerf3 using two different transport protocols: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Precipitation (rainfall) measurements were conducted simultaneously. The results show a notable decrease in the throughput when moderate rainfall (about 1 mm per hour) is present, about 16 percent for UDP and 28 percent for TCP. The data also show that the throughput varies during different hours of the day, with around 21 percent for UDP and 32 percent for TCP. The highest throughput is received at night and early mornings for both transport protocols. The throughput achieved through the Starlink network with the TCP protocol fluctuates more than on 4G mobile networks. In conclusion, our study provides further knowledge about the effects of precipitation and hourly variability with TCP and UDP on Starlink's performance, specifically when operated at latitudes outside of Starlink's main coverage area.**

Keywords-starlink; leo-antennas; network; tcp; udp; weather; precipitation; iperf3; ping; throughput; latency; internet measurements.

I. Introduction

This is an extended version of our research paper "Throughput Analysis of Starlink Satellite Internet: Study on the Effects of Precipitation and Hourly Variability with TCP and UDP", including more figures of the data collected as well as a comparison between Starlink connectivity and 4G [1].

Starlink provides broadband connectivity mainly over Central Europe and the main regions of the United States (within the latitudes of ±55 degrees). Regions at higher latitudes, e.g., Scandinavia, are covered by fewer satellites but still receive good enough service for sparsely populated areas [2]. The satellite distribution, which is seen in Figure 2, is a screenshot of a live Starlink satellite map, where more than 4000 satellites were active at the time of the study [3]. In the northern parts of the world, there is a clear decrease in satellite density orbiting around the globe in comparison with central parts of the world. The data path for the Starlink network is visualised in Figure 1, showing both the ground station and a "Point of Presence" (PoP) that is used to transfer data between the user antenna and the Internet. The Starlink system makes use of ground stations scattered around the world to be able to connect the satellites to the PoPs. The ground stations are connected via leased fibre to the closest PoP [4]. Aggregated data is then able to travel between the ground station and the PoP, where the data enters the Internet as regular traffic [5]. SpaceX has not revealed where Starlink's PoP and ground stations are located.

Due to the LEO satellites' limited coverage and high travelling speed, the satellites quickly move out of range from user antennas and ground stations. To connect a satellite within range, the Starlink system performs a network reconfiguration every 15 seconds [6]. This process introduces a short interruption, but it is necessary to maintain a connection to the satellite constellation.

The effect of precipitation on the Starlink system performance has been investigated in Central Europe (Germany and the Netherlands) [7], but remains unexplored in Scandinavia. Previous papers have provided data on Starlink's performance over "Transmission Control Protocol" (TCP) [8] and "User Datagram Protocol" (UDP) [7]. However, no studies have been found comparing the two protocols over the Starlink network in Scandinavia.

This study examines the throughput performance of the Starlink system, how it is affected by moderate rainfall and how the throughput varies by hourly variability when operated in Stockholm, Sweden. In addition, throughput comparisons are made using two different transport protocols: TCP and UDP.

This paper is structured as follows: Section II gives insight into TCP and UDP measurements on the Starlink system. Section III describes the measurement setup and Section IV presents an analysis of the results obtained from the experiments. The results are then further discussed in Section V. The paper is concluded, and future work is explored, in Section VI.

II. Related work

This section covers studies of Starlink's performance related to TCP and UDP measurements. 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 TCP protocol re-transmits

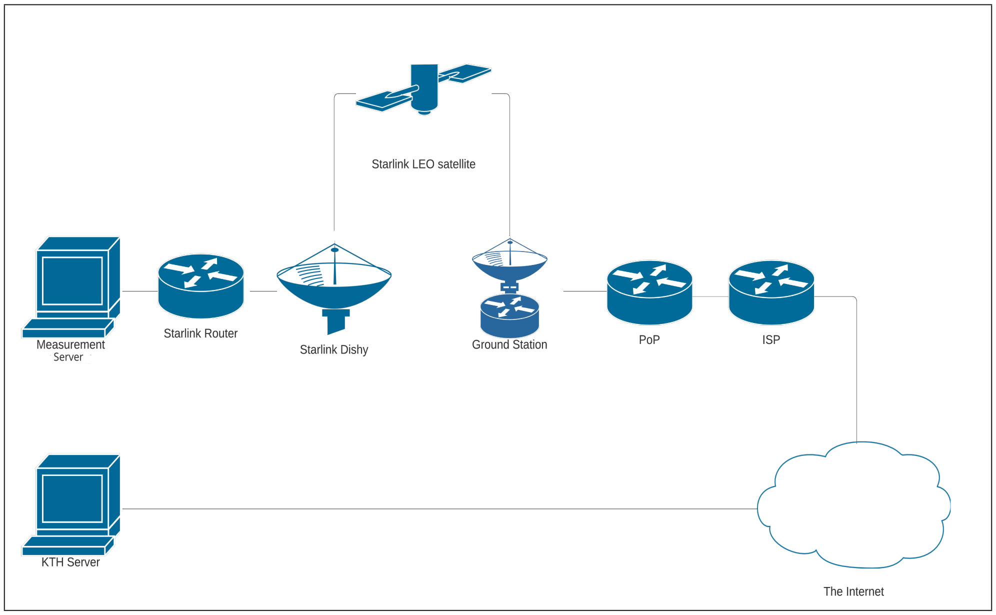

Figure 1. Data path for throughput measurements.

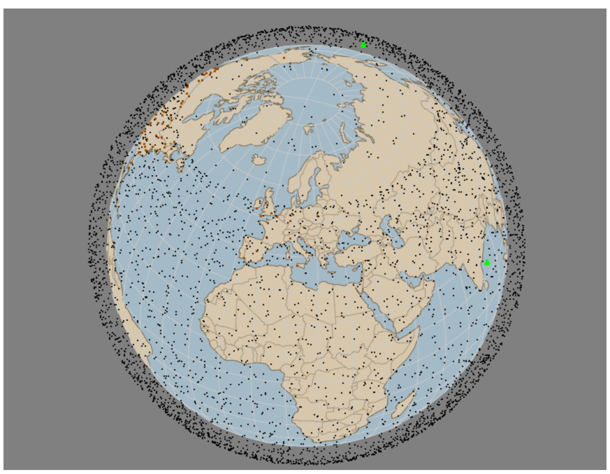

Figure 2. Screenshot taken of live map during data collection period showing over 4000 active Starlink satellites [3].

data if an error occurs. An error could, for example, occur due to packet loss, corrupt data or data being transmitted in the wrong order. The re-transmission process ensures data integrity at the cost of throughput due to an increase in total transmission time [9]. Parallel TCP connections can be used to achieve higher bandwidth. The number of parallel connections for maximum bandwidth utilisation depends on the network bandwidth available.

UDP is a transport protocol that, unlike TCP, does not require an established connection before data transmission. The transmission rate when using the UDP protocol is decided by the sender. This allows high transfer speed by using the entire link bandwidth. However, a static transmission rate can cause packet loss if the receiver is incapable of receiving data at the same rate as it is sent.

A. Previous studies of UDP

The "WetLinks" paper by Laniewski et al. [7] presents a large dataset of Starlink performance measurements gathered through experiments conducted in Germany and the Netherlands. This data set allowed the authors to analyse the correlation between Starlink's performance and weather conditions. The authors collected weather data both independently and from national weather services in their respective countries. In the paper, UDP was used to measure the throughput of Starlink during different weather conditions. The two measurement locations give a somewhat better view of Starlink's performance than from just one location. However, both places are located at latitudes with dense concentrations of Starlink satellites. In contrast, our paper reports measurements made at a location with much fewer Starlink satellites in nearby orbits [2]. The "WetLinks" paper reports UDP throughput in the range of 170-250 Mbps (median 210 Mbps) during days without precipitation. The paper also includes an analysis of how performance varies over the 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 reports that the minimum average throughput throughout a day is approximately 20% lower than the maximum. The median UDP throughput decreased by 17% when it was raining, highlighting the impact of moderate rain showers on Starlink's performance.

B. Previous studies of TCP

The majority of internet traffic is sent with TCP [10]. High levels of packet loss, which can be caused by, for example, interruptions in the satellite connection, are expected to negatively affect TCP throughput and have a large impact on end-user performance. Michel et al. [8] measured TCP throughput (using Speedtest by Ookla [11]) at the UCLouvain campus in Louvain-la-Neuve, Belgium. The reported TCP throughput range was 100-250 Mbps (median 178 Mbps), which is considerably lower than the UDP throughput reported in the "WetLinks" paper [7].

III. Method

In our study, the throughput data is collected using a Starlink "Dishy McFlatface" antenna [12] located on the roof of the Electrum building in Kista, Stockholm (Figure 3). The Starlink device is directly connected to a server from which all measurements are conducted (Figure 1). The weather data is collected using a "Davis Rain Collector" [13] (rain bucket) (Figure 4) located next to the antenna.

The measurements are designed to give a real-life estimate of the system performance expected from Starlink Internet connectivity in Scandinavia.

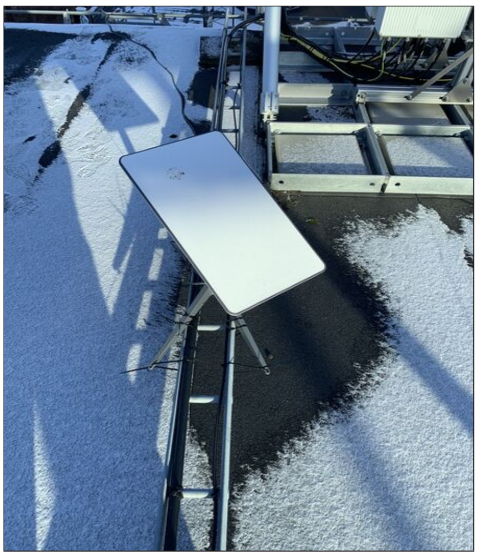

Figure 3. The Starlink user antenna "Dishy McFlatface" [12].

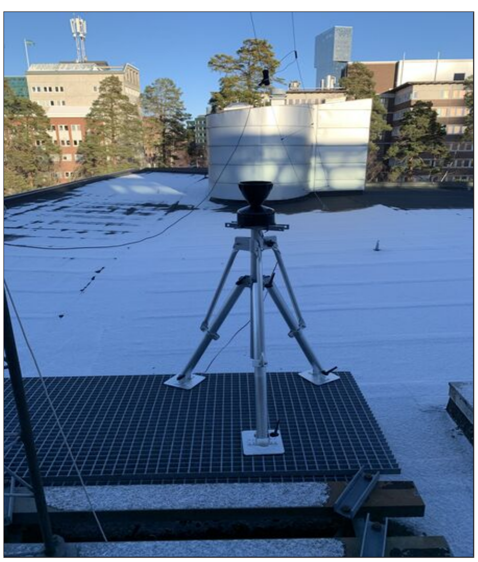

Figure 4. Davis Rain Collector [13].

TABLE I. Measurement hardware specifications for the Starlink Dishy[12]

Hardware specifications for the Starlink Dishy	
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 II. Specifications Davis 6464 Rain Collector[13]

Specifications Davis 6464 Rain Collector	
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

The throughput data collection consists of four different iPerf3 measurements for TCP and UDP, scheduled to run in series. Since the Starlink network undergoes a complete reconfiguration every 15 seconds, each measurement runs for 40 seconds. This duration ensures that at least two reconfigurations occur and allows the TCP connection to readjust its speed, providing more realistic real-world performance results. The iPerf3 measurement for UDP is limited to a bitrate of 250 Mbps to prevent unnecessary network load, alongside a configured buffer size of 1400 bytes to reduce packet loss [14]. For TCP connections, the iPerf3 command is set to use 8 parallel streams with a buffer size of 128 kB.

IV. Results and Analysis

This section presents and analyses the results from the study, categorised into three sections based on the findings.

A. *Precipitation*

The following section contains a comparison between three consecutive days with rain being present on the third day. The day with rain is referred to as "the rainy day". Figure 6 and Figure 7 show the throughput measured in the interval 8:00-22:00. To get a clearer view of the data, a rolling average is applied to the data and can be seen in Figure 8 for TCP and Figure 9 for UDP. Figure 10 (TCP) and Figure 11 (UDP) illustrate the days using Kernel Density Estimation (KDE) [15], providing a clearer picture of how throughput is distributed across the different days. Over the three days, the median throughput for TCP was 120 Mbit/s on the first day, 118 Mbit/s on the second, and 86 Mbit/s on the third, rainy day. For UDP, the throughput was 194 Mbit/s, 202 Mbit/s, and 169 Mbit/s, respectively. This corresponds to an approximate 28% decrease in TCP throughput and a ~16% decrease in UDP throughput on the rainy day. Figure 5 presents the measured throughput for TCP and UDP on the rainy day. The blue dots represent the amount of rainfall in one-minute intervals, with a total measured rainfall of 15 mm during April 14th, 2024. This is well in agreement with the data provided by The Swedish Meteorological and Hydrological Institute (SMHI) for that date [16]. The TCP throughput is significantly affected, even though the rainfall is classified as moderate (less than 4 mm/hour) [17].

TABLE III. Comparison of median throughput (Mbit/s) of the two days without precipitation (Day 1 & Day 2) and the day with precipitation (Day 3).

Median throughput [Mbit/s]	Day 1	Day 2	Day 3
TCP	120	118	86
UDP	194	202	169

TABLE IV. Summary of the data on the day with precipitation.

Description	Data
TCP decrease on rainy day	~ 28%
UDP decrease on rainy day	~ 16%
Total rainfall [mm]	15 mm (April 14, 2024)
Rainfall intensity	Moderate <(4 mm/hour)

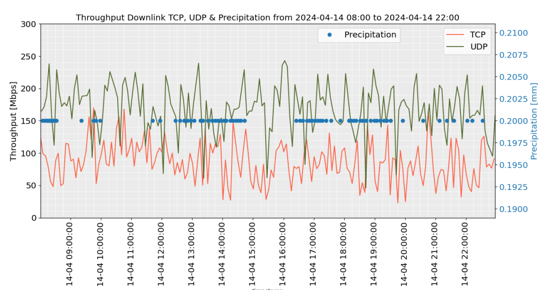

Figure 5. Measured TCP and UDP throughput during the rainy day. The blue dots represent the amount of rainfall for one minute.

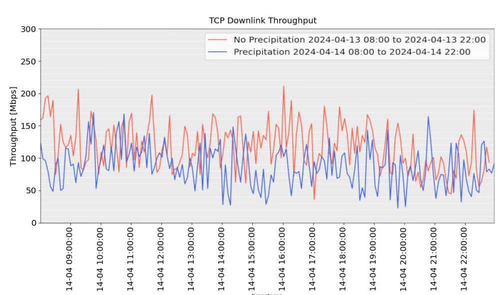

Figure 6. TCP: Throughput on the rainy day (blue) vs a day without rain (red).

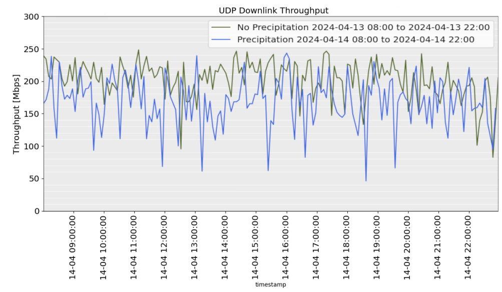

Figure 7. UDP: Throughput on the rainy day (blue) vs a day without rain (green).

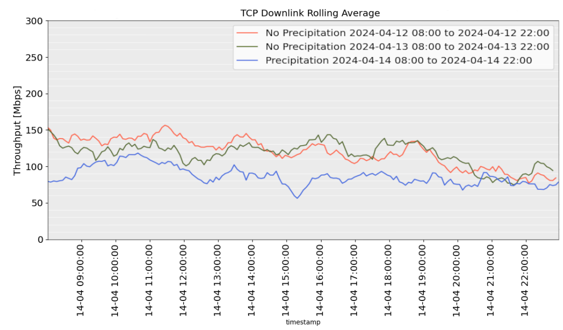

Figure 8. TCP: Throughput the rainy day (blue) vs two days without rain (red and green) using a rolling average on every 10th measurement.

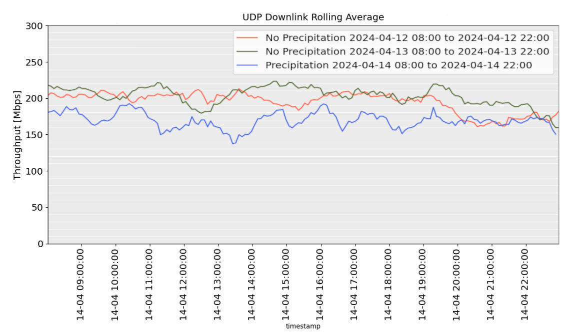

Figure 9. UDP: Throughput the rainy day (blue) vs two days without rain (red and green) using a rolling average on every 10th measurement.

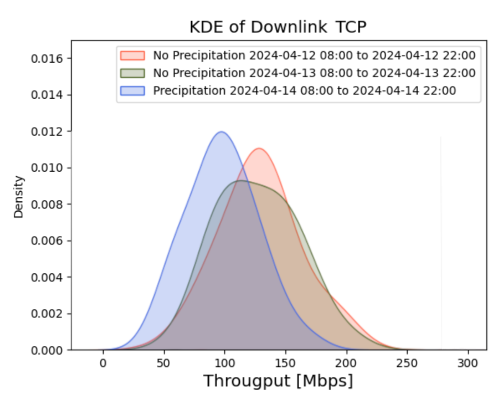

Figure 10. TCP: Probability density function for throughput measurements on the rainy day (blue) vs two days without rain (red and green), using *Seaborn* KDE-plots, with a bandwidth of 0.5 [18].

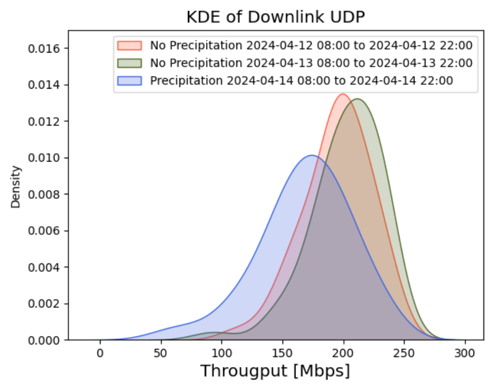

Figure 11. UDP: Throughput density measurement on the rainy day (blue) vs two days without rain (red and green), using *Seaborn* KDE-plots, with a bandwidth of 0.5 [18].

B. Hourly variations

Figure 12 shows the throughput data for TCP (red) and UDP (green) during 72 hours without rain. As can be seen, there is a significant decrease in Starlink throughput during the daytime compared to the night. The highest throughput was measured during the nights and early mornings, while the lowest throughput was observed in the late afternoon and evenings.

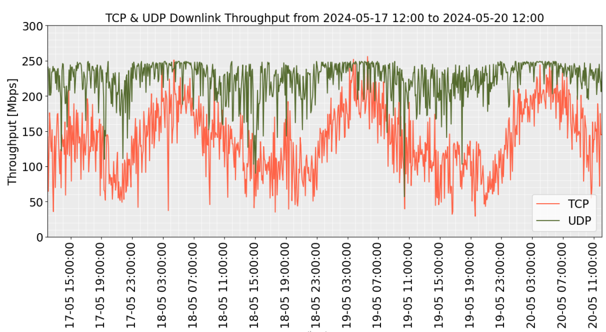

Figure 12. Throughput data from TCP (red) and UDP (green) for a 72-hour rain-free period.

C. Internet protocol

Figure 14 shows the hourly variations in throughput over seven days with and without precipitation. As seen in Figure 14, the mean throughput for UDP peaks in the early morning with a mean throughput 243 Mbit/s at 04:00-05:00. The lowest throughput occurs at around 21:00 with a mean of 185 Mbit/s. In contrast, the TCP measurements in Figure 14 show much lower mean throughput. The highest mean for TCP throughput is observed at around 05.00 with 188 Mbit/s, while the lowest mean is found at around 21.00 with 66 Mbit/s. By calculating the difference between the 75th and 25th quantile (IQR), we find an average difference of 46.05 Mbit/s for UDP and 41.88 Mbit/s for TCP. The average mean throughput for UDP is 208 Mbit/s, while for TCP, it is 132 Mbit/s, resulting in a ~57% higher mean for UDP compared to TCP. To get a sense of the variability, we express the average interquartile range as a percentage of the average median. This analysis shows that for UDP, the throughput varied by ~21%, and for TCP, it varied by ~32%.

TABLE V. SUMMARY OF TCP AND UDP THROUGHPUT MEASUREMENTS

Throughput [Mbit/s]	UDP	TCP
Highest mean	243	188
Lowest mean	185	66
Average mean	208	132
IQR (75th–25th percentile)	46.05	41.88
IQR as % of median	~ 21%	~ 32%

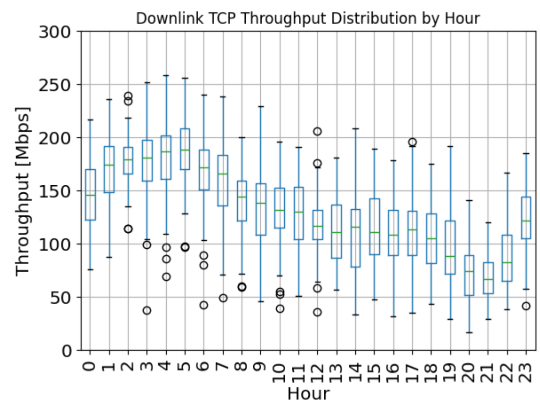

Figure 13. Boxplot of TCP throughput data from 7 consecutive days.

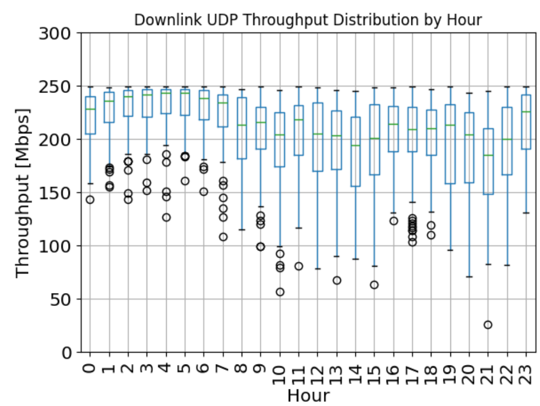

Figure 14. Boxplot of UDP throughput data from 7 consecutive days.

D. Validation analysis

According to the Starlink website, a throughput between 111 Mbps and 212 Mbps is expected at the location of the Starlink antenna within the 20th and the 80th percentile [19]. Figure 15 and Figure 16 show the TCP and UDP throughput within the 20th and 80th percentile over 6 days. With the TCP protocol, the distribution is similar to the numbers given by Starlink. As for the UDP protocol, the results show a higher average throughput.

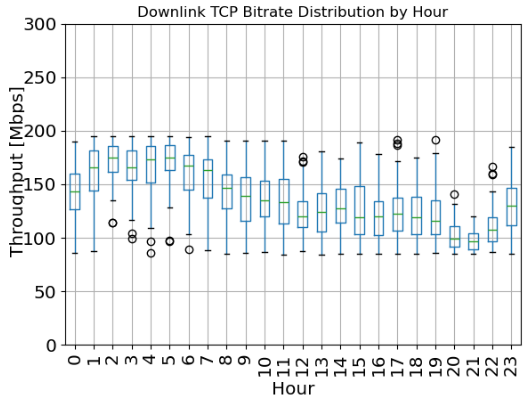

Figure 15. TCP: Throughput distribution by the hour for the 20th to 80th percentile, using box plots. The data is taken from 6 days without rain.

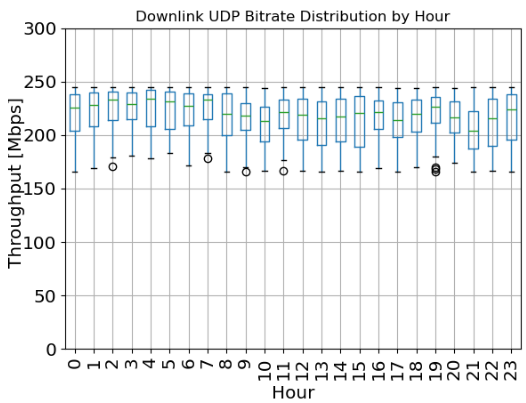

Figure 16. UDP: Throughput distribution by the hour for the 20th to 80th percentile, using box plots. The data is taken from 6 days without rain.

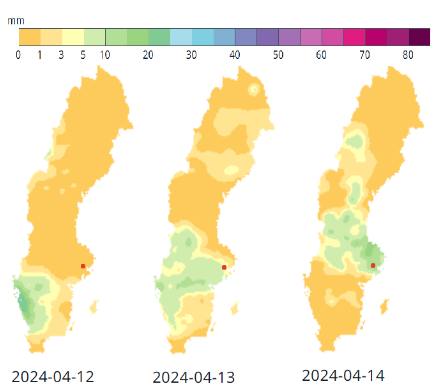

Figure 17. Data of precipitation (rainfall) from SMHI [16] during the testing dates. The red dot indicates the position of the test equipment.

The protocol used by Starlink to set the estimated throughput is not specified. However, the throughput results for both the TCP and UDP measurements are within the stated throughput range.

To validate the rain collector measurements, the data were compared with SMHI data. Figure 17 presents data from SMHI, which show precipitation at the test location during the same date as the measurements in Subsection IV-A [16]. It also verifies the two days without rainfall, which corresponds with our precipitation measurements.

V. Discussion

Our results show that Starlink's downlink throughput is affected by rain. This is expected, as terrestrial antennas generally struggle to transmit and receive signals during precipitation [20], especially at higher frequencies. Starlink operates in three bands above 10 GHz [21], where rain attenuation is more significant [22]. These include the Ku-band (10.7–14.5 GHz), Ka-band (17.3–30.0 GHz), and E-band (71–76 GHz and 81–86 GHz) [21].

The Ku-band, used for both uplink and downlink communication with Starlink user terminals, is the focus of our study, as rain measurements were collected at the user terminal location. The higher-frequency Ka and E bands are used for communication between satellites and ground stations [4]. Since these bands are more susceptible to rain attenuation [22], further investigation is needed to analyse the throughput impact of precipitation at ground stations.

The Starlink system shows a distinct variation in throughput depending on the time of day. The throughput is higher during the night and early mornings than during the day and evenings. The cause of this pattern could be that the data traffic is higher during the day, implying a higher load on the network. Hence, areas with a lower density of Starlink satellites may be more affected by network load, since more users need to share the same capacity.

Laniewski et al. [7] concluded that the throughput for UDP varies by ±10% during the day. This is similar to our results. For TCP, our data shows that the throughput varies by ±30%. The variation is expected because of the inherent properties of the two transport protocols.

The Starlink system's TCP variation can be compared to 4G cellular networks to give perspective on the results. Garcia et al. conducted a study that included a comparison of network throughput, depending on the hour of the day. The study used the TCP protocol over different 4G cellular network operators [23]. The operator with the most fluctuations in throughput during the day varied between approximately 35-45 Mbit/s, resulting in a daily variation of ±12.5%. The throughput for 4G shows a significantly lower fluctuation than Starlink's throughput using the TCP protocol. This illustrates how the TCP protocol can have less variable throughput within a network under certain circumstances. Since TCP is a connection-oriented protocol, latency also impacts the throughput [24]. The performance impact due to latency depends on the congestion control algorithm.

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 larger impact on throughput. Congestion control algorithms are designed for network environments with different characteristics than LEO satellite networks [25]. The LEO satellite network is a new kind of network environment, with no specialised algorithm for the network's congestion. The Starlink network environment includes a reconfiguration of the entire network every 15 seconds, and the current congestion control algorithms are not adapted to such reconfigurations. 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 BBR being able to adapt to the LEO network the best. According to the authors [26], BBR adapted best to the simulated LEO satellite network. 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 research experiments in that paper. Our study did not have latency and congestion control algorithm analysis within its scope, although it would be an interesting topic for future studies. Expanding on the testing done by Barbosa et al. is also an area worth exploring. By doing a similar test on a real-world LEO satellite constellation, there would be a better understanding to gain of how different TCP congestion control algorithms affect satellite internet throughput and latency.

VI. Conclusion and Future Work

This study shows that for a Starlink satellite terminal in Stockholm, Sweden, the throughput varies dramatically with precipitation, time of day, and choice of transport protocol.

For future Starlink users and researchers, it is important to understand the limitations and variations in throughput depending on these factors. However, Starlink is constantly being updated and changed, which will have an effect on future performance.

There are still issues that deserve examination within the Starlink system. Possible future work includes:

- Measuring packet loss, latency and jitter.
- Testing different methods to measure throughput.
- Testing throughput and other parameters with the Starlink API. [27].
- Examining Starlink's performance in relation to satellite alignments.
- Examining how throughput via the Starlink network is affected by rain at the ground station.

Acknowledgment

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