Throughput Analysis of Starlink Satellite Internet: Study on the Effects of Precipitation and Hourly Variability with TCP and UDP

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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. How the throughput is affected by precipitation, time-of-day and different transport protocols are issues that have received a lot of interest. This affects particularly areas at higher latitudes which are covered by fewer satellites compared to Central Europe and the main regions of the United States. The present study was conducted in Stockholm, Sweden, at a latitude of 59.3 degrees north, well north of the main coverage area for Starlink. The experiments consist of throughput measurements with the internet measurement tool iPerf3 for two different transport protocols: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Precipitation (rainfall) measurements were conducted simultaneously. The results show a notable performance hit in the throughput when moderate rainfall (about 1 mm per hour) is present, about 16 percent for UDP and about 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. 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

Starlink provides broadband connectivity mainly over Central Europe and the main regions of the United States (within the latitudes of ±55 degrees). Areas at higher latitudes, e.g., Scandinavia, are covered by fewer satellites but still receive good enough service for sparsely populated regions [1]. The effect of precipitation on the Starlink system performance has been investigated in Central Europe (Germany and the Netherlands) [2], but remains unexplored in Scandinavia. Previous papers have provided data on Starlink's performance over "Transmission Control Protocol" (TCP) [3] and "User Datagram Protocol" (UDP) [2]. However, no studies has been found comparing the two protocols over the Starlink network.

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

This paper is structured as follows: Section II will give insight into UDP and TCP 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 the findings in this paper.

A. Previous studies of UDP

The major advantage of using UDP for the throughput measurements is that the protocol has no congestion control, meaning that the sender will not throttle the transfer speed when data is lost during transmission. The "WetLinks" paper by Laniewski et al. [2] presents a large dataset of Starlink performance measurements, gathered through experiments conducted in Germany and the Netherlands. This dataset 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 a dense concentration of Starlink satellites. In contrast, our paper reports measurements done at a location with much fewer Starlink satellites in nearby orbits [1]. The "WetLinks" paper reports a UDP throughput range from 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 [4]. High levels of packet loss, e.g., caused by interrupts in the satellite connection, is expected to negatively affect the TCP throughput

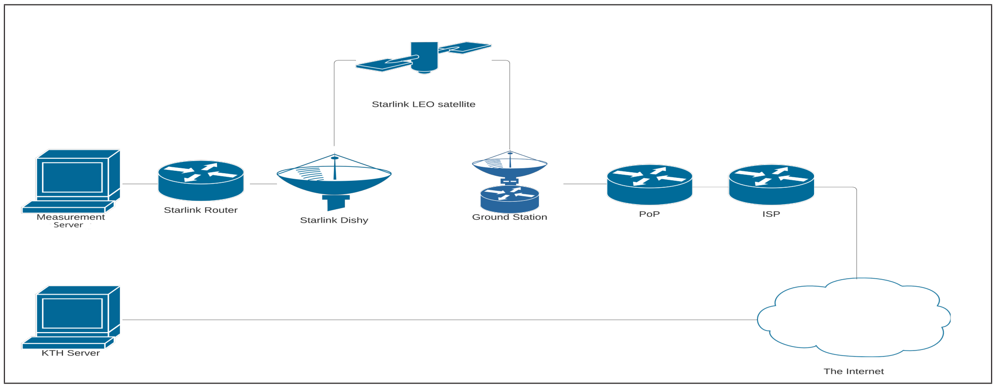


Figure 1: Data path for throughput measurements.

and have a large impact on the end-users performance. Michel et al. [3] measured TCP throughput (using Speedtest by Ookla [5]) 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 [2].

III. Method

In our study, the throughput data is collected using a Starlink "Dishy McFlatface" antenna [6] located on the roof of "Electrum" building in Kista, Stockholm (Figure 2). 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" [7] (rain bucket) (Figure 3) 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. 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 length of 1400 bytes to reduce packet loss [8]. For TCP connections, the iPerf3 command is set to use 8 parallel streams with a buffer length of 128 kB.

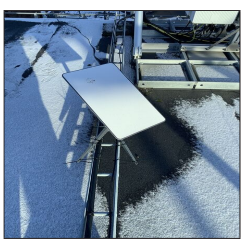


Figure 2: The Starlink user antenna "Dishy McFlatface" [6].

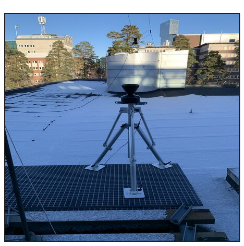


Figure 3: Davis Rain Collector [7].

IV. Results | Analysis

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

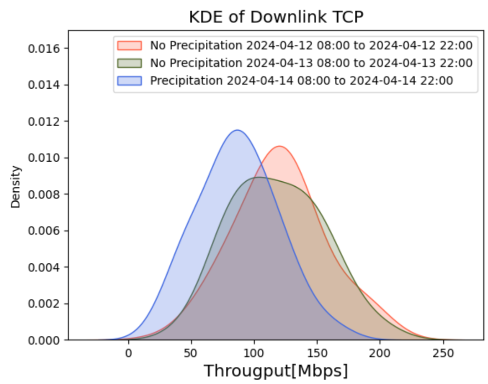
A. Precipitation

In Figure 4, the throughput for both TCP (Figure 4a.) and UDP (Figure 4b.) on three different days with and without precipitation is illustrated using Kernel Density Estimation (KDE) [9]. As can be seen, the average throughput is lower on the day with precipitation for both protocols. 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, which had precipitation. 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 day with recorded precipitation. Figure 5 presents the measured throughput using UDP and TCP during the day with precipitation. The blue dots represent the amount of rainfall in a one-minute interval, 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 [10]. The TCP throughput is significantly affected, even though the rainfall is classified as moderate (less than 4 mm/hour) [11].

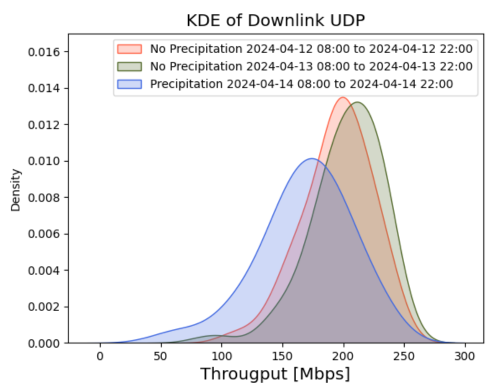
B. Hourly variability

Figure 6 shows the throughput data from TCP (red) and UDP (green) during 72 hours without rain. As can be seen, there is a significant reduction in Starlink performance during

 ISBN: 978-1-68558-276-0



a) TCP



b) UDP

Figure 4: Comparison of throughput for a day with precipitation (blue) vs two days without precipitation (red and green), using *Seaborn* KDE-plots, with a bandwidth of 0.5 [12].

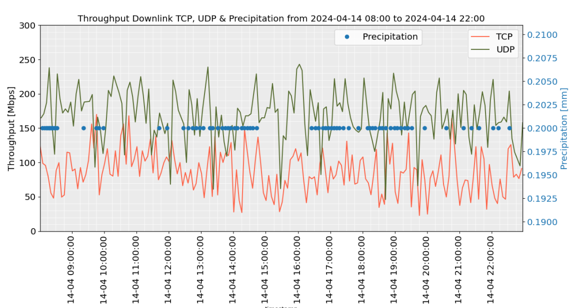


Figure 5: Measured UDP and TCP throughput during the day with rainfall. The blue dots represent the amount of rainfall for one minute.

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.

C. *Internet protocol*

Figure 7 shows a detailed analysis of the hourly variations in throughput over seven days with and without precipitation. As seen in Figure 7b, the mean throughput for UDP at peaks in the early morning with a mean throughput 243 Mbit/s at

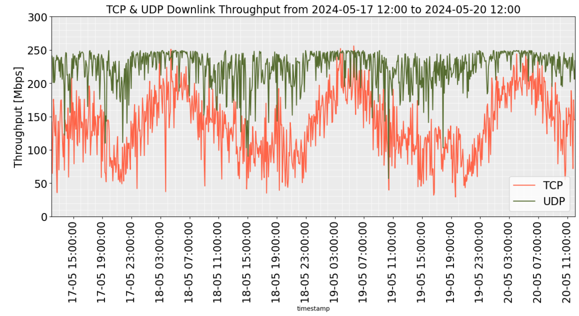
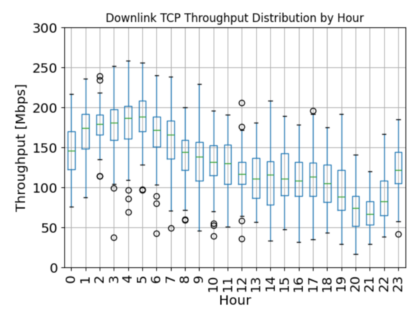
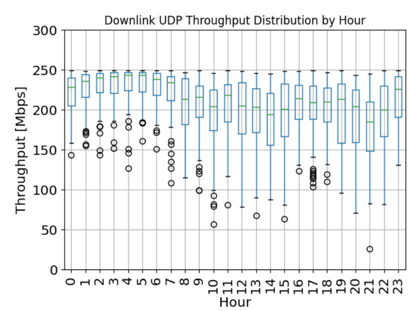


Figure 6: Throughput data from TCP (red) and UDP (green) for a 72-hour rain-free period.

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 7a show a 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 57.58% higher mean for UDP compared to TCP. To get a sense of the variability, we expressed the average IQR as a percentage of the average median. This analysis shows that for UDP, the throughput varied by approximately 21.18%, and for TCP, it varied by approximately 31.89%.



a) TCP



b) UDP

Figure 7: Downlink throughput distribution per hour.

 ISBN: 978-1-68558-276-0

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 [13], especially at higher frequencies. Starlink operates in three bands above 10 GHz [14], where rain attenuation is more significant [15]. 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) [14].

The Ku-band, used for both uplink and downlink communication with Starlink user terminals [16], 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 [16]. Since these bands are more susceptible to rain attenuation [15], further investigation is needed to analyse the throughput impact from precipitation at ground station.

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 throughout 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. [2] 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 different inherent properties of the two transport protocols used.

VI. Conclusion and Future Work

This study has shown 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 a number of issues that still need to be examined within the Starlink system. Possible future work could be:

- Measuring latency and jitter.
- Testing different methods to measure throughput.
- Testing throughput and other parameters with the Starlink API [17].
- Examining Starlink's performance in relation to satellite alignments.
- Examining how throughput via Starlink network is affected by rain at the ground station.

Acknowledgment

This study was supported by the Sustainable Mobile Autonomous and Resilient 6G SatCom research center (SMART 6GSAT), funded by the Swedish Foundation for Strategic Research.

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