SPACOMM 2025

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SPACOMM 2025 Editors

Timothy T Pham, Jet Propulsion Laboratory, NASA, USA

SPACOMM 2025

Forward

The Seventeenth International Conference on Advances in Satellite and Space Communications (SPACOMM 2025), held between May 18-22, 2025 in Nice, France, continued a series of events attempting to evaluate the state of the art on academia and industry on the satellite, radar, and antennas based communications bringing together scientists and practitioners with challenging issues, achievements, and lessons learnt.

Significant efforts have been allotted to design and deploy global navigation satellite communications systems, Satellite navigation technologies, applications, and services experience still challenges related to signal processing, security, performance, and accuracy. Theories and practices on system-in-package RF design techniques, filters, passive circuits, microwaves, frequency handling, radars, antennas, and radio communications and radio waves propagation have been implemented. Services based on their use are now available, especially those for global positioning and navigation. For example, it is critical to identify the location of targets or the direction of arrival of any signal for civilians or on-purpose applications; smarts antennas and advanced active filters are playing a crucial role. Also progress has been made for transmission strategies; multiantenna systems can be used to increase the transmission speed without need for more bandwidth or power. Special techniques and strategies have been developed and implemented in electronic warfare target location systems.

We welcomed academic, research and industry contributions. The conference had the following tracks:

- Satellite and space communications
- Satellites and nano-satellites
- Satellite/space communications-based applications

We take here the opportunity to warmly thank all the members of the SPACOMM 2025 technical program committee, as well as all the reviewers. The creation of such a high quality conference program would not have been possible without their involvement. We also kindly thank all the authors who dedicated much of their time and effort to contribute to SPACOMM 2025. We truly believe that, thanks to all these efforts, the final conference program consisted of top quality contributions.

We also thank the members of the SPACOMM 2025 organizing committee for their help in handling the logistics and for their work that made this professional meeting a success.

We hope that SPACOMM 2025 was a successful international forum for the exchange of ideas and results between academia and industry and to promote further progress in the domain of satellites and space communications. We also hope that Nice provided a pleasant environment during the conference and everyone saved some time to enjoy the historic charm of the city.

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Table of Contents

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

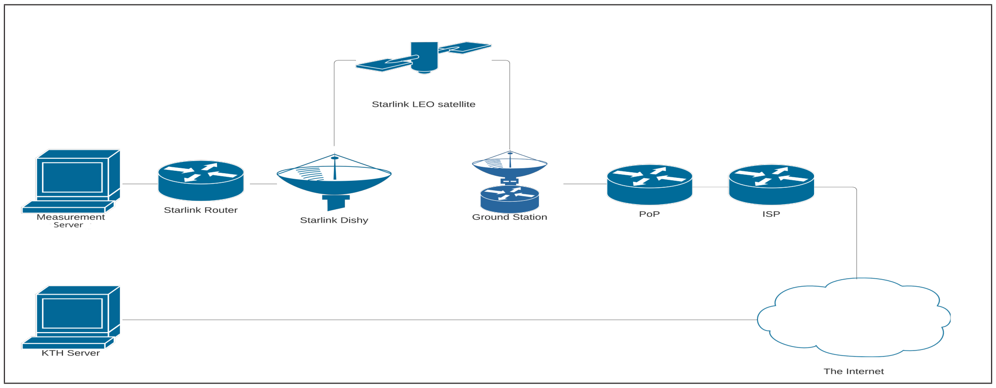


Figure 1: Data path for throughput measurements.

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.

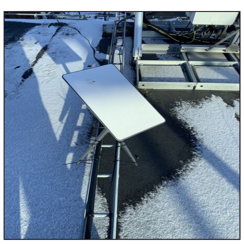


Figure 2: The Starlink user antenna "Dishy McFlatface" [6].

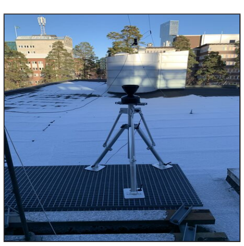


Figure 3: Davis Rain Collector [7].

IV. Results | Analysis

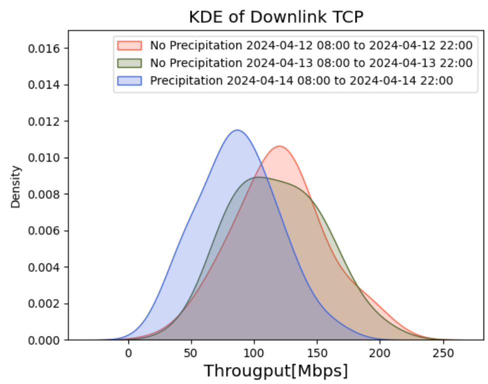
This section presents and analyses the results from the study, categorised in three sections based on the findings.

A. Precipitation

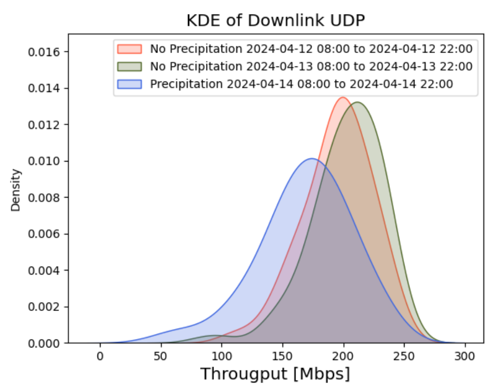
In Figure 4, the throughput for both TCP (Figure 4a.) and UDP (Figure 4b.) on three different days with and without precipitation is illustrated using Kernel Density Estimation (KDE) [9]. As can be seen, the average throughput is lower on the day with precipitation for both protocols. Over the three 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



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].

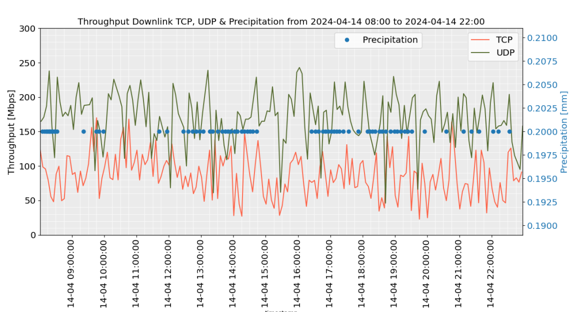


Figure 5: Measured UDP and TCP throughput during the day with rainfall. The blue dots represent the amount of rainfall for one minute.

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

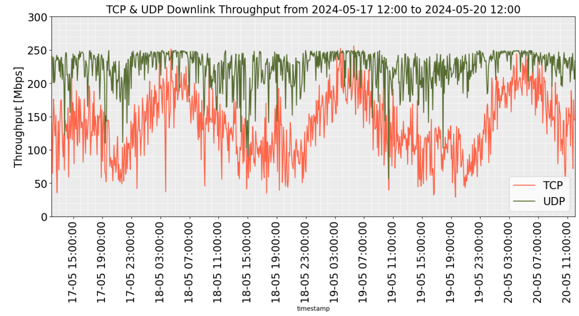
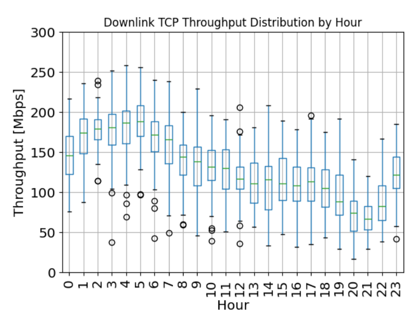
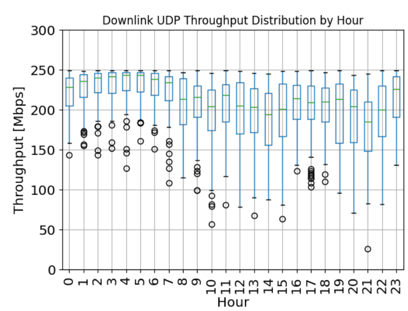


Figure 6: Throughput data from TCP (red) and UDP (green) for a 72-hour rain-free period.

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.

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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

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Modeling of Multi-Hop DTN-Based Lunar Communications for the Evaluation of Traffic Prioritization

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***Abstract*—The use of the Moon-to-Earth communication link is expected to increase in the coming years due to the various planned missions. As a result, the infrastructure specifically designed for the challenges of the space environment has to be further developed. More precisely, the Delay- and Disruption-Tolerant Network (DTN) with Bundle Protocol (BP) needs to be adapted to cope with the high transmission rate and the limited bandwidth. This includes the assessment of Quality of Service (QoS), especially traffic prioritization, which is the focus of this work. The state-of-the-art channel modeling for the Earth-to-Moon link is extended to model multi-hop scenarios. The model takes into account the differences between space-based communication and atmospheric entry, thus enhancing the realism of the results. Simulations for one-hop, two-hop, and three-hop paths showed a positive impact on the performance of high priority bundles. Additionally, it was found that the improvement due to traffic prioritization was linked to the routing chosen, suggesting that high priority information should be sent over fewer hops while low priority information should be forwarded over longer routes. The study concludes that traffic prioritization is recommended for situations in which high priority packages need to be delivered within a certain time threshold, and it emphasizes linking routing to the priority.**

Keywords-Solar System Internet (SSI); Delay- and Disruption Tolerant Networks (DTN); Bundle Protocol (BP); space communications; lunar communications; traffic prioritization

I. Introduction

The Moon is the closest celestial object in space to Earth, making it an essential piece in the future of space exploration [1]. This is reflected in the amount of planned missions: over 40 in the time frame of 2018 to 2030 by European Space Agency (ESA), National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA) and Indian Space Research Organisation (ISRO), among others. One key factor deciding the success of these missions is the existence of a suitable communication infrastructure. The design of such an infrastructure is an especially challenging task in outer space, where the communication link is defined as "highly stressed".

The concepts of Delay- and Disruption-Tolerant Network (DTN) and Bundle Protocol (BP) were developed to address these issues. They do so by implementing a packet-switching mechanism which is resistant to long periods without connectivity, and to the lack of an end-to-end path. Nevertheless, other obstacles, such as the bottlenecks created by the strain of the many mentioned missions on the bandwidth are not yet solved. The main example of this is the Lunar Gateway, which will be the first space station beyond Earth's orbit, and will serve as a communication hub and relay between Earth and the Moon. The European System Providing Refueling, Infrastructure and Telecommunications (ESPRIT) module will provide a maximum of 25 MBit/s [2], but the average scientific mission is expected to take up to 20 MBit/s of this bandwidth [3], meaning that the combination of telemetry, tracking and command (TT&C), basic communication and several science missions will regularly surpass the maximum bandwidth provided by the gateway, leading to long queuing times and even bundle drops.

Traffic prioritization, a Quality of Service (QoS) mechanism, can optimize bandwidth usage by prioritizing urgent data. Although the current BP definition lacks QoS management (RFC 9171), there is an approach presented by Algarra et al. in [4], which aims to implement several QoS parameters in an extension block. One of them is the aforementioned traffic prioritization, which is demonstrated in the previous work of Algarra et al. to improve the delay for high priority information [5]. Nevertheless, the research done is based on the assumption that the Earth-to-Moon communication will happen through a direct communication link, which will not be the case for many missions [6]. Some will rely on relays to have more frequent communication windows, and some may not have a direct-to-Earth link at all, especially the missions landing on the dark side of the Moon. The deployment and use of relay satellites is a necessary step for those missions to have a connection. Therefore, a more realistic study needs to be conducted, including multi-hop paths.

This paper analyzes the effect of traffic prioritization on multi-hop Moon-to-Earth communication links by adapting Algarra et al.'s [4] model to represent a flexible number of hops. Associated with these modifications is the necessary re-evaluation of traffic prioritization in DTN with BP. Therefore, simulations of different multi-hop paths will compare the delay of packages using three priority classes to the delay without traffic prioritization implemented. Additionally, other findings might reveal from the study of hop variations, that are beneficial for further development of the space communication link.

This paper is organized as follows: Section II will give the necessary background information, including DTN, BP, QoS and Markov chains. In Section III the work of Algarra et al. [4] is described in addition to other related works. Then the adapted model and all its associated components are elaborated in Section IV. Section V presents an analysis and evaluation of the experiments conducted with the implemented model. The final Section VI summarizes the paper and gives an outlook on future work.

II. Background

A. DTN

Space communication links are characterized by intermittent connectivity, long delays, asymmetric data rates, and high error rates. DTN addresses these challenges by using store-and-forward message switching, replacing the end-to-end path of terrestrial internet with a more fitting hop-by-hop approach, as seen in Figure 1.

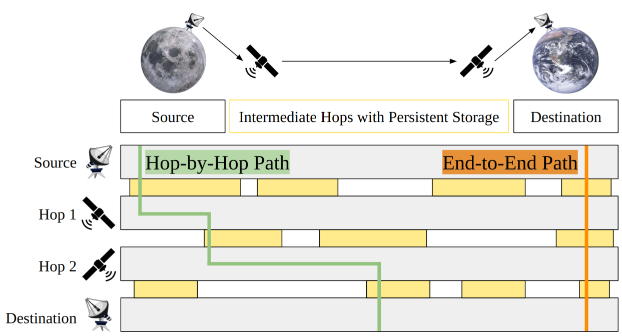

Figure 1. Hop-By-Hop vs End-To-End

Since direct communication is rare or non-existent, this system is always faster at package delivery than the end-to-end alternative, and it takes the same amount of time in the worst case [7]. The entire message or parts of it are therefore moved on a hop-by-hop basis, from the persistent storage of a node to the persistent storage of the next node. This ensures messages are stored until an appropriate link becomes available.

B. BP

The store-and-forward message switching of DTN is realized by the BP, which operates as an overlay on top of the transport and below the application layer (see Figure 2). By doing so, terrestrial protocols can still be used despite the challenging characteristics. Since the underlying protocols remain unchanged, integration is seamless [7].

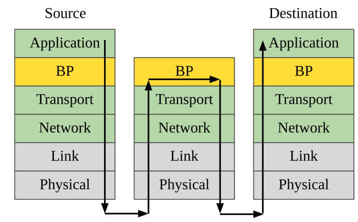

Figure 2. Bundle Protocol (BP)

The messages to be sent are encapsulated into a bundle, along with all the necessary metadata for the information to traverse the network and be decoded at the destination. A bundle consists of three types of blocks:

- Primary Bundle Block: It holds crucial information, such as the source node ID, the destination node ID, and the creation time among others. It is protected from modifications by the Block Integrity Block (BIB) [8].
- Extension Blocks: They are optional blocks that include additional information, such as the age of the bundle or its hop count. Because these blocks are only optional, not all nodes on the path may be able to process all types of extension blocks.
- Payload Block: It contains the actual data to be transmitted. Since this data should not be altered, it is also protected by the BIB.

III. Related work

A. QoS in BP

Traffic prioritization in BP has been implemented before within the Class of Service block defined in RFC 5050 [9], which defined “expedited”, “bulk” and “normal” classes. However, this classification was found to be insufficient, leading to the development of the Extended Class of Service (ECOS) specified in the Consultative Committee for Space Data Systems (CCSDS) BP Specification [10], which added the classes “critical”, “streaming”, “ordinal”, and “reliable”. Nevertheless, this approach remained inflexible due to its predefined usage of each class and lack of specification for message handling and ordering. Additionally, the inclusion of retransmission schemes within traffic prioritization reduced its adaptability [10]. Despite these drawbacks, ECOS was implemented in the Interplanetary Overlay Network (ION) [11].

Apollonio et al. [12] examined ECOS with Contact Graph Routing (CGR), the routing algorithm for DTN, in an Earth-Moon scenario. Their findings showed that CGR effectively handled prioritization: selecting the best routes for “streaming,” maximizing bandwidth for “bulk,” and prioritizing “critical” bundles, reinforcing this paper’s approach. However, they assumed uniform loss rates, while real-world conditions vary due to uncorrelated (e.g., thermal loss) or correlated (e.g., atmospheric or solar effects) losses. The novelty presented in this paper is the use of a multi-hop model to validate results under realistic conditions.

Related work by Pan et al. [13] categorized deep space communication into Near-Earth, interstellar, and near-planet links, each with associated loss equations, but lacked a unified loss model. Chu et al.[14] proposed a four-state Markov chain for low Earth orbit with two error and two good states. The similarities with the three-state Markov chain discussed in Section III-B supports the use of Markov chains for space communication, while the differences stem from focusing on error sequences rather than on the entire orbit.

B. Previous work

The basis of this work is the discrete Markov chain used by Algarra et al. [4]. It is designed to model a direct communication link between Earth and a node in space (see Figure 3). It consists of three states:

- Success: The transmission was received.
- Short-Term Loss: The transmission failed due to short-term loss. These losses include antenna pointing errors, interferences, or light atmospheric weather.
- Long-Term Loss: The transmission failed due to long-term loss. This includes solar storms, where the interferences are so severe that the channel appears blocked.

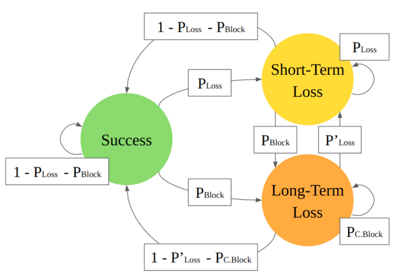

Figure 3. Markov Model of a Node-to-Node Communication Link [4]

P_{Loss} is with 4.3% the probability of experiencing pointing errors, interferences, or light atmospheric weather. P_{Block}, the probability of entering the long-term loss state, is 0.003%, derived from the likelihood of a C, M, or X-class solar flare per second. Because flares last seconds to minutes, the probability of remaining in this state is much higher, set at 99% to reflect the average flare duration.

Since these conditions are given node-to-node, this Markov model is used as a basis for the model of this work explained in Section IV.

The QoS block proposed in [4], [5] and [15] is the model being simulated in this work, since it improves upon ECOS by strictly separating QoS parameters into blocks with clear handling definitions. Instead of worded labels, numerical prioritization is used, ensuring scalability. The standard sets three main priority classes (critical, high priority, and low priority), as well as sub-priorities within the high and low priority classes [4]. This adds granularity and flexibility to the prioritization scheme, which is now able to represent a wide range of latency requirements.

When simulating the proposed model, the study showed a significant improvement in the latency experienced by the critical information, and a moderate improvement for the high priority information. This was at the expense of the low priority information, which performed worse than if no traffic prioritization had been applied (First-In-First-Out (FIFO) approach). Nevertheless, this trade-off is considered desirable since, by definition, low priority data is not time-sensitive, and a longer latency does not affect its validity at arrival. It was then concluded that traffic prioritization is an essential QoS mechanism to be included in BP, since it solves the problem of time-sensitive information being delayed at bottlenecks, and that the proposed extension block covered the previously unfulfilled requirements.

IV. Model

To evaluate the system under more realistic conditions, the channel and its characteristics need to be modeled, starting with the losses. These can be of two types:

- Uncorrelated losses: Their occurrence is sporadic and short, and they are limited in time and space. Sources of uncorrelated losses are thermal loss or short interferences, for example.
- Correlated losses: They keep reoccurring for a long period, resulting in multiple packages lost in a row. Examples of causes of such losses are atmospheric and space weather, like storms and solar flares respectively.

To assess communication link losses, this work assumes the transmission path to start at a lunar node (e.g., astronaut, rover, or mission equipment) and reach an Earth ground station via relay satellites. This transmission has therefore several stages:

- Space setting (via Radio Frequency (RF) [16]):
  - The transmission starts at the lunar source and traverses the exosphere of the Moon, a very thin layer of gas that can develop no atmospheric disturbances [17].
  - It then travels through outer space exposed to the Sun without cover. Solar radiation is usually uniform and does not disrupt the transmission, but solar flares result in a radiation peal which is a source for correlated loss.
- Atmospheric setting (via Free Space Optical (FSO) [16]):
  - Once it leaves outer space, the transmission travels through Earth's atmosphere towards its destination. Since Earth's atmosphere is much thicker than the Moon's, there can be weather disturbances during the transmission. The losses taken into account from these disturbances are aerosols as uncorrelated losses, and clouds as correlated losses.

Both stages might encounter uncorrelated losses, such as small interferences and pointing errors.

Using this loss classification to extend the previous Markov model presented in Section III-B, the more generic model can be derived seen in Figure 4.

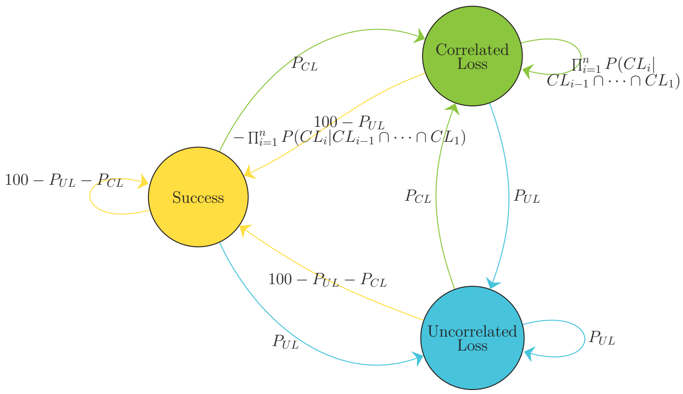

Figure 4. Markov Model of a Multi-Hop Communication Link

The Markov chain abstracts a link between Earth and deep space missions, differentiating between atmospheric and space environments. To ensure realistic transition probabilities, the simulation uses two Markov chains — one for each stage of the communication link. A boundary is needed in order to determine which Markov chain applies. The International Space Station (ISS) was chosen because it is the closest fixed node to Earth, at 400 km from the ground.

This work considers realistic transition values for the Markov model, which can be found in Table I. For the uncorrelated losses, pointing errors and interference probabilities are based on a study of expected erasure in typical satellite-to-ground systems and apply equally to space and atmospheric settings [18]; and aerosol probabilities come from real-time weather data [19]. For the correlated losses, the cloud entry probabilities also come from [19], and the solar storm probabilities follow Nishizuka et al.'s study on solar flare occurrences [20].

TABLE I. Correlated and Uncorrelated Losses for the Space and Atmospheric Settings

Setting	Loss Type		Probability
Atmoshperic	Uncorrelated	Pointing errors and interferences	1.8%
		Aerosols	2%
	Correlated	Clouds	0.00029%
Space	Uncorrelated	Pointing errors and interferences	1.8%
	Correlated	Solar storms	0.0025%

All probabilities within the Markov chain are taken as constant, except for the probabilities of staying in correlated loss, which are dependent on time. The probability of cloud persistence is taken from a study on persistent cloud cover over time [21], using partial cloud coverage. The probability of a solar storm continuing in time is based on Guo et al. [22] and their study of Quasi-periodic pulsation (QPP) in solar flares. Following a log-normal distribution, the graph models solar storm duration, deriving the probability of persistence over time.

V. Results

The setup of the experiments is a replica of the previous work by Algarra et. al [4] described in Section III-B. Each run includes an experiment with the critical, Quasi-Real-Time (QRT), and Store-and-Forward (S&F) priority classes, as well as a FIFO-based experiment to compare the impact of traffic prioritization against a benchmark. All three priority classes carry equal traffic volumes, and the FIFO experiment handles the combined volume. Each simulation spans 500 simulated days to ensure rare events, such as solar storms, are captured.

The novelty lies in the requested Markov chains according to the link, and in the analysis of three arrangements depicting potential real-world scenarios:

- Direct communication (one-hop): the distance taken is 405 500 km, which represents the Earth-Moon link at apogee. It enables comparison between the benchmark (previous work) and the modified model.
- Relayed communication with two hops: the distances taken are 70 000 km from the Moon to the Lunar Gateway, and 335 500 km from the Lunar Gateway to Earth. As noted in Section I, the Lunar Gateway will enhance bandwidth for critical missions, making it essential in the analysis of traffic prioritization.
- Relayed communication with three hops: the distances taken are 70 000 km from the Moon to the Lunar Gateway, 335 100 km from the Lunar Gateway to the ISS, and 400 km from the ISS to the ground station on Earth. The ISS serves as the boundary between the atmospheric and space settings, ensuring each link corresponds to only one environment.

The results hereby presented show the end-to-end delay for the information sent, which is generated at a rate that would create no queue under ideal circumstances. The Cumulative Distribution Function (CDF) graphs show the percentage of bundles arriving at or below a certain point in time. Especially interesting are the 2.5 s and 5 s marks, which represents the limit set by ESA for communication to be considered QRT, and twice this limit for reference purposes respectively [4].

A. One-Hop Scenario

Figure 5 shows the end-to-end delay of the direct communication scenario. 73% of critical bundles arrive within the 2.5 s mark, compared to 60% for QRT, 48% for FIFO, and 43% for S&F. The latter is the only curve not reaching 100% deliverability before 12 s.

97% of the critical bundles arrive within the 5 s mark, with 92% of QRT and only 85% of FIFO bundles. Despite performing the worst, 74% of S&F bundles arrive within 5 s, which is still a high percentage. This trade-off is desirable, as both critical and QRT outperform FIFO.

This end-to-end delay closely matches the previous work [4], showing that the split environments in the adapted Markov model did not significantly affect the link's overall

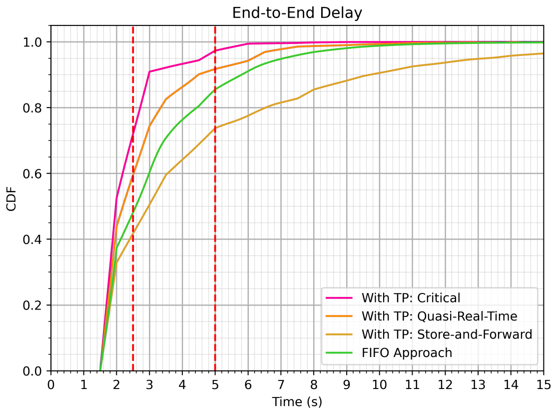

Figure 5. End-to-End Delay in the One-Hop Scenario

modeling. These findings validate Algarra's work and allow this work to test the traffic prioritization system in a multi-hop scenario.

B. *Two-Hop Scenario*

The results depicted in Figure 6 show that the main difference with the previous scenario is that the QRT and FIFO curves are much closer now, although the same general order is maintained: Critical 65%, QRT 55%, FIFO 53%, and S&F 45% at the 2.5 s mark. None reach 100% deliverability within the 5 s mark, but all exceed 85%. Lastly, the curve for critical bundles remains steep but delayed, indicating that higher loss from multiple hops requires further study.

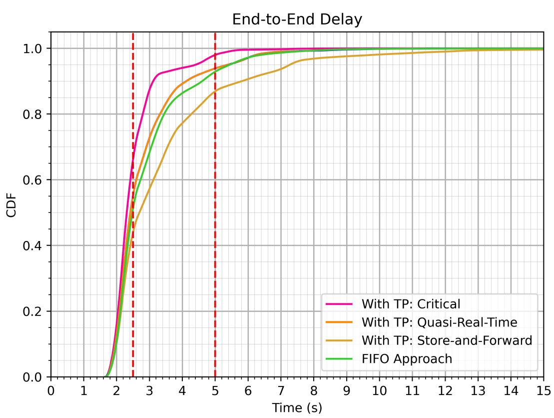

Figure 6. End-to-End Delay in the Two-Hop Scenario

All in all, despite the added hop, critical bundles still outperform FIFO by 12% at the cost of S&F bundles.

C. *Three-Hop Scenario*

Figure 7 shows the resulting end-to-end delay for the three-hop scenario. At the 2.5 s mark, less than 40% of the bundles have arrived for all priority classes. Nevertheless, the curve increases steeply, and at the 5 s mark the results show 99% deliverability for critical, 98% deliverability for FIFO and QRT, and 83% deliverability for S&F.

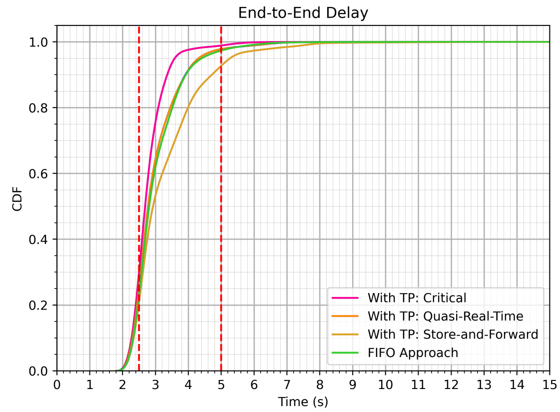

Figure 7. End-to-End Delay in the Three-Hop Scenario

The higher error rates are reflected in the higher average delays, but the amount of large delays decreases, suggesting that shorter service times and faster loss recovery result in higher throughput and more equal distribution of priority classes across nodes.

D. *Evaluation*

In the analysis of the one-hop scenario, great similarities appeared to Algarra et al.'s work [4], not only in the end-to-end delay, but also in the Bundle Delivery and Bundle Loss Ratio. Therefore, the modifications to the Markov chain in this paper did not compromise the reproducibility of their results. Despite being less detailed in its loss modeling, their approach still effectively represented the Earth-to-Moon communication link. This is consistent with the space setting having a much higher influence on the communication link than the atmospheric setting, which became apparent from analyzing the hop-by-hop delay of the second and third scenario, in which it was shown that the atmospheric setting introduces less loss than the space setting.

The overall outcome of the traffic prioritization evaluation is that in all experiments the critical class always performed better than all other classes, regardless of the number of hops. The QRT class also performed better than S&F and the FIFO approach, which is desirable as the QRT class is reserved for time-sensitive data. Nevertheless, the extent of the improvement depends on the number of hops; with the critical class having the largest improvement in the direct communication scenario. Based on that outcome, it is concluded that a change in the routing according to the priority class of the bundle is beneficial. On the one hand, critical and high priority bundles should be sent as directly as possible to their destination to avoid multiple service times and minimize the risk of being blocked by potential loss more than once. On the other hand, lower priority bundles may be routed through multiple hop paths for them to benefit from the higher throughput achieved through faster retransmission attempts and spread widely

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in the net of nodes improving their chances to be serviced next.

VI. Conclusion and Future Work

A. Conclusion

The Earth-Moon communication infrastructure must evolve to support future missions and their needs, requiring robust and reliable communication mechanisms [6]. DTN with BP is expected to be the standard due to its hop-by-hop approach, ideal for the characteristics of space communications. However, it lacks QoS assessments to optimize bandwidth, ensure reliability, and meet delivery time requirements.

Previous work proposed implementing QoS parameters via an extension block in BP, and further research on traffic prioritization using a Markov chain-based Earth-Moon link simulation showed performance gains, particularly for critical bundles [4]. This was done assuming direct communication links between Earth and Moon. Giving that these are unlikely when looking at the future Moon missions, this work modeled a multi-hop Markov chain extending previous work to simulate different link combinations. The model includes the states of success, correlated loss (caused by clouds and solar storms), and uncorrelated loss (caused by aerosols, interferences, and pointing errors), and separates atmospheric and space settings.

When analyzing the impact of traffic prioritization on multi-hop paths, all experiments showed improved performance for critical and high priority bundles compared to FIFO, supporting the recommendation to implement traffic prioritization in BP. Additionally, low priority bundles performed better with more hops due to faster retransmissions, while the performance gain of high priority bundles decreased as the number of hops increased. Therefore, adjusting routing based on bundle priority benefits both high and low priority bundles.

B. Future Work

Future research should validate the effects of routing based on bundle priority. Supporting that, further experiments using the Markov chain model could refine traffic distribution and explore other queueing algorithms with a focus on fairness (as proposed by Algarra et al. [4]), to assess the impact of traffic prioritization on multi-hop paths.

Enhancing the model is also needed for more precise outcomes. While the data was carefully researched, some values - such as cloud entry probability - require more accurate data collection. Additionally, omitted loss factors (such as atmospheric scintillation) could be included for more realistic modeling where necessary.

The Markov model can further support QoS research through the testing of error correction algorithms. It can also be used to determine the benefits of using FSO or RF depending on the link characteristics, providing insights into routing and loss factors.

Another application area of the model could be the computation of expected successful passes by incorporating contact windows and integrating them with loss conditions, enabling a more accurate assessment of communication success. Additionally, the identification of the underlying conditions that may lead to these intermittent transmission patterns invites further investigation.

Finally, QoS studies remain incomplete, lacking real-world deployment on a satellite or spacecraft. The demonstration of the performance gain in this paper should result in an implementation of traffic prioritization into BP lastingly enhancing the communication link.

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