Breaking Through the Clouds: Performance Insights into Starlink's Latency and Packet Loss

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***Abstract*—Our modern era is experiencing a rapid evolution in satellite Internet access. However, it is unclear how well these systems perform and what we can expect from Internet access via satellites. Previous research has studied the performance and resilience of such systems, uncovering several drawbacks (e.g., high packet loss and unstable performance). In this work, we thoroughly investigate the characteristics of the Starlink network. We scrutinize the TLS handshake latency, packet loss, and the diurnal latency variation to establish a correlation between these factors. To achieve this, we utilize historical data measured by RIPE Atlas and Cloudflare Radar from 2022-01-01 to 2024-06-30.**

We find no statistically significant correlation between latency and packet loss in the Starlink satellite network. However, we discover an intriguing pattern suggesting that Starlink exhibits specific latencies more consistently than others. This finding contradicts recent research that claims a significantly better performance of Starlink with median latencies substantially lower than 80 ms. Furthermore, our findings reveal significant geographical variations, where even highly developed countries such as Germany experience packet loss ratios exceeding 10%.

Additionally, we examined Starlink's routing behavior, which reveals two sudden spikes in latency. The first spike is attributable to the transition between satellite and terrestrial networks, while the second is seemingly unrelated to Starlink.

I. Introduction

Internet access is challenging in remote regions and areas with unreliable terrestrial infrastructure (e.g., during wars or natural disasters). Consequently, businesses have explored the concept of Internet access via Low-Earth Orbit (LEO) satellites. Since space is largely inaccessible, satellites are resilient to many catastrophes and other threats. Additionally, communication occurs at the speed of light, resulting in low latencies at low Earth orbits. Satellites were expected to be predictable due to well-defined properties of a constellation, including the positioning of ground stations, flight paths of satellites, and the positions of neighboring satellites. However, satellite Internet access has been observed to exhibit significant variation in latency and packet loss. In this study, we examine the largest Satellite Network Operator (SNO): Starlink, and aim to address the following **Research Questions:**

1) How does Starlink perform in terms of latency and packet loss?
2) To what extent do latency and packet loss characteristics in Starlink's network correlate?
3) How do packets route through Starlink's network and how do network paths impact latency?

Data from RIPE Atlas and Cloudflare Radar is used to address the research questions. The data was collected programmatically from 2022 to 2024. We summarize our findings from the analysis of this longitudinal data as follows.

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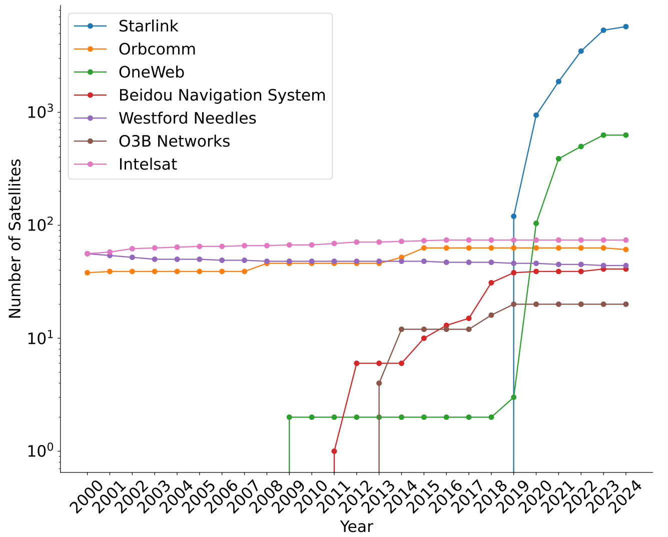


Fig. 1: Growth of number of satellites in satellite constellations from 2000 to June 2024 (according to N2YO [1]).

Classification	2018	2019	2020	2021	2022	2023	2024
Starlink	0	120	943	1871	3481	5326	6396
Orbcomm	63	63	63	63	63	63	61
OneWeb	2	3	104	388	498	628	628
Beidou	31	38	39	39	39	41	41
O3B	16	20	20	20	20	20	20
Intelsat	74	74	74	74	74	74	74

TABLE I: Growth of number of satellite in satellite constellations from 2017 to June 2024 (according to N2YO [1]).

Starlink Latency Improvements from 2022 to 2024: The median latency for Starlink has shown significant improvement over the period from 2022 to 2024. The data demonstrates that the median latency has decreased, with the lowest observed median latency on a single weekday being approximately 80 ms in 2024. This improvement suggests that Starlink has been optimizing its network infrastructure, potentially through the addition of more satellites and ground stations, resulting in better performance.

Bimodal Distribution of Latencies: The latency data exhibits a bimodal distribution, with two distinct peaks. The first peak represents lower latencies (approximately 80–100 ms), while the second peak represents higher latencies (approximately 150–250 ms). This bimodal distribution indicates that Starlink produces two distinct latency ranges with particularly high frequency. The reasons for this pattern could be related to factors such as the positioning of ground stations, satellite orbits, weather conditions, and potentially different subscription models.

Packet Loss Rates Above 10% for Countries with High Ground Station Density: Despite the high density of ground stations in some countries, packet loss rates may exceed 10 %. For example, Germany, a country with numerous ground stations, experiences packet loss ratios exceeding 10 %. This finding suggests that factors other than ground station density, such as network congestion, satellite hardware limitations, or environmental conditions, significantly influence packet loss rates.

The remainder of this paper is organized as follows: We present a brief background and related work in Section II. Section III describes the methodology, specifically the process of data collection. The research questions are addressed in Sections IV to VI, including the data analysis of network latency, packet loss, and traceroute measurements. Finally, Section VII concludes with a comprehensive overview of the findings.

II. Background and Related Work

A. Background

From a user's perspective, satellite communication exchanges packets with a target the same way as terrestrial internet connections (except for the physical layer [2]). The difference lies in the communication between the user and the first terrestrial hop. The user is provided with an antenna that allows communication with the provider's satellites. The satellites are within a specific satellite constellation at Low-Earth Orbit (LEO) or Geostationary-Earth Orbit (GEO). The altitude of the constellation has a major impact on latency. Equation (1) shows the minimal latencies of the GEO and LEO constellations. The LEO constellation provides a far better latency in an ideal case.

$$\frac{2 \cdot 35\,786\,km}{300\,000\,\frac{km}{s}} \approx 0.240\,s \qquad \frac{2 \cdot 550\,km}{300\,000\,\frac{km}{s}} \approx 0.004\,s \tag{1}$$

The broad process of satellite communication works as follows. The sender utilizes an antenna for communicating with the satellites. It sends packets to a satellite, which routes packets to their receiver. The satellites may use an Inter-Satellite Link (ISL) to send packets to other satellites until a suitable Ground Station (GS) is found. The GS is usually connected to a terrestrial ISP, which is capable of communicating with the target. The complicated part is routing the packets through the satellite constellation itself. Such a route is called a bent-pipe. The simplest case is sending packets to the ground station right after they have been received by a satellite. This is called a 1-hop-bent-pipe. Often, 1-hop-bent-pipes are not possible or not ideal. With n hops, the bent-pipe is called an n-hop-bent-pipe [3].

Country	Number of Probes	Country	Number of Probes
Philippines	3	Greece	1
Switzerland	1	Poland	1
United Kingdom	11	Italy	4
France	18	Benin	2
Kiribati	2	Czechia	1
Spain	4	Honduras	1
Canada	11	Falkland Islands	1
Réunion	1	Virgin Islands, U.S.	1
Belgium	2	United States	53
Austria	4	Netherlands	2
Haiti	3	Australia	8
Sweden	1	Germany	10

TABLE II: The number of probes per country in the AS14593 on the RIPE Atlas measurement platform.

B. Satellite Numbers in Different Satellite Constellations

In recent years, satellite technology has advanced rapidly, driven primarily by the growing demand for global connectivity and communications. Consequently, companies have constructed their own satellite constellations, resulting in a total of more than 29 000 objects in space at the time of this writing. As the satellite count is highly relevant for the performance of an SNO, we collected the numbers of satellites per constellation until June 2024 from N2YO. Figure 1 shows various satellite constellations with the number of satellites they comprised per year. Table I shows the corresponding numbers, starting in 2017. We can observe that Starlink is by far the largest constellation in terms of number of satellites. At the time of this writing, it comprises 6396 satellites. The Starlink constellation grew from 2022 to 2023 by nearly 2000 satellites. OneWeb, Starlink's closest competitor, has a total of 628 satellites with no growth between 2023 and 2024. Other satellite communication constellations such as Orbcomm or Intelsat did not grow at all, or even experienced a reduction in satellites. Only Starlink and OneWeb have seen significant growth in recent years. We note that this is due to the requirement of LEO constellations (i.e., Starlink and OneWeb) to have significantly more satellites, compared to GEO constellations (e.g., Intelsat and O3B).

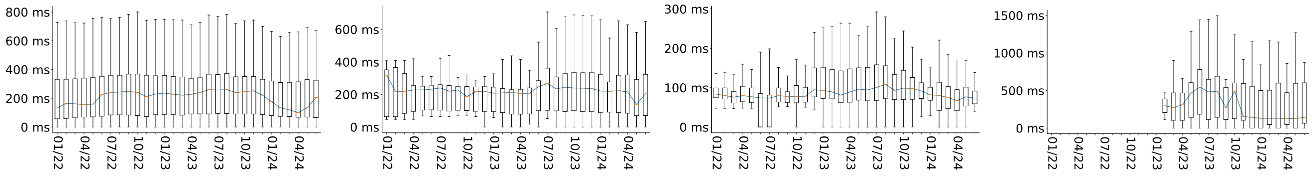
C. Related Work

SNOss have been in existence for several decades, beginning in the late 1990s, when Iridium announced its plans to build a mega-satellite constellation [4], [5]. Even though their initial commercial model proved unsustainable, modern SNOs have access to newer, cost-effective technologies. With the emergence of Starlink, OneWeb, Orbcomm, and others, research has taken the first steps in elucidating how "satellite Internet" might function optimally in the future. In 2020, the first mega constellation simulators Hypatia [6] and Starperf [7] were developed. However, this direction was not further explored as it became apparent that the simulators did not accurately model real-world conditions. Therefore, research shifted toward performing measurements on existing constellations. Performance of satellite network operators was presented in various publications [8], [9], [10], [11], [12], [13], [3], [14], [15]. Most measurements were performed on the Starlink constellation, due to its relative affordability and widespread accessibility, even for non-business customers. Resilience to disasters has been analyzed by Stevensetal. [16]. It is also worth mentioning the influence of weather [17], mobility [18], [19], and solar magnetic storms [9], [20], [21]. All of these factors must be taken into account when implementing routing [22], [23], [24] in a satellite constellation. This includes ISLs [25], [26], the orbital dynamics of satellites [27], [28], and the strategic placement of GSs [29].

In optimal conditions, Starlink could complement 6G deployment [30]. However, the most significant problem is the lack of knowledge about the operational characteristics of Starlink. Therefore, research has attempted to extract the firmware [31], [32].

Also, with the onset of the war in Ukraine, a new issue is the use of satellite communication in conflicts: it operates independently of a terrestrial infrastructure in the conflict zone and could even exacerbate the war [33], [34], [35].

However, existing literature predominantly concentrates on Starlink deployment in a lab scenario (i.e., in nearly ideal conditions).



(a) USA (b) Canada (c) Germany (d) Philippines

Fig. 2: The history of median latencies from 01/2022 to 06/2024 for the USA, Canada, Germany, and the Philippines according to RIPE Atlas data.

It remains unclear how Starlink performs from the user's perspective, where the network might suffer from external influences. This study presents a novel perspective by using RIPE Atlas and Cloudflare Radar to facilitate comparison with the performance distribution of Starlink users. Additionally, this research provides a much longer time series interval that depicts the performance development from 01/2022 to 06/2024.

III. Methodology

For analysis, we use RIPE Atlas [36] and Cloudflare Radar [37]. From RIPE Atlas, we analyze built-in measurements of all registered Starlink probes. Built-in measurements are continuously running measurements that perform measurements from probes toward root servers (**.root-servers.org*). The frequency of each measurement type varies (e.g., Ping runs every 240s and Traceroute every 1800s). We do not include any additional custom measurements. From Cloudflare Radar, we include aggregated latency windows.

The resulting data from RIPE Atlas and Cloudflare Radar is stored in a PostgreSQL database. The data is exported into Parquet files, which we publish to allow for reproduction of our results[1]. The database stores several measurement types, such as Ping, Traceroute, TLS, HTTP, Disconnect Events, DNS measurements, and details of the RIPE Atlas probes connected via AS14593 origin-Autonomous System (AS), and information on all Starlink satellites launched until 06/2024. The whole database comprises $\approx$ 150 GB in PostgreSQL ($\approx$ 37 GB in Parquet files). At the time of measurement, 146 relevant probes were connected to RIPE Atlas. Table II shows the number of probes per country found in the RIPE Atlas measurement platform.

A. Reproducibility

To enhance the reproducibility of our findings, we provide access to the raw data, source code, and supplementary materials associated with this study. These resources are publicly available under an open-access license. Although these materials are currently withheld to maintain the anonymity of the manuscript, we are committed to transparency and will ensure that all relevant information is accessible upon publication. This approach aligns with best practices in research integrity and supports the scientific community's efforts to validate and build upon our work.

IV. Longitudal View: 2022–2024

A. Latency

To determine the performance of Starlink, we analyzed TLS handshake latency over the period 01/2022 to 06/2024. The data was obtained from the RIPE Atlas TLS tests, collected by built-in measurements (i.e., measurements that run continuously in each individual probe at a regular time interval).

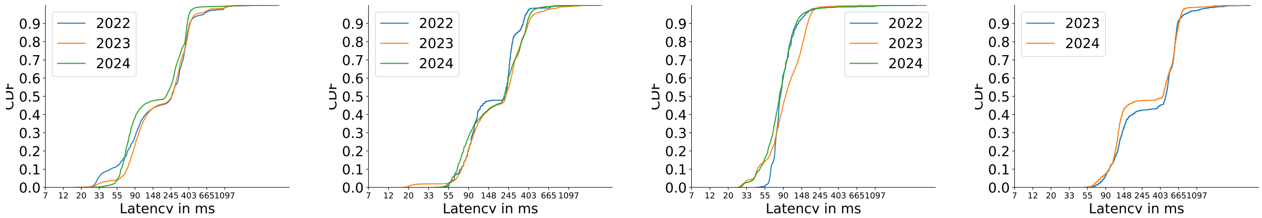
Figure 2 shows the history of median latencies from January 2022 to June 2024 for the USA, Canada, Germany, and the Philippines. The median latencies typically range from 100 to 150 ms for most countries. Comparing the results of 2022 with those from 2023 reveals that most of the observed countries show an increase in latency in the last months of 2022 (mostly in December). At the end of 2023, latency started to decrease again. In the last few months until June 2024, we observe an increase in latency again. We perform a fine-grained analysis of latency variation in Section V, examining latency across weekly temporal patterns.

Figure 3 illustrates the CDF plots of 2022 to 2024. We observe similar performance in 2022 and 2024, but an increase in latency in 2023, corroborating our earlier observations from Figure 2. The CDF is also continuous up to a certain point, where it flattens out, followed by a stronger increase again. This is also observed for curves from other countries (e.g., France). This observation suggests that specific latency ranges are encountered more frequently. The range varies from country to country, but is usually located between 150 and 250 ms.

It becomes apparent that there is a bimodal distribution present (i.e., there is a large gap within the latencies for most countries). By 2024, this pattern is became more pronounced. At this point, it is not clear why the bimodal distribution occurs, but we hypothesize that either the measurements were not consistent enough for such a pattern to occur or the gap is a characteristics of the Starlink system. The latter would suggest that Starlink serves certain latencies better than others, meaning that some users experience lower latencies under certain conditions, while others encounter higher latencies. These conditions could include subscription models, geographic differences between countries, weather, user altitude, or GS availability. In addition, we find that approximately half of the measurements are below 100 ms, while the other half are above 100 ms. This contradicts previous studies suggesting that Starlink performance is mostly below 100,ms [3], [6], [11], [13].

Figure 4 shows the median latencies in European countries. Northwestern Europe exhibits the best latencies, probably due to the presence of more GSs, as illustrated in Figure 5. The southern and eastern European countries have higher latencies. Greece in particular has a high average latency. One reason could be the absence of GSs in the Eastern European region. Italy, on the other hand, experiences a high average latency, despite GSs being present in the country. The issue may be related to a more mountainous topographu, such as northern Italy and Greece.

[1]https://github.com/diic-starlink/performance-insights-into-starlink



(a) USA (b) Canada (c) Germany (d) Philippines

Fig. 3: CDF of RIPE Atlas TLS latencies in the USA, Canada, Germany, and the Philippines from 2022 to 2024.

B. Packet Loss

Packet loss was quantified by analyzing the RIPE Atlas built-in ping measurement data spanning January 2022 to June 2024. Table III and Figure 6 present our results. They reveal different values when comparing countries. Overall, most countries exhibit packet loss ratios between one and four percent, with some having even lower values. The Czech Republic demonstrates the lowest packet loss rate at 0.23 %, followed by Chile at 0.24 %. The Philippines exhibit the highest packet loss rate at 18.27 %. However, it is unclear what the underlying pattern is, as some countries exhibit anomalously high packet loss results, while their adjacent countries do not (e.g., Germany at 10.52 % and Austria at 0.73 %).

Germany and the USA exhibit peaks in late 2022, followed by reduced packet loss in 2023. However, the winter of 2023 also demonstrates an increase in packet loss for all countries in Figure 3, which might be related to the Starlink user base expansion (see Section VI-B). The packet loss persisted until June 2024, when the packet loss for all four visualized countries declined significantly. It remains uncertain whether this pattern will continue in the following months.

Sent	Received	Country	Packet Loss Ratio in %
2 150 628	2 134 905	Austria	0.73
65 021 654	62 438 854	Australia	3.97
22 727 113	22 211 676	Belgium	2.27
1 176 124	1 168 114	Benin	0.68
124 263 104	121 160 149	Canada	2.50
2843	2832	Switzerland	0.39
3 626 230	3 617 474	Chile	0.24
8 092 876	8 074 360	Czechia	0.23
96 089 885	85 983 781	Germany	10.52
21 714 610	21 001 677	Spain	3.28
432 934	418 925	Falkland Islands	3.24
321 919 833	299 847 062	France	6.86
83 840 509	80 720 387	United Kingdom	3.72
12 522 224	12 318 835	Greece	1.62
271 185	265 100	Guam	2.24
18 472 787	18 217 243	Haiti	1.38
37 188 354	35 583 136	Italy	4.32
4 160 290	3 829 356	Kiribati	7.95
127 756	121 937	Madagascar	4.55
20 450 037	17 548 642	Netherlands	14.19
26 654 399	21 785 387	Philippines	18.27
18 739 794	18 670 207	Poland	0.37
7 047 181	6 967 111	Réunion	1.14
9 975 257	9 922 734	Sweden	0.53
578 852 548	557 475 491	United States	3.69
18 571 694	18 463 935	Virgin Islands, U.S.	0.58

TABLE III: RIPE Atlas packet loss from January 2022 to June 2024.

C. Correlation of Latency and Packet Loss

TLS handshake latency and packet loss are closely connected. As latency increases, we anticipate packet loss to increase and vice versa. We examined the period from January 2022 to June 2024 and used the overall packet loss and median latency per month to assess a possible correlation.

We analyzed individual years to gain a better understanding of the trajectory of the correlation in 2022, 2023, and 2024 (up to the end of June). Figure 7 shows the individual correlation values from 2022 to 2024. Overall, the data yields no conclusive results. The correlation coefficients indicate values that are not close to 0, 1, or -1. However, this varies by country. Some countries show stronger correlation values (e.g., Greece in 2022), while others do not exhibit significant correlations. Overall, we cannot establish a correlation between latency and packet loss for Starlink. However, we also cannot assert that the two variables are uncorrelated.

It is probable that other variables need to be taken into account to draw definitive conclusions (e.g., the number of users, the capacity

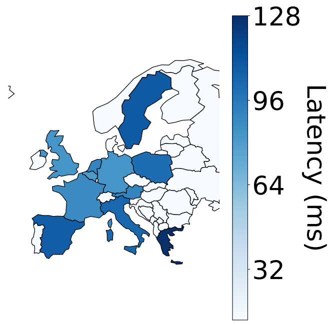


Fig. 4: Heatmap of median latencies in 2024 in Europe from Cloudflare Radar.

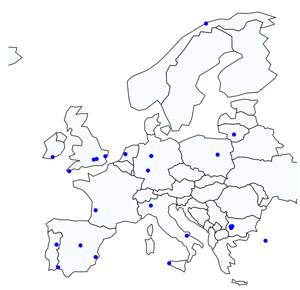
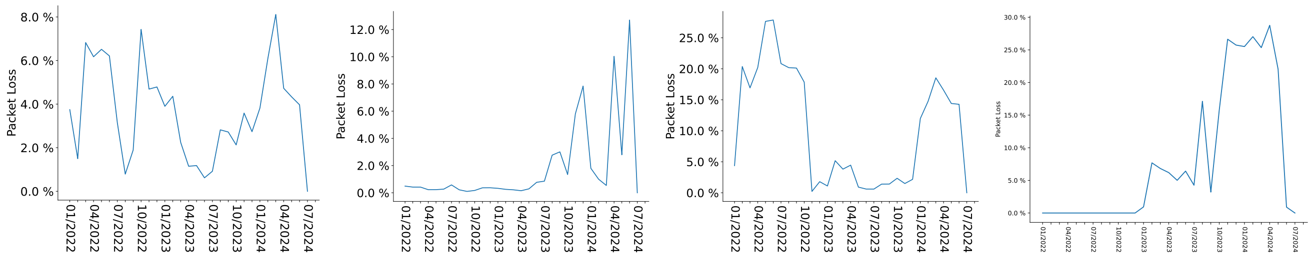


Fig. 5: Map of the Ground Stations in Europe according to the Unofficial Starlink Global Gateways & PoPs Map [38].



(a) USA (b) Canada (c) Germany (d) Philippines

Fig. 6: Packet loss from 2022-01-01 to 2024-06-30 according to RIPE Atlas ping measurements in the USA, Canada, Germany and the Philippines.

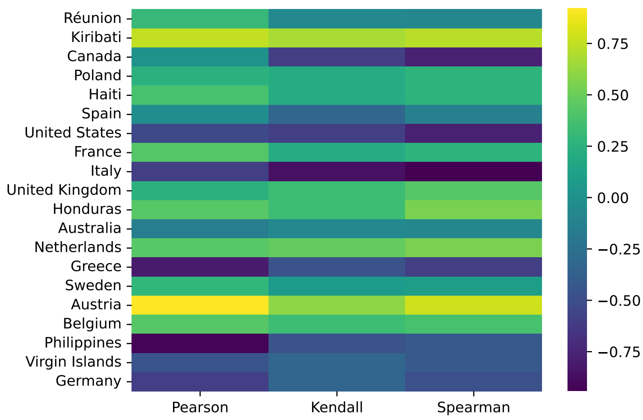


Fig. 7: Individual correlation of latency and packet loss in 2024.

of the constellation [39], the intensity of solar magnetic storms (see Section VI-A), geographical differences between countries, the presence of GSs).

1) Correlation with the Number of Probes: We sought to explain the lack of correlation between latency and packet loss by correlating the results with the number of probes per country. It is possible that the lack of data causes a correlation between latency and packet loss to be undetectable. One possibility is to examine the number of probes available for each country. Therefore, we utilized the data from Figure 7 and correlated it with the number of probes available for RIPE Atlas in each country.

We used the correlation values with the number of probes per country. This resulted in the following correlation coefficients: Pearson correlation: ≈ -0.44, Kendall correlation: ≈ -0.44, Spearman correlation: ≈ -0.53. Since the correlation coefficients do not approach values close to 0, 1, or -1, we cannot establish a correlation with the number of probes. It appears that, the lack of probes does not cause the inconclusive correlation values for latency and packet loss, but alternative factors that have not yet been determined.

V. Weekdays and Diurnal Variations

The question remains whether latencies vary across weekdays. Using the TLS handshake latency measurements built into RIPE Atlas, we analyzed different weekdays from 2022 to 2024. We examined the measurements using standard statistical metrics (median, average, maximum, and minimum latency). The results for Germany are presented in Table V. We can conclude that there is no discernible pattern that differentiates one weekday from another. This consistency persists over the years.

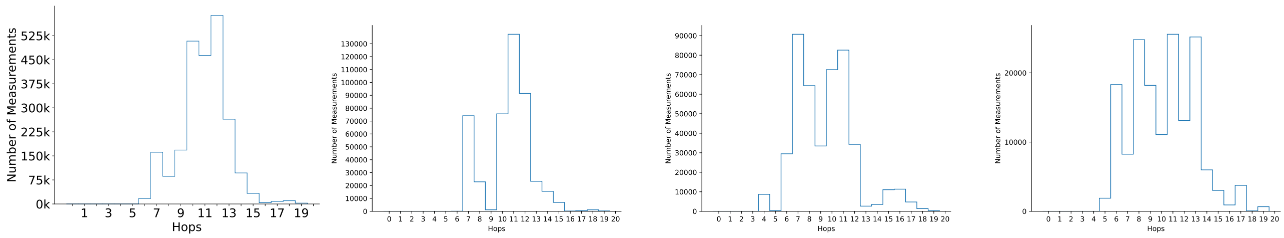
However, Table V also provides an interesting comparison between 2022, 2023, and 2024. In 2022, the median TLS handshake latency ranged between 81 and 84 ms. The average latency was approximately 20 ms higher. Peak latencies were as low as 43 ms. In 2023, the median latencies were significantly higher at 94–98 ms. The average latency was 14 ms higher at maximum, indicating a more stable connection, even if the performance was worse than in 2022. However, 2023 achieved a notably improved peak performance of 26 ms. In 2024, Starlink achieved similar median

	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.
2022							
Med.	20.06	20.08	20.07	20.08	20.08	20.07	20.05
Avg.	15.81	17.23	16.97	16.36	15.94	16.14	16.05
Max.	50.14	50.03	50.07	50.02	40.96	40.51	50.02
Min.	0.05	0.11	0.12	0.03	0.03	0.02	0.02
2023							
Med.	1.07	1.09	1.26	1.22	1.22	1.05	1.04
Avg.	1.53	1.97	2.39	2.58	2.21	2.13	1.73
Max.	13.43	13.59	15.60	25.82	25.93	29.11	13.46
Min.	0.14	0.13	0.11	0.14	0.15	0.12	0.14
2024							
Med.	13.39	12.95	14.05	14.09	14.01	13.80	13.14
Avg.	12.64	12.31	13.19	13.68	13.44	13.70	13.14
Max.	30.23	27.21	25.33	28.49	29.69	29.75	29.95
Min.	0.95	0.52	0.92	0.94	0.94	0.82	0.81

TABLE IV: Packet loss in % per weekday in Germany according to RIPE Atlas ping measurements.

	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.
2022							
Median	84	82	82	84	83	81	83
Average	100	100	106	97	99	99	93
Maximum	1211	3090	3056	703	1229	1106	672
Minimum	47	43	46	47	47	47	46
2023							
Median	95	98	94	95	94	95	96
Average	111	111	108	109	107	108	108
Maximum	1245	1227	1233	707	1088	1220	1052
Minimum	28	26	27	27	27	27	27
2024							
Median	80	81	80	79	81	80	81
Average	97	93	104	105	95	95	95
Maximum	3147	1592	4374	3624	4368	1230	1320
Minimum	26	26	26	26	26	27	26

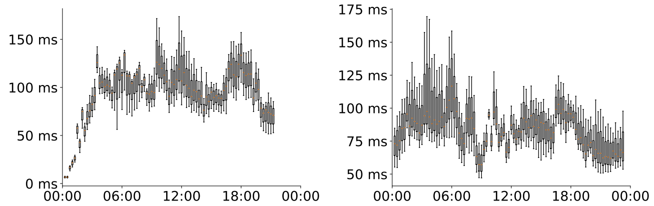
TABLE V: RIPE Atlas TLS latencies in ms per weekday in Germany.



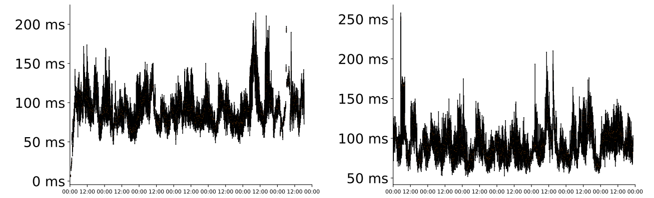
(a) USA (b) Canada (c) Germany (d) Philippines

Fig. 8: Number of hops of traceroute measurements on RIPE Atlas from probes to *k.root-servers.org*.

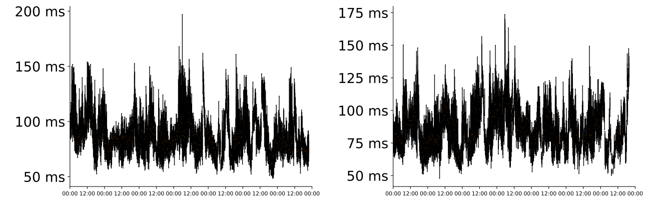
and average latencies compared to 2022, while also maintaining the peak performance observed in 2023.



(a) Monday, 2024-04-01 (b) Tuesday, 2024-04-02



(c) 2024-04-01 to 2024-04-08 (d) 2024-04-08 to 2024-04-15



(e) 2024-04-15 to 2024-04-22 (f) 2024-04-22 to 2024-04-29

Fig. 9: Cloudflare Radar latencies for the first four weeks of April 2024.

Cloudflare Radar provides a different perspective on the data as it is collected via the Cloudflare Radar speedtest, rather than the TLS handshake measurement used in RIPE Atlas. We utilized this data to analyze how Starlink performance fluctuates over the course of a day. Similar results have been observed with RIPE Atlas measurements. For completeness and availability, we chose to analyze data from April 2024. We examined single days as well as the development over the week. Figure 9a and Figure 9b show the latency patterns for the first two days of April 2024. On April 1st and April 2nd, a diurnal variation is clearly evident. To further investigate the diurnal variation, we analyzed the rest of the month. Figure 9 shows the weeks between 2024-04-01 and 2024-04-29. The latency varies during this time, which we attribute to be caused by diurnal variation. Therefore, we conclude that Starlink exhibits a diurnal variation over the hours of the day, but not across different days of the week (as demonstrated in Table V).

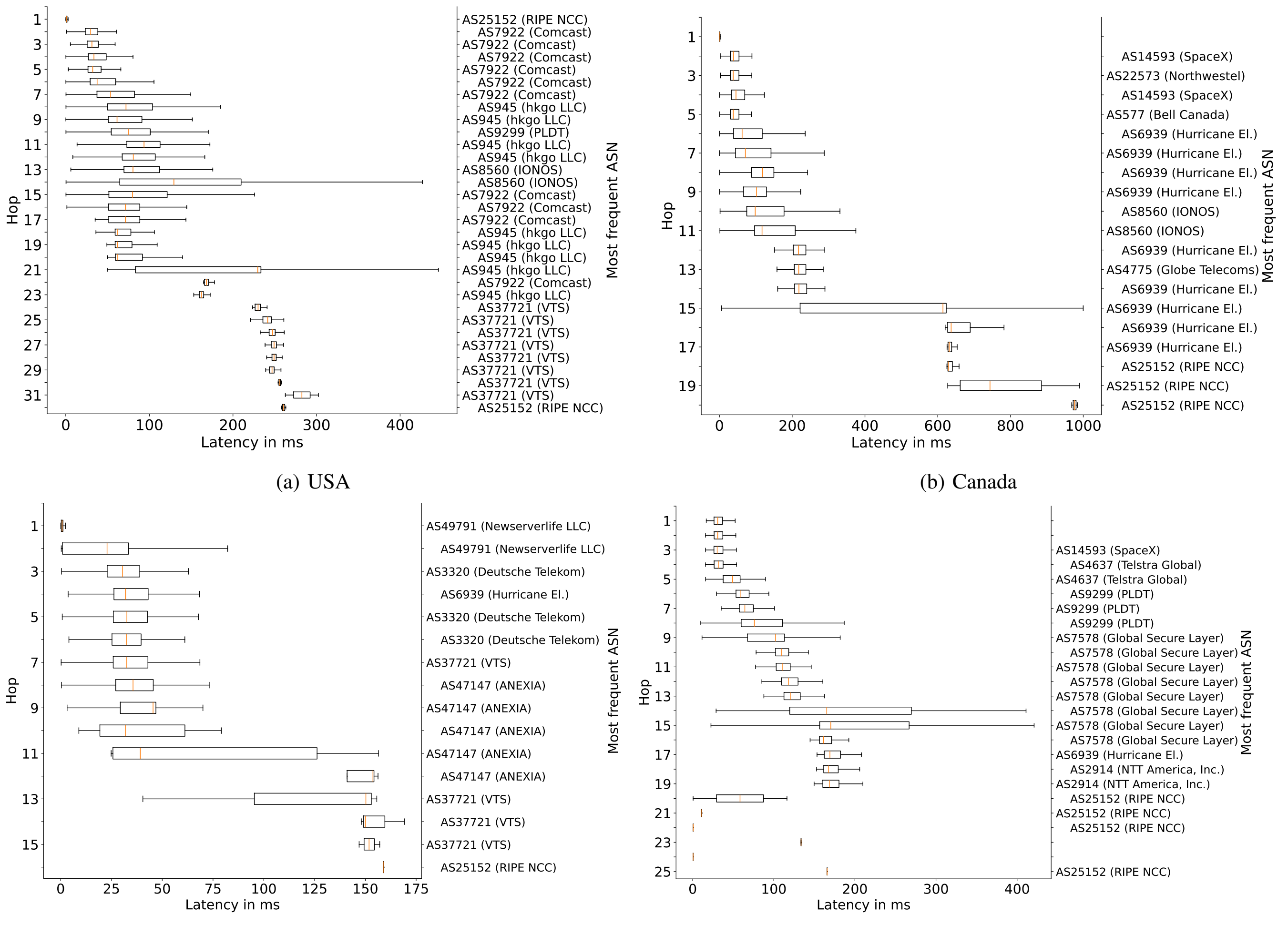
VI. Network Paths

Hops per Route: We conducted a closer examination of the routing behavior of Starlink. For this, we utilized the traceroute measurements built into RIPE Atlas probes. Figure 8 shows the histogram of the number of hops per route for the USA, Canada, Germany, and the Philippines. The histograms indicate that most routes require between six and thirteen hops. Note that this does not include the individual satellites in the Starlink constellation. These are not detectable by the traceroute measurement due to the fact that they operate below the IP layer (which traceroute cannot detect). For the exact number of hops, a traceroute operating below the IP layer would be necessary.

Latency per Hop: We analyzed the change in latency from hop to hop (measured in traceroute). Figure 10 shows how the latency progresses in successive hops. We observed dramatic differences between the target root servers. Therefore, we focused on traceroute measurements to the target *k.root-servers.org*. It becomes apparent that there is at least one hop that is associated with a significant increase in latency. We hypothesize that this is usually the hop between the user's antenna and the provider's GS. This hop increases latency significantly as it is routed through the entire satellite constellation including signal transmission from and to Earth. The satellites serve as middleboxes that cannot be detected by using a traceroute measurement. Therefore, such a behavior is consistent with the expected network architecture. We also observe that another substantial increase may occur in a later hop (e.g., in Figure 10b). To determine the responsible network segment, we have mapped the most common AS to the specific hop. The AS is acquired by using IPinfo data for the IPs associated with each hop. Usually, Starlink is no longer a dominant part of the trace after the fifth hop. Therefore, Starlink external network entities are responsible for the second major increase.

A. *Influence of Solar Magnetic Storms*

Recent research [9] has claimed that solar magnetic storms have a significant impact on the performance of Starlink. We have investigated TLS handshake latency data and correlated it with the intensity of solar magnetic storms. The intensity of solar magnetic storms is conventionally measured by the Kp index [40] (a value between zero and nine). Historic Kp indices are provided by the G. F. Z. [41]. We hypothesized that as the intensity of solar magnetic storms increases, the latency would also increase. Therefore, we used the average Kp index over a single day and correlated it with the median latency over a single day. The following correlations were obtained: Pearson correlation: $\approx$ 0.03, Kendall correlation:



(a) USA

(b) Canada

(c) Germany

(d) Philippines

Fig. 10: Average latency per hop in the USA, Canada, Germany, and the Philippines on RIPE Atlas.

≈ 0.01, and Spearman correlation: ≈ 0.01. These values are close to zero (i.e., the dimensions are almost orthogonal). Thus, we concluded that latency and Kp index are not statistically correlated in our dataset.

B. Starlink User Numbers

Utilization plays an important role in the variation of the presented measurements. Unfortunately, the exact user numbers are not published. However, other sources provide estimates.

One source of user numbers is Starlink's X page [42], [43]. It mentions Starlink having more than four million users. APNIC also provides a list of user numbers per AS [44]. In total, it lists 16 512 033 users distributed among 114 countries. The most users are concentrated in the USA (2 634 629), Yemen (1 511 944), the Philippines (1 213 642), Nigeria (1 171 687), and Mexico (1 122 041). However, those numbers are far higher than the ones officially published by Starlink, which suggests the numbers are significantly overestimated. Additionally, it is not entirely clear how the numbers were derived.

Please note that both sources are not sufficiently reliable for rigorous analytical purposes [45].

VII. Conclusion

In summary, our analysis of historical network measurements data from January 2022 to June 2024, utilizing metrics from RIPE Atlas and Cloudflare Radar, reveals critical insights into the performance of networked satellite systems, particularly regarding latency and packet loss, thereby addressing our research questions on their operational efficiency.

Research Question (RQ) 1: *How do networked satellite systems perform in terms of latency and packet loss?*

We analyzed the TLS handshake latency and found that the Starlink latency was approximately 80 ms median in 2024. The latency has improved since 2022 to reach 26 ms minimum, 80 ms median, and 100 ms average latency. We observed a behavior in the latency characterized by a bimodal distribution. The bimodal distribution reflects the behavior of serving two ranges of latency particularly well. First lower latencies ($\approx$ 80–100 ms) and second, higher latencies ($\approx$ 150–250 ms) with a large gap in between. This pattern appears in most countries and is more pronounced in 2024 compared to 2022. The reason for this pattern is unclear. We hypothesize that the reasons are related to the location of a probe. Specifically, we postulate that GS positioning, satellite orbits, and weather are the most relevant factors for varying performance. Different subscription models may also contribute to this phenomenon.

We also examined packet loss and found a wide variation from country to country. Countries such as the Philippines have packet loss ratios as high as 18 %, while the Czech Republic and Chile have less than 0.25 %. On the other hand, Central European countries such as Germany and the Netherlands have high packet loss ratios. Overall, most countries have a packet loss ratio of 1 to 4 %.

RQ 2: *Do latency and packet loss correlate?*

We expected packet loss and latency to exhibit correlation, therefore we analyzed their relationship. We separated the values by year and by country. The results were inconclusive, meaning we could not establish a correlation between latency and packet loss. We surmise that there are other parameters that affect the relationship between latency and packet loss that have not been adequately investigated. These factors include the version of the Starlink terminal, the weather, the satellite hardware components, or the measurement targets.

RQ 3: *What happens to latency when routing through the Starlink constellation?*

First, we determined the number of hops a route typically traverses. We found that most routes encompass 6 to 13 hops, excluding hops through the Starlink constellation, as we can infer from the change in latency per hop. The histogram of hops also exhibits the aforementioned bimodal distribution, which may be related to the pattern we found for latencies.

Finally, we conclude that Starlink currently provides reliable and consistent performance. It should be noted that Starlink has not yet reached its full potential, as demonstrated by the trend over the last few years. The infrastructure is likely to expand and offer enhanced performance in countries that currently show suboptimal results.

Appendix A
Ethical Considerations

This study does not raise any ethical concerns. It complies with the ethical guidelines outlined in [46] and [47].

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