Team Thunkers: Project Starlink Report

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1 ABSTRACT

This research project aimed to investigate the latency performance of probes in the Starlink network across various regions globally. The study involved collecting latency data from the probes for a 24-hour period in different regions, including North America, Europe, and Oceania. The data collected from the probes were analyzed using statistical methods to determine the average and maximum latency values across the regions. The results showed each region had defining characteristics, but no general trend can be observed across the entire global network. Overall, the study highlights the potential limitations of satellite internet technology and the importance of considering the geographic location when assessing its performance. The findings of this study may have implications for policymakers and internet service providers who seek to expand internet access to remote areas where traditional internet infrastructure is limited.

CCS Concepts: • **Networks** → Network reliability.

Additional Key Words and Phrases: Starlink Network, Network Latency

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Here is the **repository** of the code for this project.

2 INTRODUCTION

Starlink satellites are a network of low Earth orbit (LEO) satellites designed and operated by SpaceX, a private space exploration company founded by Elon Musk [1]. The aim of Starlink is to provide high-speed, low-latency broadband internet to areas of the world that currently lack reliable internet access. As of April 2023, there are over 1,600 Starlink satellites in orbit, with plans to eventually launch tens of thousands more [3]. The satellites are relatively small and weigh around 260 kg each [4]. They operate in a constellation formation, with each satellite communicating with four others in orbit and with ground stations on Earth.

The Starlink satellites use advanced technology, such as ion thrusters and autonomous collision avoidance systems, to maintain their position in orbit and avoid collisions with other space objects [1]. They are also equipped with advanced lasers to enable communication between satellites and ground stations, allowing for faster data transfer and lower latency. Moreover, Starlink is a network of low Earth orbit satellites designed to provide high-speed, low-latency network connectivity between end hosts on the ground. LEO satellites orbit the Earth at a few hundred kilometers altitude, which allows them to transmit data wirelessly using radio waves between hosts on the ground.

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This eliminates the need for long-haul fiber connections for transmitting data between hosts in different parts of the world. [5]

The Starlink network has three components: a set of LEO satellites, user terminals, and ground stations. User terminals are purchased and deployed by end-users and wirelessly communicate with the orbiting satellites. Each terminal can only contact a subset of all satellites in orbit, with the satellite map showing which geographical region is within reach of an orbiting satellite. Users point their terminals to the sky and the terminal will select the nearest satellite to use for the connection. As one satellite fades out of reach, another should ideally come into view and start covering the area. The ground stations act as the other end of the communication and connect user terminals to the fiber infrastructure of the Internet, allowing users to reach the Internet infrastructure on the ground. [2]

The project aims to measure latency and network paths between Starlink user terminals and bing.com, capturing variations in latency and comparing profiles of different user terminals.

3 METHODOLOGY

RIPE Atlas is a platform used for conducting measurements on the Internet, such as measuring latency, traceroutes, and DNS queries. The platform is a large-scale, globally distributed network measurement infrastructure operated by the RIPE NCC [2]. To use RIPE Atlas for conducting measurements, we first need to register an account with the RIPE NCC and obtain an API key. The API key is required to access the RIPE Atlas API, which allows us to query probes, submit measurement requests, and retrieve measurement results. Once we have obtained the API key, we can use the Python programming language and RIPE Atlas' Cousteau library to interact with the RIPE Atlas API. We can then write Python scripts that use the Cousteau library to submit measurement requests, retrieve measurement results, and perform data analysis.

Before creating the measurements, we need to collect the set of probes that will be used to perform the pings. To do this, we used RIPE Atlas' public probes API, which returns all probes in a pagination format by default. To narrow the probes to those on the Starlink network, we supplied query parameters to the probes API call. We required that the probe should be connected, includes a Starlink tag, and be part of ASN 14593, which is the ASN of the Starlink network. This gave back a relatively small list of probes from which we extracted the probe IDs and would use them in the measurement request.

To conduct measurements using RIPE Atlas, we first need to define the measurement parameters, such as the target address, the measurement type (e.g. DNS, ping, traceroute), and the measurement interval (whether it's one-off or in an appropriate start and stop time interval). We can then submit the measurement request to the RIPE Atlas API using the Cousteau library. After the measurement is completed, we can retrieve the measurement results from the RIPE Atlas API using the Cousteau library. We then used RIPE Atlas' Sagan library to parse each ping result and extract the average RTT across the 3 packets sent in the ping. We can then analyze the results using Python libraries such as Pandas and Matplotlib to visualize the data and draw conclusions.

In this report, we use bing.com as the target in the ping measurements. Originally, we planned to use google.com as the target, however, due to rate-limiting issues from RIPE Atlas, it was not possible to schedule the amount of measurements we needed over the course of a day. We chose bing.com as the alternative target since it has similar availability to google.com and the network traffic should be comparable.

Overall, we used the RIPE Atlas platform for conducting Internet measurements which involved registering an account, obtaining an API key, writing Python scripts using the Cousteau library, submitting measurement requests, retrieving measurement results and parsing them using the Sagan library, and performing data analysis.

4 DATA AND RESULTS

We made the measurement creation request on April 23, including the first 25 probes from our probes API query made at the same time. The request specified that each probe should make a ping measurement to bing.com every 15 minutes for exactly one day. After the day had passed, all of the data was available to request and analyze.

4.1 General

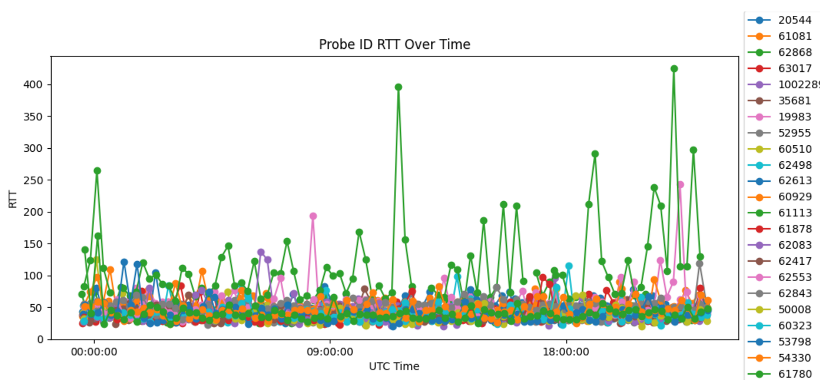

Fig. 1. Plot of each probe over time

Our measurement returned 23 international probes from three distinct geographical regions: North America, Europe, and Oceania. The majority of these probes emanated from the United States of America, totaling thirteen in number, followed by Germany with three probes, and Australia with two probes. The remaining probes originated from Poland, the United Kingdom, France, Canada, and Austria, with a solitary representation each. In general, our measurements were a success. All probes were able to respond to the measurement request with the exception of probe ID 61113 (from USA) which was unreachable and had 100 percent packet loss. Interestingly, the remainder of the probes had 0 percent packet loss. Finally, due to the rate-limiting of the RIPE Atlas API (there cannot be more than 25 concurrent requests), we requested 25 probes for the measurement, however, only 23 ended up participating.

Our analysis of the acquired probes did not reveal any discernible patterns or trends across all probes. However, we did observe periodic and cyclic changes in the Round Trip Time (RTT) metric. Specifically, we detected fluctuations in RTT measurements, where the RTT time experienced peak highs followed by lows in a cyclical manner over the span of a day. This observation suggests that the underlying network infrastructure may be subject to intermittent congestion or routing issues, which can result in fluctuations in the latency of network traffic. Another potential reason for these variations is that the Starlink is inherently unstable due to satellites constantly changing their position and their area of coverage. Probes at one point in time may have a good connection to a nearby satellite, but after a short period of time, there may not be any close satellites, thus increasing the latency. Further analysis is required to ascertain the root cause of these RTT variations and their potential impact on network performance. As such, we decided to dig deeper into the regional patterns of latency across the probes.

4.2 Regional

In this experiment, an analysis was conducted to examine the spatial distribution of probes and to explore potential correlations between their geographic location and temporal patterns. The underlying hypothesis posits that probes located in close proximity to one another are likely to exhibit analogous temporal trends.

The present study investigated latency variations across different geographic regions, namely Europe, USA1, Oceania, and USA2. Analysis of the data revealed marked fluctuations in average latency across all regions. USA1 and Europe had the closest average latency whereas USA2 and Oceania had high average latencies. Notably, the probes in USA2 and Europe failed to send measurements for all time values, possibly accounting for the high observable latencies in these regions. This observation is particularly pertinent for USA2, where the probe with identifier 61113 exhibited either really high latencies or complete failure to collect measurements, thereby increasing the overall average latency for this probe. Although this probe was most likely an outlier, it is important to understand the effect of these failures on latency changes throughout a period of time. Refer to the following subsections for more details for each region.

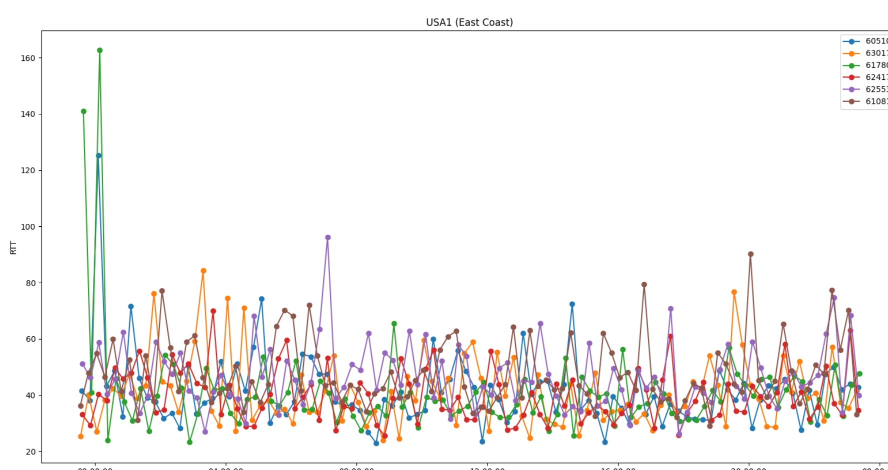

Fig. 2. Graph of RTT vs. UTC Time for the East Coast and Canada

4.2.1 USA1. There were 6 probes on the east coast of the USA. The probes are 60510, 63017, 61780, 62417, 62553, and 61081. The average latency (in milliseconds) for each probe was 41.366 m.s., 40.86 m.s., 41.245 m.s., 39.774 m.s., 46.679 m.s., and 47.926 m.s., respectively. The average latency in this region was 42.975 m.s and the median latency was 40.864 m.s. All probes read latency values for all timestamps in this region.

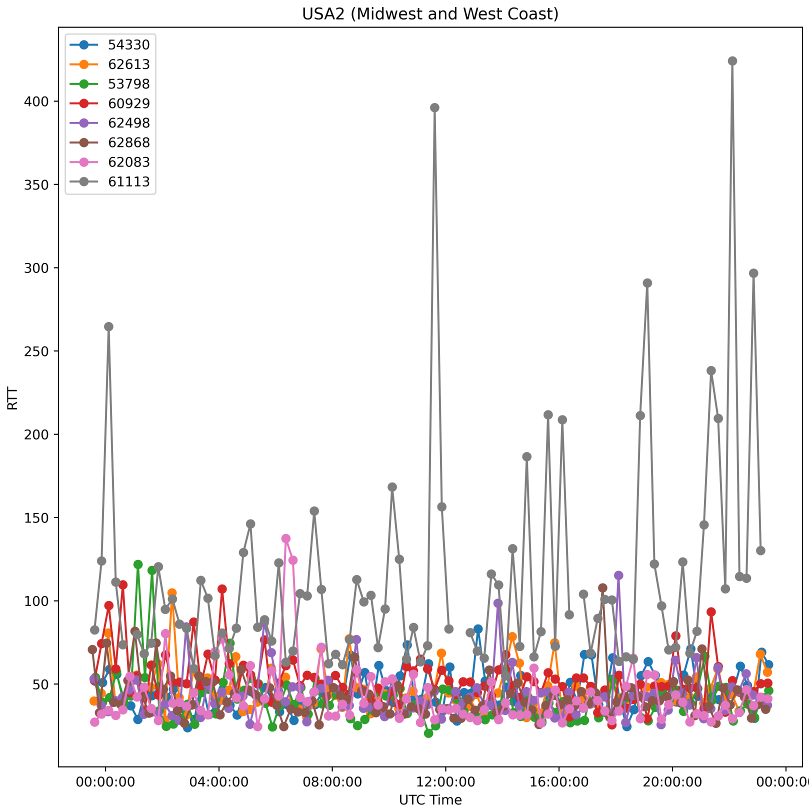

Fig. 3. Graph of RTT vs. UTC Time for the Midwest and West Coast

4.2.2 USA2. There were 8 probes on the West coast of the USA. The probes are 54330, 62613, 53798, 60929, 62498, 62868, 62083, and 61113. The average latency (in milliseconds) for each probe was 45.481 m.s., 46.458 m.s., 40.71 m.s., 52.936 m.s., 43.373 m.s., 42.558 m.s., 42.127 m.s., and 113.751 respectively. The average latency in this region was 53.029 m.s and the median latency was 44.497 m.s.

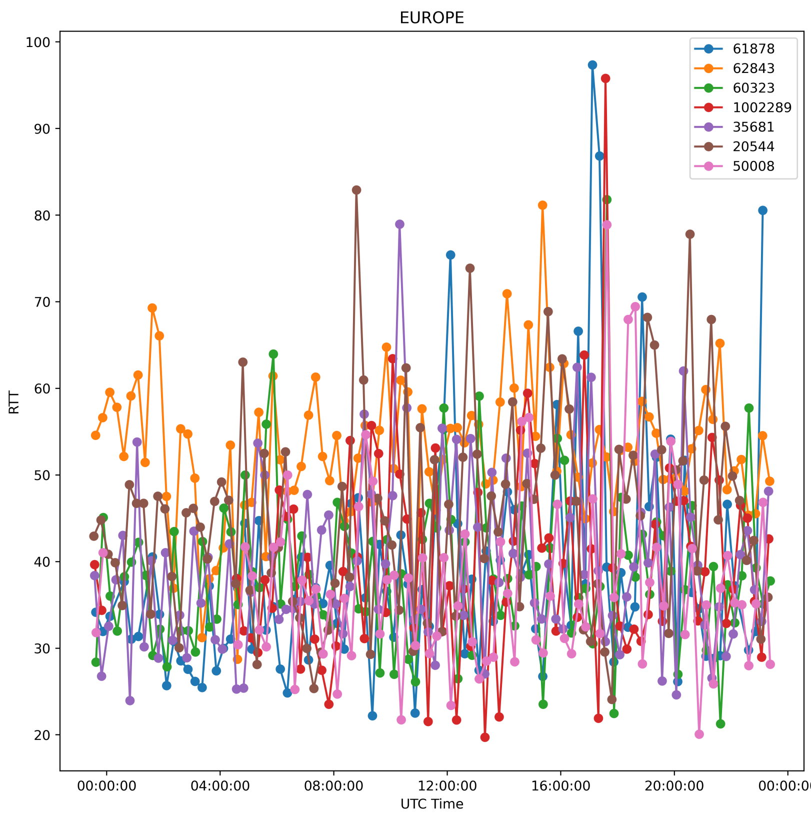

Fig. 4. Graph of RTT vs. UTC Time for Europe

4.2.3 Europe. There were 7 probes in the European region. The probes are 61878, 62843, 60323, 1002289, 35681, 20544, and 50008. The average latency (in milliseconds) for each probe was 38.833 m.s., 52.807 m.s., 38.966 m.s., 39.884 m.s., 39.591 m.s., 45.304 m.s., and 37.498 m.s. respectively. Probes 1002289 and 50008 did not have measurements for some time stamps (with a 100% packet loss). The average latency in this region was 42.039 m.s and the median latency was 40.091 m.s.

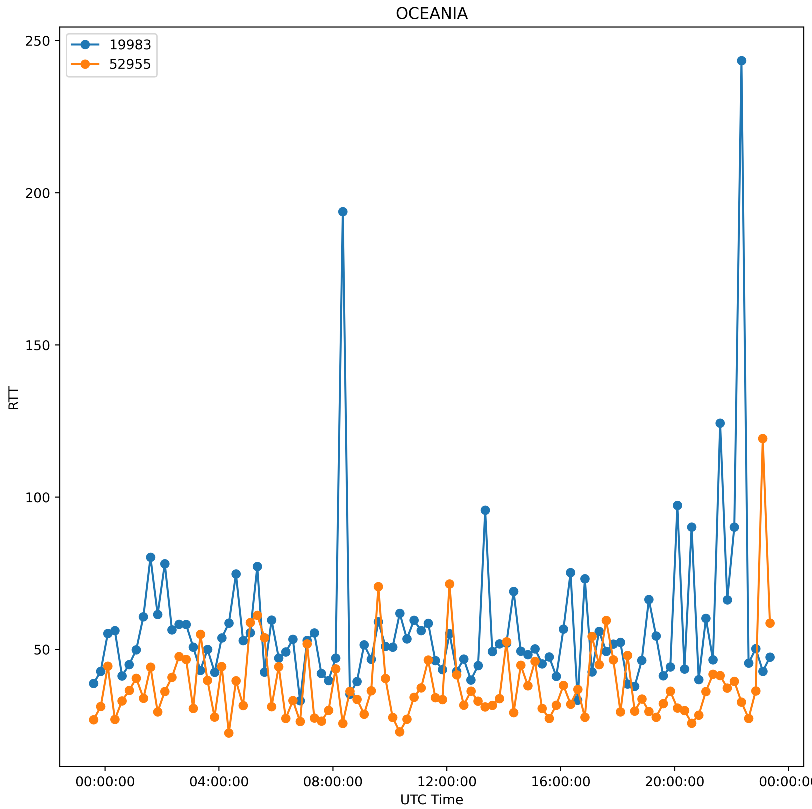

Fig. 5. Graph of RTT vs. UTC Time for Oceania

4.2.4 Oceania. There were 2 probes in the Oceania region. The probes are 19983 and 52955. The average latency (in milliseconds) for each probe was 57.364 m.s. and 38.159 m.s respectively. The average latency in this region was 47.761 m.s and the median latency was 44.195 m.s. All probes read latency values for all timestamps in this region.

5 ANALYSIS

The aim of this study is to investigate any discernible geographical and temporal patterns in the data gathered from the RIPE Atlas API. In this section, we present noteworthy observations pertaining to the geographic regions of our probes, as well as temporal trends observed in latencies across all probes during specific time intervals. Additionally, we endeavor to provide plausible explanations for the observed data, despite the limited probe metadata available to us through the API.

5.1 General

The present study reveals that latencies exhibit fluctuations throughout the day, suggesting the dynamic nature of networks, particularly in the context of a global network. Given the intricate and expansive nature of such a complex system, there is no one-size-fits-all temporal trend observed across all probes. We observed a diversity of latency profiles in our probes, ranging from low to high. We observed the ability of probes to take consistent measurements and others that experienced massive amounts of packet loss. We observed temporary cyclic patterns in the latency fluctuations and others that had peaks and drops in latencies around certain times. All in all, each probe offered a unique insight into individual aspects of networks. Despite this variability, we attempted to identify temporal patterns by clustering probes based on their geographic proximity, with the expectation that clustering would enhance the visibility of such patterns. Our study underscores the importance of examining each probe's unique contribution toward understanding the distinct features of network behavior.

5.2 Regional

In our efforts to find trends throughout our probes, we decided to split the probes into geographical regions where there are clusters of probes. The intuition for this division is that probes in geographical regions might have similar trends in changes in latencies throughout the day. When we divided the probes into geographical clusters, we were able to see more clearly that there were some temporal trends.

Despite our best efforts to explain some of the more perplexing observations using the metadata associated with each probe, certain aspects of the data remain difficult to rationalize. Our analyses revealed that USA1 probes generally exhibited the most erratic fluctuations in network latency, while USA2 probes generally demonstrated less variability in latency values, with most values remaining within a particular range except for sporadic peaks and drops. In contrast, probes located in Europe displayed the highest packet loss rates, and those in Oceania generally recorded the highest peak latencies. We note, however, that each region's probe data was limited ($n < 10$), and that outliers, such as significant jumps in latencies or packet loss, could significantly impact the data and subsequent analyses. For a more in-depth examination of the individual regions and their corresponding probes, please refer to the following sections.

5.3 USA1

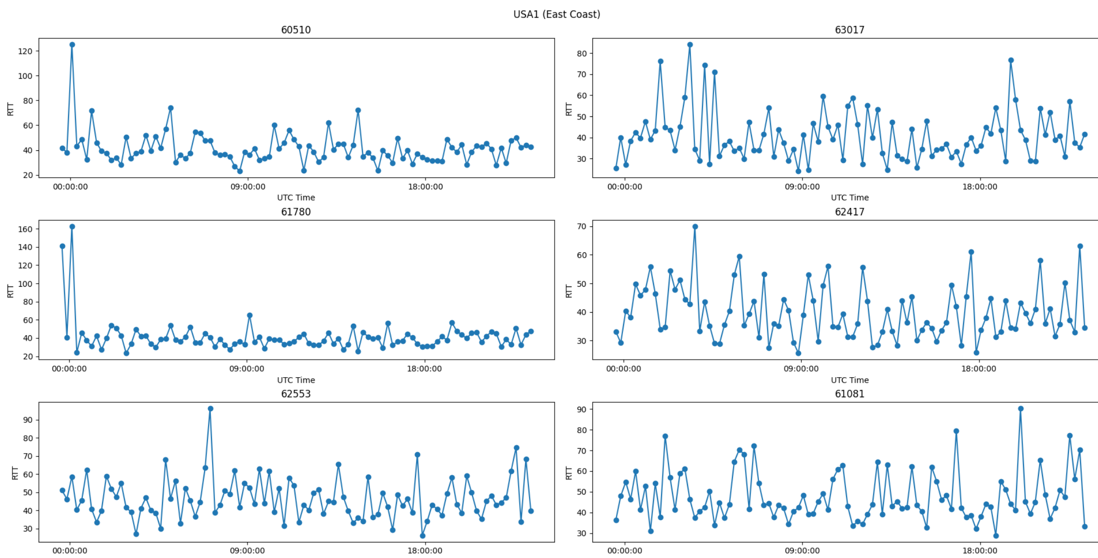

Fig. 6. Individual Graph of RTT vs. UTC Time for USA1

The probes in this region exhibit interesting temporal patterns. Specifically, we have observed that Probes 60510, 61780, and 62553 demonstrate similar behavior in that they display high latencies during the hours of 00:00 to 9:00 UTC time. Notably, Probes 60510 and 61780 exhibit peaks and regions of constant values that bear resemblance to each other, a phenomenon which could be attributed to their geographic proximity in the USA1. Probe 61081, on the other hand, displays latency peaks after 18:00 UTC time.

The remaining probes, 63017 and 62417, exhibit peak latency values during the hours of 00:00 to 9:00 UTC time and around/after 18:00 UTC time. These probes demonstrate patterns where their latencies tend to remain stable for a certain duration, followed by drops and peaks. Remarkably, these drops and peaks are indicative of periods of stability, as they tend to precede or succeed intervals of stable latencies. For instance, Probe 63017 and Probe 62417 demonstrate this pattern between 9:00 UTC and 12:00 UTC and 12:00 UTC and 18:00 UTC and from 6:00 UTC to 12:00 UTC, respectively.

Generally, the probes of USA1 demonstrated erratic fluctuations. Nonetheless, the fluctuations may be attributed, at least in part, to the continuous movement of the satellites. Consequently, there exists a certain degree of reliance on the quality and underlying infrastructure of the satellite, which could account for the unpredictability of the fluctuations observed in USA1.

5.4 USA2

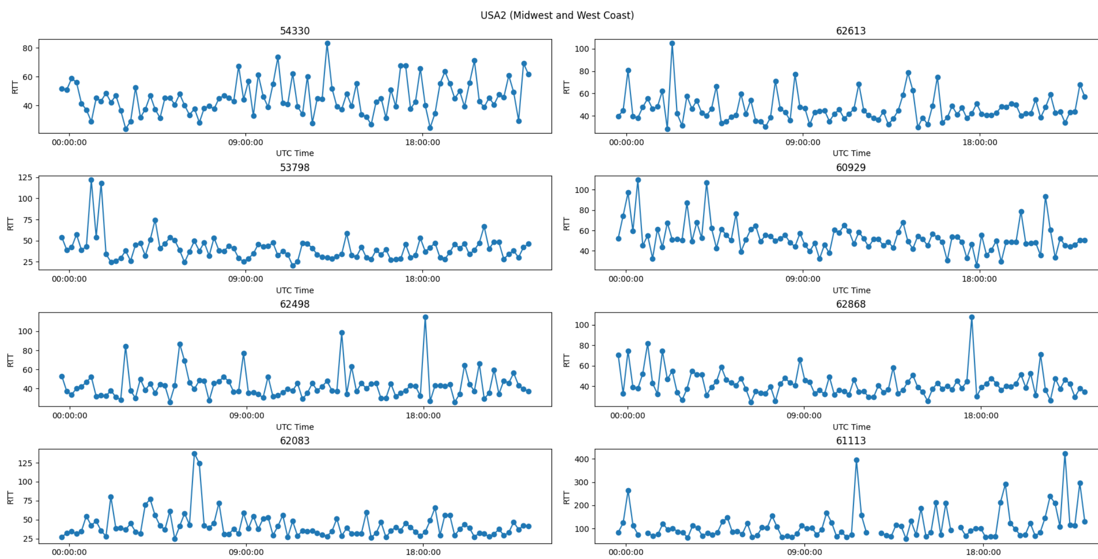

Fig. 7. Individual Graph of RTT vs. UTC Time for USA2

Generally speaking, the USA2 plots exhibit a higher degree of stability in comparison to other regions. Specifically, these plots display more constant latency values and have extended intervals of reduced latency variation. Unlike other regions, there are minimal instances of sharp, drastic peaks in USA2.

Probe 54330 demonstrates a notable drop in latency values leading up to 9:00 UTC, after which latency values begin to fluctuate more widely. Probes 53798 and 62083 share commonalities in that they exhibit high latency peaks during the initial hours of measurement collection (00:00 UTC to 9:00 UTC) followed by periods of relatively stable latencies. Probe 62498 demonstrates pronounced cyclic temporal trends, as it displays regular peaks in latency at three-hour intervals until 18:00 UTC with stable latencies observed between these peaks.

Probes 60929 and 62868 display similar patterns with peak latency values before 9:00 UTC and after 18:00 UTC, with intermittent periods of stability. Probe 62613, in contrast, experiences most of its latency fluctuations before 18:00 UTC. Notably, Probe 61113 demonstrates the opposite trend, with most of its latency fluctuations occurring after 18:00 UTC. It is important to mention that this probe has missing data entries, which accounts for the unconnected components in the time plot.

5.5 Europe

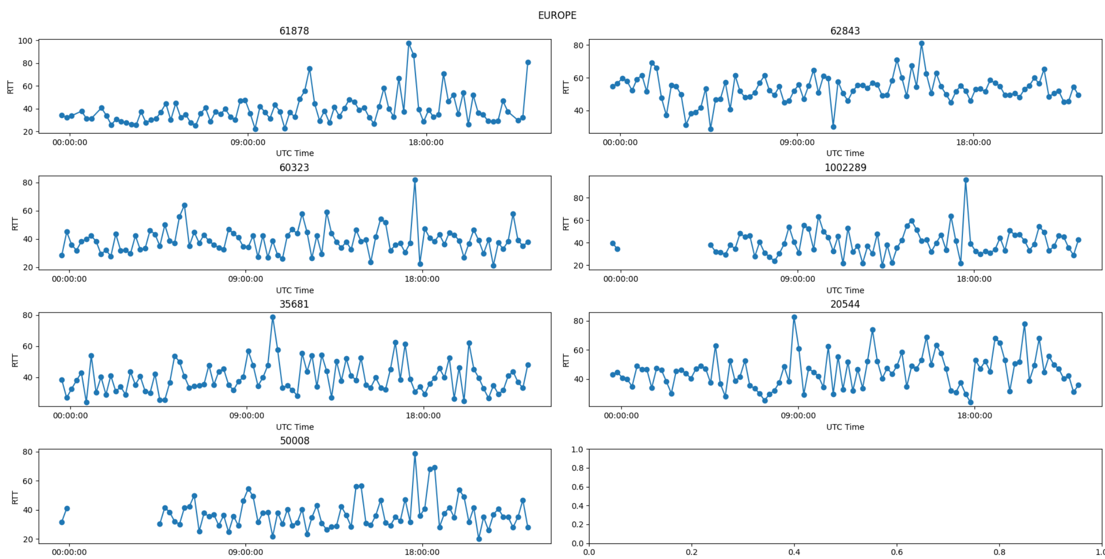

Fig. 8. Individual Graph of RTT vs. UTC Time for Europe

The probes in Europe had noticeably more missing data. Probe 61878 had consistent latency values until approximately 11:00 UTC where there were noticeably more fluctuations and higher latency values. Probe 60323 is similar to the aforementioned probe in that a few of the major peaks aligned around the same time. This can be seen at 11:00 UTC and 18:00 UTC. Otherwise, Probe 60323 exhibited consistent cyclic fluctuations in latencies up until 9:00 UTC. Probes 35681 and 20544 had constant and unpredictable fluctuations in latencies. Probe 62843 is an interesting probe because its latencies often had downward fluctuations as opposed to upward fluctuations like most other probes in the European region. Probes 1002289 and 50008 had packet loss between 00:00 and 9:00 UTC and had fluctuation towards higher latency values with a peak at 18:00 UTC. Both 1002289 and 50008 are in Germany, so the missing packets can suggest a problem with the German network between 0:00 UTC and 9:00 UTC. These probes are the most telling of geo-temporal trends at this instance. Altogether, these findings shed light on the diverse range of behaviors exhibited by European probes.

5.6 Oceania

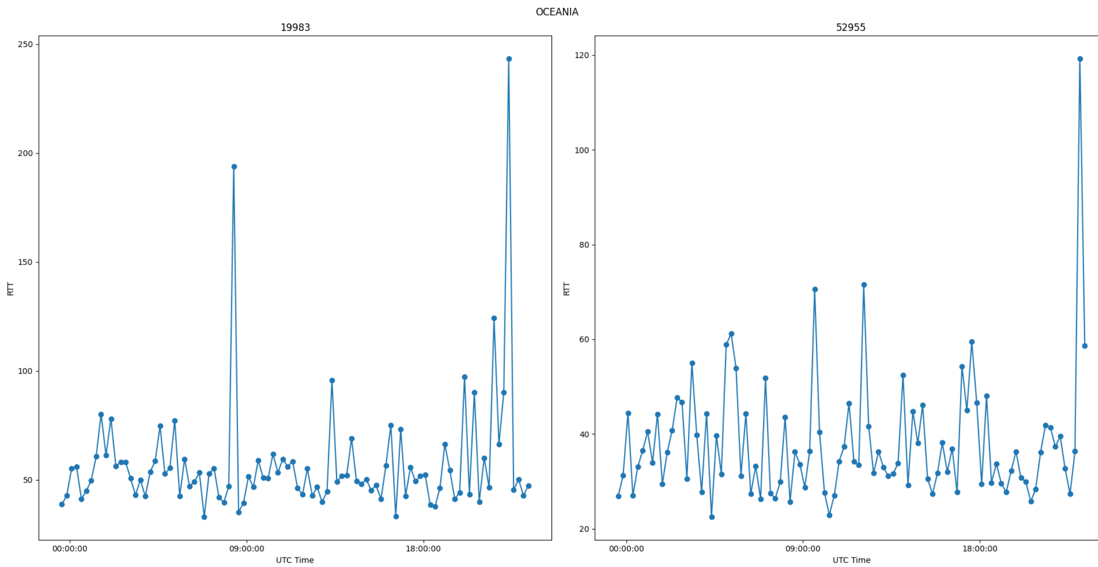

Fig. 9. Individual Graph of RTT vs. UTC Time for Oceania

Oceania had two probes 19983 and 529555. Both probes had unpredictable fluctuations with one or two peaks with the largest peak occurring after 18:00 UTC, which signifies a temporal correlation when latency particularly increases. It is important to note that peak latency is significantly higher (practically 2x as high) compared to the peak latency of most probes in other regions. One reason that could explain the high peak latencies is that the ground stations are further away in Oceania. There are also fewer satellites, which can cause issues with load balancing.

6 CONCLUSION

To conclude, the Starlink Probes exhibit subpar performance in comparison to the advertised claims. Particularly, the largest recorded latency values are observed in the Oceania region, indicating that satellite internet, in its current state, may not be the transformative technology it was purported to be. Our analysis showed that USA1 was generally more erratic in observed latency measurements compared to other regions. USA2 generally had more periods were latency was more consistent compared to other regions. Europe generally had the highest packet loss rates due to the German satellites, partially because there were few European satellites, so there was a large effect of a couple of outliers on the entire region. Finally, Oceania generally had the highest peak latencies compared to most probes in other regions.

To mitigate the limitations of our study, future investigations could consider conducting long-term experiments, such as measuring latency values twice per month for an entire year, to reduce the impact of unforeseeable events, such as the German power outage that occurred during our data collection. Additionally, increasing the number of probes deployed per region may enable the identification of potential areas of high and low connectivity. However, this approach necessitates significant resources in terms of the required number of credits to conduct the measurements. Still, the presence of a larger sample size (with geographical diversity) can offer a more nuanced understanding of how the satellite network operates in different regions and at times.

7 SELECTIVE PROBING (EXTRA CREDIT)

Given a collection of probes and a limited budget, we have to be selective as to which probes we use to conduct the measurements. A metric of redundancy should be used to reject probes that do not provide any extra information from some other probe in the selected set. One reasonable metric of redundancy would be the geographical location of each probe. It is important to note that user terminals in the Starlink network can only contact a subset of all satellites in orbit. Thus, if two probes are very close to each other, they will be conducting measurements using the same satellites, which will lead to redundant information.

One tool we could use to make more informed geographical decisions is the Starlink satellite map, which is a live map of all Starlink satellites, ground stations, and the corresponding coverage areas. We want to select probes that are near different ground stations and have different satellite coverage. The satellite map also provides an intensity map, which shows the relative connectivity of different regions in the world. We could further narrow down which probes to use by the connectivity of their regions, making sure to test areas with varying levels of intensity.

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