Evaluating Resiliency and Performance of Networked Satellite Systems

Evaluierung der Resilienz und Leistung von Vernetzten Satelliten Systemen

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Universitätsmasterarbeit
zur Erlangung des akademischen Grades

Master of Science
(M. Sc.)

im Studiengang
IT Systems Engineering

eingereicht am 11. November 2024 am
Fachgebiet Data-Intensive Internet Computing der
Digital-Engineering-Fakultät
der Universität Potsdam

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Abstract

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1 Introduction

1.1 Motivation

1.2 Related Work

Network satellite operators exist for quite a while, starting the late 90s, when Iridium launched their plans to deploy a mega satellite constellation [Cha02]. Even if their plan did not work out, modern times face newer technologies, giving other providers the possibility to achieve what Iridium couldn't. With the rise of Starlink, OneWeb, Orbcomm, and others, research has made steps to figuring out how "satellite internet" might work. In 2020, research started to make their first steps by building the first mega constellation simulators [Kas+20; LLL20]. However, research did not advance in this direction as too many variables have to be taken into consideration. Therefore, research turned to performing measurements on existing constellations. Performance of networked satellite operators was presented in [Akp24; Gar+23; Izh+24; Ma+23; Mic+22; Moh+24; Pek21; Ram+23; Seg20]. However, it has to be noted that most measurements on existing systems were performed on the Starlink constellation, due to low cost and high availability. Resilience against catastrophes has been described by Stevens et al. [Ste+24]. It is also worthwhile mentioning the influence of weather [Lan+24b], mobility [Lan+24a], and solar magnetic storms [Fan+22; HLL22; Ma+23]. All these factors have to be taken into consideration when performing routing [Bho+23; Han18; ZY22]. This includes looking at Inter-Satellite Links (ISLs) [Hau+20; SFH22], the navigation of satellites [Kas+23; SKR24], and the positioning of Ground Station (GS)s [VSC21].

In perfect conditions, this might supplement 6G deployment [Lin+21]. However, the most dominant problem is the lack of knowledge about the functionality of Starlink. Therefore, people tried to extract the firmware [Ram23; Wou21].

Also, with the start of the war in Ukrained, people observed a new problem with satellite networked being used in conflicts as they are independent of a terrestrial infrastructure in the conflict zone [Abe24; Dav24; Rig24].

1.3 Research Questions

Link mentioned platforms to chapters of the individual measurement platforms.

In the following thesis, we want to solve the following research questions.

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

Packet loss and latency are the main factors for the performance of a network. Recent research stated high packet loss values, but mostly idealized latency values. This thesis shall take a look at those two performance characteristics. To solve this research question, we will use RIPE Atlas and Cloudflare Radar.

Research Question 2: Do latency and packet loss correlate?

It is expected that a rising latency correlates with a rising packet loss and vice versa due to the need of retransmits. It is in question whether this is the case for networked satellite systems.
If it appears that there is no clear correlation observable, what factors might influence the correlation?
To solve this research question, we will use the data obtained from RQ 1 (i.e., data from RIPE Atlas and Cloudflare Radar).

Research Question 3: How do networked satellite systems route?

Networked satellite systems face a severe challenge when routing a packet. Additionally, to the routing problem, they need to find an ideal route through their satellite constellation involving sending data to a ground station.
This thesis takes a look at the routing behavior of networked satellite systems.
To solve this research question, we will use traceroute data from RIPE Atlas.

2 Background

2.1 Satellite Communication Explained

A satellite communication system has the target to send packets from a sender, connected via a Satellite Network Operator (SNO), to a receiver connected to a terrestrial ISP.

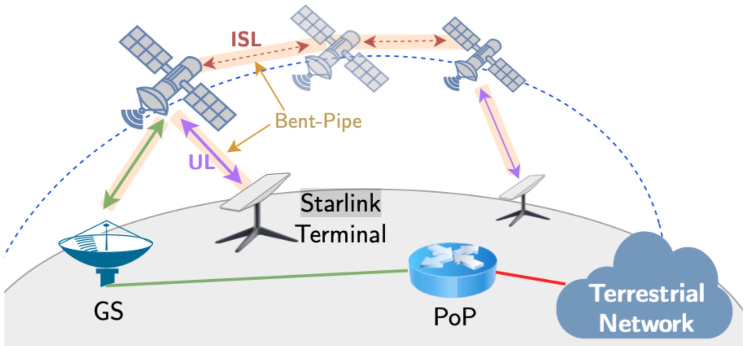


Figure 2.1: Schematics of Satellite Communication [Moh+24].

The structure is illustrated in Figure 2.1. Initially, there is a sender connected to a satellite antenna provided by the specific SNO. The satellite antenna is also colloquially called "dishy". From the senders' perspective, there is no different use compared to a traditional terrestrial internet connection. The antenna sends packets to a satellite that might either forward the packets to another satellite or directly send them to a nearby GS (also called Point of Presence (PoP)). The GS serves as an "entry point" to the terrestrial internet. A GS can forward packets through wired connections, so they will reach the receiver eventually.

The technology of communicating with satellites will not be explained here. Amongst others, it is described by Pratt et al. [PA19].

Theoretically, the propagation of data in satellite communication happens at the speed of light. However, the latencies still vary a lot depending on the choice of SNO. Each of them provides a different satellite constellation. One of the dominating factors is the altitude of the satellites in the constellation. The higher the satellites are positioned, the more region a single satellite covers. Therefore, fewer satellites are required to cover a specific region, which reduces costs. Usually, SNOs structure the earth's surface in cells that receive coverage by at least one satellite. In the case of Starlink, the world is divided in cells in the form of a hexagon with a diameter of $\approx 24.13\ km$. That translates to a single satellite being able to cover approximately $379\ km^2$ [Pek21].

Overall, one differentiates between Geostationary Orbit (GEO) (35'786 km altitude), Medium-Earth Orbit (MEO) (2'000 - 35'786 km altitude), and Low-Earth Orbit (LEO) (< 2'000 km altitude) satellite constellations. One can see in Equation 2.1 and 2.2 that this has a significant impact on the latency.

$$\frac{2 \cdot 35'786km}{300'000\frac{km}{s}} \approx 0.240s \tag{2.1}$$

$$\frac{2 \cdot 550km}{300'000\frac{km}{s}} \approx 0.004s \tag{2.2}$$

A GEO constellation has a minimum latency of around 240 ms, as shown in Equation 2.1, assuming a packet needs to reach a satellite in GEO altitude and get back to the earth's surface. On the other hand, Equation 2.2 shows that a LEO satellite constellation at an altitude of 550 km (like in the case of Starlink) has a minimum latency of only 4 ms. Research has shown that also in practice LEO constellations are superior compared to GEO constellations, especially in terms of latency [Ram+23; Seg20]. However, terrestrial internet still performed better compared to LEO constellations [Ma+23; Moh+24].

2.1.1 Bent-Pipes

Ground stations are required for satellites to route packets to a receiver. Depending on the location of the sender, the first satellite on the route might have to forward packets to a different satellite (using an Inter-Satellite Link (ISL)) in order to reach a region with a GS. Such a route is called "Bent-Pipe". Depending on the number of satellites on the route, it is called an "n-hop-bent-pipe". If there is only a single satellite involved, it is a 1-hop-bent-pipe.

It is in question how the bent-pipe influences the performance and behavior of a networked satellite system. Research still discusses whether bent-pipes provide a positive ([Hau+20]) or negative ([Moh+24]) impact.

Table 2.1: Different networked satellite ISPs

ISP	Category	Customer Group
Starlink	LEO	Private & Business
OneWeb	LEO	Business
HughesNet	GEO	Private & Business
Intelsat	GEO	Business
Viasat	GEO	Business
Orbcomm	GEO	Business
Iridium	GEO	Private & Business

2.2 Usecase of Networked Satellite Systems

Networked satellite systems are around for quite a while since humanity posses both satellites and the internet. The internet has become a key-technology for communication in nearly every aspect of the society. Having no access to the internet will result in significant drawbacks. However, internet requires a complex infrastructure with high cost. Especially in distant location with little population, building such an infrastructure will not be affordable.

Therefore, people came up with the idea of using satellites to communicate with distant locations. In theory, only three satellites are required to communicate with any point on earth. The cost of providing this number of satellites is much less compared to the costs of providing a terrestrial network infrastructure with similar accessibility.

There is one group of people that will not receive terrestrial network infrastructure: people on boats and planes. While there is cellular internet access, it is not offered on the sea and in the high sky. Therefore, the only option of internet access is satellite internet, which is served all over the world.

Additionally, networked satellite systems are much more resilient to physical influences like earthquakes, terrorist attacks, or storms [Ste+24]. Terrestrial infrastructure can be destroyed easily and therefore especially governments contracted networked satellite system ISPs.

2.3 Satellite Network Operators

There are a couple of SNO out there providing internet access via satellite network.

Table 2.1 shows different SNO for networked satellite systems. They differentiate mostly by providing either a LEO or GEO service. The only LEO SNOs are Starlink and OneWeb. Starlink has an economical advantage over most of its competitors as they are a subcompany of SpaceX. SpaceX is a company providing spacecraft manufacturing and launch services. This makes the launch of satellites less tedious compared to Starlink's competitors.

Kohnmann [Koh24] reported about intentions of Amazon launching a networked satellite provider called Kuiper. It is planned to be launched by the end of 2026, after two test satellites were already launched. However, there is no data yet availalbe.

2.4 Satellite Network Simulators

Amongst concrete measurements, one can also simulate networked satellite systems. This became increasingly interesting when the constellations were composed of many more satellites compared to traditional GEO satellite constellations. For example, LEO constellations comprise hundreds to thousands of satellites, which implies a highly complex system.

Sadly, measurements are often highly difficult as they either require acquiring satellite hardware or recruiting users that already posses the required hardware. Simulation would tackle both problems, while maintaining low cost. To the best of our knowledge, we found two networked satellite simulators for LEO constellations.

2.4.1 StarPerf

StarPerf[1] [LLL20] is a mega-constellation performance simulation platform. It specifically aims at measuring the impact of the movements of satellites. Also, it measures performance in different areas. However, setting it up required, amongst others, Matlab and STK. This made the project difficult and expensive to test. Therefore, we did not advance in trying out *StarPerf*.

2.4.2 Hypatia

Hypatia[2] [Kas+20] is another LEO network simulation framework, released in 2020 just like *StarPerf*. It aims at a low-level simulation on packet-level and visualizes the data. Unlike *StarPerf*, it only requires a Python3 installation. Sadly, running simulations with Hypatia is highly complex as it requires the user to define, amongst others, the satellites, ground stations, and points of presence. This information is

1 SpaceNetLab/StarPerf_Simulator
2 snkas/hypatia

hardly available, which renders the simulations barely usable. Also Hypatia is not maintained anymore.

2.4.3 Problems of Network Simulators

To the best of our knowledge, research has stopped relying on simulators since 2020. There is proper hardware available that allows testing in the real world. Testing in the real world has the advantage as it takes more variables into account. Crucial factors for the performance of a networked satellite system are the weather, congestion, solar magnetic storms, material failure, and many more. Those cannot be ideally tested with simulations and will eventually produce wrong results. Therefore, for further research of this thesis, simulations will not be used.

2.5 Growth of Satellite Constellations

Recent years saw a rapid development of satellite technology, especially due to the growing demand of global connectivity and communication. Therefore, companies constructed their own satellite constellations leading to a total number of more than 29’000 objects (according to N2YO in September 2024) in space at the time of writing.

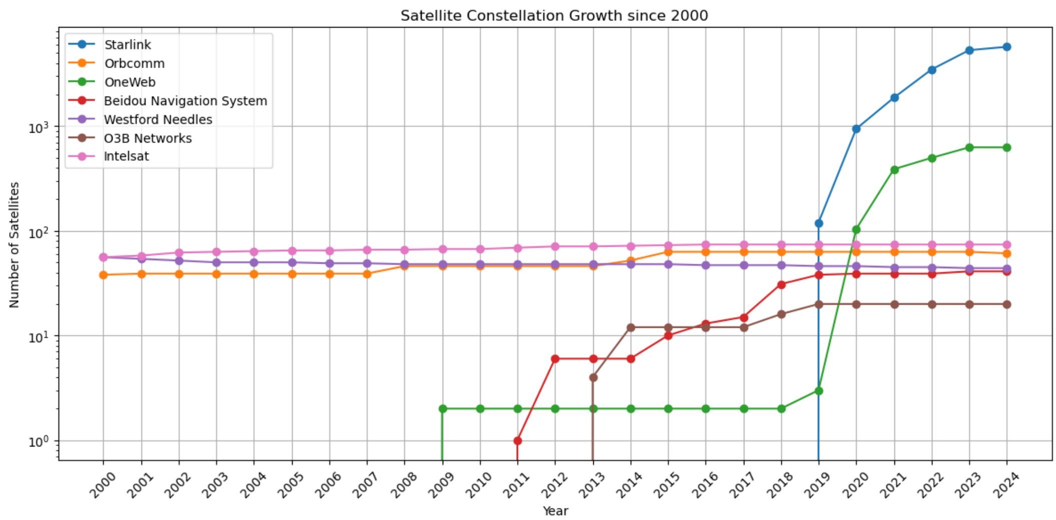


Figure 2.2: Growth of number of satellites in different satellite constellation from 2000 to 2024 (note the logarithmic scale).

Table 2.2: Growth of various satellite constellations from 2017 to 2024

Classification	2017	2018	2019	2020	2021	2022	2023	2024
Starlink	0	0	120	943	1871	3481	5326	6396
Orbcomm	63	63	63	63	63	63	63	61
OneWeb	2	2	3	104	388	498	628	628
Beidou	15	31	38	39	39	39	41	41
Westford Needles	47	47	46	46	45	45	44	44
O3B Networks	12	16	20	20	20	20	20	20
Intelsat	74	74	74	74	74	74	74	74

Figure 2.2 shows various satellite constellations with the number of satellites it consisted of per year. Table 2.2 show the corresponding numbers, starting in 2017. One can see that Starlink is by far the numerically largest constellation. At the time of writing, it has 6'396 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 change between 2023 and 2024.

Other satellite communication constellations like Orbcomm or Intelsat did not grow at all, or even lost satellites. Only Starlink and OneWeb see significant growth in recent years. However, this is also due to the requirement of LEO constellations (i.e., Starlink and OneWeb) of having largely more satellites, compared to GEO constellations (e.g., Intelsat and O3B Networks).

3 Methodology

3.1 Measurement Platforms

The following chapter describes the measurement platforms that were used to measure and collect data.

3.1.1 RIPE Atlas

RIPE Atlas is an open measurement platform to perform basic measurements on the internet. It holds more than ten thousand probes that serve as start points. A probe is machine that has the RIPE Atlas probe software installed. A user can request a probe for a measurement (e.g., a ping from a probe to a RIPE NCC root server).

RIPE Atlas offers the following basic types of measurements:

- Ping
- Traceroute
- (Dis)connection Events
- DNS Lookup
- DNS TLDs
- HTTP
- TLS (SSL) GET Certificate

RIPE Atlas offers the possibility to start measurements via the web interface or an API. While the web interface is sufficient for most use cases, it is also quite limited. Using the API offers more possibilities (e.g., turning DoH queries into DoTLS by adding `"tls": true` into the definition of the measurement).

Additionally, each registered probe performs measurements on a regular basis in fixed time intervals (e.g., each probe performs every 240 seconds a ping measurement against all RIPE NCC root servers). Those measurements are called built-in measurements. They run always when the probe is only and connected to the RIPE

Atlas network. The built-in measurements are the ones used for the data of this thesis within a specified time interval (usually January 2022 to June 2024).

Downloading the results of a measurement also works by accessing the API. For previous results, one can access the REST API that stores all results ever measured. For more up-to-date results, one can use the Streaming API that sends the most recent results to a subscribed socket. Theoretically, the API is rate-limited, but we did not encounter problems even when bulk-downloading larger datasets. Still, ethical crawling was used.

RIPE Atlas offered 150 Starlink probes (i.e., probes with ASN14593) at the time of writing. Table **??** in the appendix shows the number of probes per country. The originating country is determined by RIPE Atlas. As most metrics rely on larger amounts, you will find countries with more probes more reflected in the analysis in Chapter 4.

3.1.2 Cloudflare Radar

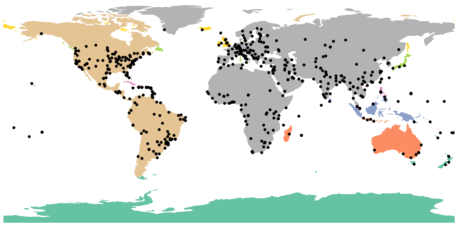
Cloudflare manages a vast amount of traffic on the internet. Initially, it served the purpose of protecting servers from attacks. Today amongst others, it also manages traffic, and sells data. In 2020, Cloudflare released data that has been held internal. This new platform is Cloudflare Radar (CFR). CFR offers various statistics on the internet ranging from security statistics over latency measurements to bot ratios per country.

For the purpose of this thesis, we are mostly interested in the performance measurements. CFR offers performance measurements within their Internet Quality Index (IQI). It is the collection of measurements performed through their Internet Speed Test [Clo; Dav23]. As target, CFR uses a fixed set of Cloudflare servers.

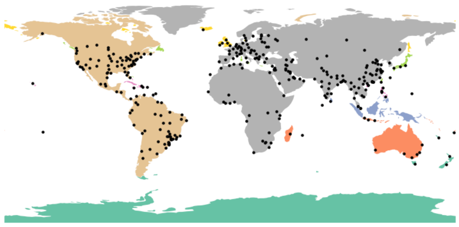
endwraptable

Takeaway: Difference of RIPE Atlas and Cloudflare Radar

Measurements performed in CFR and RIPE Atlas differentiate in the targeted servers (root servers vs. Cloudflare servers), the measurement probe (RIPE Atlas probe vs. browser), and the metric used (TLS vs. Time to First Byte). Cloudflare's servers are expected to have a better latency (they claim to be 50ms away from 95 % of the earth's population; State September 17, 2024).



(a) Locations of Root Servers (all *.root-servers.org together) [roo24]



(b) Locations of Cloudflare Data Centers [Clo24]

3.1.3 OONI

3.1.4 N2YO

N2YO is a platform collecting data about satellites in space. It is a data integration platform collecting data from different platforms like Celestrak and Space-Track.

For the purpose of this thesis, N2YO is used to find information on the development of various satellite constellations. Therefore, we want to find the following information:

- Satellite ID (also formerly called Norad ID)
- Satellite Name
- Launch Date
- Decay Date (if applicable)
- Classification (if applicable)

Each satellite receives a unique ID, centrally given to all satellites launched. It is a continuous number starting at 1. The satellite with ID 1 is the rocket body of Sputnik 1. Sputnik 1 itself holds ID 2.

The data is obtained by a web crawler that parses the HTML page and finds the information needed. There is also the possibility of getting the data by API, but the API is rate-limited. Parsing HTML is inefficient, but still a quicker approach compared to using the API.

3.2 Data Collection

For analysis, we create a dataset containing measurements from various sources about networked satellite systems. Sadly, only data from Starlink devices was included in the thesis as other satellite network systems did not have sufficient data openly available.

The data originates from RIPE Atlas, Cloudflare Radar, OONI, and N2YO. While N2YO provides data about satellites, the others hold measurement results. In the case of N2YO, the website was crawled, while the others provide API access.

The process of data collection is illustrated in Figure 3.2.

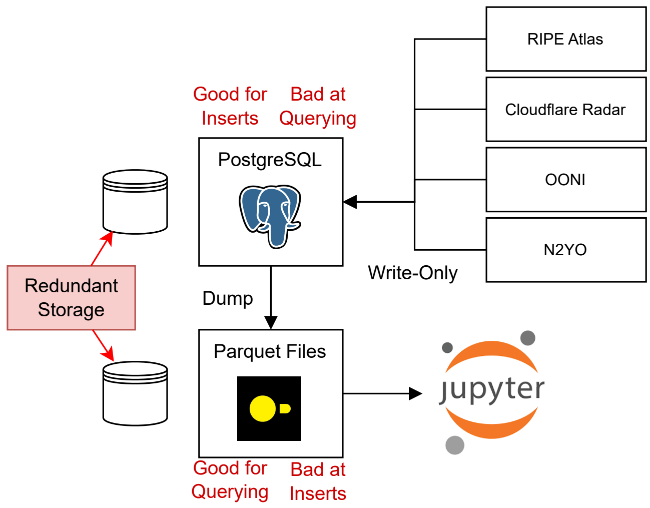


Figure 3.2: Architecture of Data Collection

The data is collected from each platform and inserted into a PostgreSQL database. The database shall allow producers to quickly insert new data (i.e., new rows). Transactional databases are the best choice for that, e.g., PostgreSQL. To quickly analyze data, an analytical database is the best choice. For that purpose, Parquet files can be used. Therefore, the data from PostgreSQL is dumped into the Parquet files. This creates a redundant storage, for the sake of analysis speed.

The resulting data format is shown in Figure 3.3.

The database includes Ping, Traceroute, TLS, HTTP, Disconnect Event, and DNS measurement data, as well as information about the RIPE Atlas probes and all satellites ever launched (including rocket bodies). The whole database comprises more than 150 GB.

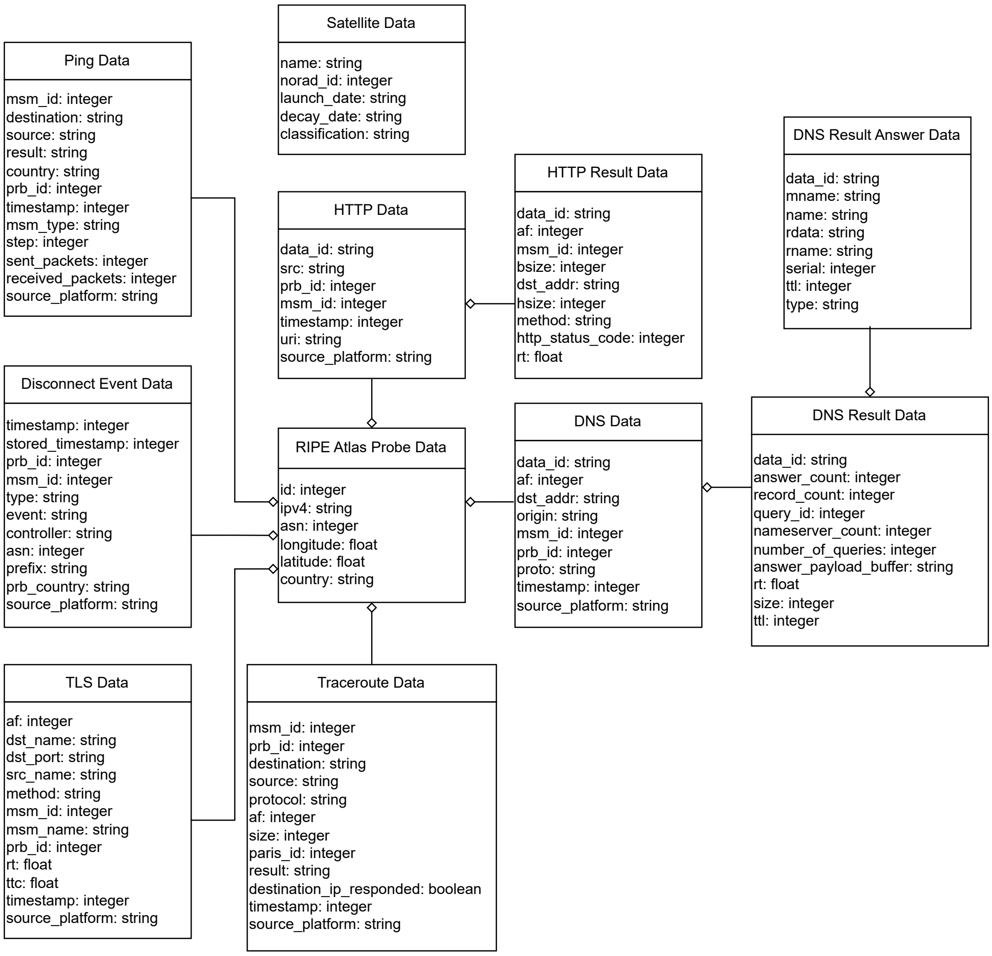


Figure 3.3: ER Diagram of Data Schema in PostgreSQL Database.

Additionally, the analysis uses data from IPinfo. This data is however not included in the dataset and has to be obtained from IPinfo itself.

RIPE Atlas Data

RIPE Atlas offers various probes connected via networked satellite systems. At the moment of writing, all of those probes are connected via Starlink. Therefore, all the data from RIPE Atlas probes is Starlink data.

Probes are computers running the probe software from RIPE Atlas. They are centrally connected to the RIPE Atlas servers and can be used by any person to perform measurements against them. The possible measurements are defined by the RIPE Atlas REST API.

Overall, there are 150 probes from 26 countries. Each probe performs basic measurements on a regular schedule (so-called built-in measurements). The built-in measurements are the main source of data and serve as historical record. This allows to analyze data from 2022. Even if there is Starlink data prior to 2022, it originates from very little probes and therefore will not be considered in this thesis to avoid unreliable data.

3.3 Reproducibility of Results and Data

The code to reproduce the results and data is uploaded to GitHub[3]. The user is only required to have a running internet connection and an installation of Nix and Docker. Follow the instructions provided by the repository to obtain the results and data by yourself[4].

3 See https://github.com/starlink-thesis-diic/starlink-thesis

4 The scripts might not work, if data format in the sources has changed since the last update of the scripts.

4 Results

4.1 Performance of Networked Satellite Systems

4.1.1 Latency over whole Data Range

The performance of Starlink latency has changed over time. To determine latency, we looked at TLS handshake latency. The data originates from the RIPE Atlas TLS data that has been collected by built-in measurements (i.e., measurements that are continuously running in each individual probe in a fixed time interval).

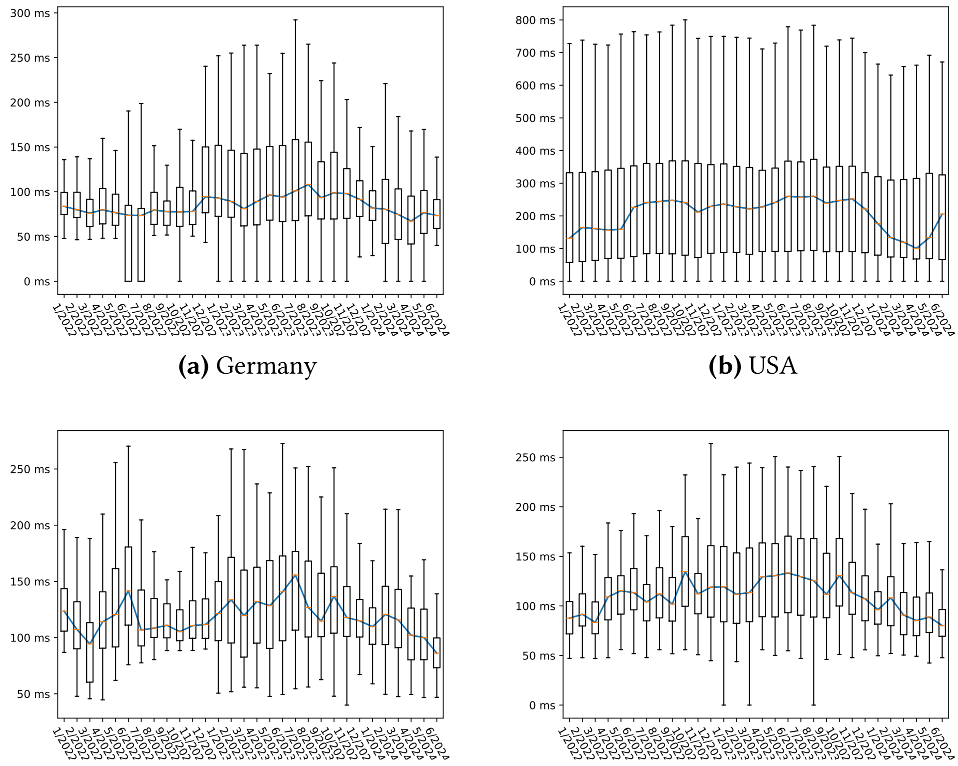
Figure 4.1 shows the history of median TLS handshake latencies from January 2022 until June 2024 for Germany, the United States, Poland, and Austria[5].

One can see that the median TLS handshake latency is usually at around 100 to 150 ms for most countries. However, in 2022 the latency was lower compared to 2023. Most of the countries observed show an upwards trend in the late months of 2022 (most of the time in December). In the late months of 2023, the latency starts to decline again. In the last couple of months, we observe an increase in latency once again. We assume the reason for the rise is the congestion of the Starlink network. In the recent time, Starlink extended their availability across more countries allowing more users, especially those in countries with less networking infrastructure, to access the network. On the contrary, Starlink also launched more satellites (2022: 3481, 2024: 6000+; see Chapter 2.5) and added more PoP which likely reduces the congestion.

Figure 4.2 shows the median and average TLS handshake latencies in European countries. It shows that the north west of Europe experiences the best latencies, likely due to the presence of various GSs. The southern and eastern european countries experience worse latencies. Especially Greece has a high median latency. A cause could be the absence of GSs in the east-european region. Italy on the other hand side experiences a high average latency, even with GSs being present in the country.

Looking at the CDFs of the USA and Canada results in a similar observation. Figure 4.3 illustrates the CDF plots for 2022 – 2024 for the USA and Canada. We

5 These countries were chosen due to the completeness of data



(a) Germany **(b)** USA

(c) Poland **(d)** Austria

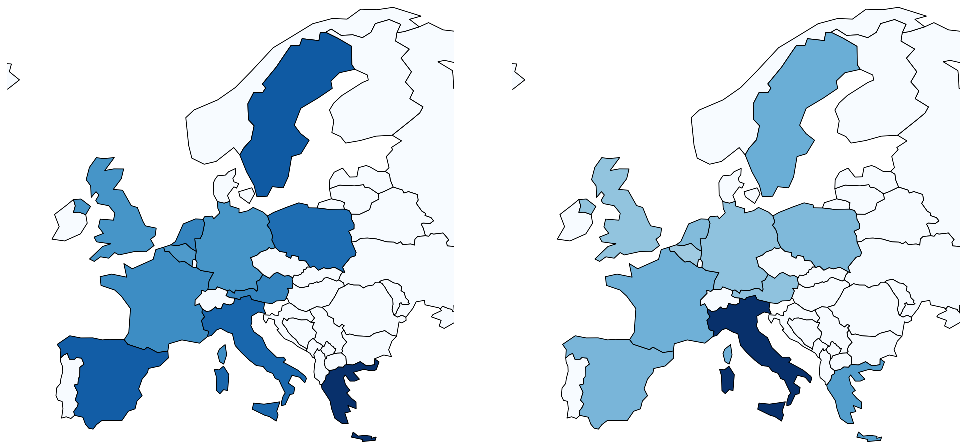
Figure 4.1: Latency History for Germany, the USA, Poland, and Austria in the period 01/2022 to 06/2024

observe similar results for other countries, but only chose Canada as it holds sufficient data for a conclusion.

We observe and similar performance of 2022 and 2024, but a drop in TLS handshake latency in 2023, similar to the conclusion we drew before.

Additionally, we conclude that approximately half of the measurement results are below 100 ms, while the other half moves above 100 ms. This opposes research suggesting Starlink performance is mostly in the sub-100 ms area [LLL20; Mic+22; Moh+24; Ram+23].

The CDF is continuous, up to a specific point, where it flattens, followed by a stronger increase once again. This is similarly observed for curves of other countries (e.g., for France and Germany in Figure 4.4). This observation suggests that there is a region of latencies that Starlink does not serve equally. The specific location of



(a) Median **(b)** Average

Figure 4.2: Heatmap of Median and Average Latencies in 2024 in Europe.

the flattening behavior varies between countries, but is usually located between 150 and 250 ms.

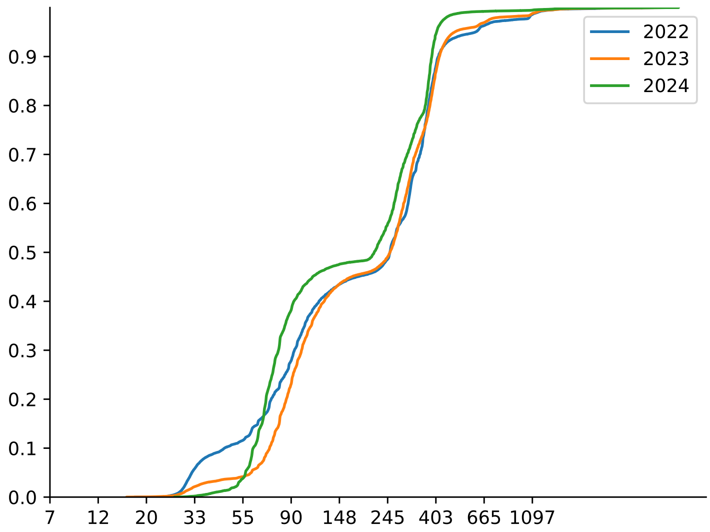
Analyzing the flattening behavior in more detail, we used an EquiWidth histogram[6] to plot the most frequent latencies. Figure 4.5 and 4.6 show the histograms for the USA, Canada, France, and Germany. It becomes apparent that there is actually a major gap between within the latencies. This gap appears for most countries. In 2024, it became even more apparent (e.g., looking at Germany, the gap was not visible in 2022, but appeared in 2024). For further countries, the appendix holds further plots (see Figures 6.1 – 6.5 and 6.6 – 6.10).

Currently, it is unclear why the gap appears, but we assume that either the measurements were consistent enough for such a pattern to occur or the gap is a special trait of the Starlink system. The latter would infer that Starlink serves specific latencies better than others.

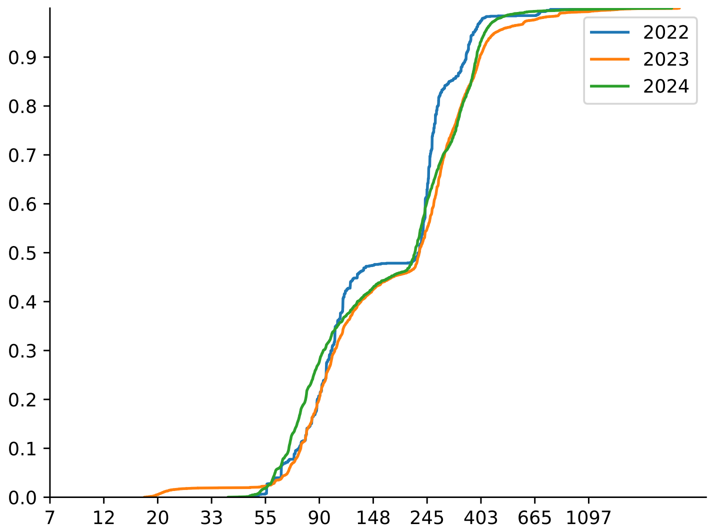
4.1.2 Latency Development on Individual Days

We used the data to look at the latency development over a single data for individual days. First, TLS handshake data was used to analyze individual days. However, it appeared that the amount of TLS measurements per hour was insufficient to make

6 A histogram that puts all values in a pre-defined number of bins, where all bins cover an equally wide data-range.

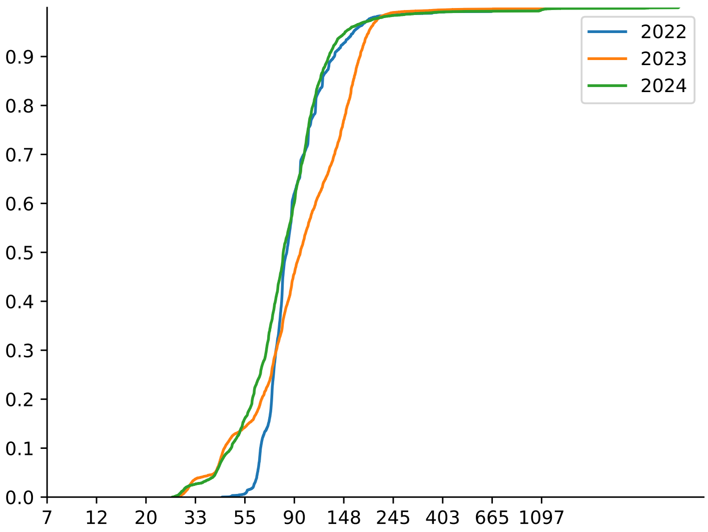


(a) USA

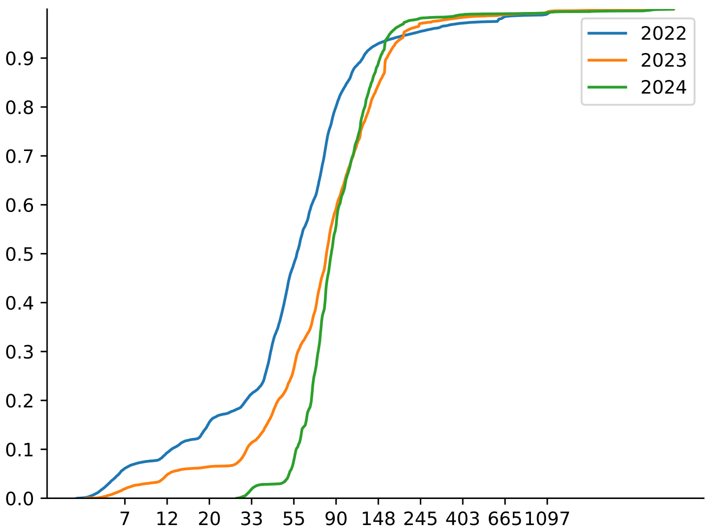


(b) Canada

Figure 4.3: CDF of Latencies in the USA and Canada

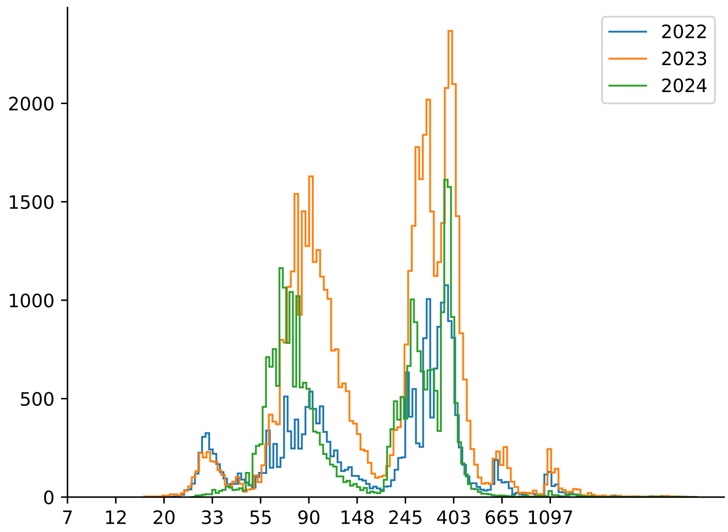


(a) Germany

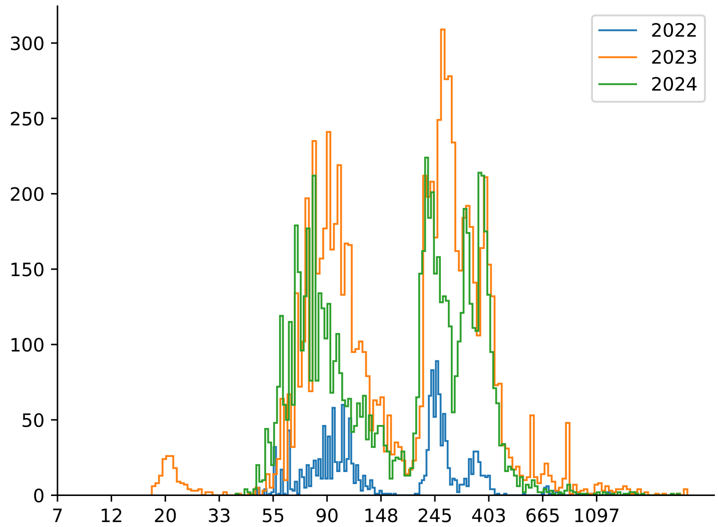


(b) France

Figure 4.4: CDF of Latencies in Germany and France

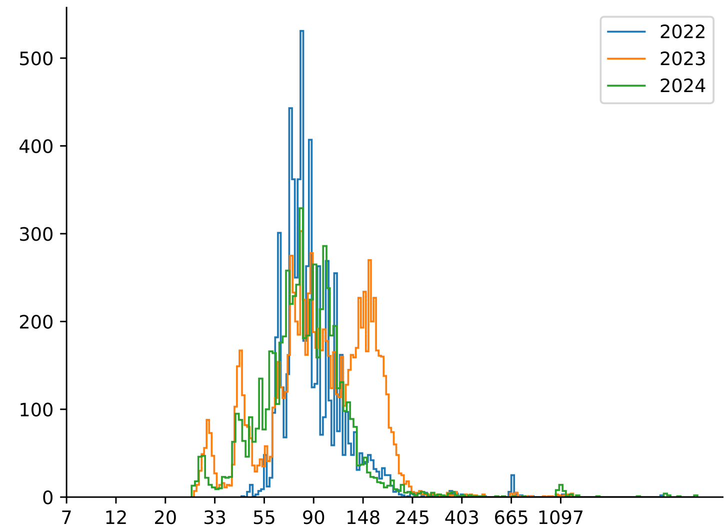


(a) USA

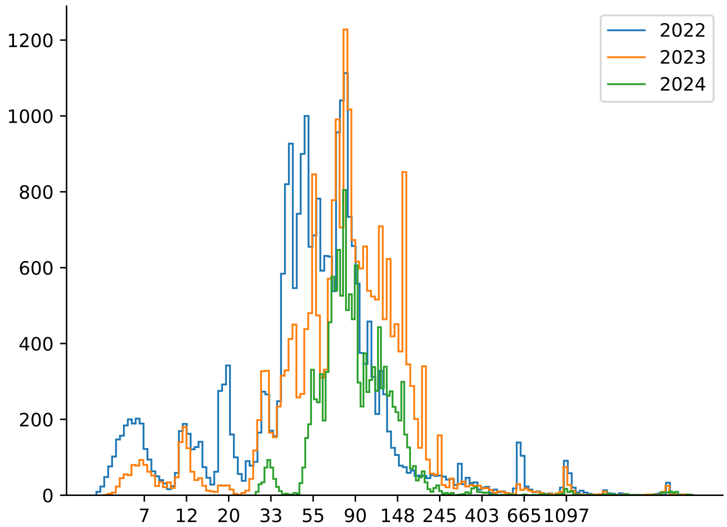


(b) Canada

Figure 4.5: EquiWidth Histogram of Latencies in the USA and Canada



(a) Germany



(b) France

Figure 4.6: EquiWidth Histogram of Latencies in Germany and France

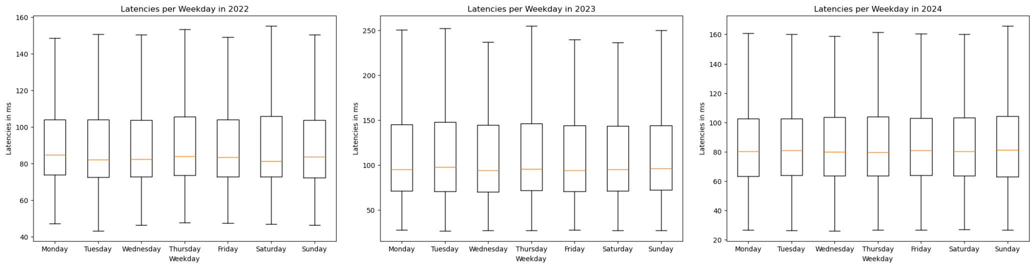


Figure 4.7: Latencies from 2022 to 2024 per Weekday.

a reasonable statement. An example of such a plot for July 9, 2024 is illustrated in Figure 6.11 in the appendix[7].

Instead, we chose to use Ping data for the analysis of individual days. Ping measurements are not representative for absolute performance metrics [Pel+13], but show a pattern.

4.1.3 Latencies on Different Weekdays

It is in question whether TLS handshake latencies vary at different days of the week. For example, the latency might be different comparing Mondays and Sundays. In the case of Starlink, we were not able to find such a pattern. Figure 4.7 illustrates the latencies that occur in each weekday.

One can see that there is no clear pattern that differentiates the individual weekdays from the others. This does not change over the course of the years.

To look in more detail on the data, we looked at the data in specific statistical aggregates (number of measurements, median, average, maximum, and minimum latency). The results are shown in Table 4.1.

They show that the latency does not vary on the individual days. Therefore, you will not have a worse latency on working days (Monday – Friday) compared to the weekend (Saturday and Sunday).

However, the table also allows for an interesting comparison between the years 2022, 2023, and 2024. In 2022, the median TLS handshake latency was between 81 and 84 ms. The average latency was about 20 ms higher. Peak latencies achieved up to 43 ms. In 2023, the median latencies were significantly higher at 94 to 98 ms. The average latency was in the worst case 14 ms higher, which indicates a more stable connection, even if the performance was worse compared to 2022. However, 2023 achieved much better peak performance at 26 ms. In 2024, Starlink achieved

7 The day was chosen at random. It holds more data than most of the other days.

Table 4.1: Weekday Statistics in Germany

	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.
2022							
#Measurements	899	895	904	903	906	918	893
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							
#Measurements	1448	1447	1443	1429	1430	1436	1462
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							
#Measurements	914	930	904	913	914	912	918
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

similar median and average latencies compared to 2022, but also achieving the peak performances from 2023.

Takeaway: Peak and Average Latency since 2022.

Starlink has managed to improve their peak latency by nearly 20 ms compared to 2022 while maintaining their median and average latencies.

4.1.4 Packet Loss from 2022 to 2024

We looked at the packet loss for the time range from 2022 to June 2024. We use the Ping measurement from the RIPE Atlas built-in measurements, which by default send three packets and collect the number of received packets. Table 4.2 shows the resulting packet losses in percent per country.

The results are surprising as some countries experience very high packet losses,

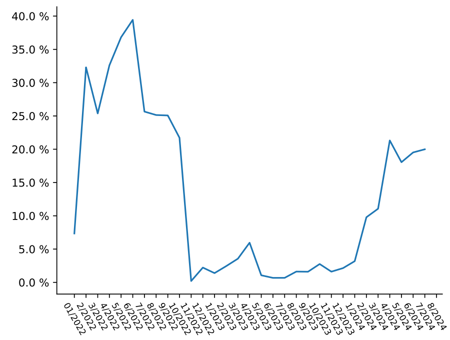
Table 4.2: Packet Loss and Latency Correlation in 2022 to June 2024

Sent	Received	Country	Packet Loss Ratio in %
2150628	2134905	Austria	0.73
65021654	62438854	Australia	3.97
22727113	22211676	Belgium	2.27
1176124	1168114	Benin	0.68
124263104	121160149	Canada	2.50
2843	2832	Switzerland	0.39
3626230	3617474	Chile	0.24
8092876	8074360	Czechia	0.23
96089885	85983781	Germany	10.52
21714610	21001677	Spain	3.28
432934	418925	Falkland Islands (Malvinas)	3.24
321919833	299847062	France	6.86
83840509	80720387	United Kingdom	3.72
12522224	12318835	Greece	1.62
271185	265100	Guam	2.24
18472787	18217243	Haiti	1.38
37188354	35583136	Italy	4.32
4160290	3829356	Kiribati	7.95
127756	121937	Madagascar	4.55
20450037	17548642	Netherlands	14.19
26654399	21785387	Philippines	18.27
18739794	18670207	Poland	0.37
7047181	6967111	Réunion	1.14
9975257	9922734	Sweden	0.53
578852548	557475491	United States	3.69
18571694	18463935	Virgin Islands, U.S.	0.58

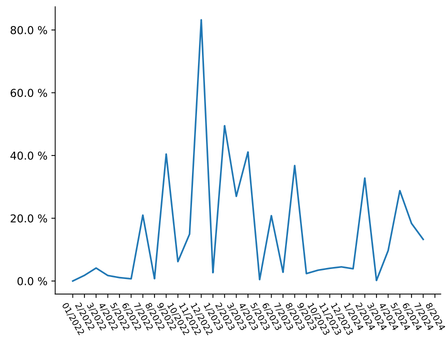
while other neighboring countries have rather low packet loss ratios. For example, Germany and Netherlands are well-developed countries with a relatively high number of GSes. One would expect a low packet loss, which is not the case. Both countries hold packet loss ratios above ten percent. On the other hand, neighboring countries like Austria do not show such a pattern. Another country with remarkably high packet loss are the Philippines, which have the highest packet loss ratio of all countries.

Overall, most countries experience packet loss ratios at one to four percent, with some having an even lower value. The lowest value has Czechia with 0.23 %, while Chile has 0.24 %.

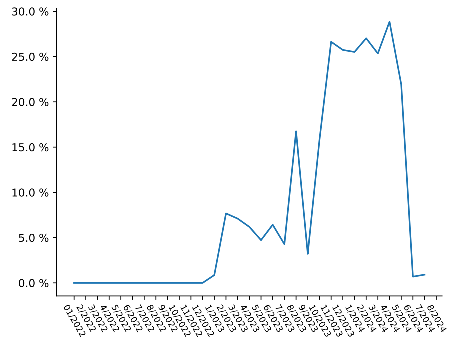
However, the time range is quite long. Therefore, we looked at the time range in a more fine-grained interval for the above-mentioned countries. Figure 4.8 show



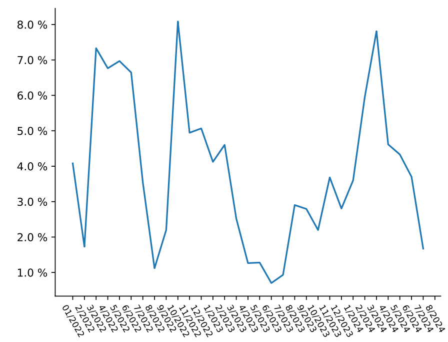
(a) Germany



(b) Netherlands



(c) Philippines



(d) USA

Figure 4.8: Packet Loss Ratios in Percent in individual Month from January 2022 to June 2024

the packet loss ratios for each month from January 2022 to June 2024 for Germany, the Netherlands, the Philippines, and the USA. The first three were chosen as they are noticeable in Table 4.2. The USA was chosen, as it holds the most data and is therefore a good comparison.

One can see that Germany experienced high volumes of packet loss in 2022 reaching as high as 40 % packet loss in June 2022. This was followed by a period of little packet loss ratios in 2023. Likely, papers taking measurements at this time will report Germany to have very little packet loss. In 2024, the trend is going back towards higher packet losses.

The Netherlands show fluctuating pattern that even reaches values of 80 % packet loss in December 2022. However, little conclusions can be made except for the assumption that the connection is highly instable.

The Philippines only hold data since 2023. Therefore, we cannot make conclusions about the packet loss in the Philippines in 2022. In 2023 however, the packet loss was around five to eight percent, until in August 2023, the packet loss rose to more than fifteen percent. In 2024, the packet loss even rose above twenty-five percent. June 2024 saw a sudden reduction in packet loss. However, there is to little time series data to determine whether this is an outlier.

The USA shows a similar pattern to Germany. In 2022, the packet loss was relatively high, followed by a reducion in 2023, followed by an increase in 2024. However, there are two key differences when comparing Germany and the USA: (1) the USA experiences lower percentages in packet loss and (2) a reduction of packet loss is suggested starting in April 2024, which does not happen for Germany.

Takeaway: Packet Loss in Starlink

The packet loss of Starlink connections is for most countries in the range of 1 – 4 %. However, there are major differences and regional proximity does not seem to play a role. Additionally, 2023 has experienced better packet loss results compared to 2022 and 2024. This is a key difference to the latency analysis, where 2023 has experienced the worst results. It seems that Starlink can only op optimize for either packet loss and latency. It is in question, whether both values correlate.

4.1.5 Latency and Packet Loss Correlation

TLS handshake latency and packet loss are closely bonded. An increase of packet loss might yield an increase in latency and vice-versa. For the data presented in the previous chapter, we looked at the interval from January 2022 to June 2024. For each month, we used the overall packet loss and the median TLS handshake latency. We used a Pearson, Kendall, and Spearman correlation to determine possible correlations between latency and packet loss. The results are shown in Table 4.3.

In a correlation, a value close to 1 or -1 shows a strong correlation. Values close to 0 do not appear to be correlated. In the results, some countries show a correlation, e.g., France or Czechia. Other countries, e.g., Canada or Australia do not show correlating values. As the number of countries with a stronger and those with a weaker correlation is equally distributed, we cannot conclude a correlation between latency and packet loss in Starlink networks.

Table 4.3: Packet Loss and Latency Correlation

Country January 2022 - June 2024	Pearson Correlation	Kendall Correlation	Spearman Correlation
Falkland Islands (Malvinas)	0.447641	0.595238	0.624282
Réunion	0.636822	0.716314	0.847658
Kiribati	0.819596	0.794851	0.801966
Canada	-0.090981	0.218391	0.280534
Poland	0.093155	-0.025287	-0.073637
Haiti	0.383601	0.670768	0.844964
Spain	-0.323940	-0.163650	-0.179434
Czechia	0.700248	0.730392	0.806351
United States	-0.556997	-0.425287	-0.610234
France	0.893576	0.664368	0.840267
Italy	-0.073752	0.181609	0.293882
United Kingdom	-0.238013	-0.227586	-0.279644
Honduras	0.415387	0.410256	0.575585
Australia	-0.025590	0.013841	0.035834
Netherlands	0.190923	0.055364	0.111952
Greece	0.249727	0.496864	0.668590
Sweden	0.678500	0.726984	0.896199
Austria	0.054429	0.039080	0.073192
Belgium	-0.082786	-0.029885	-0.031368
Philippines	0.254523	0.460118	0.676049
Virgin Islands, U.S.	0.712898	0.706384	0.878571
Germany	-0.787348	-0.549425	-0.753059

Correlation in Single Years

Analyzing single years give a better understanding of the development of correlation in the year 2022, 2023, and 2024 (until June). The Tables 4.4, 4.5, and 4.6 show the individual correlation values for the year. There are only countries displayed, where a correlation value could be calculated.

In 2022, there was little correlation at all. Likely, other factors like satellite infrastructure or presence of PoP might have been more contributing to performance issues. 2023 showed a stronger correlation compared to 2022. We assume that this is due to a more stable network. The interaction between packet loss and latency might have become more significant. In 2024, the correlation decreased once again slightly. This behavior is similar to the one observed for the latencies in recent months. A possible explanation for that is a growing user base of Starlink leading to a congestion of the system. It has to be noted that the growth of number of

Table 4.4: Packet Loss and Latency Correlation in 2022

Country 2022	Pearson Correlation	Kendall Correlation	Spearman Correlation
Canada	0.478988	0.272727	0.307692
Poland	0.601734	0.303030	0.342657
Spain	-0.286931	-0.053571	-0.037594
United States	-0.241717	-0.212121	-0.363636
France	0.177126	-0.060606	-0.083916
Italy	0.646487	0.484848	0.587413
United Kingdom	0.514397	0.363636	0.496503
Honduras	0.208592	-0.333333	-0.426573
Australia	0.870466	0.325669	0.450715
Netherlands	0.159295	-0.106873	-0.164624
Greece	0.811845	0.836660	0.853766
Austria	0.013609	-0.060606	-0.146853
Belgium	-0.283806	-0.242424	-0.272727
Germany	-0.663075	-0.303030	-0.517483

Table 4.5: Packet Loss and Latency Correlation in 2023

Country 2023	Pearson Correlation	Kendall Correlation	Spearman Correlation
Falkland Islands (Malvinas)	0.364389	0.466667	0.518072
Réunion	0.587427	0.467801	0.592125
Canada	0.370590	0.363636	0.608392
Poland	-0.261476	-0.090909	-0.216783
Haiti	0.757392	0.390673	0.529108
Spain	-0.413832	-0.160714	-0.218045
Czechia	0.415844	0.383333	0.458333
United States	-0.302660	-0.242424	-0.251748
France	0.779247	0.666667	0.818182
Italy	-0.568765	-0.272727	-0.412587
United Kingdom	-0.812772	-0.606061	-0.748252
Honduras	0.343476	0.516667	0.617754
Australia	-0.578546	-0.121212	-0.258741
Netherlands	0.212359	0.181818	0.314685
Greece	-0.268072	0.212121	0.195804
Sweden	0.515385	0.533333	0.717391
Austria	-0.294406	-0.121212	-0.125874
Belgium	0.441123	0.454545	0.573427
Philippines	-0.196523	-0.030303	-0.034965
Virgin Islands, U.S.	0.553108	0.578196	0.783080
Germany	-0.620018	-0.424242	-0.622378

Table 4.6: Packet Loss and Latency Correlation in 2024

Country 2024	Pearson Correlation	Kendall Correlation	Spearman Correlation
Réunion	0.301680	-0.066667	-0.085714
Kiribati	0.744916	0.673575	0.718421
Canada	-0.003851	-0.600000	-0.771429
Poland	0.239930	0.333333	0.371429
Haiti	0.376160	0.200000	0.257143
Spain	-0.044513	-0.333333	-0.142857
United States	-0.529555	-0.600000	-0.771429
France	0.418669	0.200000	0.257143
Italy	-0.600898	-0.866667	-0.942857
United Kingdom	0.243811	0.333333	0.428571
Honduras	0.431954	0.333333	0.542857
Australia	-0.155578	-0.066667	-0.085714
Netherlands	0.433624	0.466667	0.542857
Greece	-0.813812	-0.466667	-0.600000
Sweden	0.280194	0.066667	0.085714
Austria	0.915449	0.466667	0.600000
Belgium	0.428515	0.333333	0.371429
Philippines	-0.920833	-0.466667	-0.428571
Virgin Islands, U.S.	-0.450938	-0.333333	-0.428571
Germany	-0.603772	-0.333333	-0.485714

satellites did not increase from 2023 to 2024 as much as it did from 2022 to 2023, which might be a cause of the issue.

Correlation with the Number of Probes

It is possible that the data is insufficient resulting in a correlation between latency and packet loss being invisible. A possibility is to look at the number of probes being available for each country. Therefore, we took the data from Table 4.3 and correlated it with the number of probes available for RIPE Atlas in each country. The resulting table is shown in Figure 4.7.

We correlated the correlation values with the number of probes per country. This resulted in the following correlation values:

- Pearson Correlation: ≈ -0.44
- Kendall Correlation: ≈ -0.44
- Spearman Correlation: ≈ -0.53

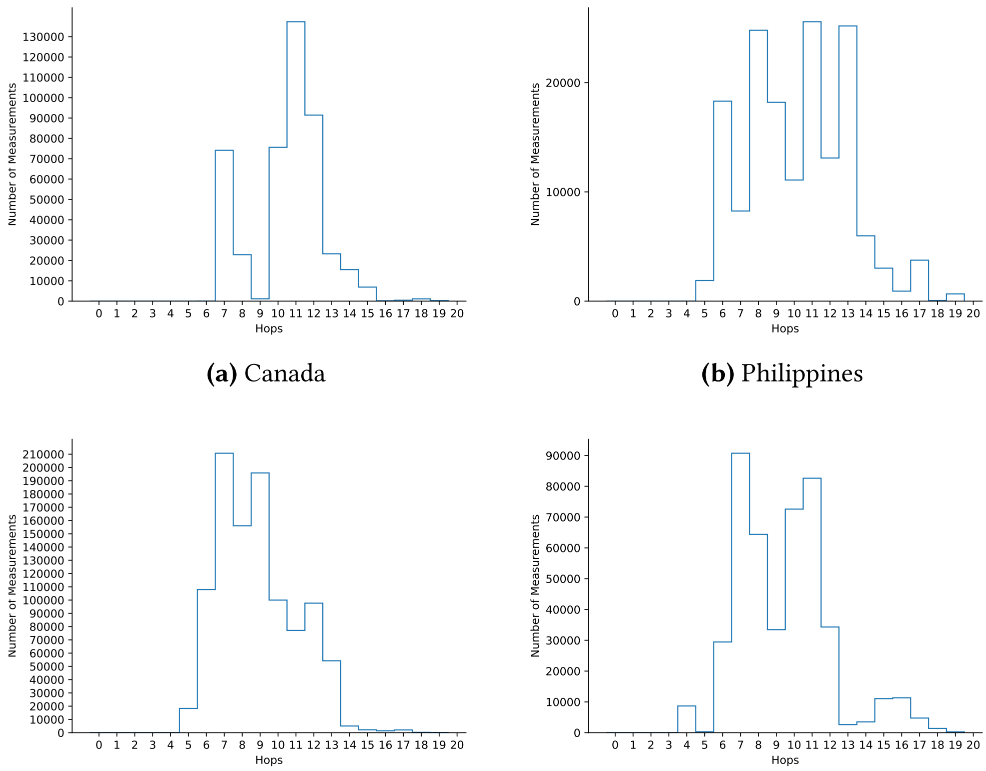
Table 4.7: Packet Loss, Latency and Number of Probes Correlation

Country Jan. 2022 - June 2024	Pearson Correlation	Kendall Correlation	Spearman Correlation	Number of Probes
Falkland Islands (Malvinas)	0.447641	0.595238	0.624282	1
Réunion	0.636822	0.716314	0.847658	1
Kiribati	0.819596	0.794851	0.801966	2
Canada	-0.090981	0.218391	0.280534	11
Poland	0.093155	-0.025287	-0.073637	1
Haiti	0.383601	0.670768	0.844964	3
Spain	-0.323940	-0.163650	-0.179434	4
Czechia	0.700248	0.730392	0.806351	1
United States	-0.556997	-0.425287	-0.610234	53
France	0.893576	0.664368	0.840267	18
Italy	-0.073752	0.181609	0.293882	4
United Kingdom	-0.238013	-0.227586	-0.279644	11
Honduras	0.415387	0.410256	0.575585	1
Australia	-0.025590	0.013841	0.035834	8
Netherlands	0.190923	0.055364	0.111952	2
Greece	0.249727	0.496864	0.668590	1
Sweden	0.678500	0.726984	0.896199	1
Austria	0.054429	0.039080	0.073192	4
Belgium	-0.082786	-0.029885	-0.031368	2
Philippines	0.254523	0.460118	0.676049	3
Virgin Islands, U.S.	0.712898	0.706384	0.878571	1
Germany	-0.787348	-0.549425	-0.753059	10

As the correlation does not reach values close to 0, 1, or -1, we cannot conclude a correlation with the number of probes.

Takeaway: The correlation of latency and packet loss.

Starlink does not show a clear pattern that indicates a correlation between TLS handshake latency and packet loss. However, this is highly dependent on the country of origin.



(a) Canada **(b)** Philippines

(c) France **(d)** Germany

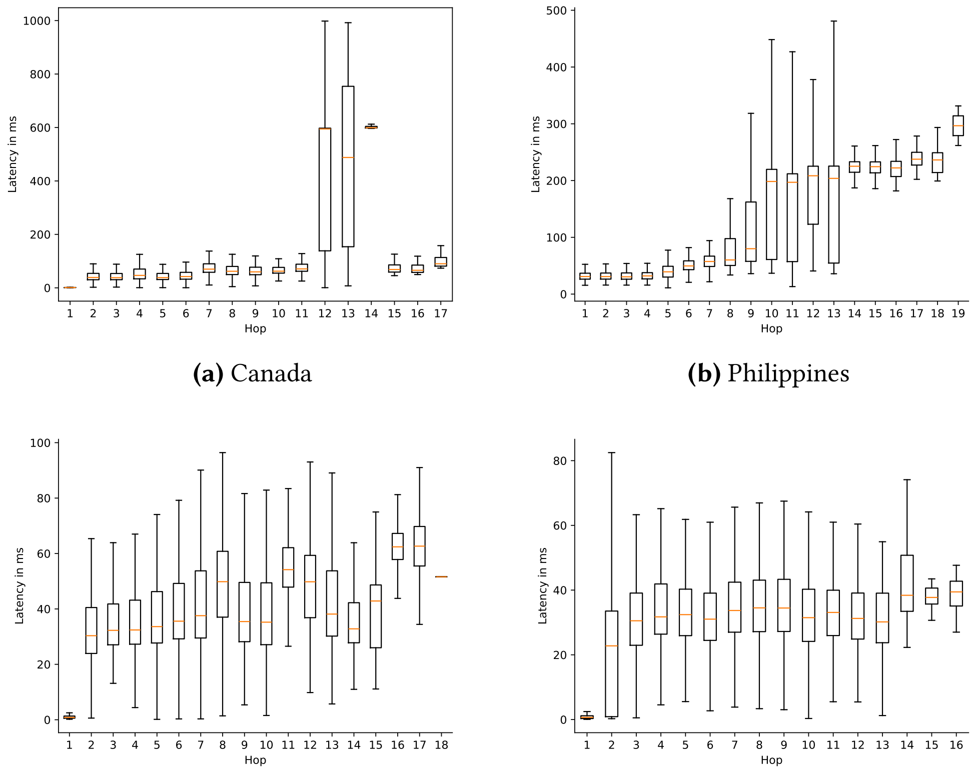
Figure 4.9: Histogram of Hops the Traceroute Measurement took.

4.2 Resilience of Networked Satellite Systems

4.2.1 Number of Hops per Route

We want to look at traceroute measurements. The first thing we analyze is the average number of hops per traceroute measurement. For that, we use the RIPE Atlas built-in traceroute measurements. Figure 4.9 shows the histogram of hops for Canada, the United Kingdom, France, and Germany. The countries were chosen due to the completeness of the data. Similar results were found when looking at other countries.

The histograms show that most routes take between seven and fourteen hops. It is interesting to note that the histograms show a similar pattern compared to the histogram for TLS handshake latencies that are shown in Chapter 4.1.1. Both



(a) Canada **(b)** Philippines

(c) France **(d)** Germany

Figure 4.10: Average Latency per Hop

histograms have a pattern that spikes at two points. We assume that there a specific reason for this correlation that is part of the Starlink network.

4.2.2 Latency per Hop

We want to a closer look on how Starlink latency behaves in each hop. To do so, we looked at each hop of the built-in measurements of RIPE Atlas and the change in round trip time from hop to hop. Figure 4.10 show how the round trip time measured in the traceroute measurement behaves with more hops. It is important to note that in rare cases the RTT does not increase with more hops, as traceroute measurements work with repetitive measurements that might yield inconsistent results in consecutive runs.

One can see that overall each hop increases the RTT slightly, but in most cases there is a hop that strongly increases the RTT. We assume that this usually is the hop from the entry into the satellite constellation toward the GS. It is not clear why this step often appears in a later hop, as the entry into the satellite constellation should appear as first or second hop.

Also, it is important to note that the behavior is different from country to country. The appendix shows further countries in Figure 6.12.

4.2.3 Disconnect Events of RIPE Atlas Probes

Probes in RIPE Atlas automatically monitor the events when they are disconnected from RIPE Atlas and when they re-connect again. Those disconnect events give evidence about the state of a network. Frequently occurring disconnect events might indicate an unhealthy network connection.

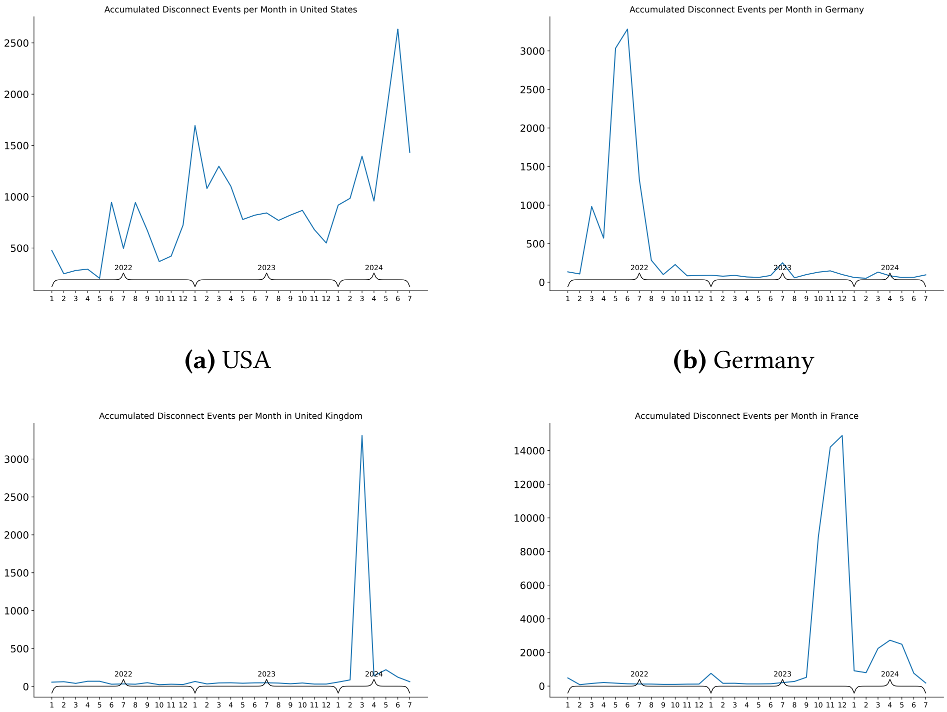
We analyzed the number of disconnect events for the Starlink probes in RIPE Atlas. Figure 4.11 shows the number of disconnect events per month in the time from January 2022 to July 2024 for the USA, Germany, the United Kingdom, and France.

One sees variously different patterns. While in Germany and the United Kingdom very little disconnect events appear for the most time, the United States show a relatively high number of disconnect events, increasing over time. The USA experiences higher levels of disconnect events in June 2024, January 2023, and May to August 2022. A clear pattern is not visible here. On the other side, Germany experiences a high number of disconnect events in May to August 2022 (which also happens in the USA), while the United Kingdom does not show such a behavior. The UK experiences a higher number of disconnect events in March 2024, but never before that. France and the United Kingdom show a very similar pattern. There is no clear pattern observable, when comparing those three countries. A similar behavior was observed for other countries.

Still, accumulating the number of disconnect events over all countries show significant spikes. Figure 4.12 illustrates the pattern. Especially September and October 2023, the beginning of 2024 and June 2024 show a much higher frequency. May and June 2022 have a significant spike.

We have to note that the data shown in Figure 4.12 does not allow making conclusions. It holds different numbers of probes over time, so an increase in disconnect events is expected. To draw conclusions for Starlink behavior, the data needs to be normalized. Chapter 4.2.3 explains this problem in more detail.

Also, the spikes in disconnection events may have been because of RIPE Atlas system problems, which occur from time to time and cause many probes to arbitrarily disconnect.



(a) USA **(b)** Germany

(c) United Kingdom **(d)** France

Figure 4.11: Number of Disconnect Events in the USA, Germany, the United Kingdom, and France from January 2022 to July 2024.

> **Takeaway: Usage of Disconnect Events**
>
> Accumulating Disconnect Events of Starlink probes seem to show a behavior that causes time intervals with higher occurrences. However, normalization is required to verify the observation. Normalization would be possible by using the active number of probes per time interval, but this was not done as it is not an easy task.

Correlation of Disconnect Events with other Metrics

One could correlate the occurrences of disconnect events with other metrics (e.g., latencies and packet loss). Usually, this is done by comparing two metrics with each other, where each metric is normalized. By normalizing, two values of the same

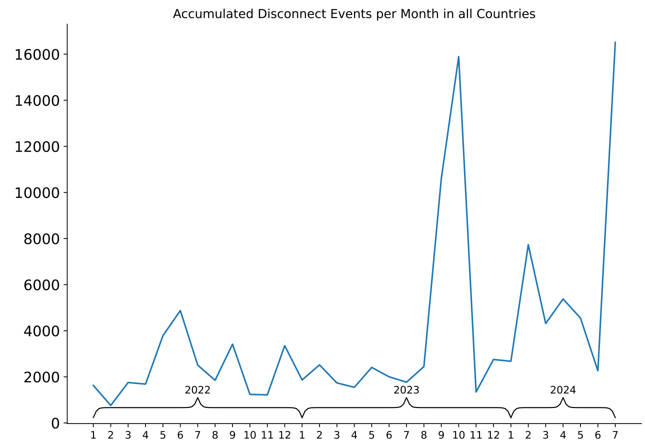


Figure 4.12: Accumulated Number of Disconnect Events per Month in all Countries

metric are comparable. In the case of disconnect events, the number of disconnect events per time interval grows with the number of probes connected. Therefore, the number of occurrences would be normalized by number of probes connected.

However, the number of probes connected within a time interval is hard to find. Some probes might be connected for a longer time than others dominating the occurrences of disconnect events. Others might be connected for a very short interval with many disconnects. Both scenarios compromise the normalization of the disconnect event occurrences, leading to not meaningful results. It might be well-possible to find a normalization method for disconnect events, but we did not invest in this direction.

Therefore, we did not proceed further in correlating disconnect events with other metrics.

4.2.4 Influence of Solarmagnetic Storms on Latency

Ma et al. [Ma+23] claimed solar magnetic storms have a significant impact on the performance of Starlink. To check on that, we conducted a study to see an actual correlation. We used the TLS handshake latency data we acquired from RIPE Atlas to correlate it with the intensity of solar magnetic storms. Solar magnetic storms are usually identified by the Kp index [Bar57]. It is a number between zero and nine, where nine indicates the strongest kind of storm. We found data historic Kp indexes on the website of the Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum, G. F. Z. [GFZ23].

To get an understanding of the influences of solar magnetic storms on Starlink performance, we will look at the intensity of the solar magnetic storm in comparison to the TLS latency. We expect that with increasing intensity of solar magnetic storms (i.e., higher Kp index), the latency will also increase. Therefore, we used the average Kp index from GFZ database over a single day and correlated it with the mean TLS handshake latency over each single day observed in our dataset. The following correlation values resulted:

- Pearson Correlation: ≈ 0.03
- Kendall Correlation: ≈ 0.01
- Spearman Correlation: ≈ 0.01

One can see that the values are nearly zero. That implies that the dimensions are nearly orthogonal. Therefore, we were not able to observe a correlation between latency and Kp index. In its extreme, the data does not correlate at all and observations form Ma et al. [Ma+23] are most likely incorrect.

Takeaway: Correlation of Starlink Latency and Solar Magnetic Storms

Starlink TLS handshake latency and solar magnetic storms do not correlate.

4.2.5 Traceroute Analysis

Looking at traceroute results, we can make conclusions about the routing behavior of Starlink network devices. In the data we gathered more than forty million traceroute measurements. Those include primarily built-in measurements from RIPE Atlas Starlink probes (ASN14593).

Reachability of Target Servers

The data contains various target servers. However, running a traceroute to them is not similarly successful. Table 4.8 shows the traceroute results for servers with at least one successful traceroute.

One sees that most servers have 34 % to 37 % success rate. However, #1, #2, and #8 have far lower success rates with less than 10 %. It is unclear why such a behavior appear, but similar was reported by Brownlee [Bro21]. However, his

Table 4.8: Success Rates of Traceroute per Target Server

	Destination	Success Events	Total Events	Success Rate
0	192.5.5.241	53447	2764536	0.019333
1	192.203.230.10	161792	2754657	0.058734
2	198.97.190.53	961501	2762322	0.348077
3	199.7.83.42	1024109	2764224	0.370487
4	199.7.91.13	1024454	2762612	0.370828
5	193.0.14.129	1025631	2770381	0.370213
6	202.12.27.33	1021441	2763754	0.369585
7	192.33.4.12	1022587	2763832	0.369989
8	192.36.148.17	223088	2763589	0.080724

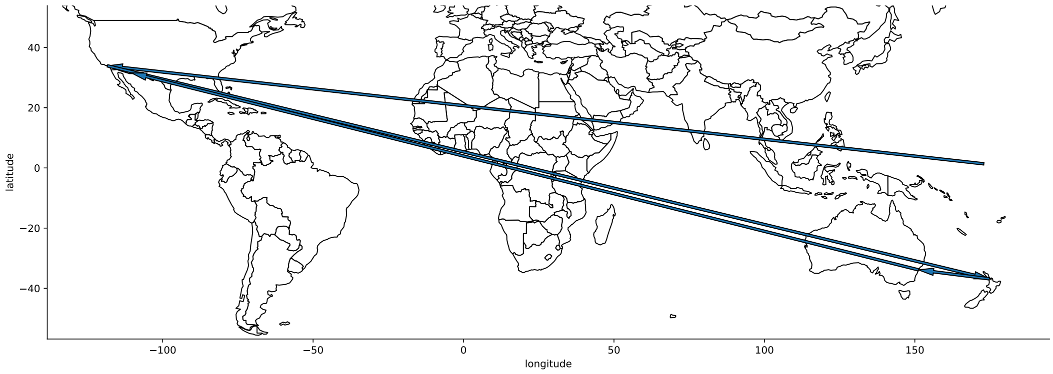


Figure 4.13: Visualization of a Traceroute from Kiribati

numbers were higher than the ones here. The numbers are still not comparable, as Brownlee performed the tests on an earlier time series (2012 −2019) and not specifically for Starlink probes.

Still, it becomes apparent that some servers do not even accept traceroutes. Table 4.9 lists those servers that never got a successful traceroute.

Table 4.9: Servers that were never reached during a Traceroute Measurement

Destination
193.0.19.60
170.247.170.2
104.237.152.132
198.41.0.4
45.33.72.12
139.162.27.28
78.46.48.134
193.0.19.59
213.133.109.134
199.9.14.201

Routing Behavior

First, we found that the satellite hops are likely invisible to the traceroute. We conclude that as there are no hops visible above water, even for probes located in remote regions, e.g., Kiribati in the Pacific Ocean. In Figure 4.13, one can see a visualization of a traceroute result from

Kiribati to *f.root-servers.net*. One can see that the first visible hop is located in New Zealand or an island to the north of New Zealand. However, if satellites were visible, we'd be able to observe more satellites.

Coming from the first insight, we can also conclude that ISLs are enabled. If they were not, we would likely not be able to see a successful traceroute from Kiribati to a location. The next closest known PoP is on Hawaii. However, the distance between both is 4000 km, which is more than a single satellite can cover [Pek21]. Aside from that, we do not observe the usage of the PoP in Hawaii, but in more distant locations, which just strengthens the argument. Therefore, we conclude that ISLs are enabled. This is special interest, as it was not clear in recent research [Hau+20].

Verify that this poses actually a privacy concern / Remove if there is no proof or no privacy concern

Privacy Concerns in Traceroute Data

One of the most important responsibilities of an Internet Service Provider (ISP) is to ensure the privacy of its users. This also includes to route traffic only in trusted countries. In the case of Starlink, we were able to observe a different behavior. We looked at a slice of the built-in traceroute measurements from German Starlink probes and analyzed their most common targets. We filtered for anycasted servers (e.g., *.root-servers.net) and bogon IPs (i.e., IPs that cannot be associated with metadata).

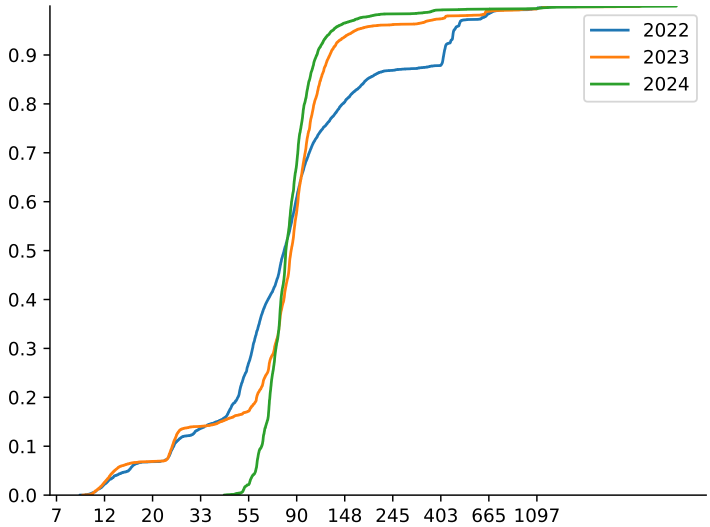
In Table 4.10, the top twenty most frequent hits of IP addresses are shown. The IP addresses are joined with data from IPinfo. As traffic goes from a German probe to an anycasted server, located in Germany, one would expect little traffic outside Germany, and none outside Europe. The top five IP addresses are located within or close to Germany, but the next five already involve traffic to the United States. Here, we observe an unexpected behavior. Assuming that the data is not flawed, this is a clear violation of guiding privacy principles.

Table 4.10: IP Hitlist for Built-In Traceroute Measurements

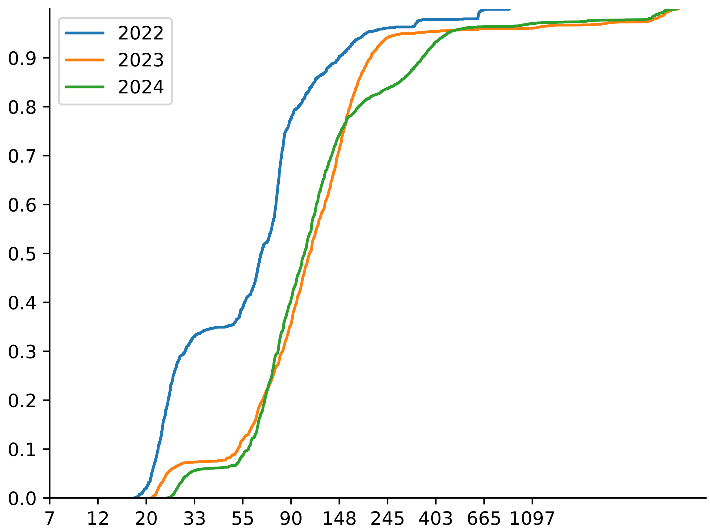
Hits	City	Country	Organization	IP Address
10634	Frankfurt am Main	Germany	AS1299	62.115.37.20
8202	Offenbach	Germany	Unknown	80.81.192.154
6207	Amsterdam	Netherlands	Unknown	193.239.116.217
5582	Frankfurt am Main	Germany	AS2914	213.198.72.18
5257	Frankfurt am Main	Germany	AS3257	89.149.137.14
4932	Chicago	United States	AS14593	206.224.65.178
4916	Chicago	United States	AS14593	206.224.65.180
4850	Chicago	United States	AS14593	206.224.65.182
4755	Chicago	United States	AS14593	206.224.65.184
4358	Miami	United States	AS49791	81.31.213.126
4333	Zürich	Switzerland	Unknown	185.1.147.30
4256	Tokyo	Japan	Unknown	210.173.176.242
4179	Chicago	United States	AS14593	206.224.65.186
4035	Chicago	United States	AS14593	206.224.65.192
4014	Frankfurt am Main	Germany	AS6762	213.144.184.30
4010	Chicago	United States	AS14593	206.224.65.190
4005	Chicago	United States	AS14593	206.224.65.188
4002	Frankfurt am Main	Germany	AS1299	62.115.124.118
3990	Singapore	Singapore	AS2497	202.232.1.69
3827	Frankfurt am Main	Germany	AS6939	72.52.92.70

5 Conclusions & Outlook

6 Appendix

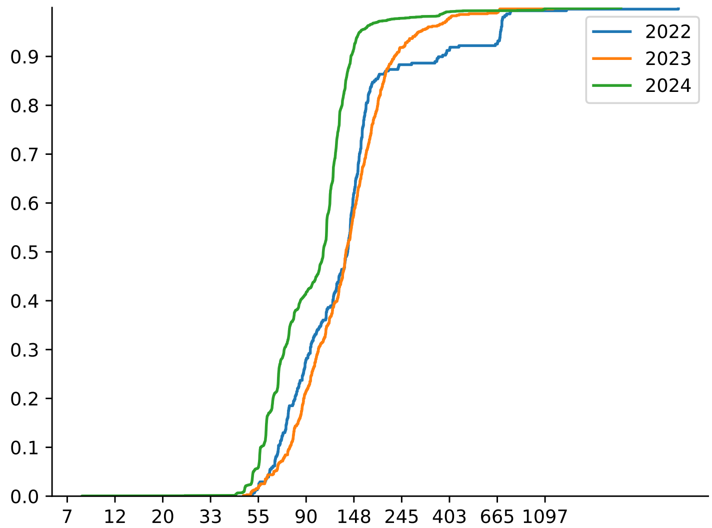


(a) United Kingdom

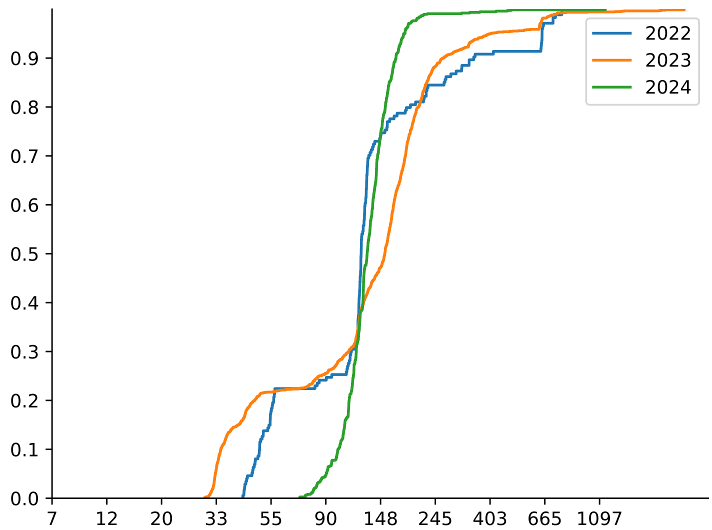


(b) Italy

Figure 6.1: CDF of Latencies in the United Kingdom and Italy

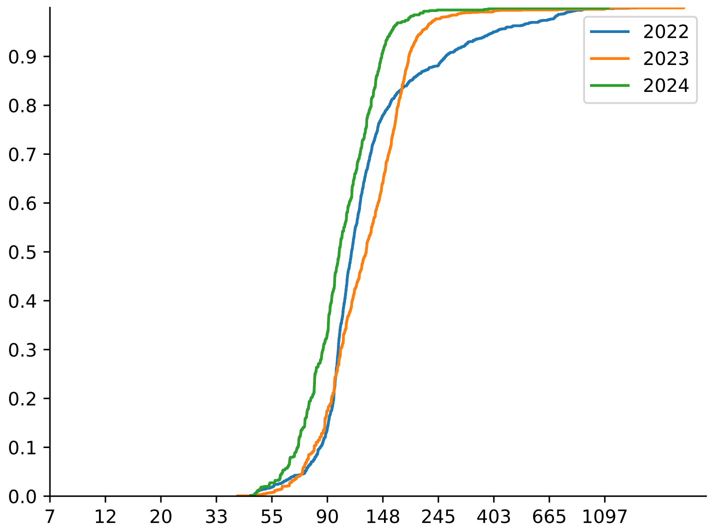


(a) Spain

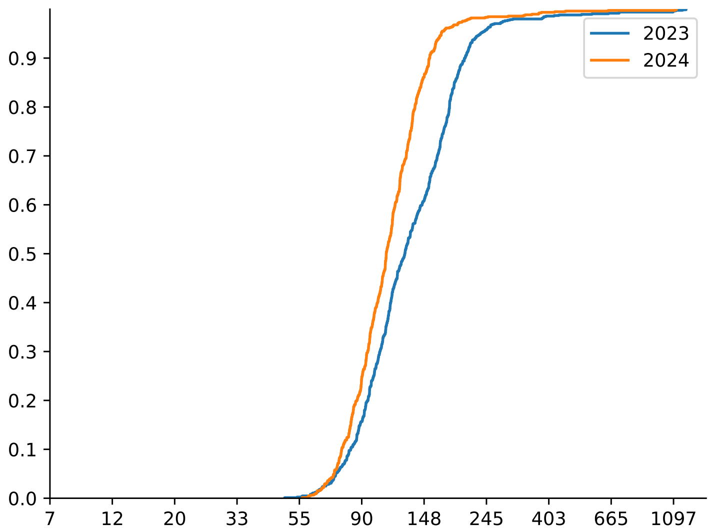


(b) Greece

Figure 6.2: CDF of Latencies in Spain and Greece

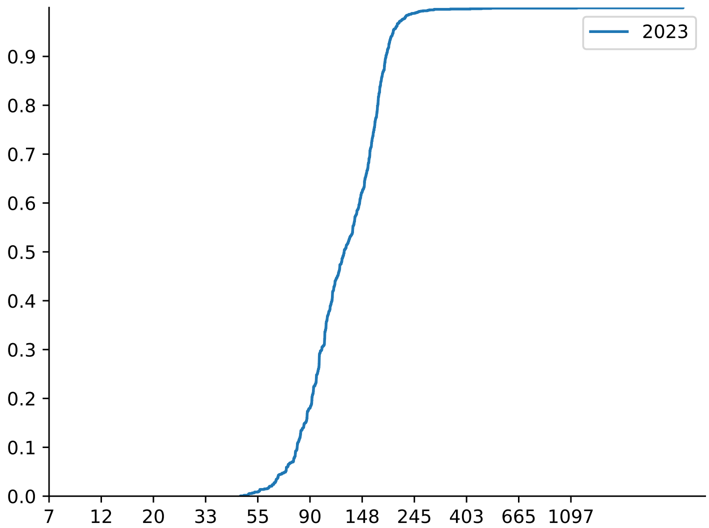


(a) Poland

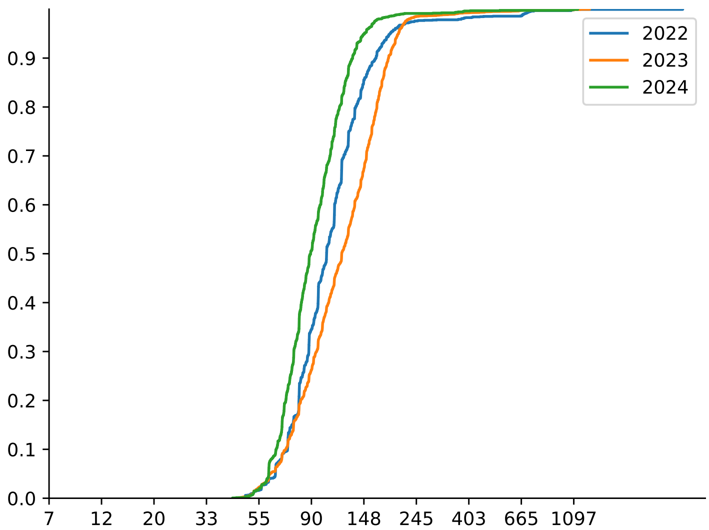


(b) Sweden

Figure 6.3: CDF of Latencies in Poland and Sweden

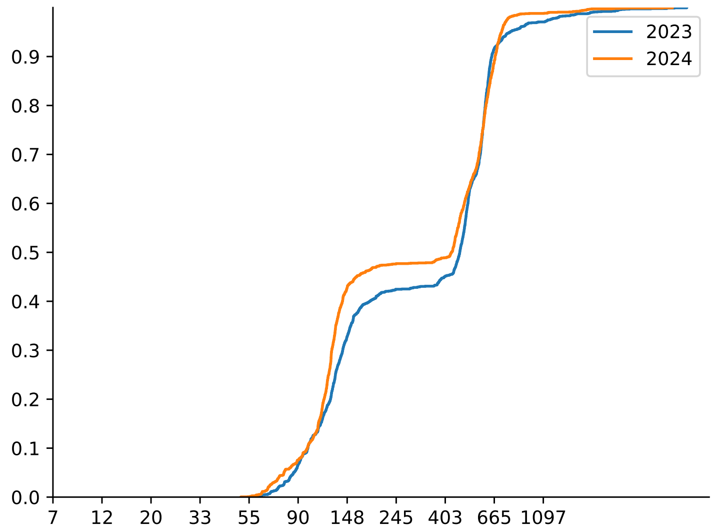


(a) Czech Republic

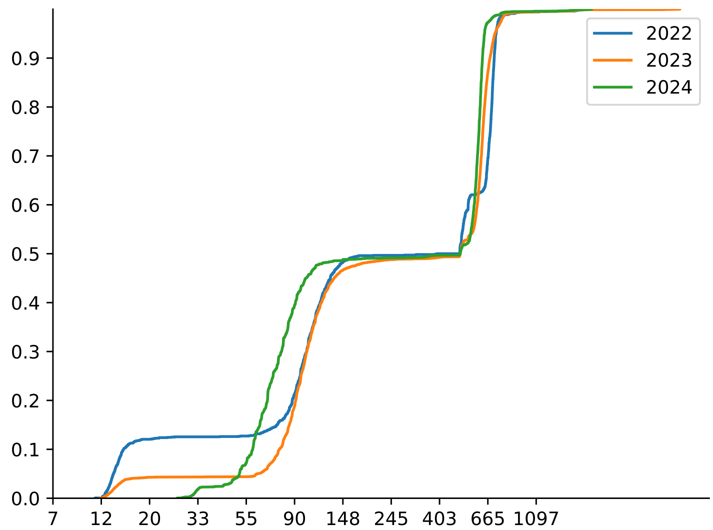


(b) Austria

Figure 6.4: CDF of Latencies in the Czech Republic and Austria

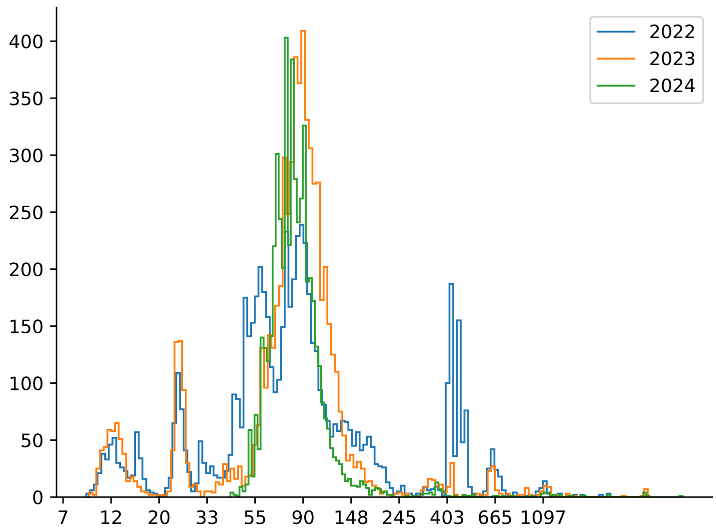


(a) Philippines

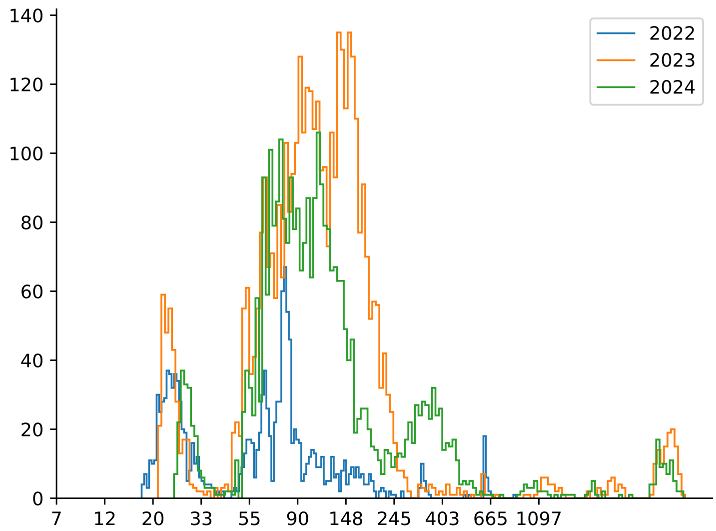


(b) Australia

Figure 6.5: EquiWidth Histogram of Latencies in the Philippines and Australia

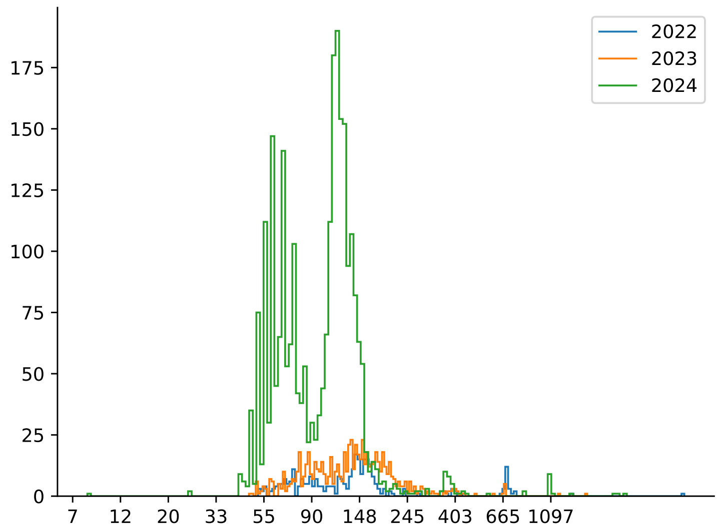


(a) United Kingdom

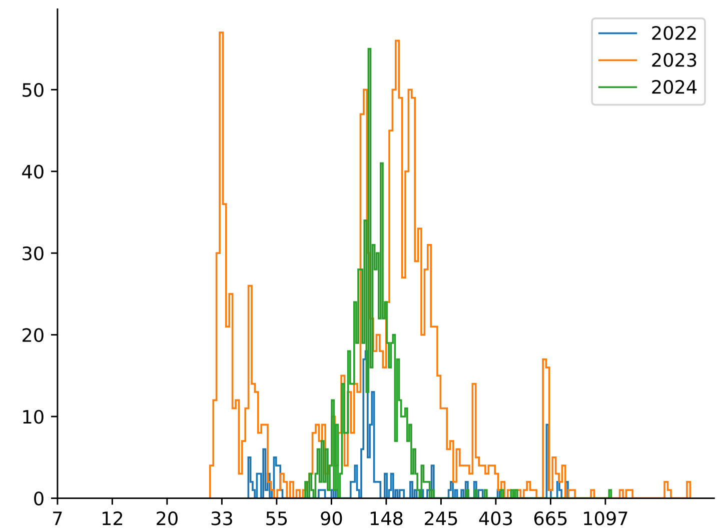


(b) Italy

Figure 6.6: EquiWidth Histogram of Latencies in the United Kingdom and Italy

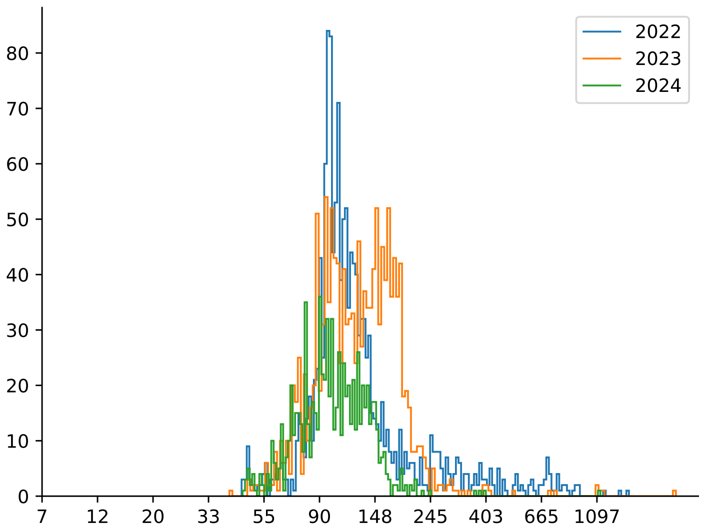


(a) Spain

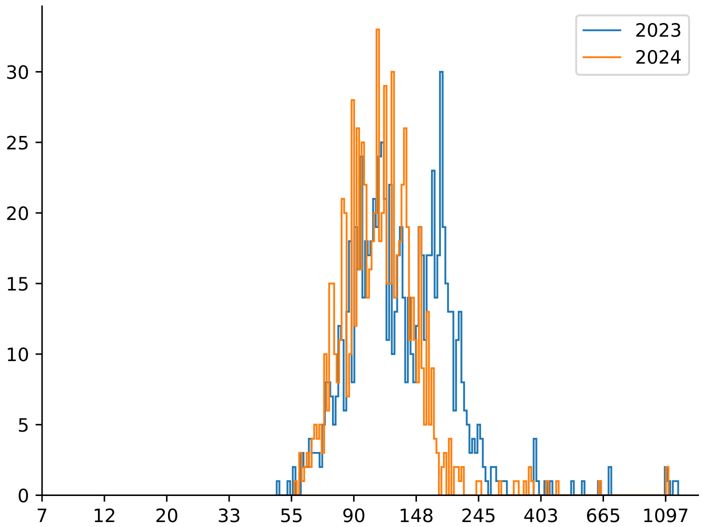


(b) Greece

Figure 6.7: EquiWidth Histogram of Latencies in Spain and Greece

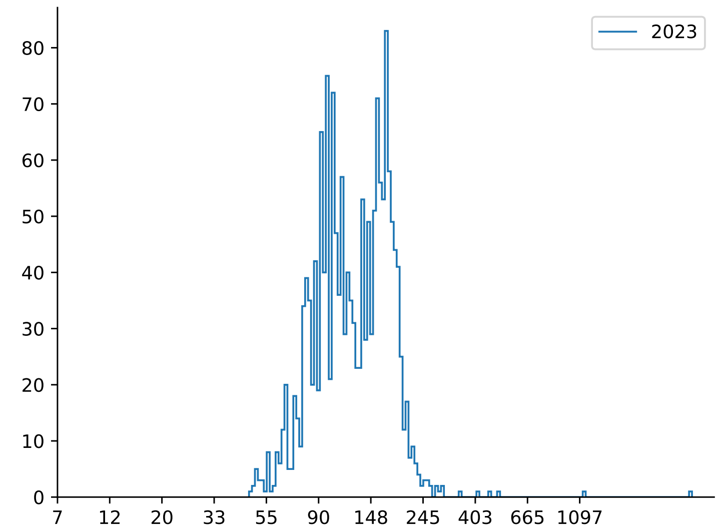


(a) Poland

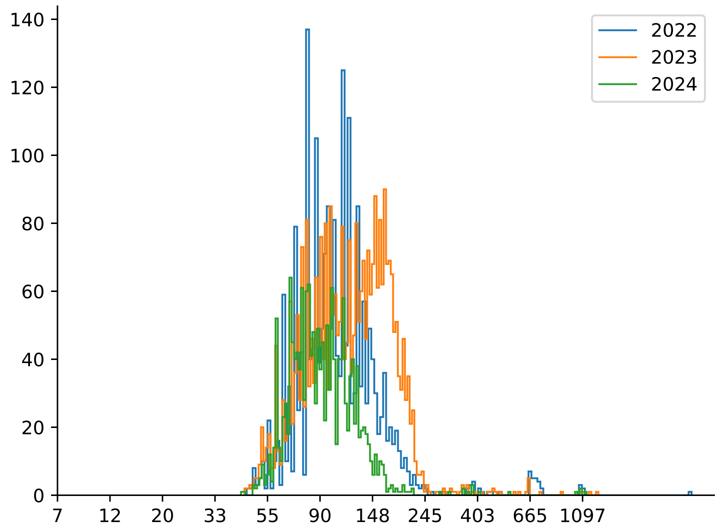


(b) Sweden

Figure 6.8: EquiWidth Histogram of Latencies in Poland and Sweden

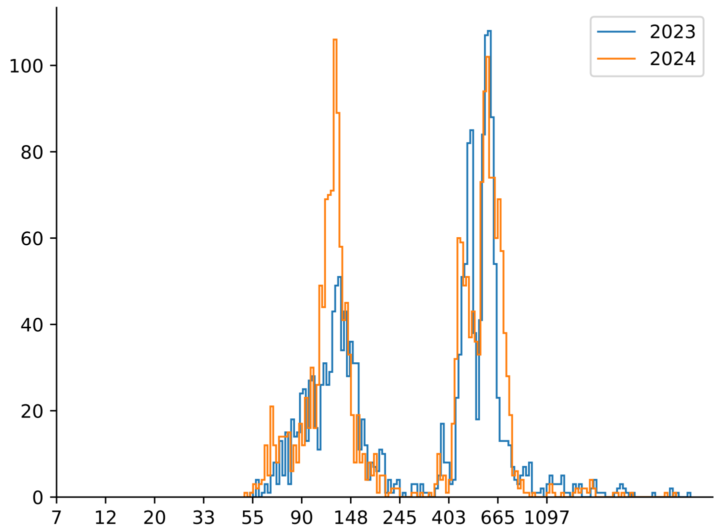


(a) Czech Republic

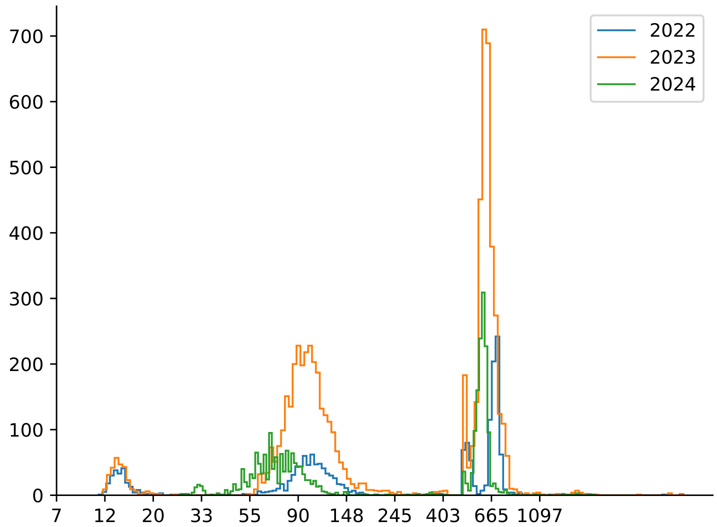


(b) Austria

Figure 6.9: EquiWidth Histogram of Latencies in the Czech Republic and Austria



(a) Philippines



(b) Australia

Figure 6.10: EquiWidth Histogram of Latencies in the Philippines and Australia

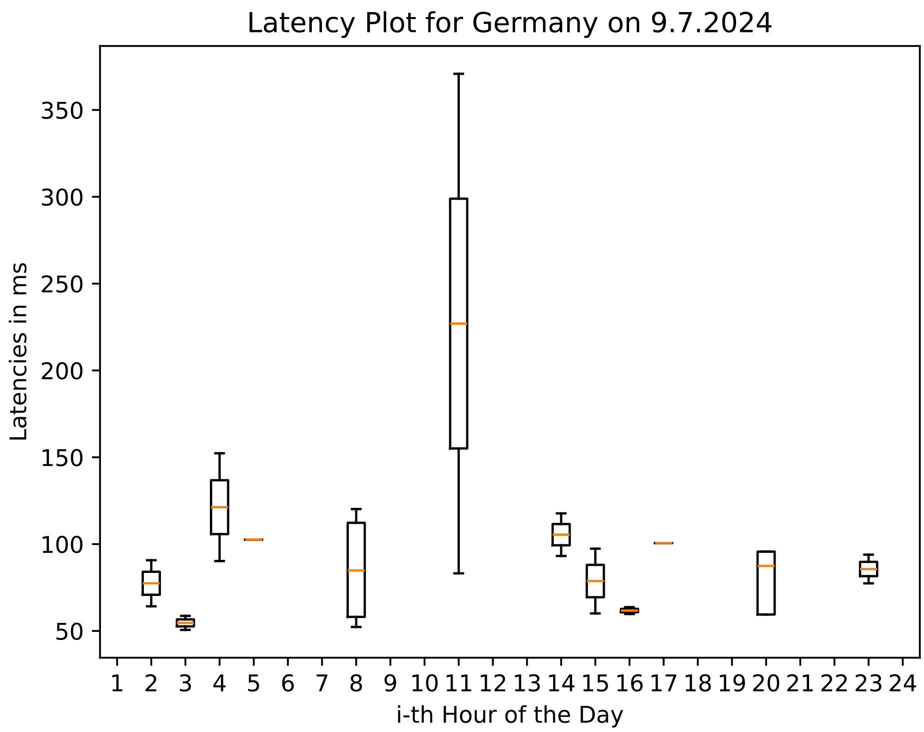
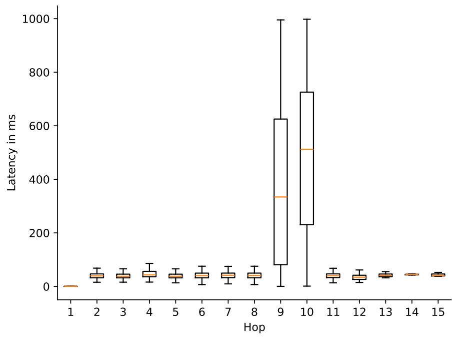
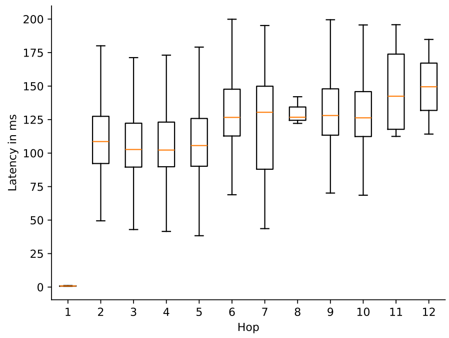


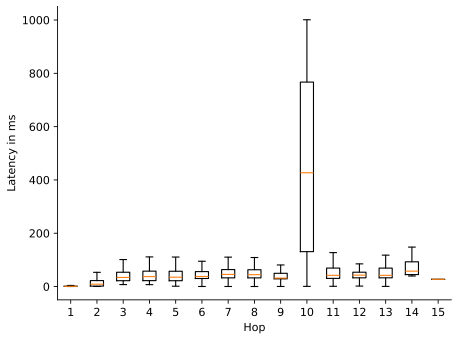
Figure 6.11: Latency over July 9, 2024, using TLS data.



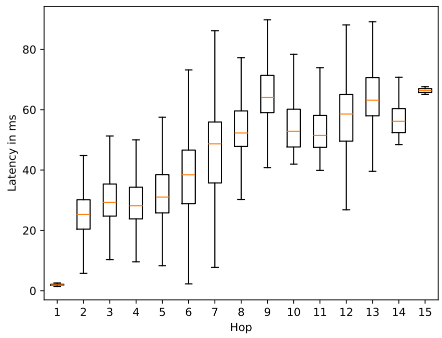
(a) Poland



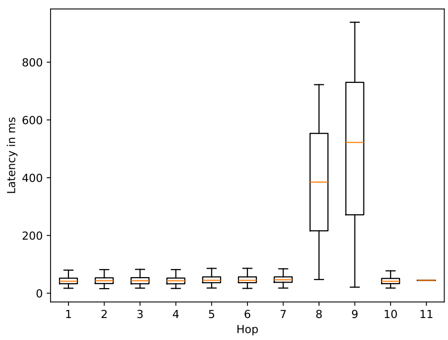
(b) Kiribati



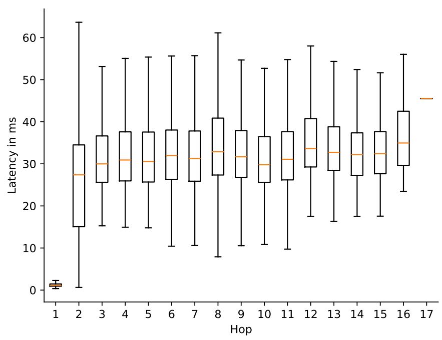
(c) Italy



(d) Spain



(e) Czech Republic



(f) United Kingdom

Figure 6.12: Average Latency per Hop

List of Acronyms

ISLs Inter-Satellite Links 1

ISL Inter-Satellite Link 4

ISP Internet Service Provider 38

LEO Low-Earth Orbit 4

MEO Medium-Earth Orbit 4

GEO Geostationary Orbit 4

PoP Point of Presence 3

GS Ground Station 1

CFR Cloudflare Radar 10

IQI Internet Quality Index 10

SNO Satellite Network Operator 3

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Declaration of Authorship

I hereby declare that this thesis is my own unaided work. All direct or indirect sources used are acknowledged as references.

Potsdam, October 8, 2024

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