Evaluating Resiliency and Performance of Networked Satellite Systems

Evaluierung der Resilienz und Leistung von vernetzten Satelliten Systemen

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Abstract

Acknowledgments

Contents

1 Introduction

1.1 List of Acronyms

ISLs Inter-Satellite Links 9

ISP Internet Service Provider 10

LEO Low-Earth Orbit 2

GEO Geostationary Orbit 2

ASN Autonomous System Number 9

PoP Point of Presence 3

1.2 Usecase of Networked Satellite Systems

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Networked sallite 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.

1.3 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 Geostationary Orbit (GEO) satellite constellations. For example, Low-Earth Orbit (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.

1.3.1 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*.

1.3.2 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

1 SpaceNetLab/StarPerf_Simulator
2 snkas/hypatia

others, the satellites, ground stations, and points of presence. This information is hardly available, which renders the simulations barely usable.

1.3.3 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.

1.4 Latency over whole Data Range

The performance of Starlink latency has changed over time. We looked at 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 ?? shows the history of median latencies from January 2022 until June 2024 for Germany, the United States, Poland, and Austria[3].

One can see that the median 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 a rise of latency in 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: 5700+) and added more Point of Presence (PoP) which likely reduces the congestion.

However, countries still vary a lot in performance. This is due to various different factors, e.g., weather, ground station infrastructure,

3 These countries were chosen due to the completeness of data

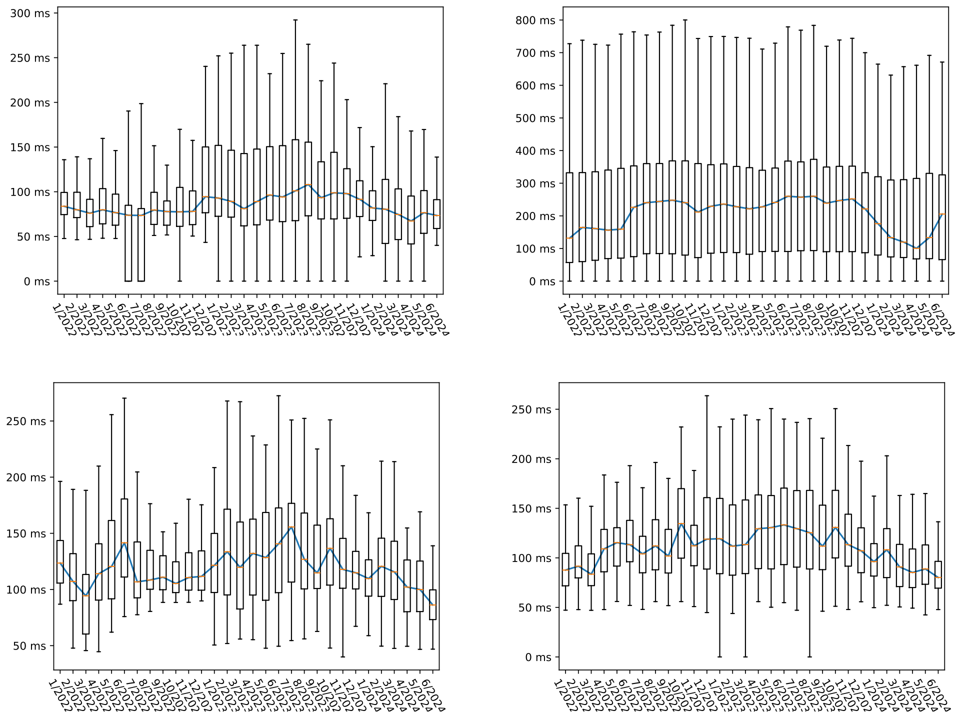

Figure 1.1: Latency History for Germany, the USA, Poland, and Austria in the period 01/2022 to 06/2024

Table 1.1: 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

1.5 Latency and Packet Loss Correlation

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 latency. We used a Pearson, Kendall, and Spearman correlation to determine possible correlations between latency and packet loss. The results are shown in Table 1.1.

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

Table 1.2: 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

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.

1.5.1 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 1.2, 1.3, and 1.4 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 1.3: 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 1.4: 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

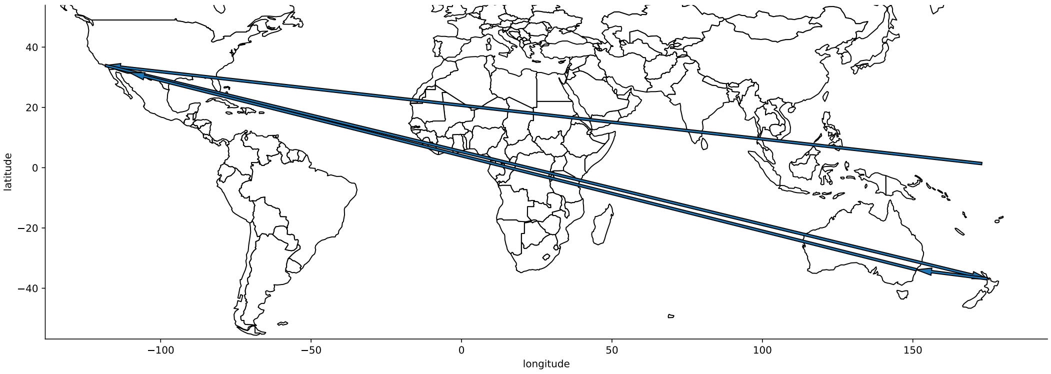

Figure 1.2: Visualization of a Traceroute from Kiribati

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.

1.6 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 probes to **.root-servers.net* for Starlink probes (Autonomous System Number (ASN) 14593).

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 1.2, 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 Inter-Satellite Links (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. Aside from that, we do not observe the usage of the PoP in Hawaii, but

Table 1.5: 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

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].

1.6.1 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 1.5, 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.

2 Conclusions & Outlook

Bibliography

[Hau+20] Yannick Hauri, Debopam Bhattacherjee, Manuel Grossmann, and Ankit Singla. **"Internet from Space" without Inter-satellite Links**. *HotNets 2020 - Proceedings of the 19th ACM Workshop on Hot Topics in Networks* (Nov. 2020), 205–211. DOI: 10.1145/3422604.3425938. URL: https://dl.acm.org/doi/10.1145/3422604.3425938 (see page 10).

[Kas+20] Simon Kassing, Debopam Bhattacherjee, André Baptista Águas, Jens Eirik Saethre, and Ankit Singla. **Exploring the "Internet from space" with Hypatia**. In: *IMC '20: ACM Internet Measurement Conference, Virtual Event, USA, October 27-29, 2020*. ACM, 2020, 214–229. DOI: 10.1145/3419394.3423635. URL: https://doi.org/10.1145/3419394.3423635 (see page 2).

[LLL20] Zeqi Lai, Hewu Li, and Jihao Li. **StarPerf: Characterizing Network Performance for Emerging Mega-Constellations**. In: *28th IEEE International Conference on Network Protocols, ICNP 2020, Madrid, Spain, October 13-16, 2020*. IEEE, 2020, 1–11. DOI: 10.1109/ICNP49622.2020.9259357. URL: https://doi.org/10.1109/ICNP49622.2020.9259357 (see page 2).

[Ste+24] Aleksandr Stevens, Blaise Iradukunda, Brad Bailey, and Ramakrishnan Durairajan. **Can LEO Satellites Enhance the Resilience of Internet to Multi-hazard Risks?** In: *Passive and Active Measurement - 25th International Conference, PAM 2024, Virtual Event, March 11-13, 2024, Proceedings, Part II*. Ed. by Philipp Richter, Vaibhav Bajpai, and Esteban Carisimo. Vol. 14538. Lecture Notes in Computer Science. Springer, 2024, 170–195. DOI: 10.1007/978-3-031-56252-5_9. URL: https://doi.org/10.1007/978-3-031-56252-5%5C_9 (see page 2).

Declaration of Authorship

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

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