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

Measurement and Analysis for Protocols (maprg), IRTF 123

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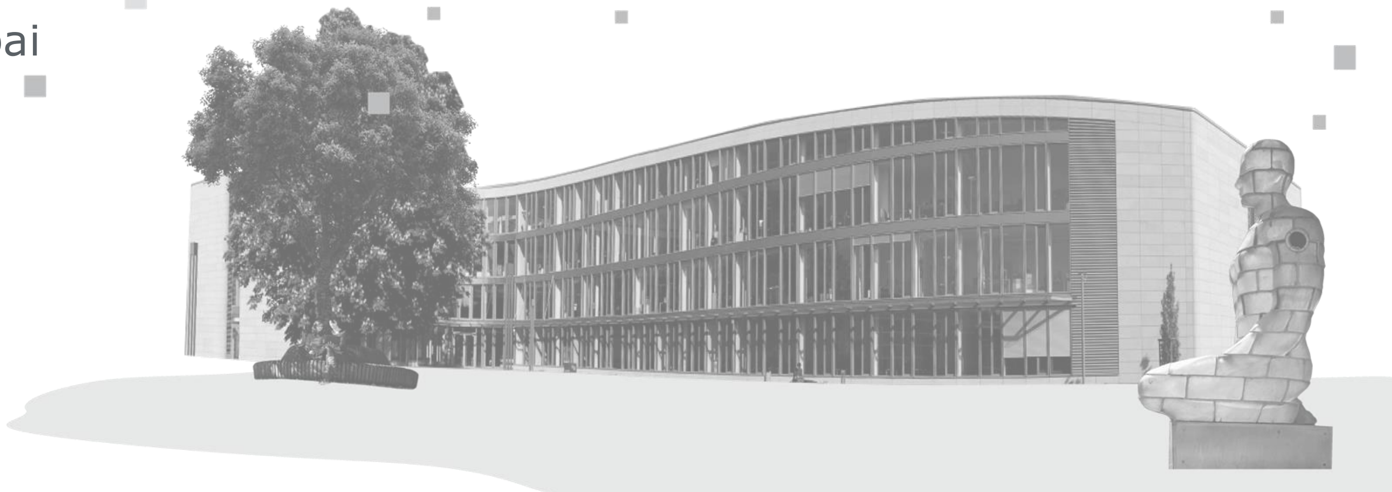
Robert Richter


Vasilis Ververis


Vaibhav Bajpai

Hasso Plattner Institute, Potsdam, Germany



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Agenda

1. Low-Earth Orbit (LEO) Satellite Constellation Background
2. Research Questions
3. Longitudinal View 01/2022 – 06/2024
   - Latency
   - Packet Loss
4. Traceroute Analysis

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Low-Earth Orbit Satellite Constellation Background

Satellite Network Operator	Altitude	# of Satellites
Starlink	≈ 550 km	6,396
OneWeb	≈ 1,200 km	628
O3B	≈ 8,062 km	20
Intelsat	≈ 35,767 km	74

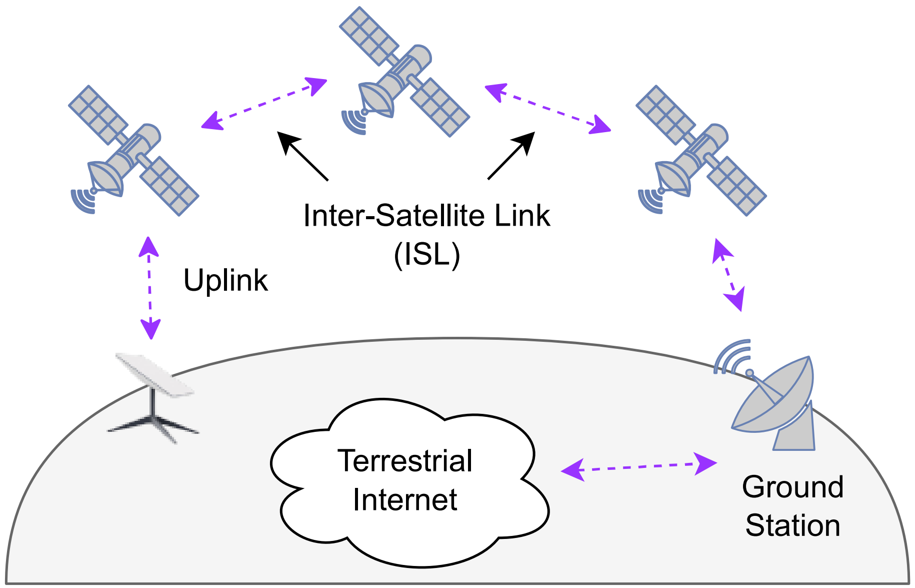


Figure 1: SNO satellite count since 2000 to 06/2024

(Some of the) Research Questions

1. How has latency and packet loss evolved since 2022?

2. What happens to latency when routing to the Starlink constellation?

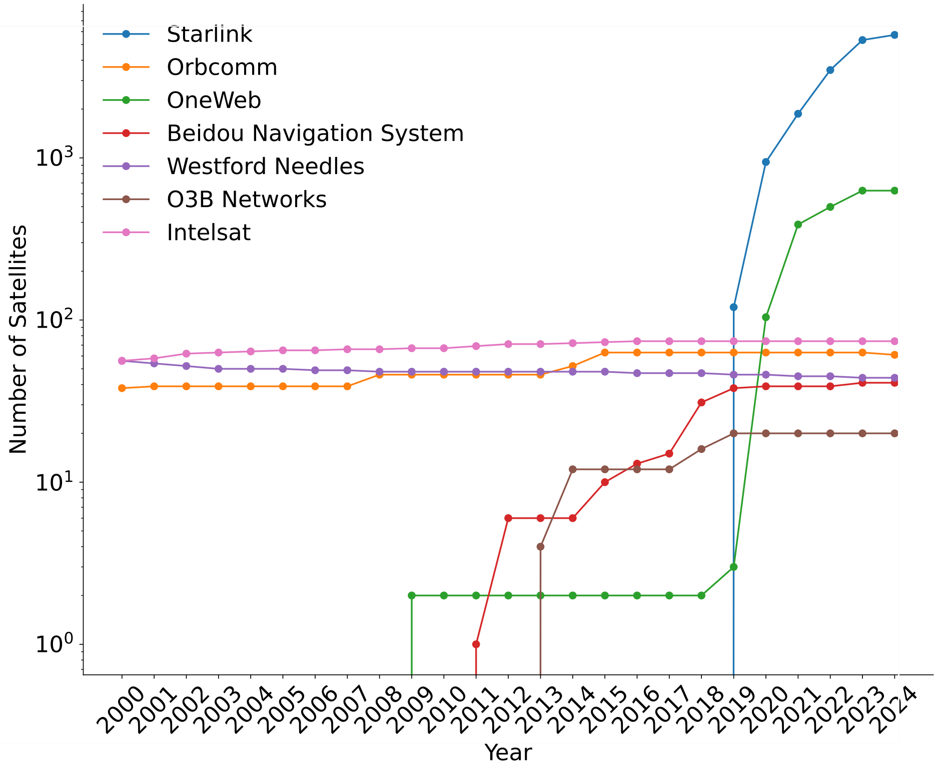


Figure 2: SNO satellite count since 2000 to 06/2024

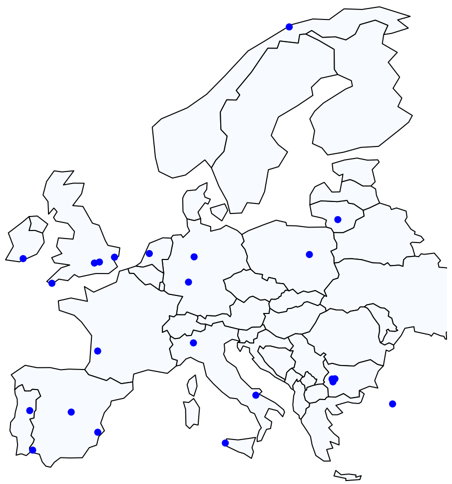


Figure 3: Starlink ground station placement in Europe as in Unofficial Starlink Global Gateways & PoPs Map

Methodology

- Timeframe 01/2022 – 06/2024
- RIPE Atlas built-in measurements from ≈ 150 probes (AS14593)
- TLS (for latency), Ping (for packet loss), and Traceroute (for routing) measurements to *k.root-servers.org*
- Data made publicly available[1]

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

1 DOI 10.5281/zenodo.15303863

How does Starlink perform in terms of TLS latency?

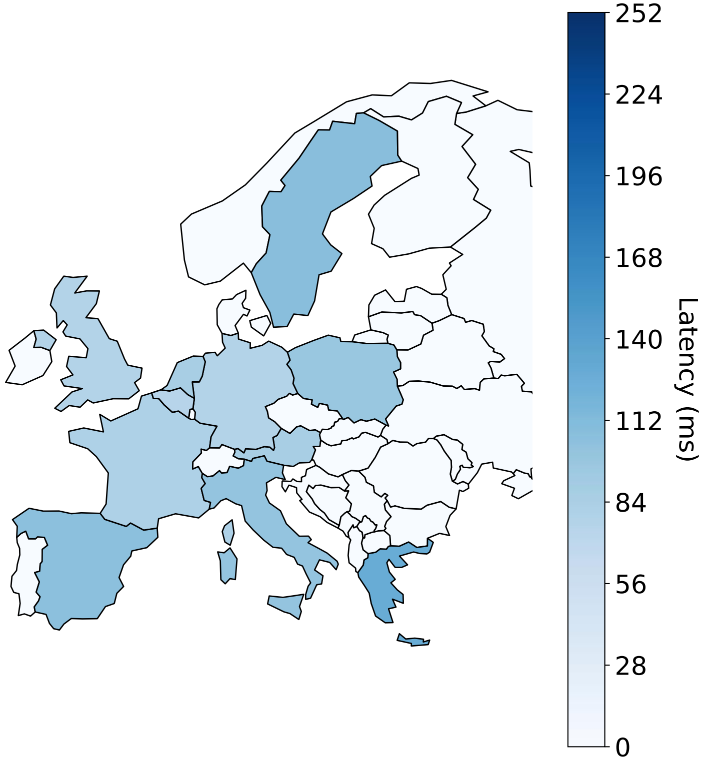


Figure 4: Median TLS Latencies in Europe in 2024

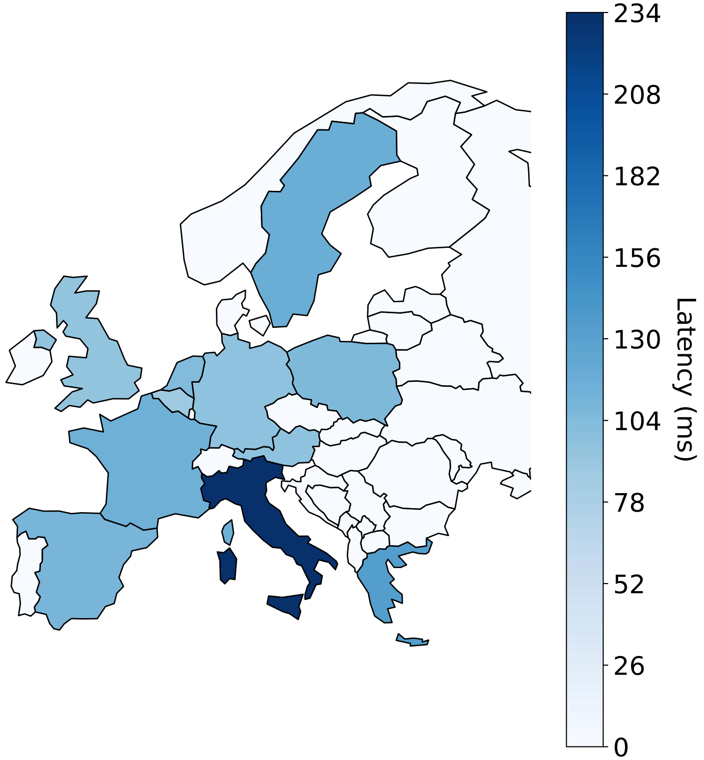


Figure 5: Average TLS Latencies in Europe in 2024

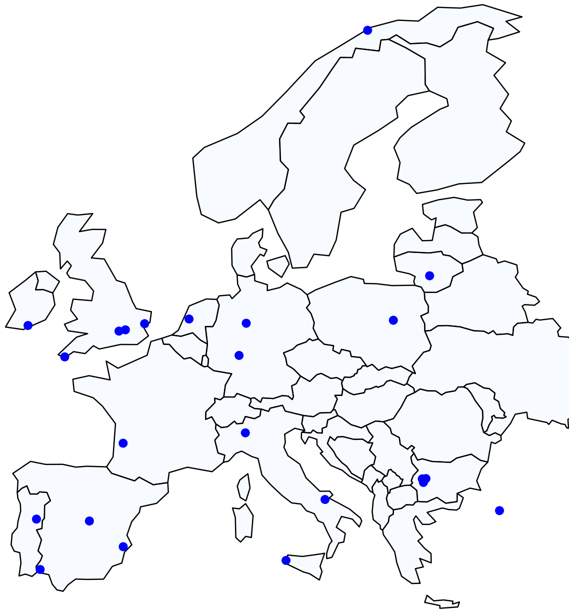


Figure 3: Starlink ground station placement in Europe as in Unofficial Starlink Global Gateways & PoPs Map

How has latency and packet loss evolved since 2022?

- Median Latencies have been much worse in 2023, compared to 2022 and 2024
- Minimum Latencies improved from 2022 to 2023
- Possible reasons:
  - Growth of Starlink satellite constellation
    - Dec. 2022: 3,481 satellites
    - Dec. 2023: 5,326 satellites
    - June 2024: 6,396 satellites
  - More ground stations
  - Improved Inter-Satellite Links (ISLs)

Ideal Starlink Latency

$$\frac{550\,km \cdot 2}{300{,}000\,\frac{km}{s}} \approx 0.004\,s$$

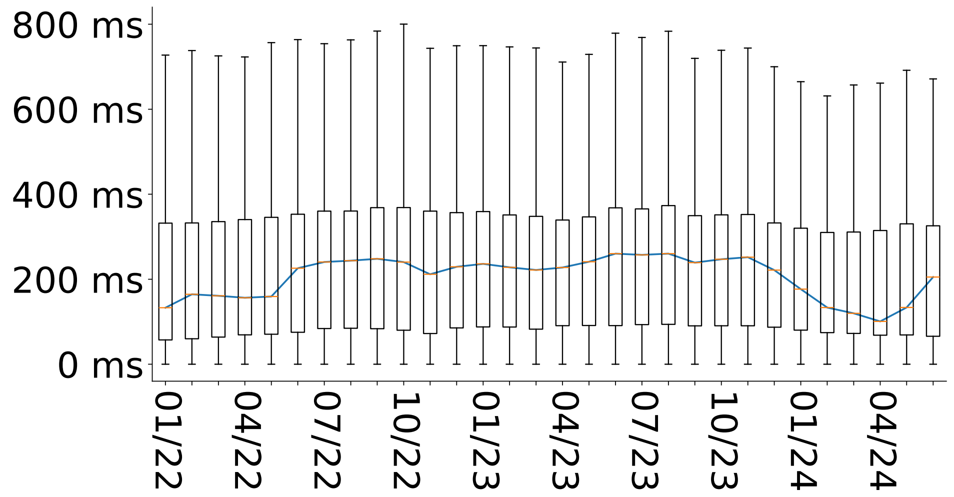


Figure 6: TLS Latencies in the USA

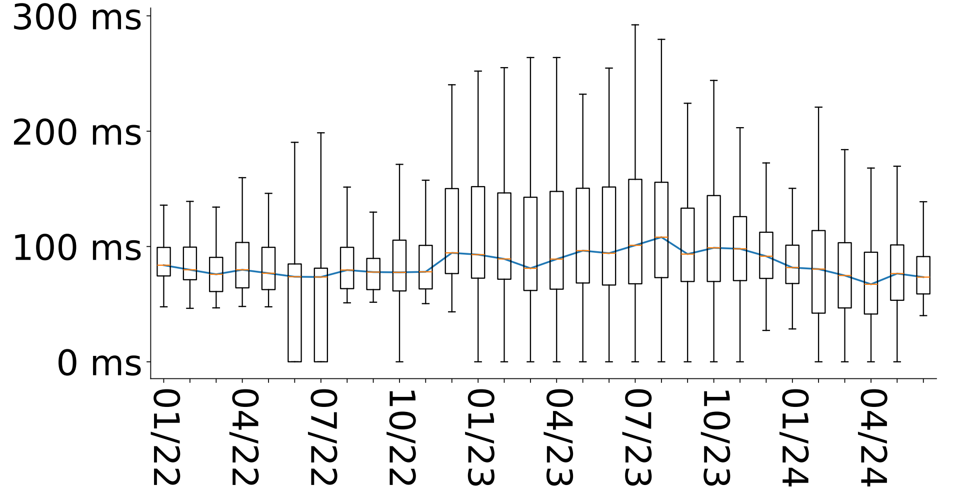


Figure 7: TLS Latencies in Germany

How does Starlink perform in terms of packet loss?

- Packet loss from Ping measurements
- Packet loss has improved consistently in 2023 across many countries
  - Worse in 2022 and 2024
  - In June 2024, consistent packet loss reduction
- Possible reason:
  - Constellation growth compared to user numbers (→ *no reliable numbers on users*)

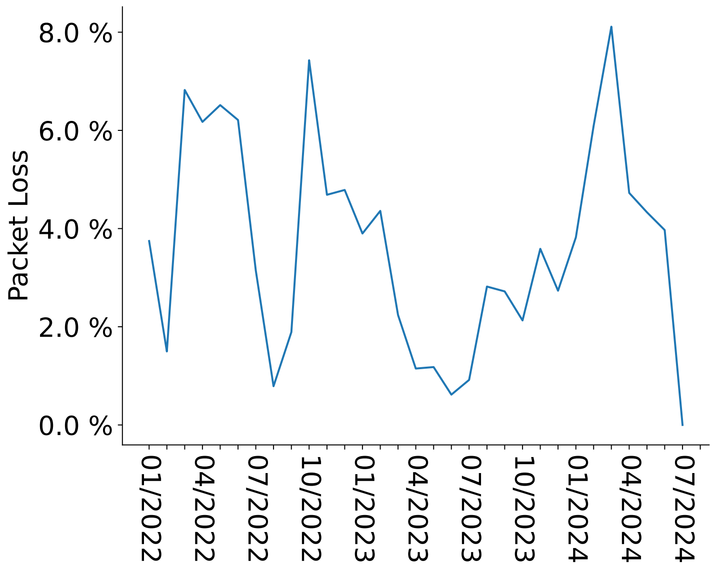


Figure 8: Packet Loss in the **USA**

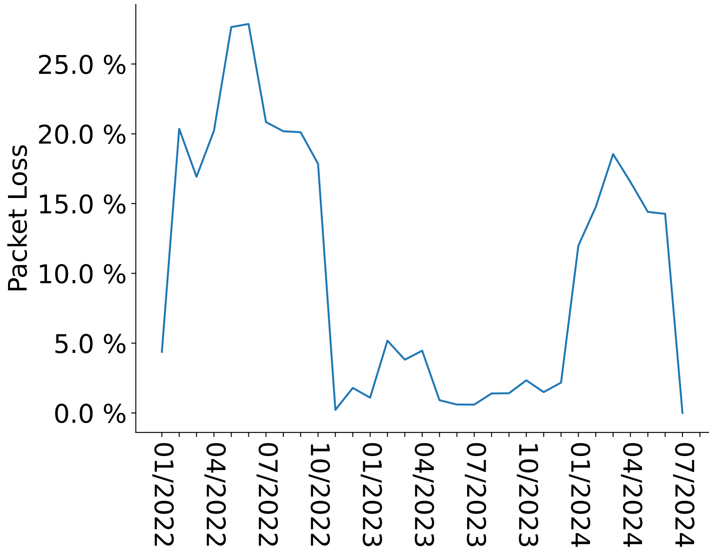


Figure 9: Packet Loss in **Germany**

What happens to latency when routing through the Starlink constellation to DNS root server?

- Two jumps in latency
- First jump related to routing through satellite constellation
- Second jump outside Starlink network

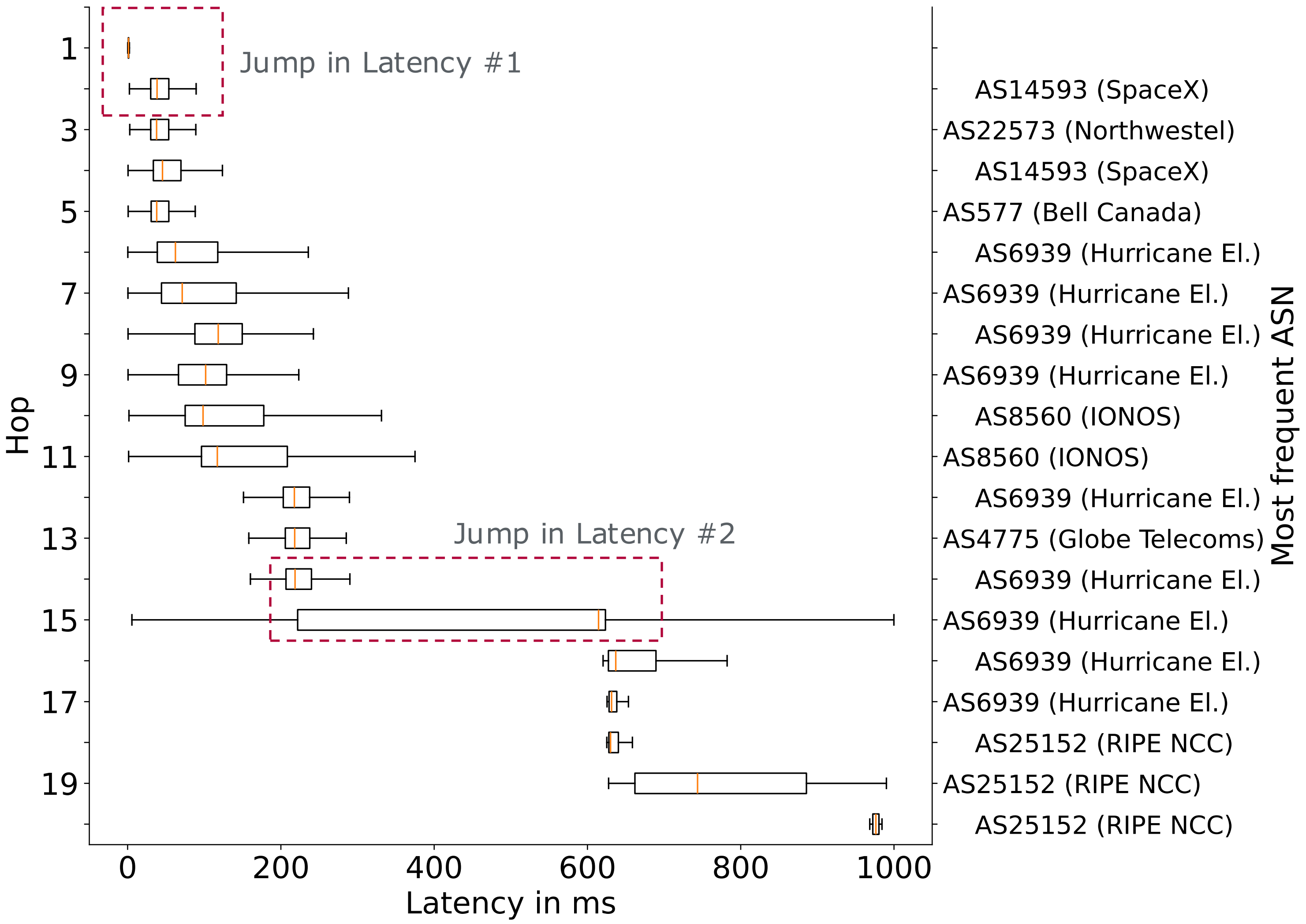


Figure 11: Starlink latency change per hop in Canada to *k.root-servers.org*

Limitations & Future Research

- Starlink is a Black Box
  - Little is known about Starlink intrinsics
  - Hard to find explanations for the data
  - Similar problems for other vendors

- Missing a theoretical model for satellite constellations

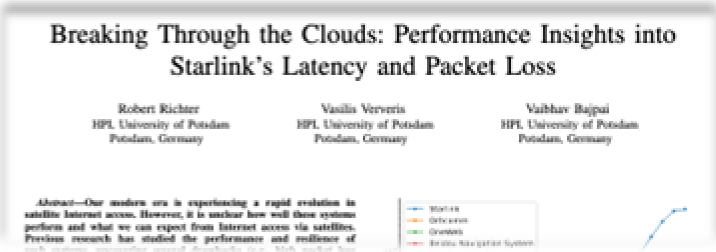
- Knowledge about the actual state of Starlink is limited
  - How many users?
  - How many ground stations & points of presence?
  - What devices are employed in individual satellites?
  - …

Conclusion

Contact me: robert.richter@hpi.de

- Residential Starlink TLS latencies ≈ 100–250 ms
- Packet loss may exceed 20% median
- Traceroute shows two latency jumps
  - First one after routing through the satellite constellation, which operates below IP layer

There's more in the paper!



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Robert Richter
HPI, University of Potsdam
Potsdam, Germany

Vasilis Ververis
HPI, University of Potsdam
Potsdam, Germany

Vaibhav Bajpai
HPI, University of Potsdam
Potsdam, Germany

Abstract—Our modern era is experiencing a rapid evolution in satellite Internet access. However, it is unclear how well these systems perform and what we can expect from Internet access via satellites. Previous research has studied the performance and resilience of

- Diurnal variation
- Bimodal distribution of Starlink latencies
- Latency & Packet loss across various countries on different weekdays
- Solar magnetic storm intensity not influencing latency

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Thank you!

[Ma23] "Network characteristics of LEO satellite constellations: A starlink-based measurement from end user", Ma et al., (May 2023)

[Raman23] "Dissecting the performance of satellite network operators", Raman et al. (November 2023)

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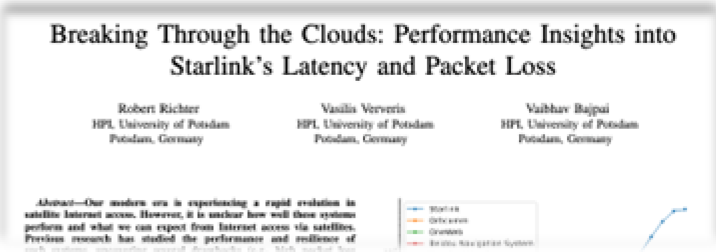

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