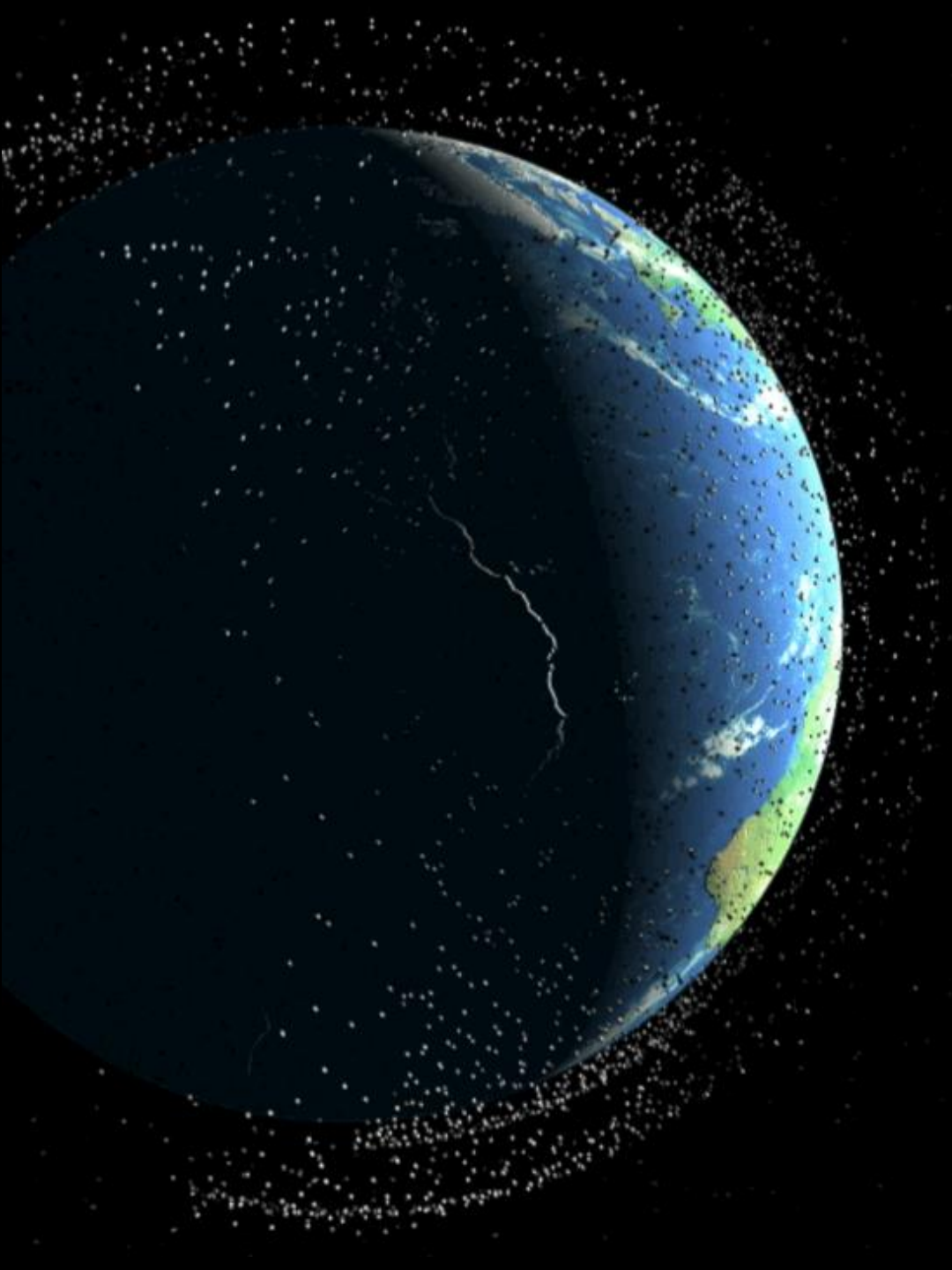

2024 THE WEB CONFERENCE ACM

A Multifaceted Look at Starlink Performance

Nitinder Mohan[DE/NL] Andrew Ferguson[GB] **Hendrik Cech**[DE]

Rohan Bose[DE] Prakita Renatin[DE] Mahesh Marina[GB]

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[GB] The University of Edinburgh, United Kingdom

[NL] Delft University of Technology, Netherlands

6G-life 5G COMPASS

Satellite Internet Access

Satellite Orbits and Constellations

TELESAT

Viasat

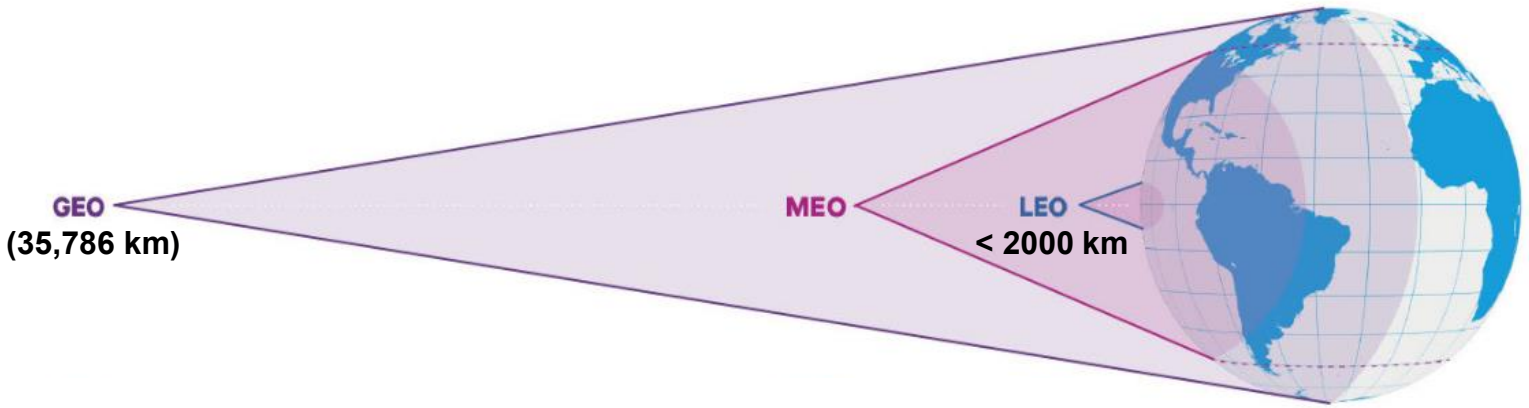
INTELSAT

STARLINK

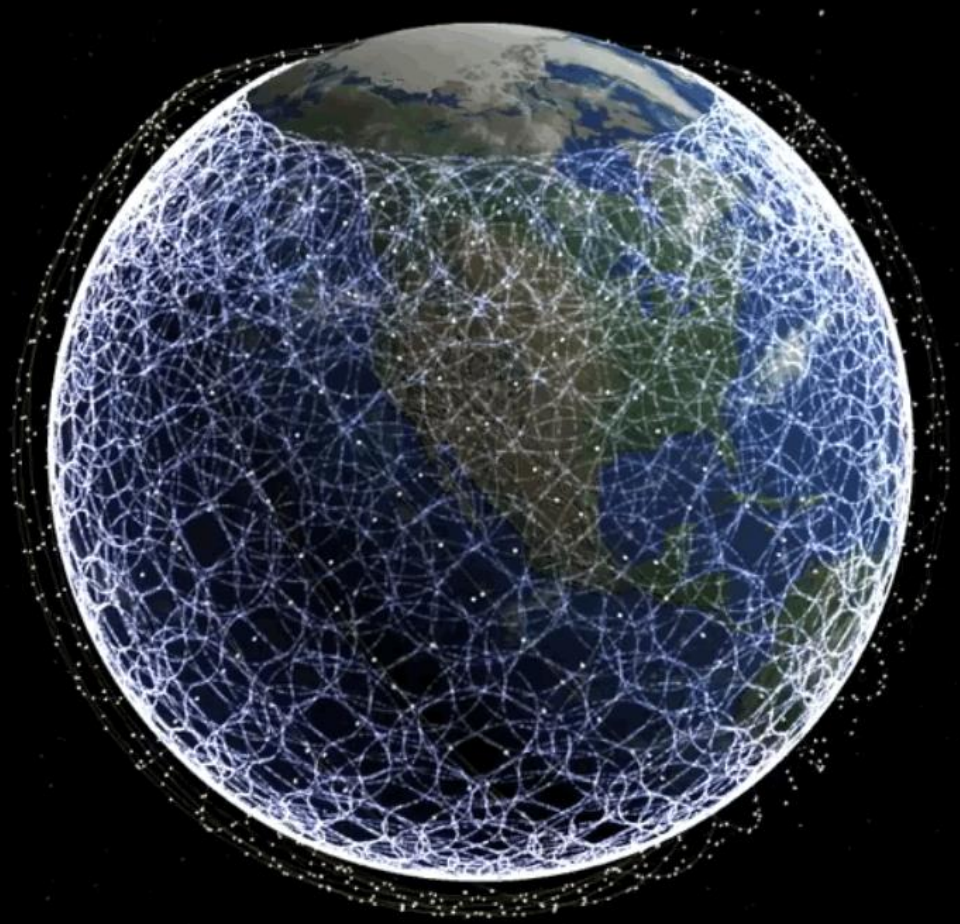
OneWeb

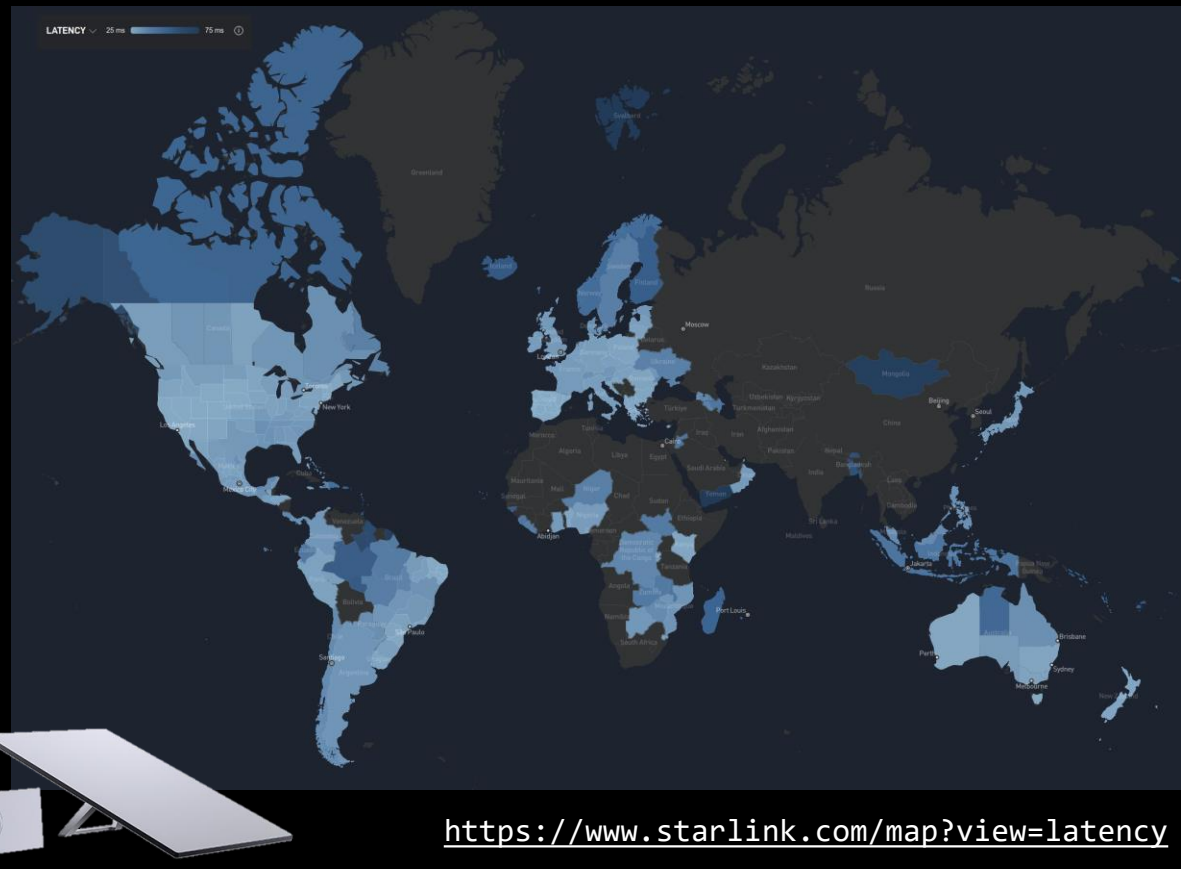
O3b mPOWER

amazon | project kuiper



Taken from Lalbakhsh, Ali, et al. "Darkening low-earth orbit satellite constellations: A review." IEEE Access 10 (2022): 24383-24394. CC BY 4.0

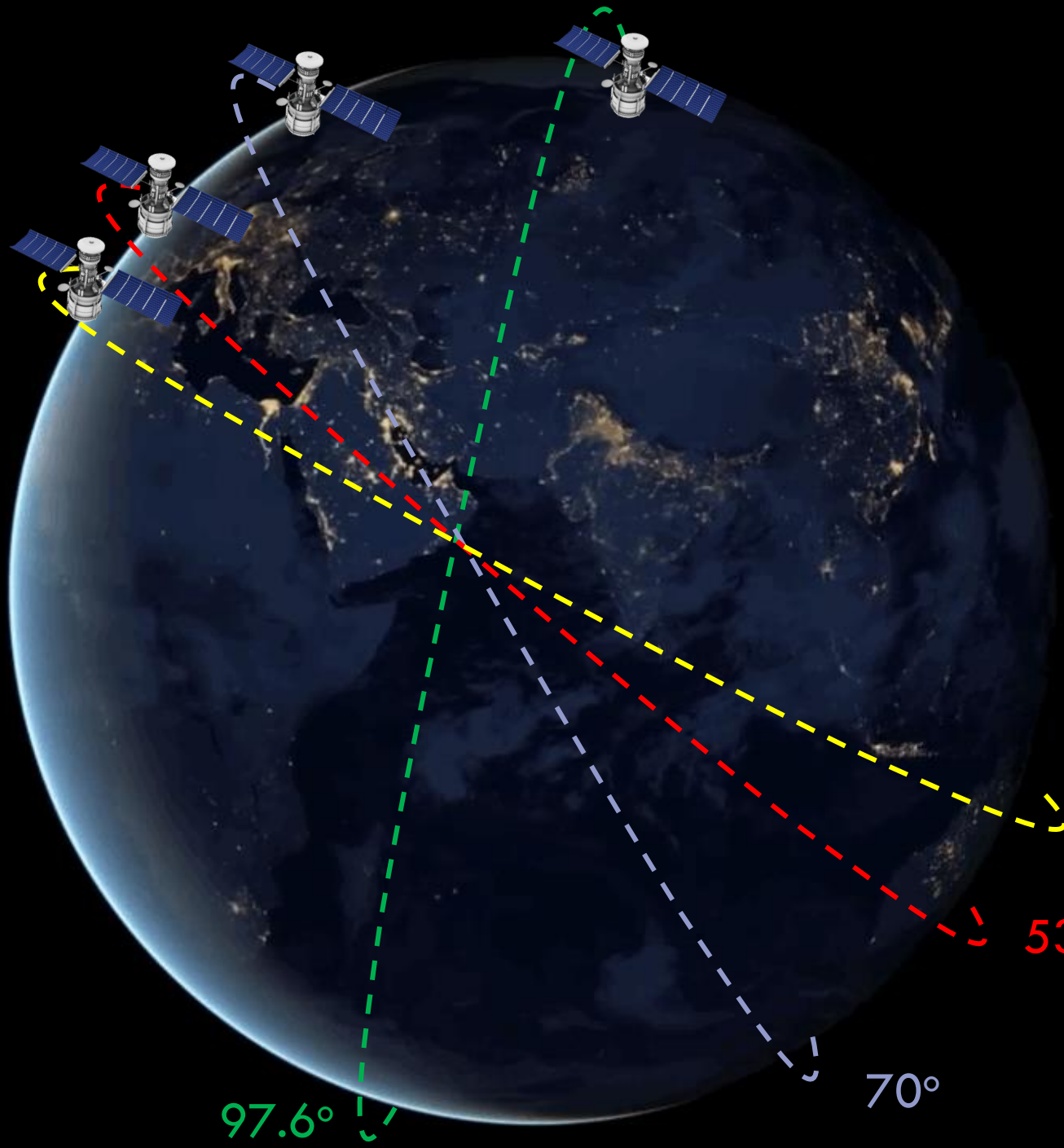




https://www.starlink.com/map?view=latency

Starlink is emerging as a “global” ISP

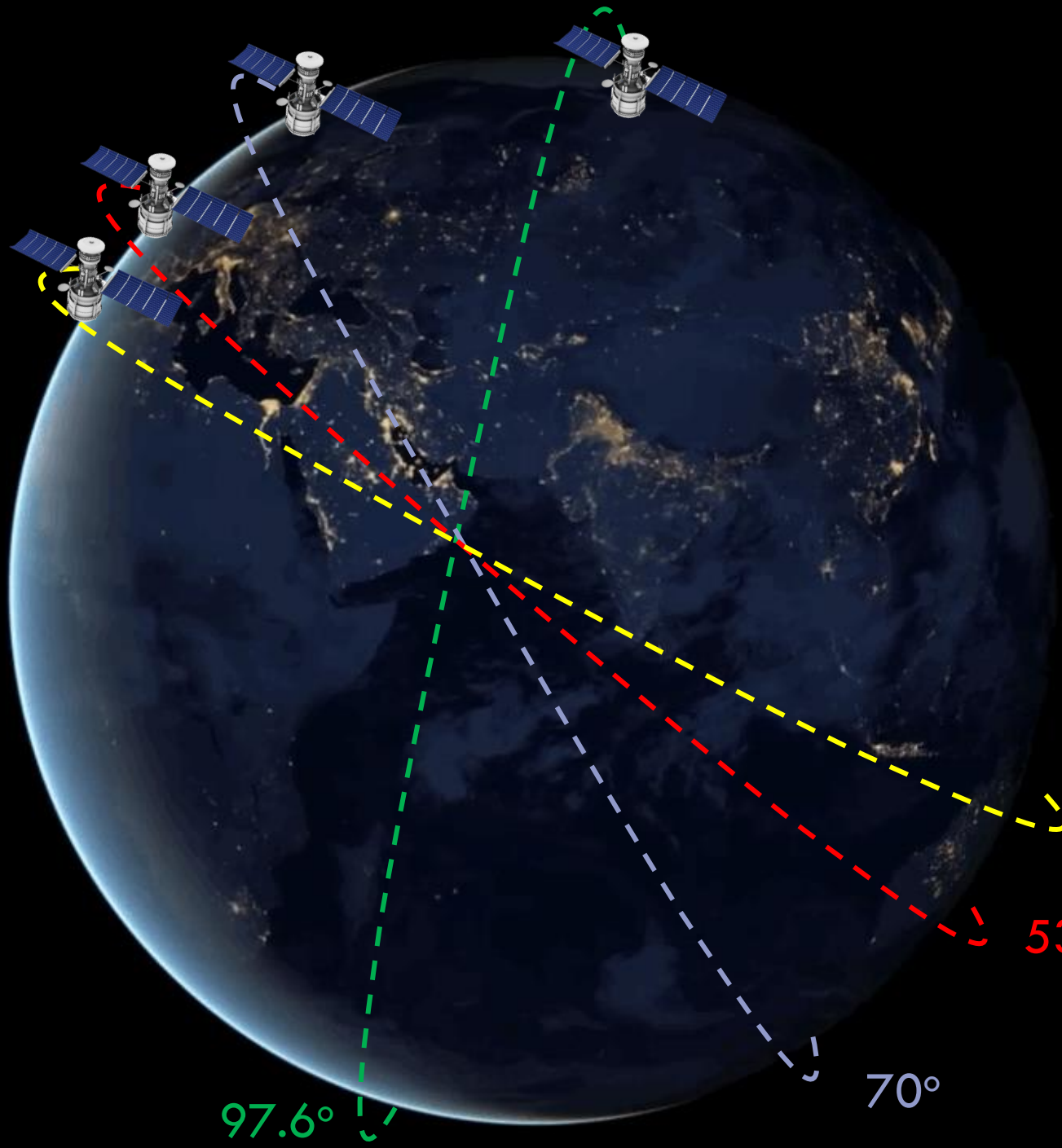
- > 7000 operational LEO satellites
- Plans to deploy 40,000+ satellites
- Satellites orbiting at 300-700 km altitude
- Aims to provide low-latency high-bandwidth connectivity globally
- Competitive performance to many terrestrial providers



(1)

Starlink satellite fleet is deployed in multiple orbits

Majority of deployed satellites are in the and 43° and 53° orbital shell



Starlink network performance is globally inconsistent due to network design and operation

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Starlink satellite fleet is deployed in multiple orbits

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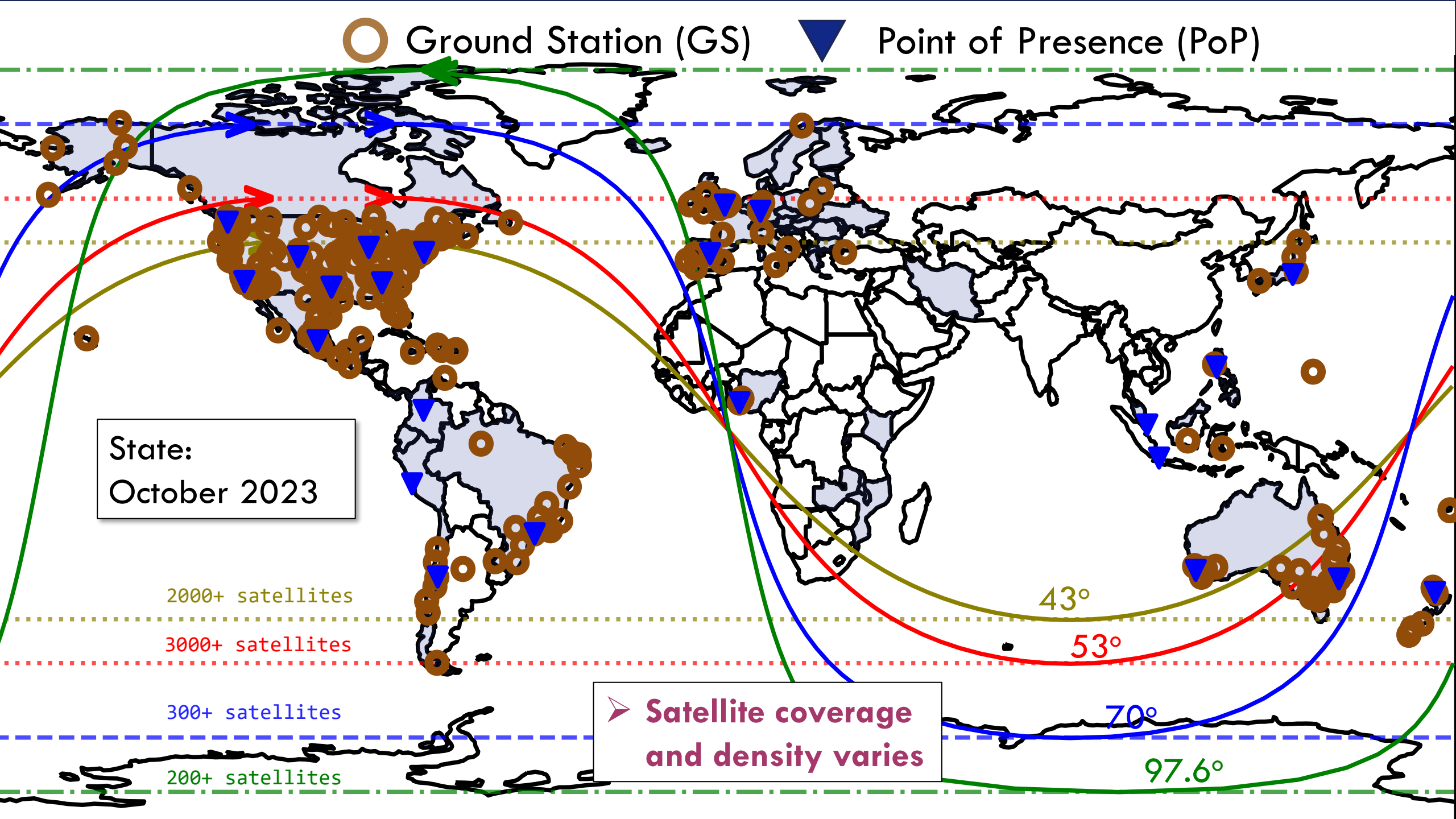
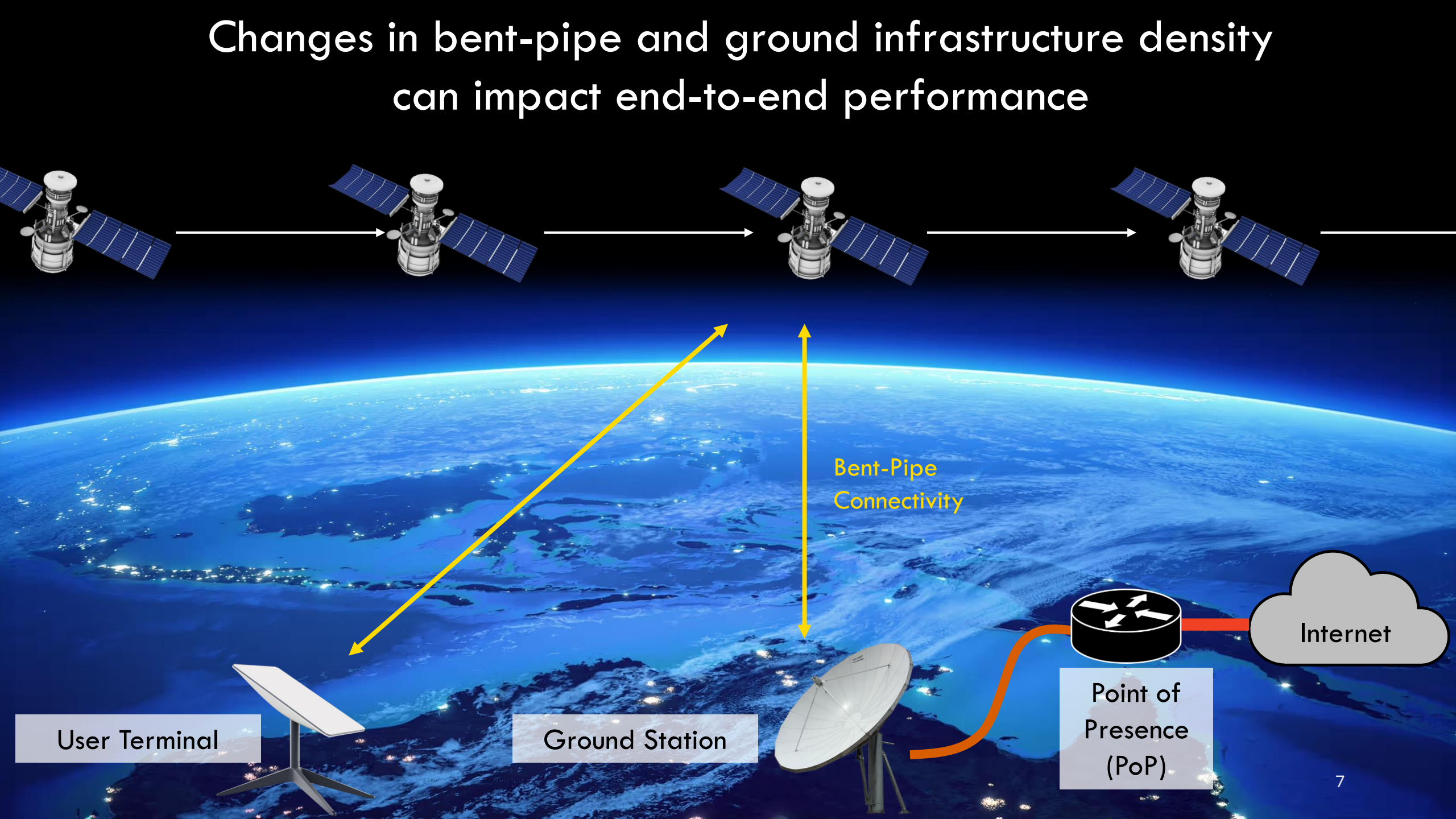

Ground Station (GS)
Point of Presence (PoP)
State:
October 2023
2000+ satellites
3000+ satellites
300+ satellites
200+ satellites
43°
53°
70°
97.6°
Satellite coverage and density varies

Changes in bent-pipe and ground infrastructure density can impact end-to-end performance



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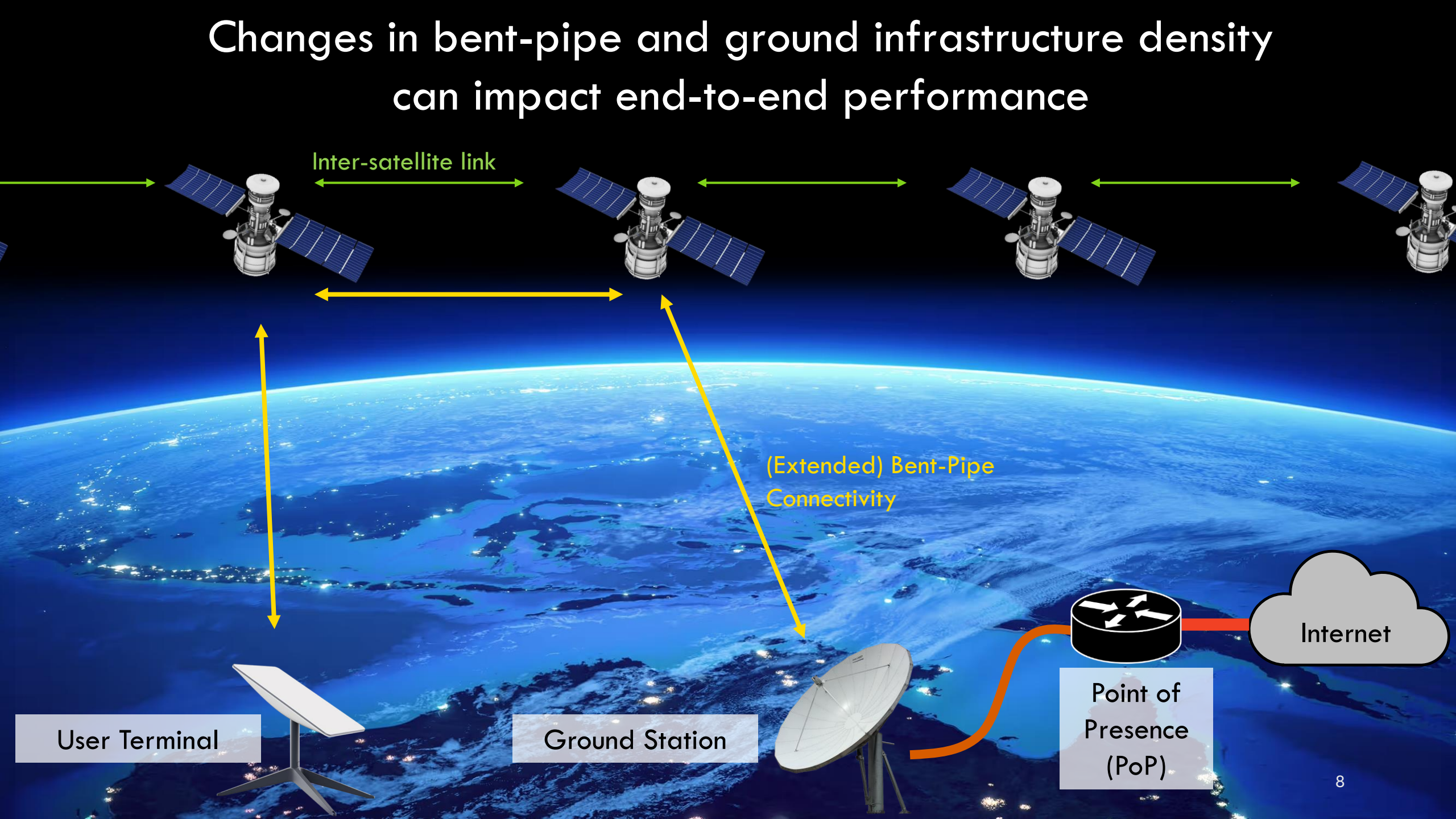


Starlink network performance is globally inconsistent due to network design and operation

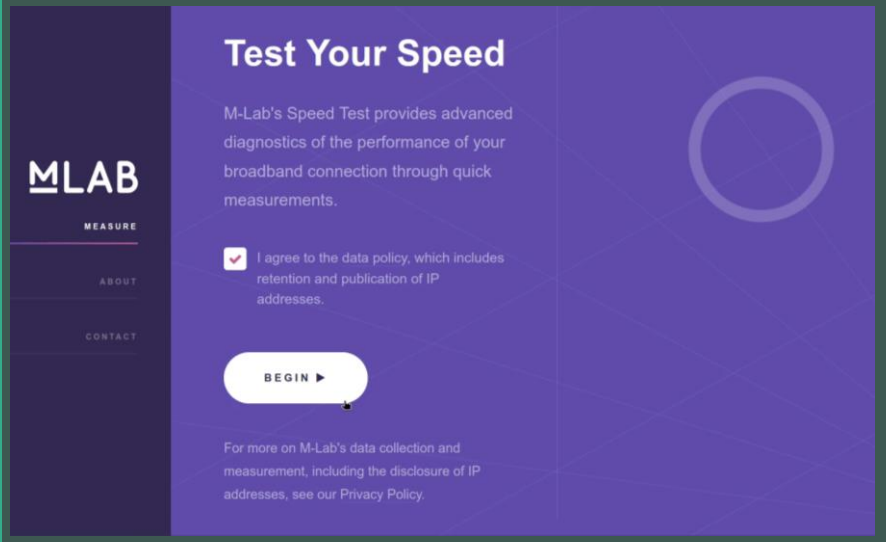
(2)

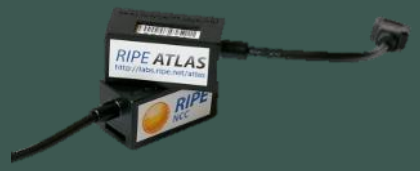
Starlink implements a “bent-pipe” architecture

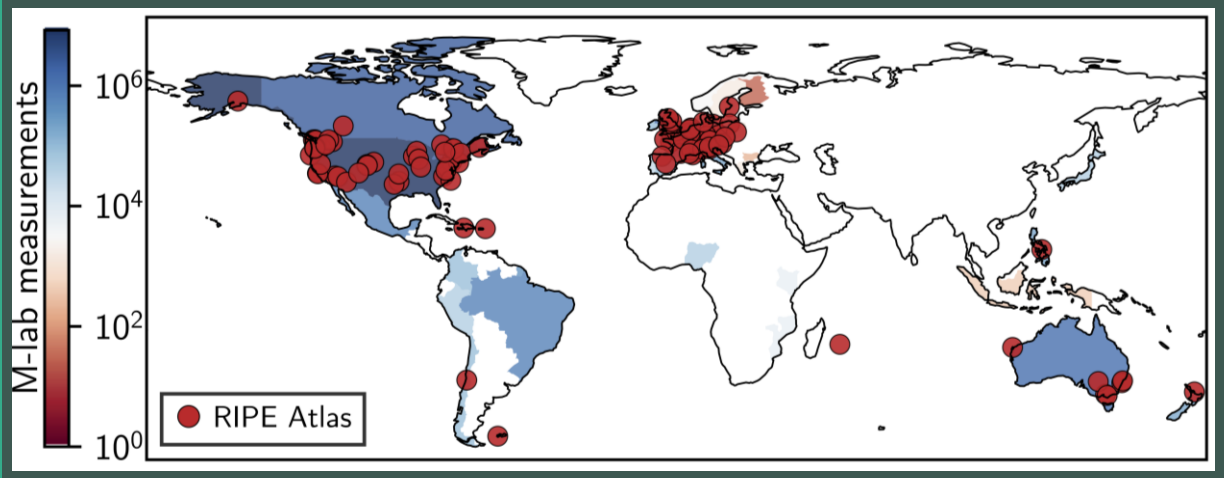
Satellites connect Starlink user terminals to Ground Stations

This work provides a multifaceted comprehensive analysis of Starlink operations and performance

Global Performance



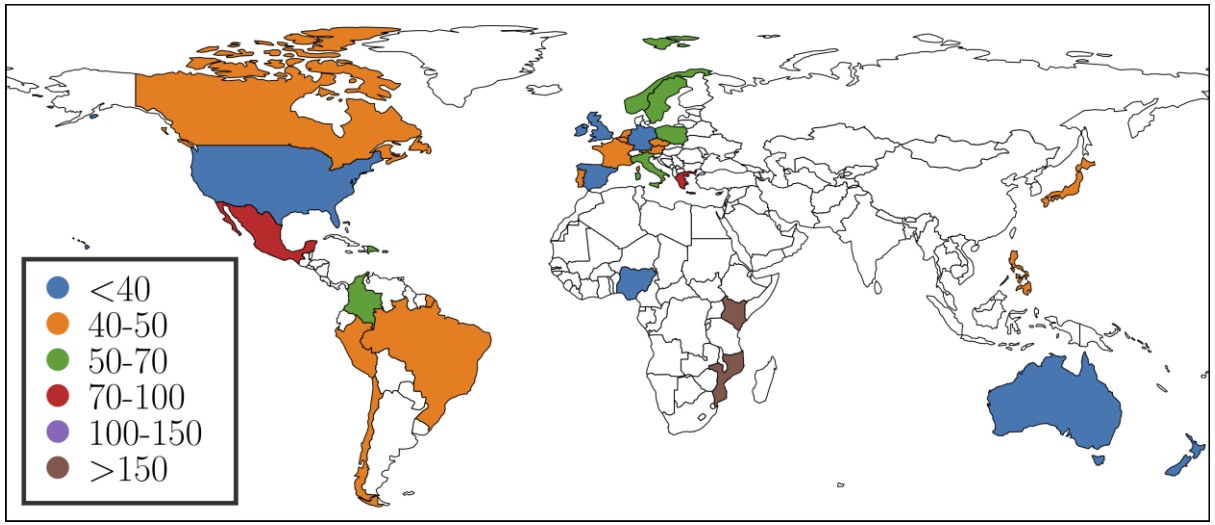




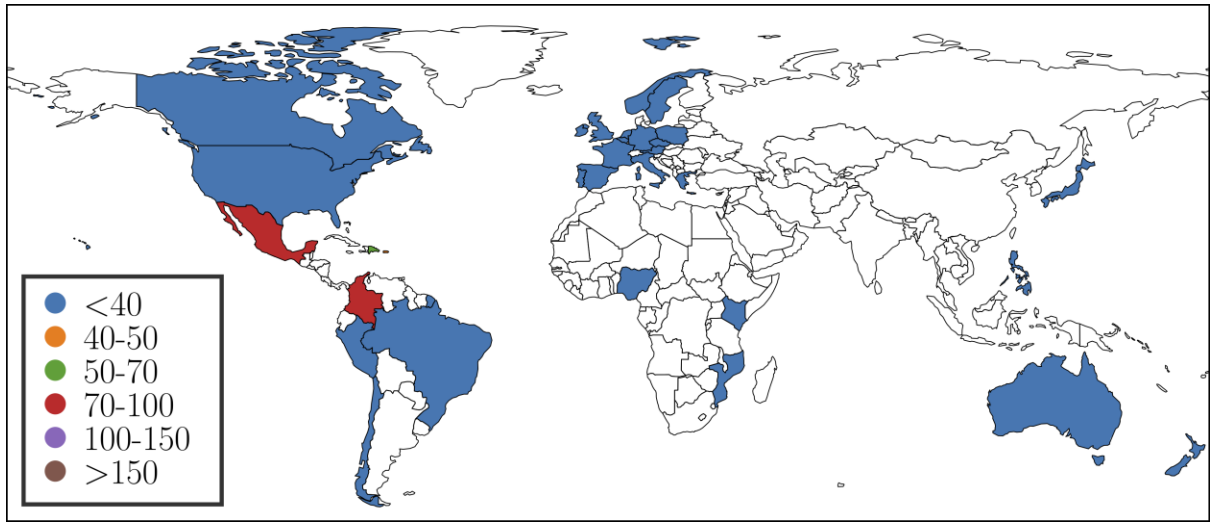
1. Crowdsourced M-Lab TCP “speed tests” from Starlink users to the nearest cloud server
   - 19.2 million data points from 34 countries
2. Targeted pings and traceroute measurements from Starlink RIPE Atlas probes
   - 98 probes from 21 countries
   - Endpoints in 145 datacenters from seven cloud operators

Global Performance

World View of Latencies



Starlink

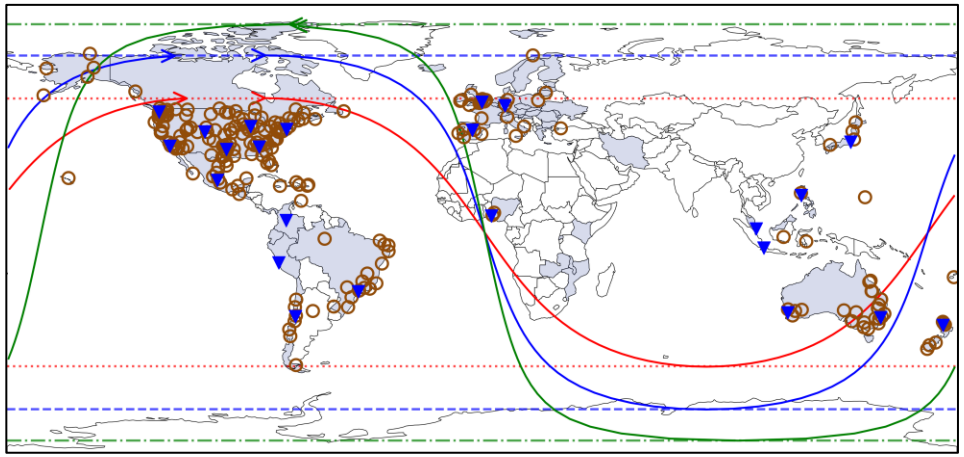


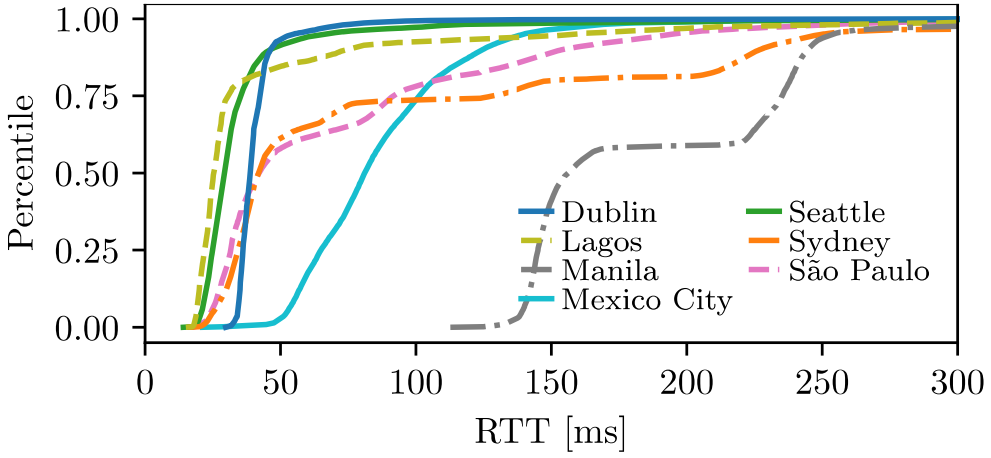
Top-3 mobile network operators

- Median latencies for Starlink is ~40-50 ms while mobile network latencies are ~30 ms
- Well-provisioned regions (such as NA and EU) enjoy the best Starlink latencies
- Starlink performs poorly in several regions with long tail latencies, e.g., Africa
- Not many regions where Starlink currently outperforms cellular

Global Performance

A Digital Divide?



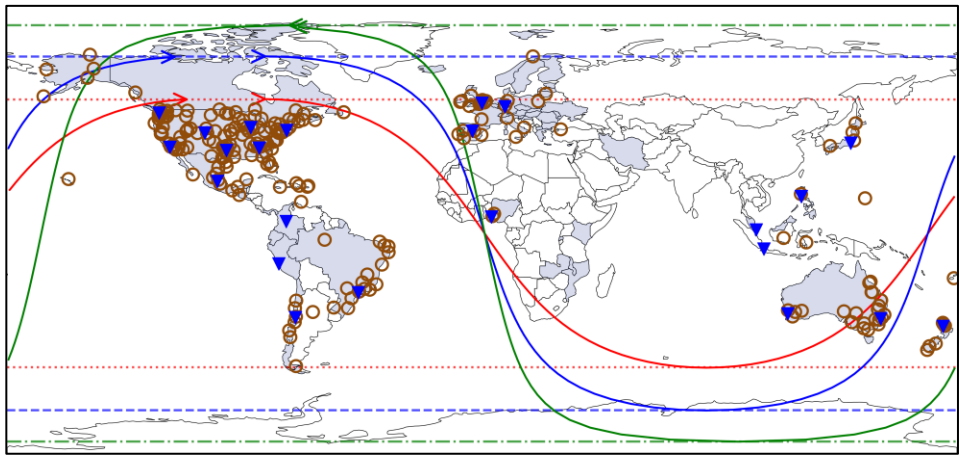


Clear impact of ground station infrastructure

- Regions with high ground station and PoP availability get better latencies

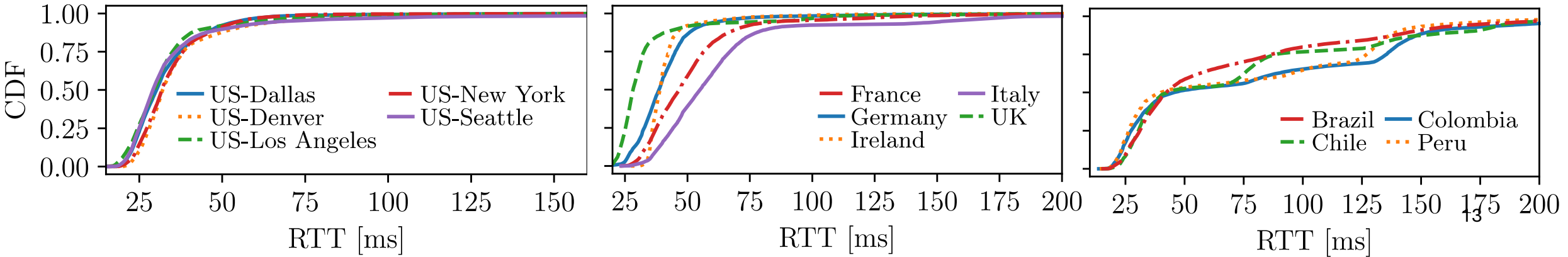
Global Performance

A Digital Divide?



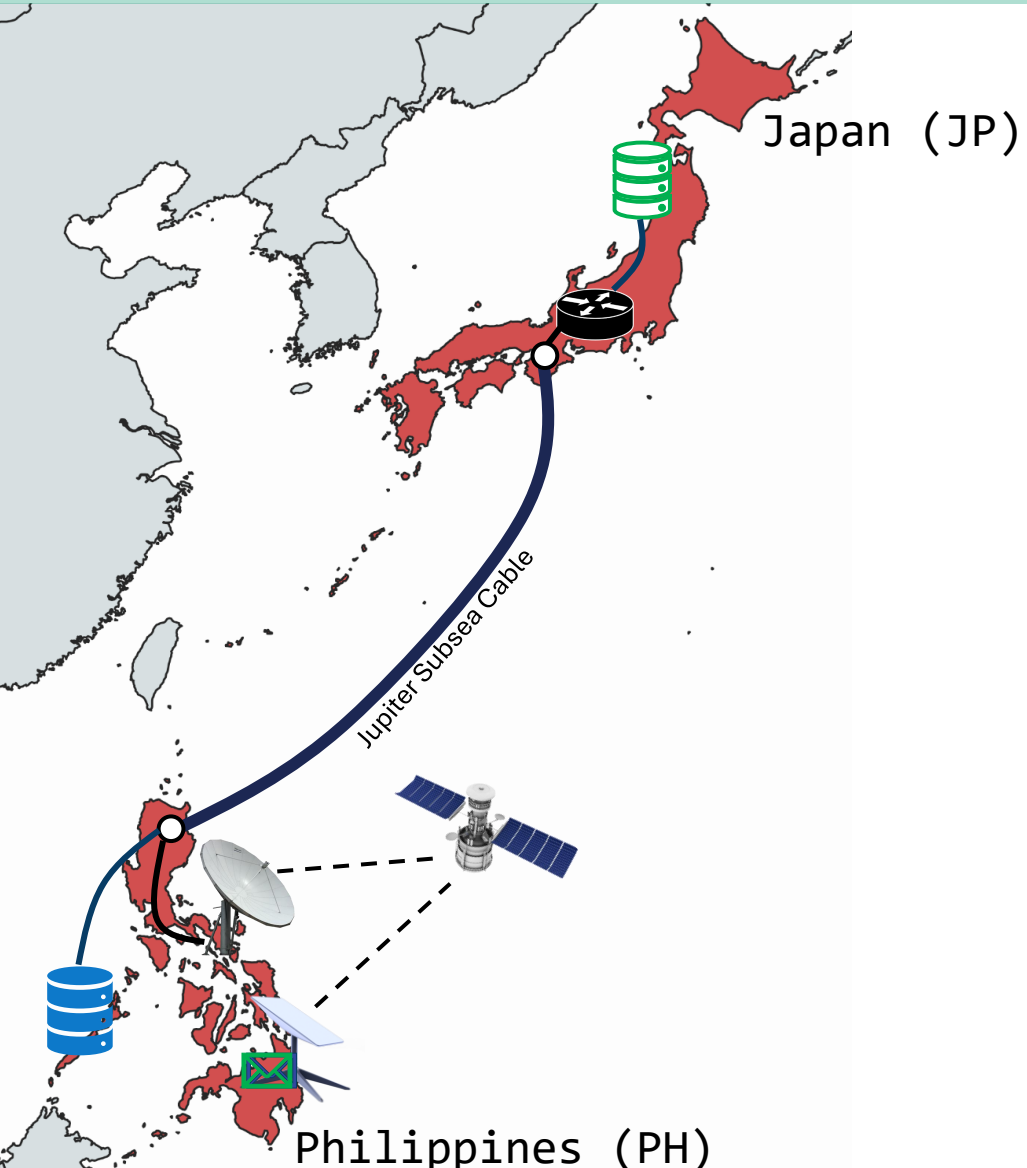
Clear impact of ground station infrastructure

- Regions with high ground station and PoP availability get better latencies
- Consistent performance across the USA due to dense ground infrastructure
- In the EU, closeness to PoPs means shorter latencies (e.g., Italy connects to a PoP in Spain)
- Significantly higher latencies in South America (SA), long distances between GSs and limited PoPs in the region



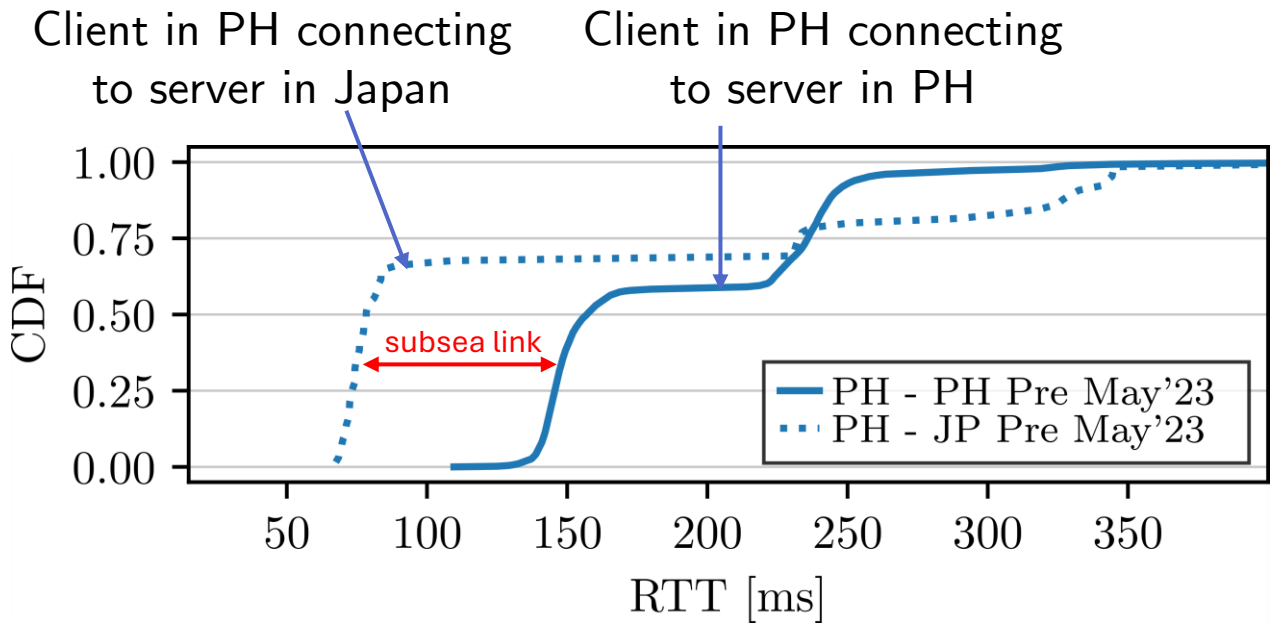
Global Performance

Impact of ground infrastructure - Philippines



Before May 2023

Starlink has a ground station in the Philippines but used the nearest PoP in Japan.



Global Performance

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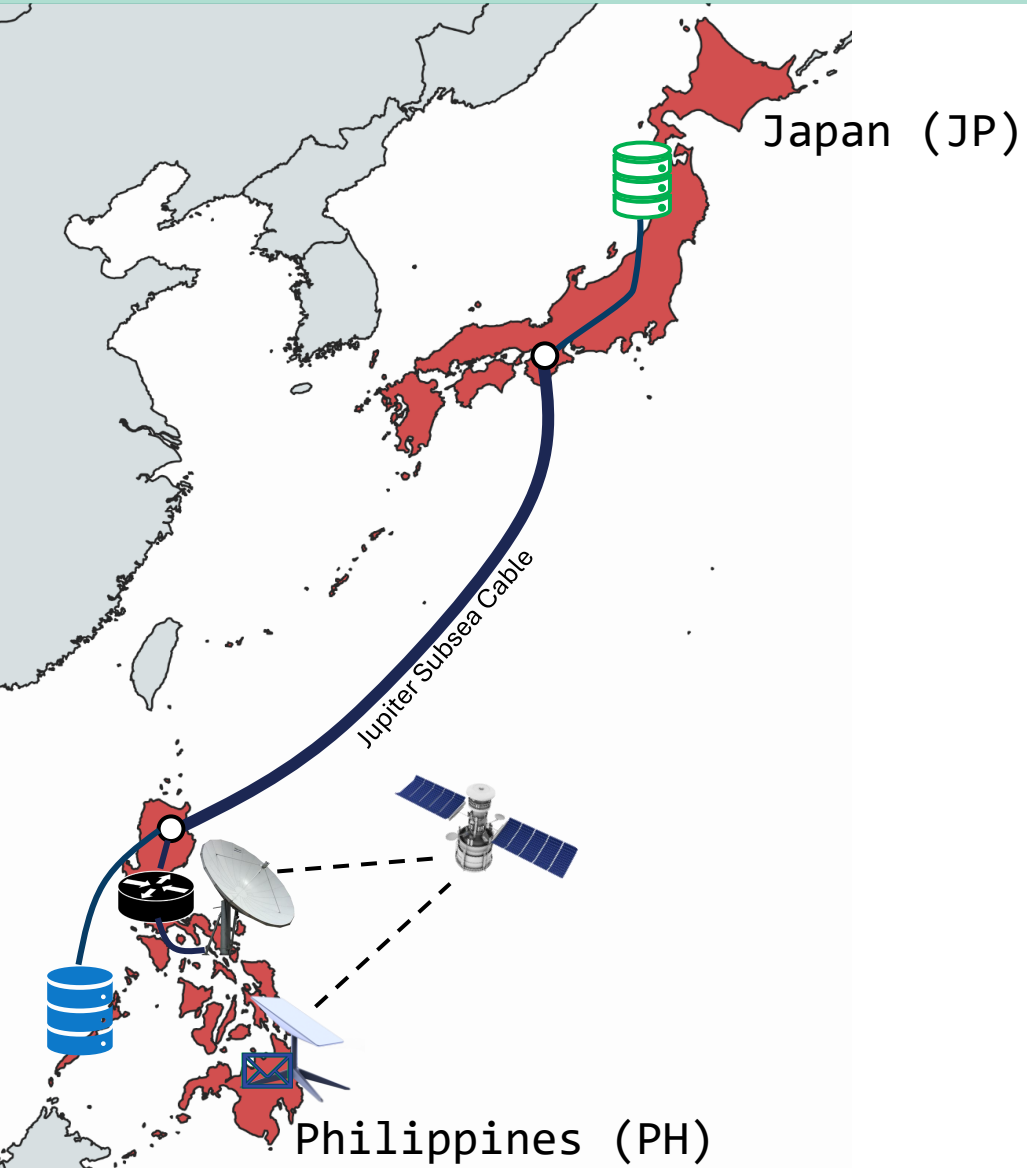
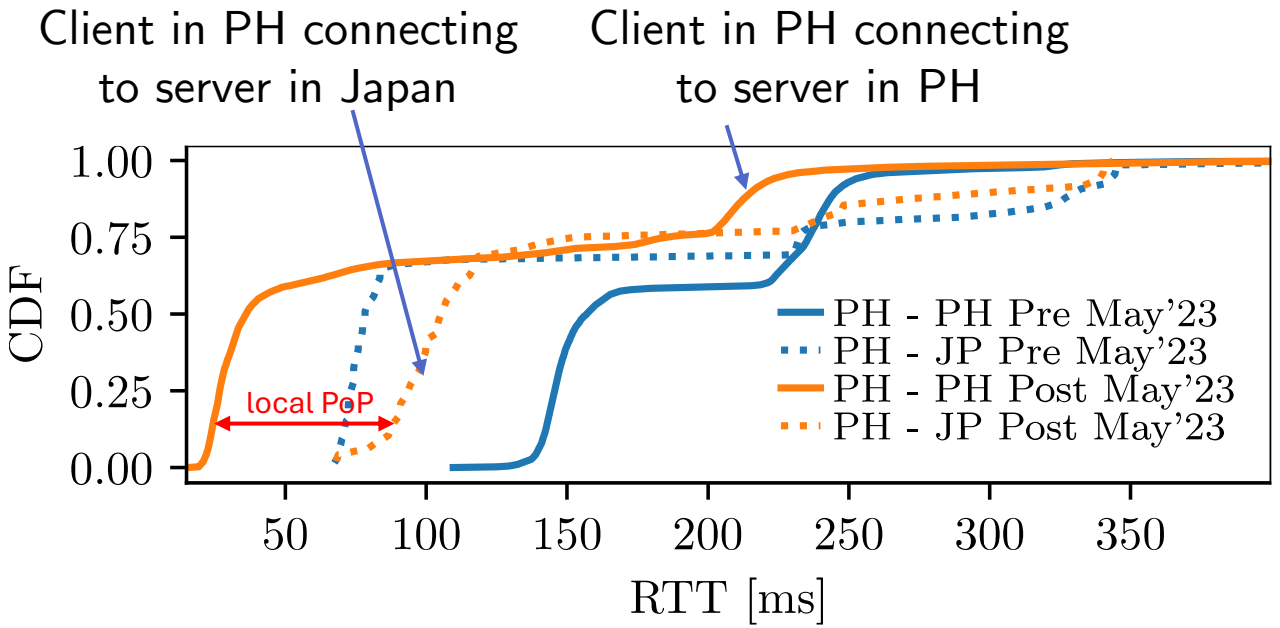


After May 2023

Starlink has a ground station and a PoP in the Philippines.



Global Performance

Inter-Satellite Links (ISLs)

- Starlink dish in Reunion Island connects to PoP in Frankfurt, Germany

Global Performance

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- GS ↔ PoP latency is < 5ms, so GS must be near Germany

Global Performance

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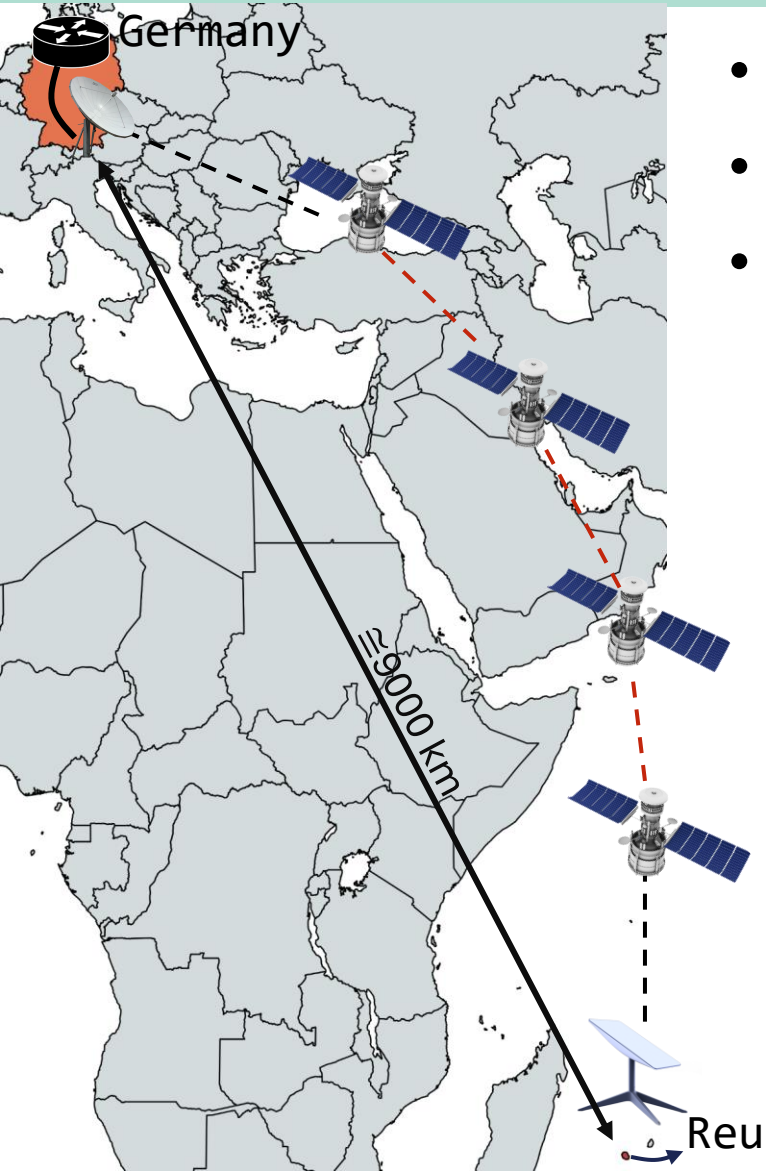

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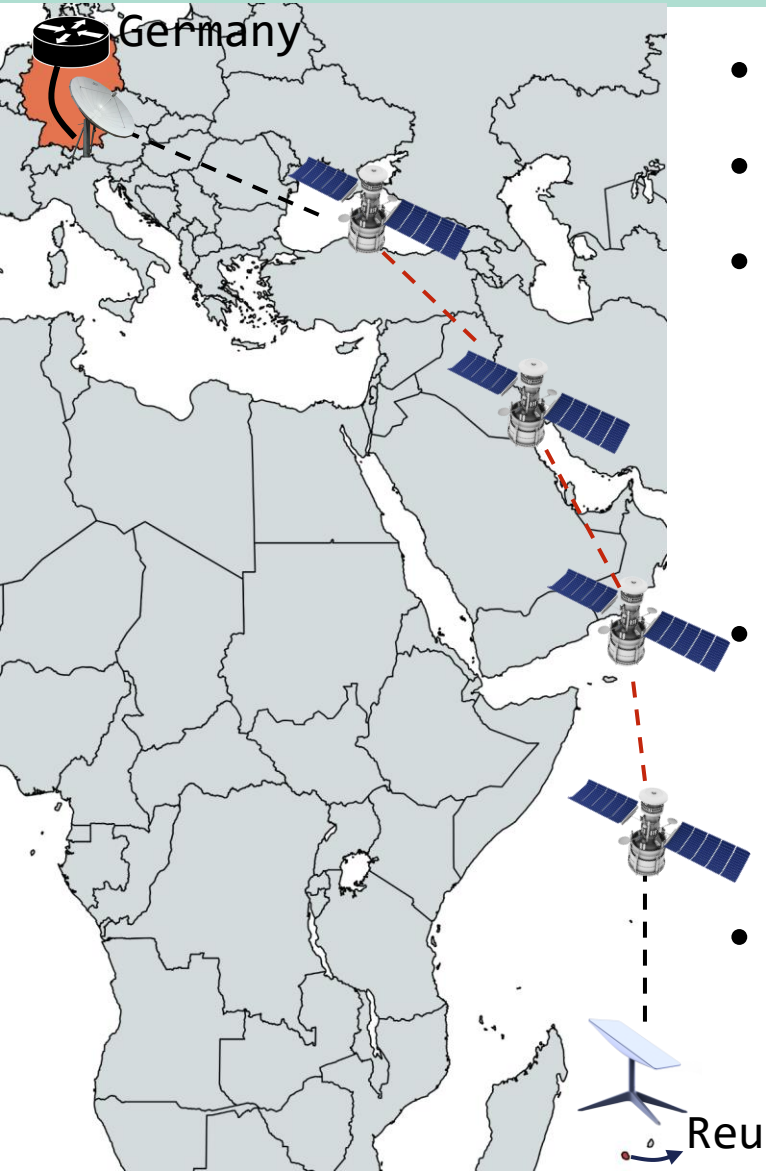
Global Performance

Inter-Satellite Links (ISLs)



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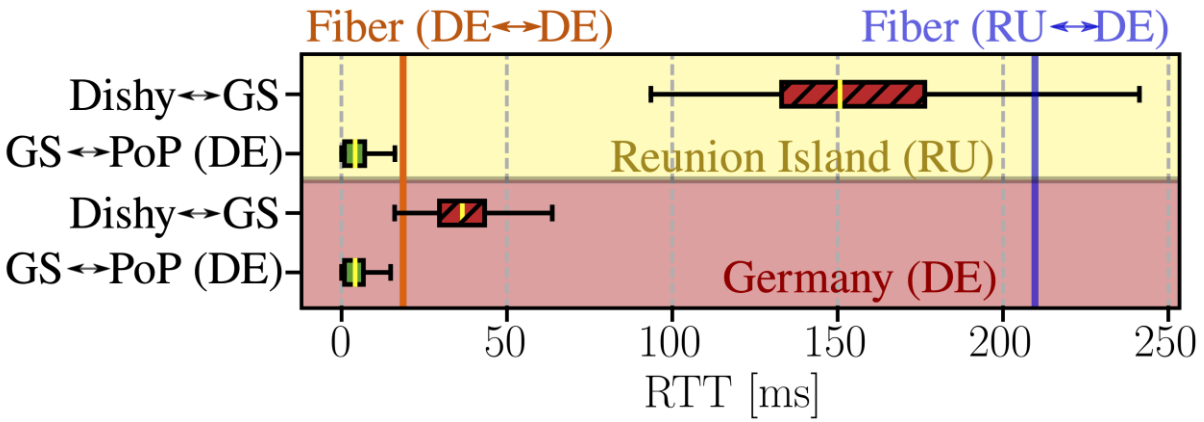
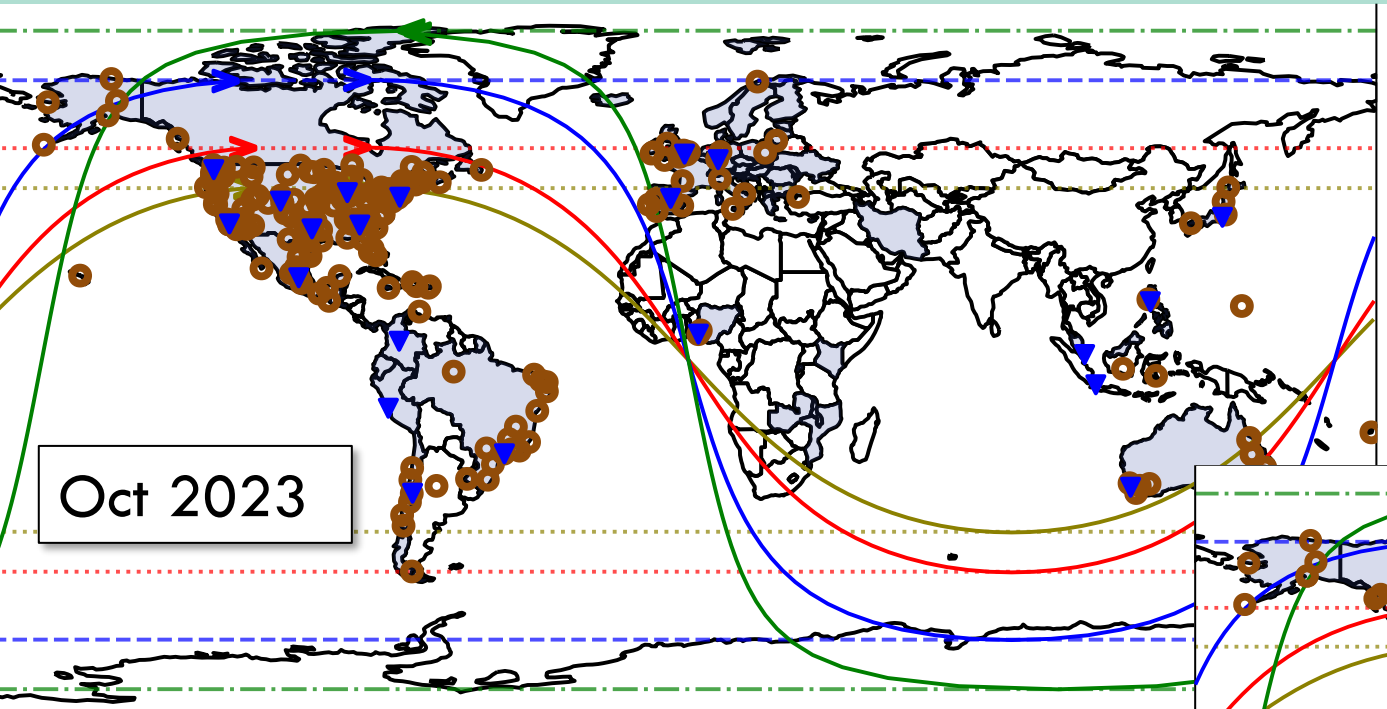


- ISLs connecting RU to Europe result in a significant latency improvement (~60 ms) compared to terrestrial fiber links

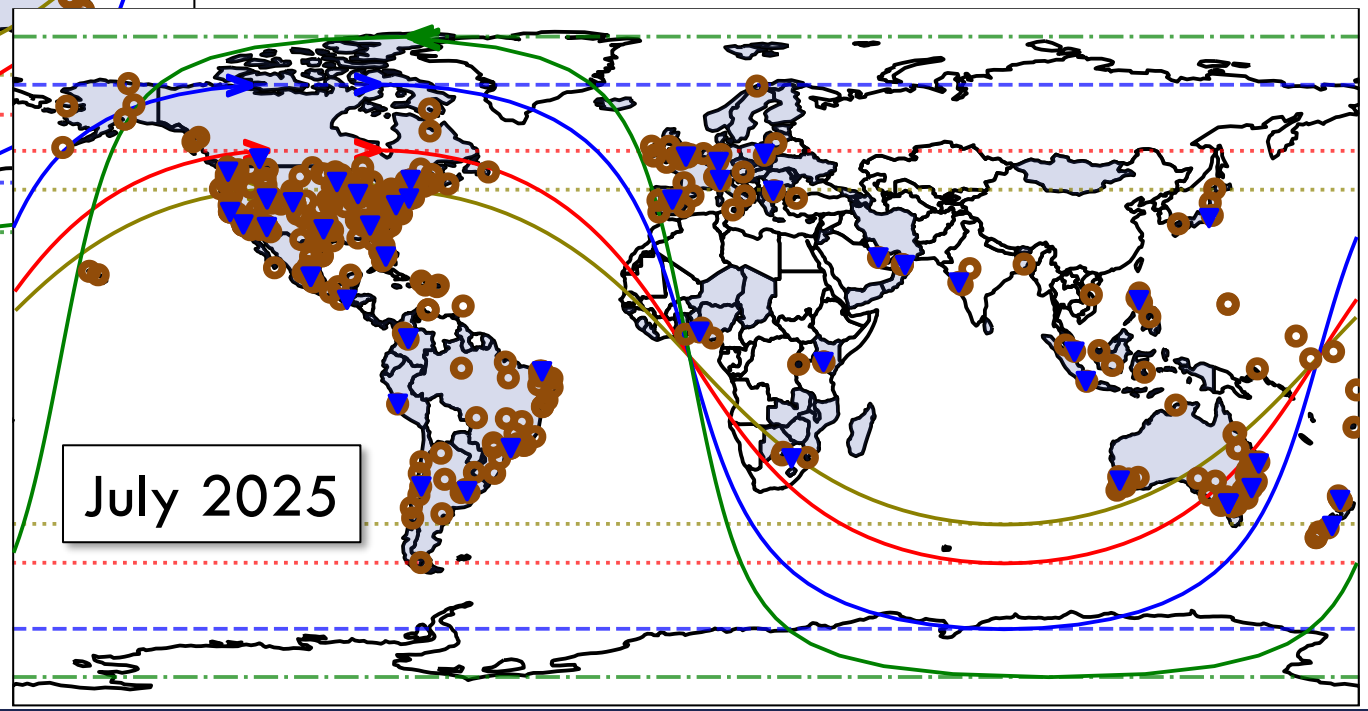
Global Performance

Infrastructure Evolution



Ground Station (GS)

Point of Presence (PoP)

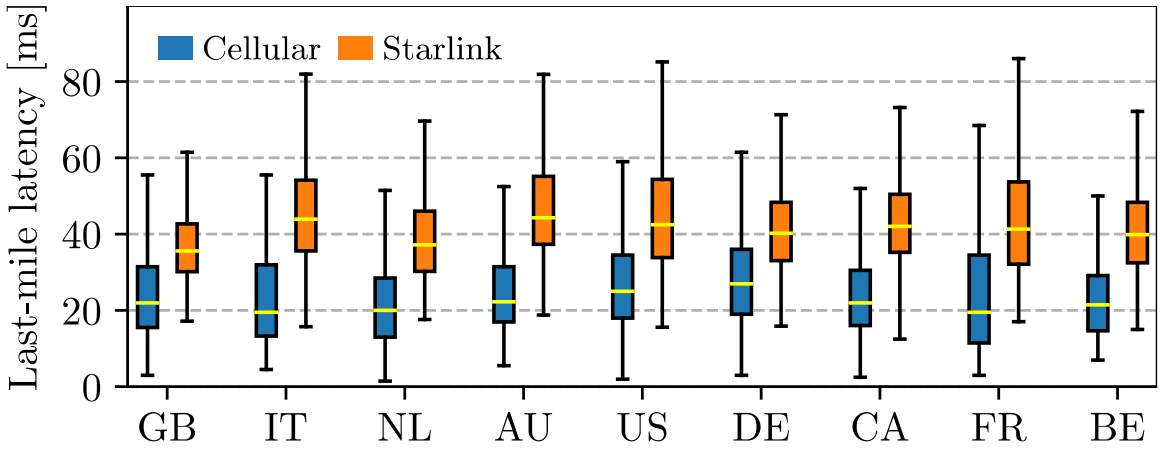


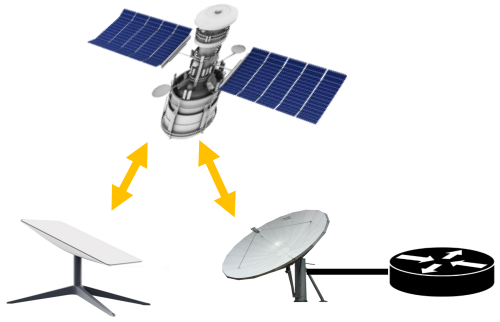
- Density increased even more in NA and EU
- PoP and GS in Kenya
- First deployments in Middle East

Global Performance

Satellite Bent-Pipe

We measured the ”bent-pipe” latency at 35 – 50 ms globally with > 100 ms outliers.





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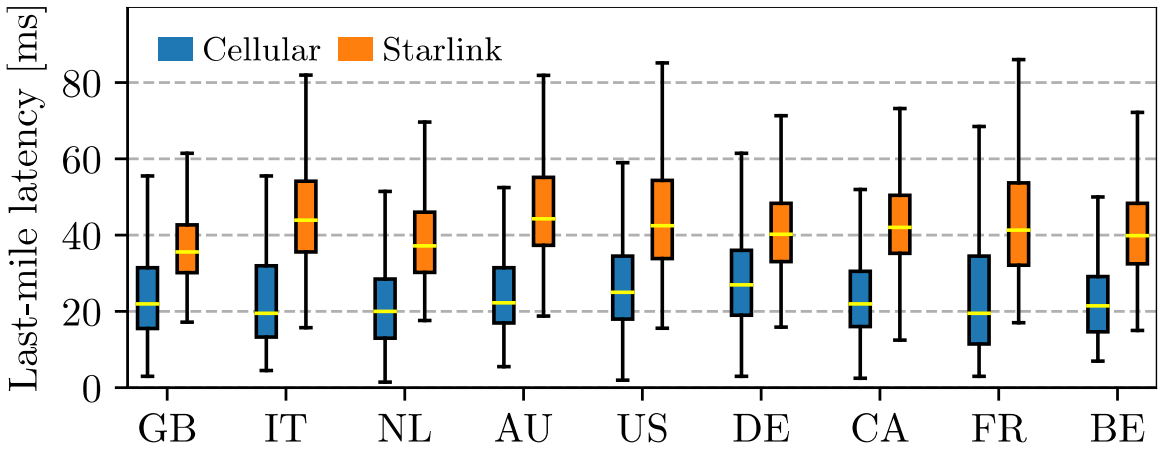
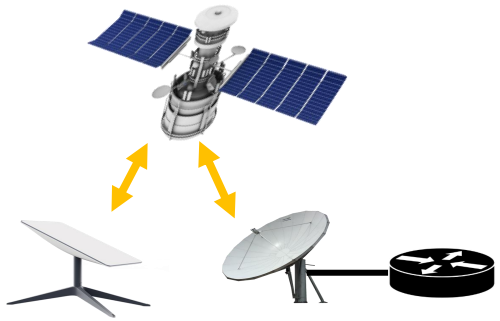




- Starlink works on improving latency

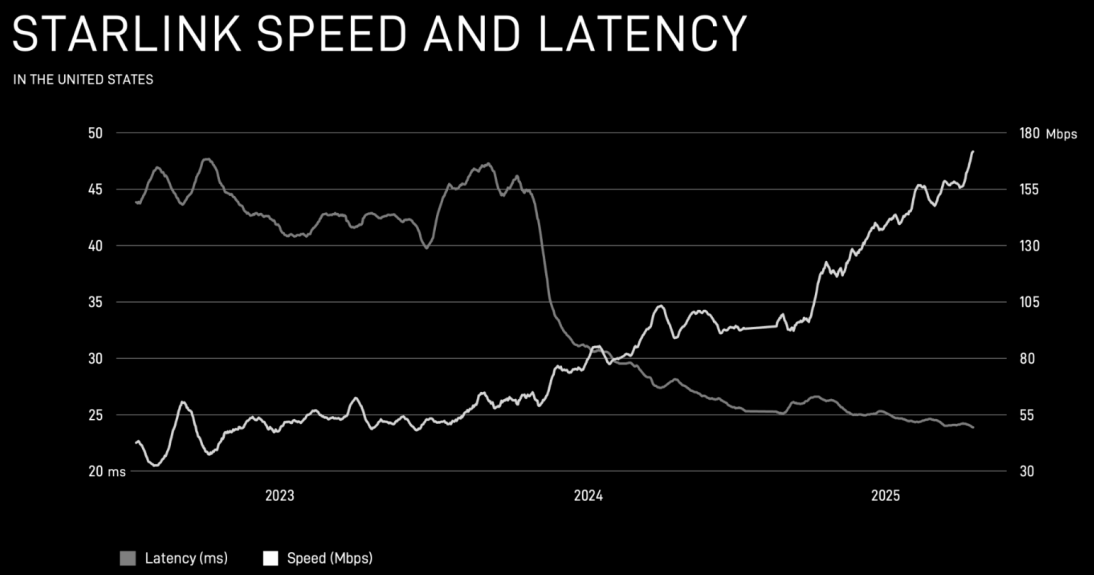
Starlink public release: 11 March 2024

SPACEX

IMPROVING STARLINK'S LATENCY

Starlink engineering teams have been focused on improving the performance of our network with the goal of delivering a service with stable 20 millisecond (ms) median latency and minimal packet loss.

Starlink public release: 14 July 2025



This work provides a multifaceted comprehensive analysis of Starlink operations and performance

Global Performance

Real-Time Web Apps

1. Zoom conferencing
   - Evaluation of Starlink for supporting low latency videoconferencing
   - RTT, jitter, bitrate, resolution, …

2. Amazon Luna cloud gaming
   - Comparison between a baseline, Starlink, and 5G
   - Delays, FPS, frame freezes, jitter, throughput, …

Real-Time Web Applications

Analysis

- Starlink achieves almost similar performance to NSA 5G cellular networks
- Compared to terrestrial, the latencies are higher and more variable, with more packet loss
- At finer granularity, we noticed *periodic degradation* in application performance

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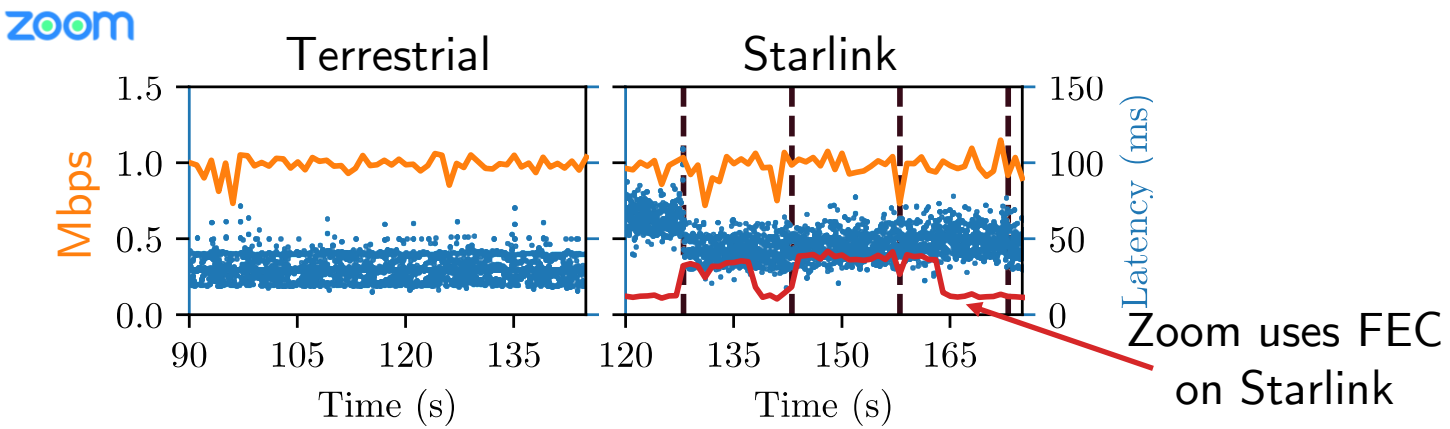

Real-Time Web Applications

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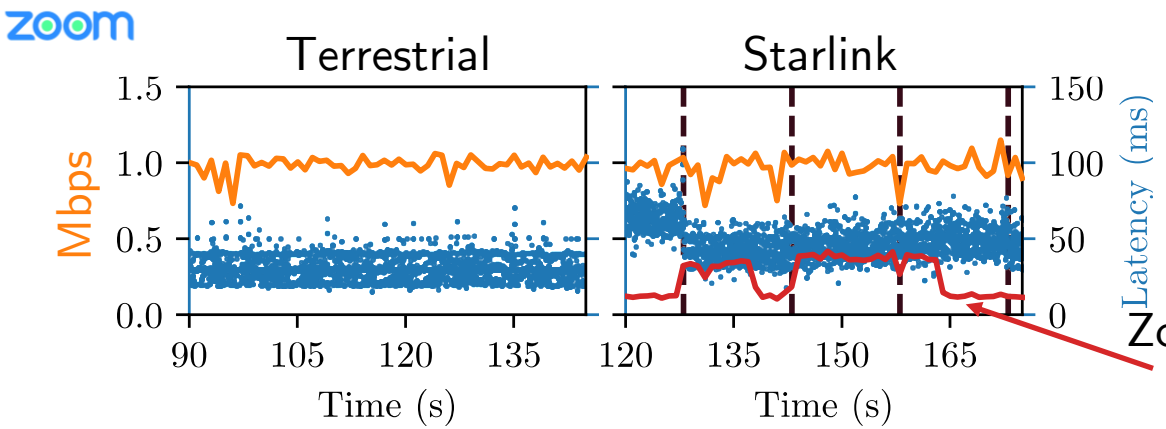
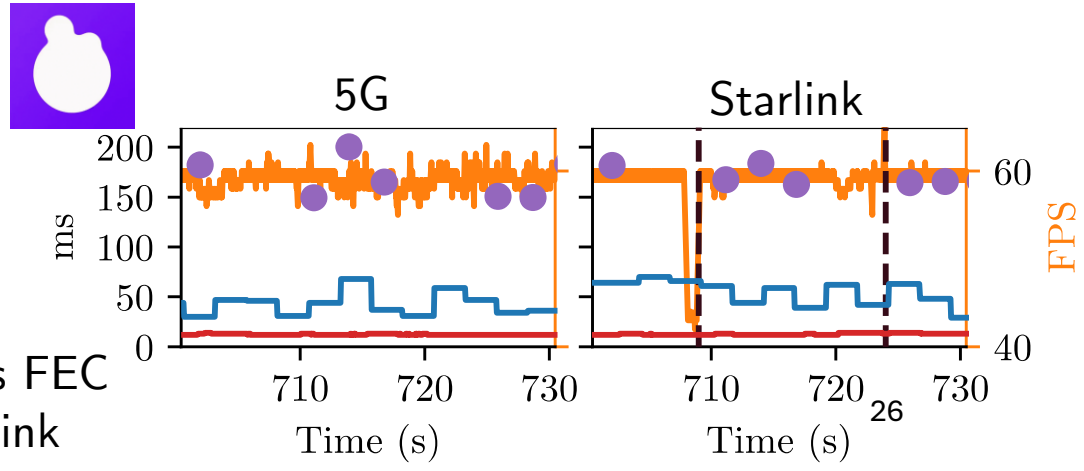
	Terrestrial	Cellular	Starlink
Idle RTT (ms)	9	46	40
Throughput (Mbps)	1000	150	220
Frames-per-second	59±1.51	59±1.68	59±1.63
Bitrate (Mbps)	23.08±0.38	22.82±4.24	22.81±2.16
Time at 1080p (%)	100	94.11	99.45
Freezes (ms/min)	0±0	0±220.34	0±119.74
Inter-frame (ms)	17±3.65	18±11.1	16±6.76
Game delay (ms)	133.53±19.79	165.82±23.55	167.13±23.12
RTT (ms)	11±13.41	39±17.06	50±16.28
Jitter buffer (ms)	15±3.27	12±1.33	15±3.35



Zoom uses FEC on Starlink

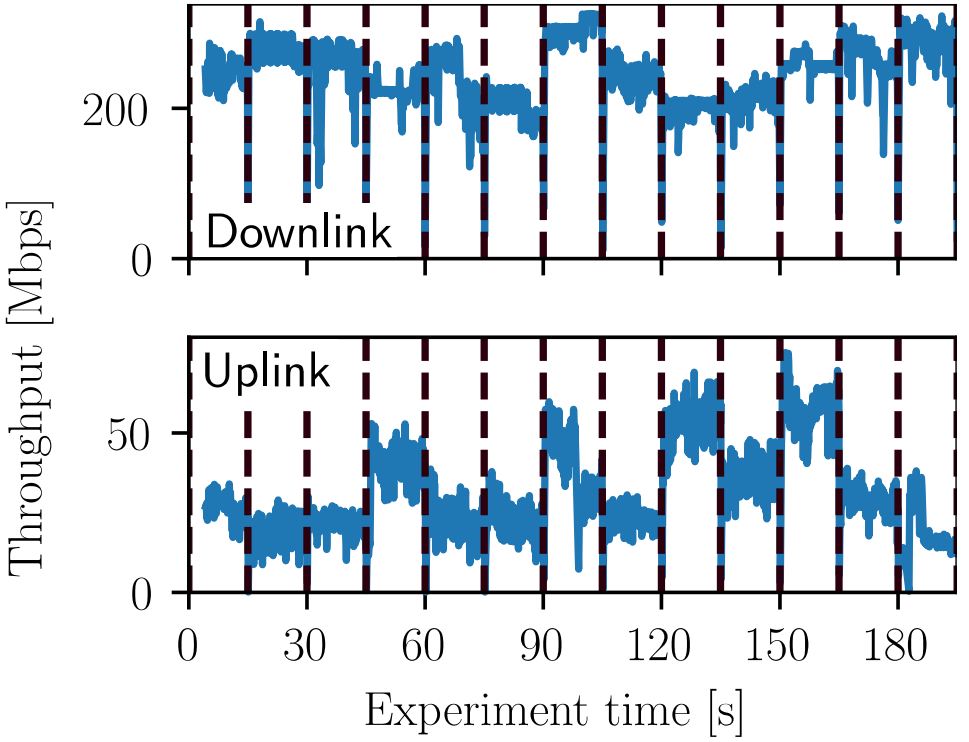


Starlink Network Operations

Analysis Overview

- Starlink throughput and latency measurements revealed sudden changes at 15-sec marks

- Research <u>hints</u> at Starlink running a *global network scheduler* that re-assigns satellites to dishes every 15 seconds

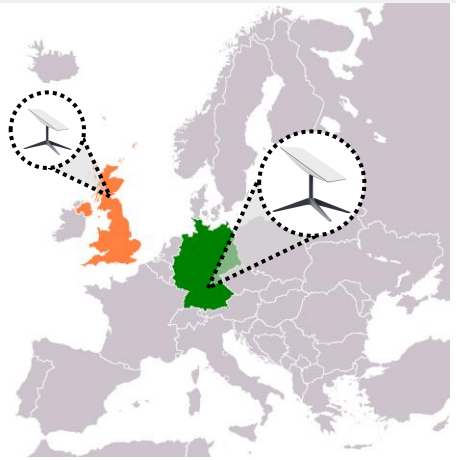


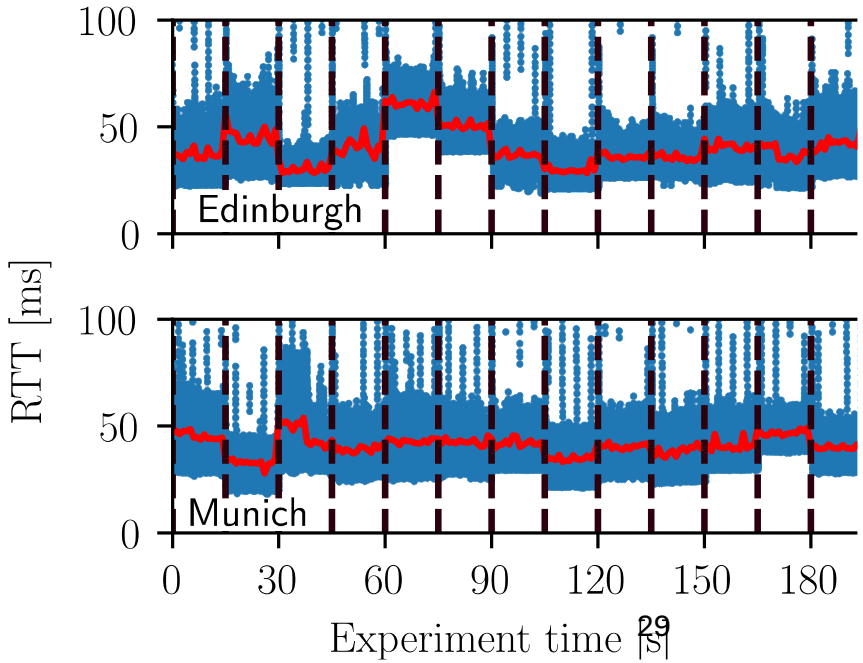
Starlink Network Operations

Fine-Grained Latency Measurements

We conduct fine-grained latency measurements using IRTT from our controlled dishes in Germany and Scotland

- Both countries are served by different satellites, GSs, and PoPs





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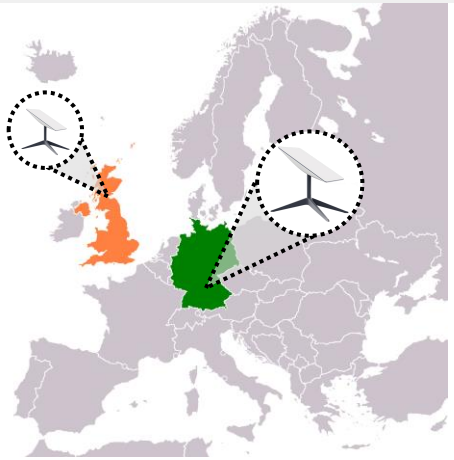
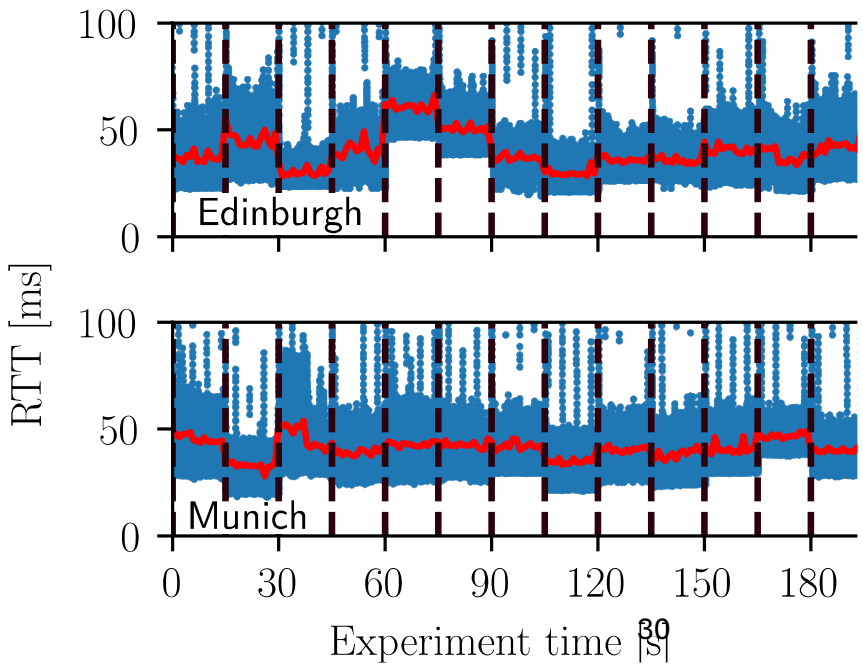


We find the following about Starlink network operations:

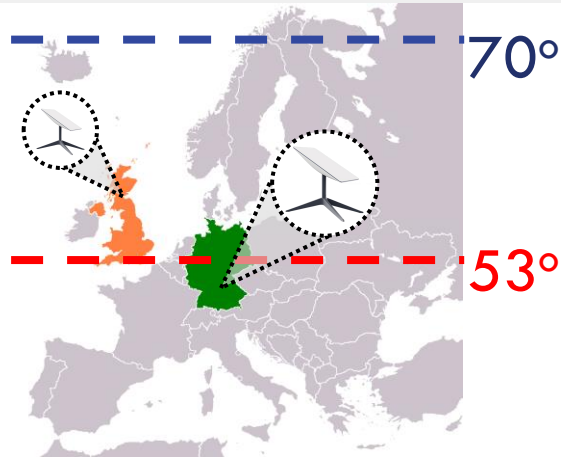
1. 15-secs reconfigurations are prevalent at all locations
2. 15-secs intervals are **globally synchronized**
3. Throughput and RTT fluctuate at the boundaries of these intervals but remain stable within



Starlink Network Operations

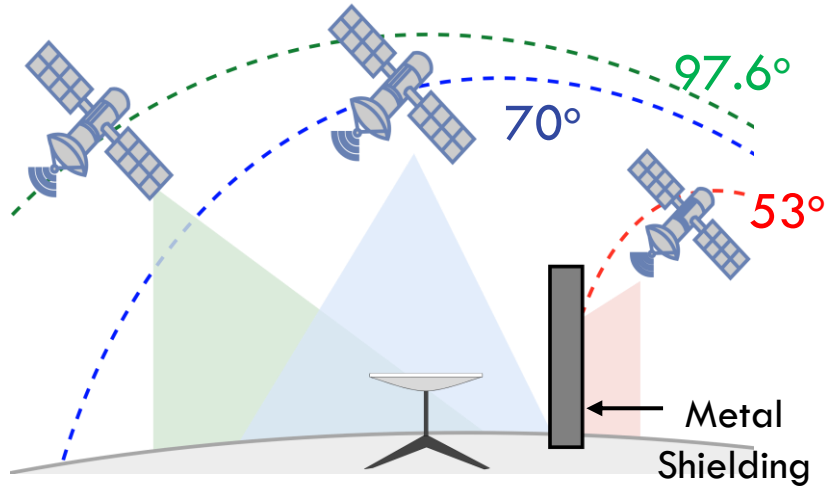
Reconfigurations = Handovers?

Hypothesis: The dish changes satellite at the 15s marks, resulting in the observed performance changes



Reason about the connected satellite

- A dish covered by 53° orbit usually has >15 satellites in its FoV at any given time
- We shield the dish in Scotland from the south, so it cannot see satellites in 53°
- Satellites in 70° and 97.6° orbits are sparse with 1-2 candidate satellites
- Tracked which satellites were within the dish's FoV through TLE and CelesTrak



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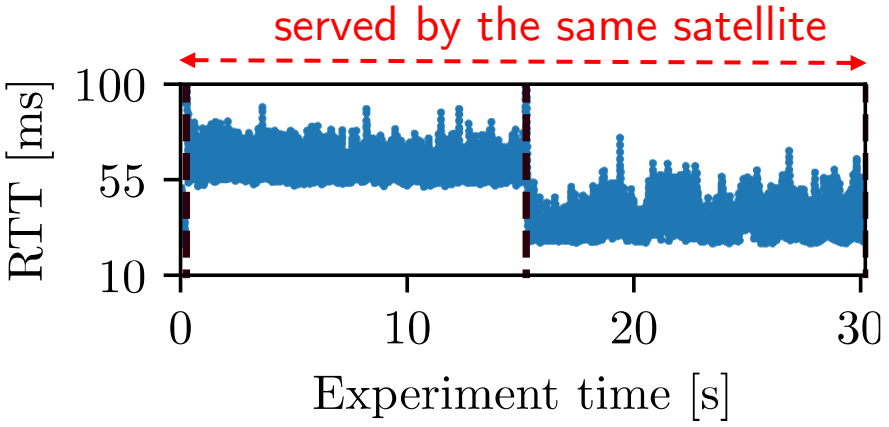
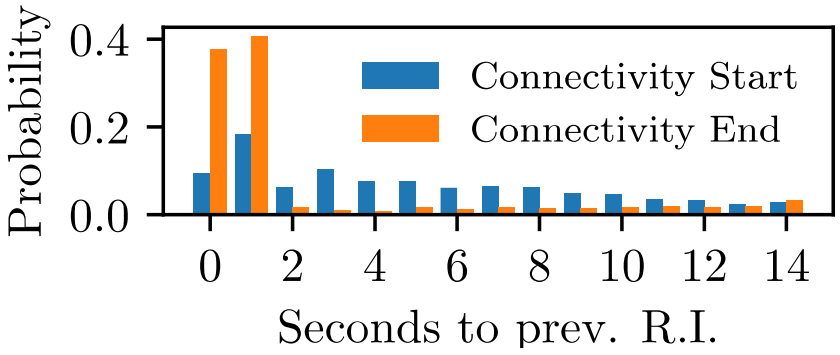
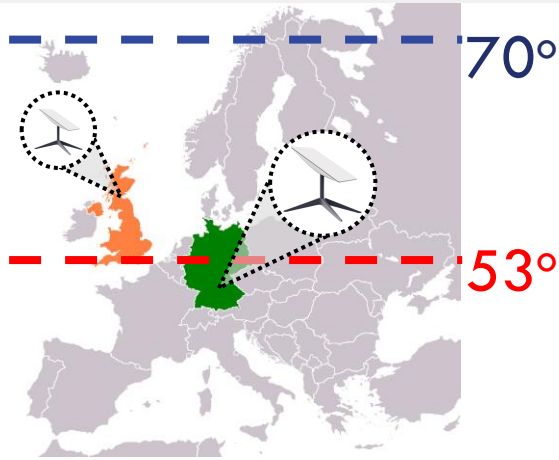
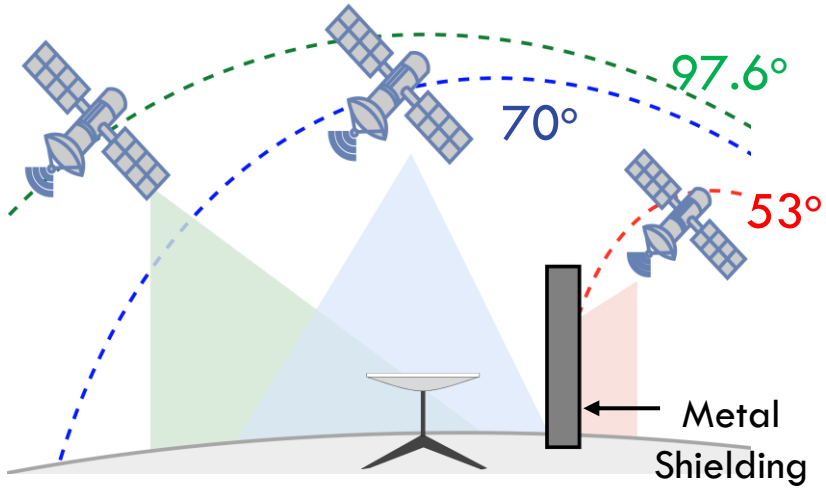






- We observed RTT and throughput shifts at interval boundaries even though the dish only had a single satellite in view
- Starlink always lost the connection at the 15-sec boundary



➢ Starlink is performing network load-balancing at 15-sec intervals but not necessarily handovers

Key Takeaways

Global Performance

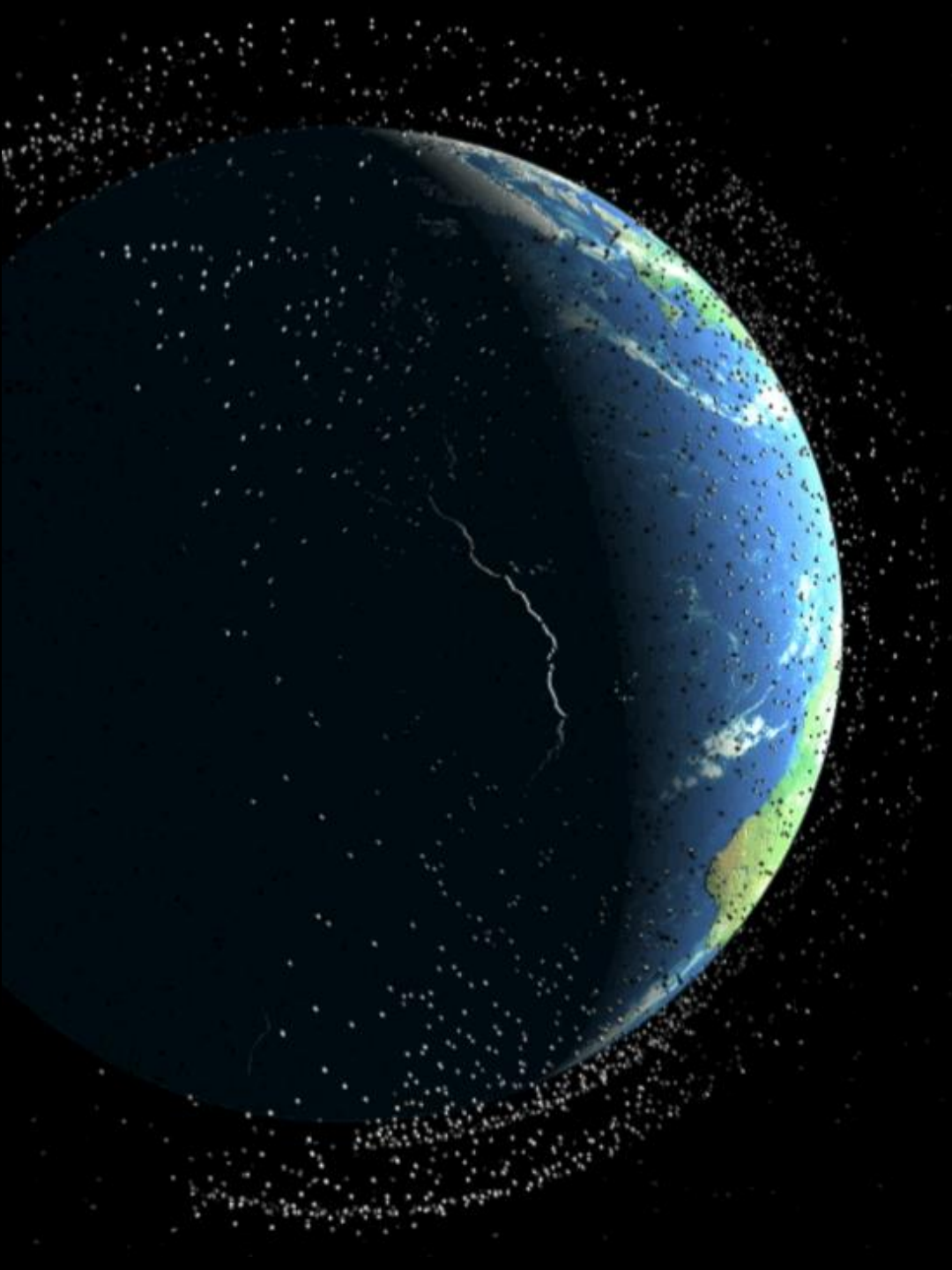
- Starlink achieves competitive performance to current cellular network deployment globally
- Performance varies globally and is dependent on (1) closeness to ground infrastructure & (2) quality of terrestrial network from PoP

Real-Time Web Apps

- Starlink performs worse than terrestrial fiber but is competitive to current 5G NSA deployment
- Starlink can support 60 FPS cloud gaming and consistent Zoom video quality without significant delays and drops
- Uplink latencies are variable; we observed periodic degradation in latency performance aligned with a 15 sec interval

Network Operations

- The last mile bent-pipe accounts for 30-40 ms latency for direct connections. Latencies can be significantly higher with ISL usage
- Starlink re-allocates its bent-pipe connection resources every 15 secs. This is either due to (i) satellite handover or (ii) satellite-GS reconfiguration
- 15-sec reconfigurations are globally synchronized



2024 THE WEB CONFERENCE ACM

A Multifaceted Look at Starlink Performance

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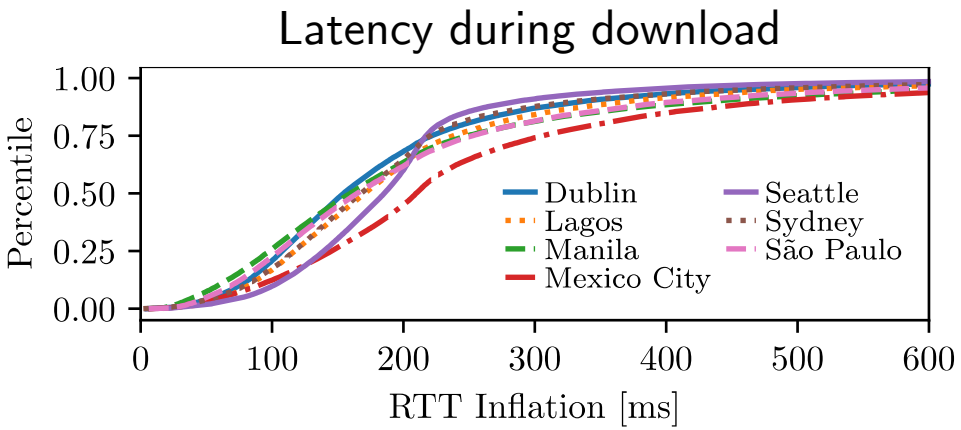
Code

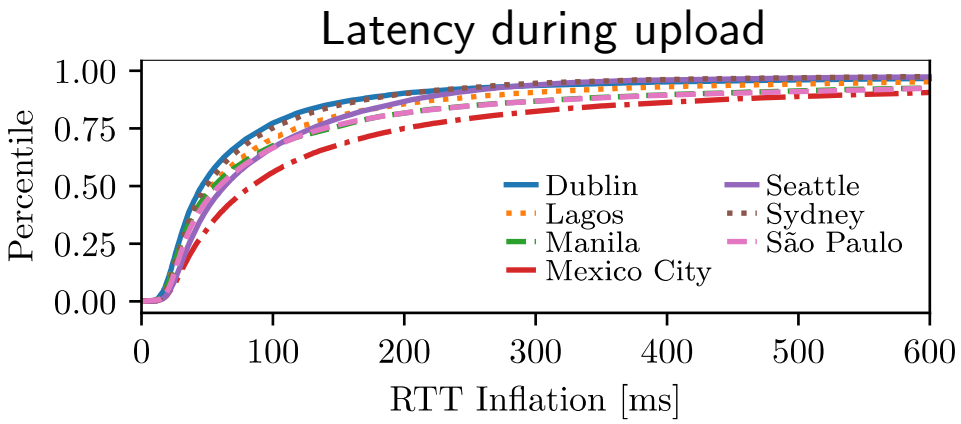
Dataset

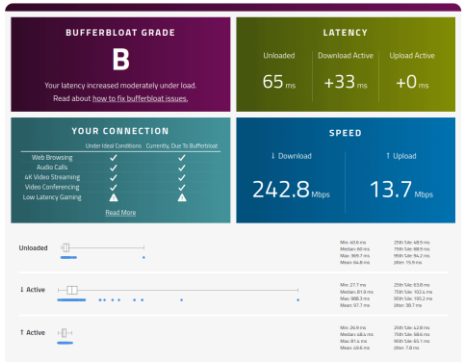
Global Performance

Queueing Delays

- Many individual reports hint that Starlink suffers from bufferbloat
- Global measurements reveal that Starlink can observe 2x - 4x RTT increase during active data transfers







Reddit

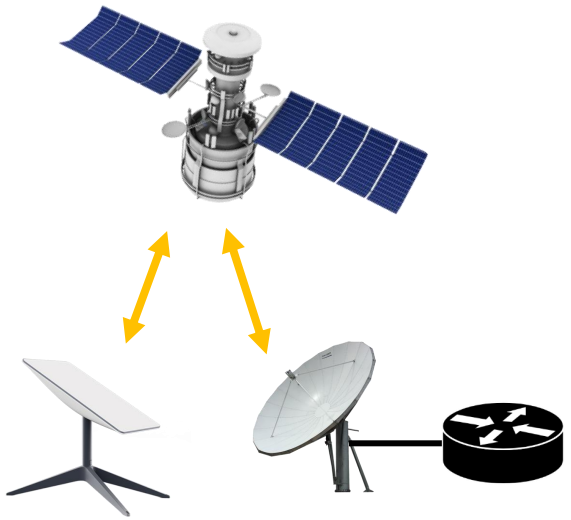
TWiT YouTube

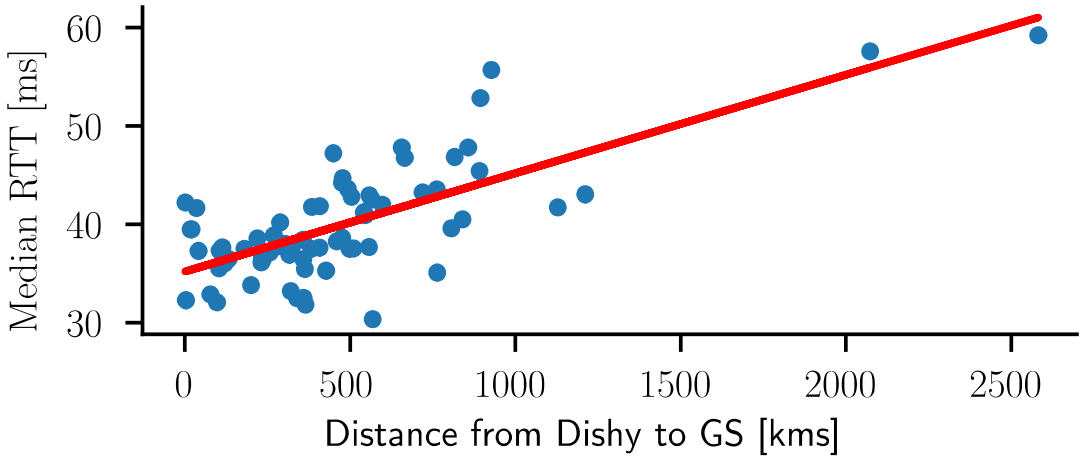
- Latencies during download are worse than upload: median > 200 ms
- Starlink is likely using Active Queue Management (AQM) strategies in the uplink

Global Performance

Bent-Pipe Performance

- Starlink maps each client to a specific PoP which does not change without complete link reconfiguration
- However, the user can be mapped to different ground stations, which can create non-optimal satellite-vs-ground link traversals





- ISL usage results in higher bent-pipe latencies but is **highly beneficial** for under-connected regions

Starlink network performance is highly dependent on ground infrastructure