Low Earth Orbiting (LEO) Satellite Networks

Past and Future Research Directions

Liz Izhikevich

Low Earth Orbit (LEO) Satellite Internet is immensely useful today

SPACE

Pentagon awards SpaceX with Ukraine contract for Starlink satellite internet

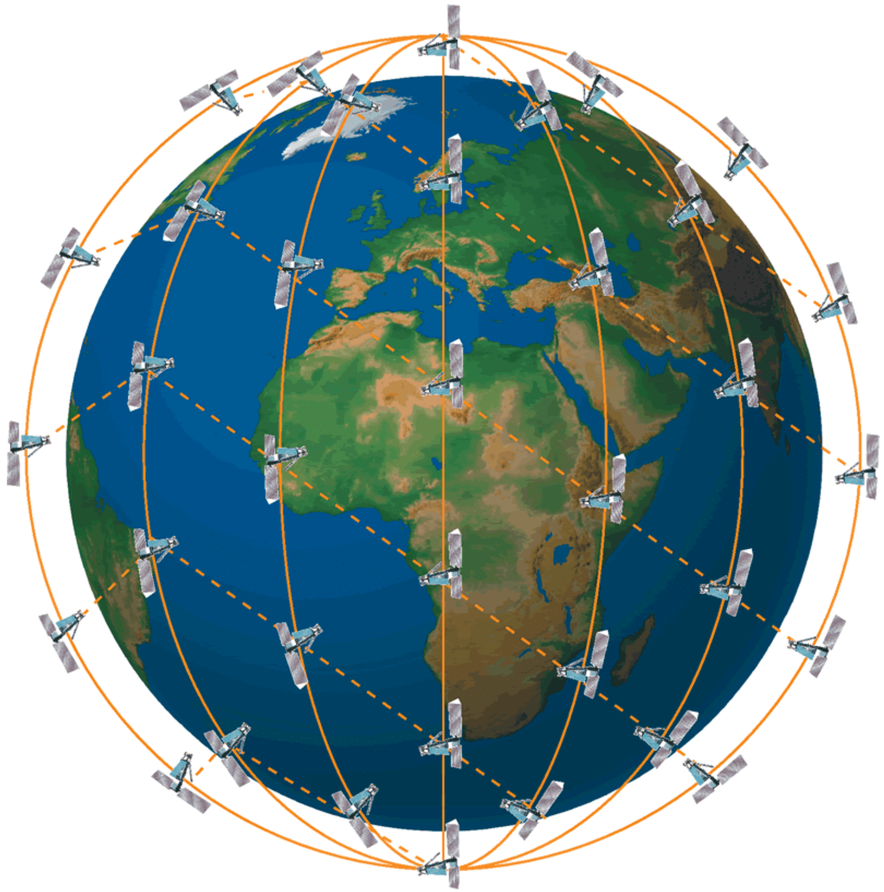
PUBLISHED THU, JUN 1 2023•12:54 PM EDT UPDATED THU, JUN 1 2023•1:53 PM EDT

Musk's Starlink connects remote Tonga villages still cut off after tsunami

By **Kirsty Needham**

February 23, 2022 12:05 AM PST · Updated a year ago

LEO Satellite Networks offer high coverage and low latency

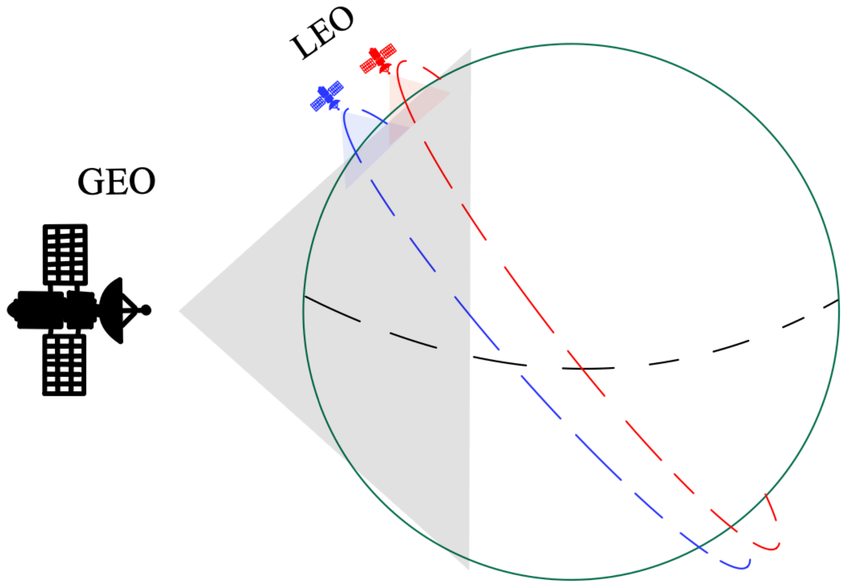


- LEO Satellites work in constellations (e.g., 100s-1000s satellites)
    - High Coverage
- LEO satellites orbit 300km -2000km from Earth
    - Low Latency: minimum RTT (~10ms), bounded by the speed of light

Internet latency standards < 100ms

Sağ, Emirhan & Kavas, Aktül. (2018). Modelling and Performance Analysis of 2.5 Gbps Inter-satellite Optical Wireless Communication (IsOWC) System in LEO Constellation. Journal of Communications. 13. 553-558. 10.12720/ jcm.13.10.553-558.

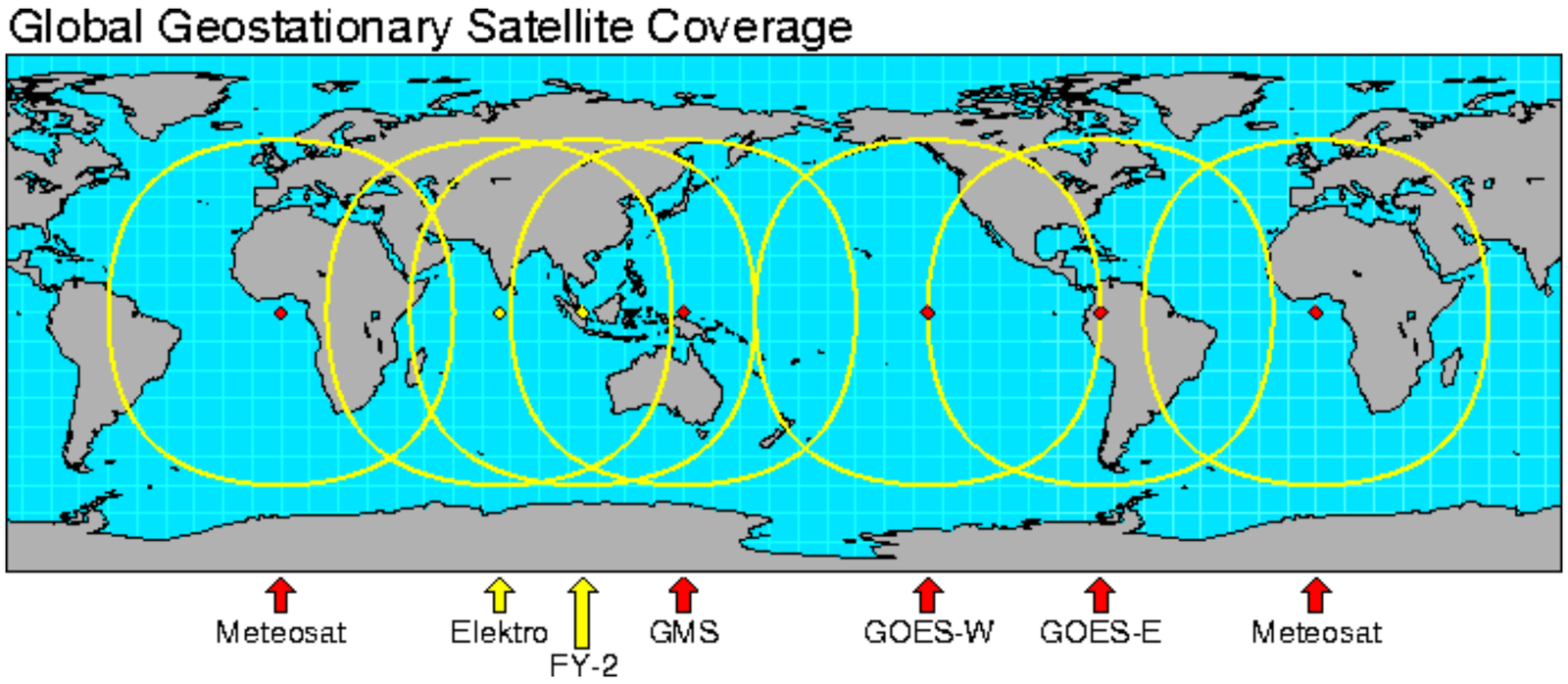
Satellite Internet is not new…for over 20 years we have used Geostationary Earth Orbits (GEO)



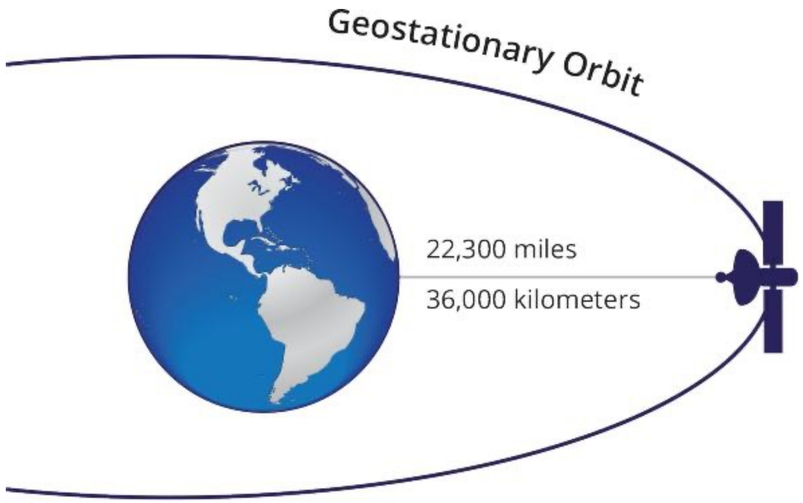
GEO: 3 km/s @ 36,000km altitude = 1 period of 24 hours = geostationary

LEO: 7 km/s @ 500km altitude = 1 period of 90 minutes = not geostationary

GEO Satellites provide wide and consistent coverage



GEO network round trip times extremely long

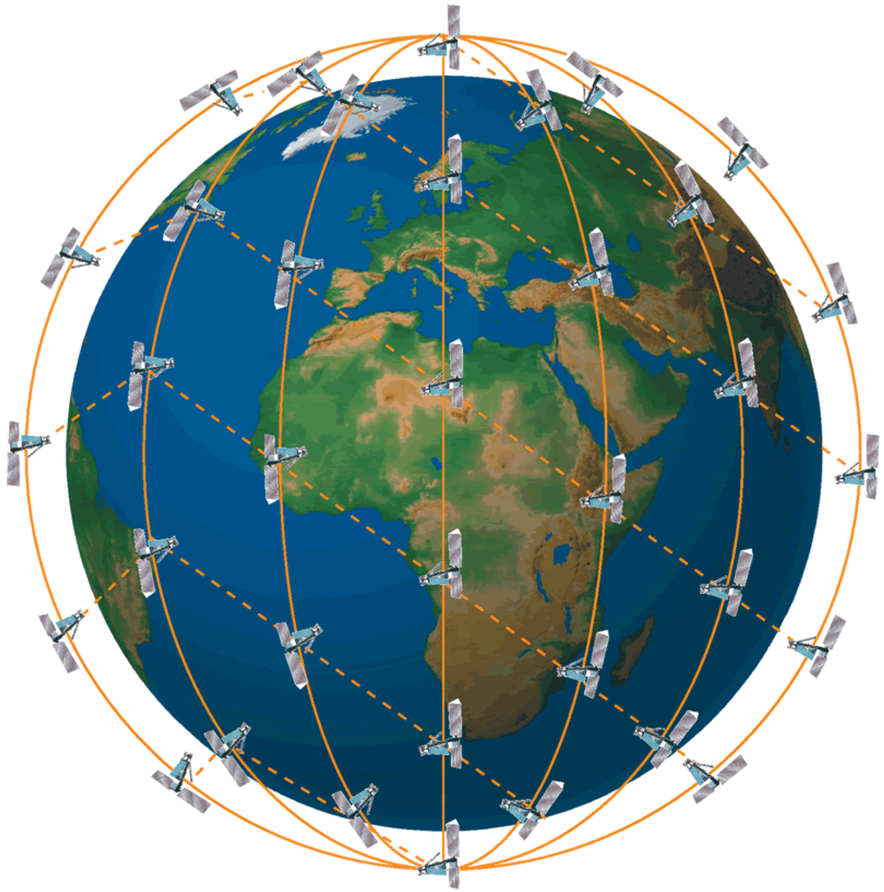


-Network speed bounded by speed of light

-minimum RTT of ~240ms

Internet latency standards < 100ms

LEO solves old problems, with new challenges



- LEO closer distance -> Lower RTT , reduced coverage
- LEO speed -> core infrastructure extremely mobile

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New LEO Satellite Networks Have Already Solved Key Challenges Today

STARLINK

amazon | project kuiper

Starlink @Starlink · 22h

Starlink is connecting more than 5M people with high-speed internet across 125 countries, territories and many other markets.

Thank you to all of our customers around the world!💫🌎❤️→ starlink.com/stories

OneWeb

OneWeb @OneWeb · May 20

We have lift off in California! Thanks to our colleagues at @SpaceX for a successful launch.

LEO Satellite Internet connects remote users

OneWeb

Contact us

OneWeb / Enterprise / Partnerships / Video - 18 Aug 2022

Customer Success Story - PDI in Alaska, USA

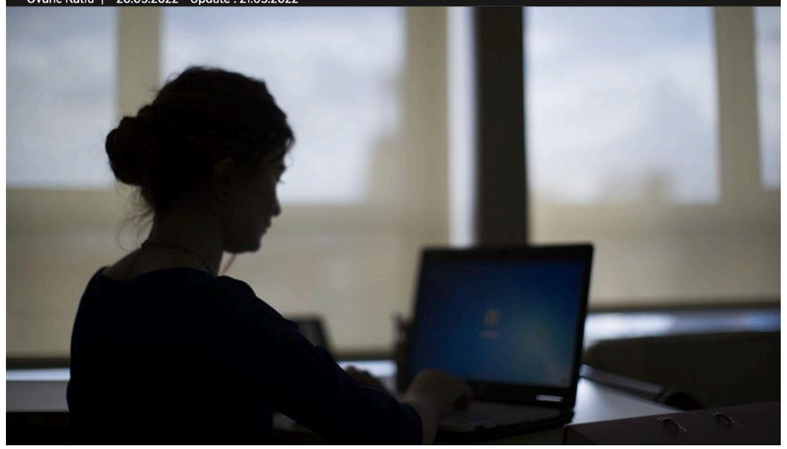
Meet the residents of Akiak Native Community in Alaska. Like many other communities in rural Alaska, Akiak has struggled with internet connectivity setbacks. Since the rollout of OneWeb commercial services in 2021, we have been connecting hard-to-reach places like Akiak, and changing lives.

ECONOMY

SpaceX to provide internet for 19K rural schools in Brazil, monitoring Amazon

Operated by SpaceX, Starlink provides internet access with more than 2,400 small satellites in low Earth orbit

Ovunc Kutlu | 20.05.2022 - Update : 21.05.2022



OneWeb / Partnerships / Press releases - 15 May 2023

OneWeb and iSAT Africa Pioneer New Solutions to Bridge the Digital Divide in Africa

New Distribution Partnership Agreement for high-speed, low-latency connectivity across Africa.

Starlink Is Now Connecting Remote Antarctic Research Camps to the Internet

After a successful test at a popular research station last September, Starlink is now connecting scientists working at remote field camps.

By **Kevin Hurler**

Published January 23, 2023 | Comments (6) | Alerts

LEO topologies cater towards specific user locations

OneWeb

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OneWeb / Enterprise / Partnerships / Video - 18 Aug 2022

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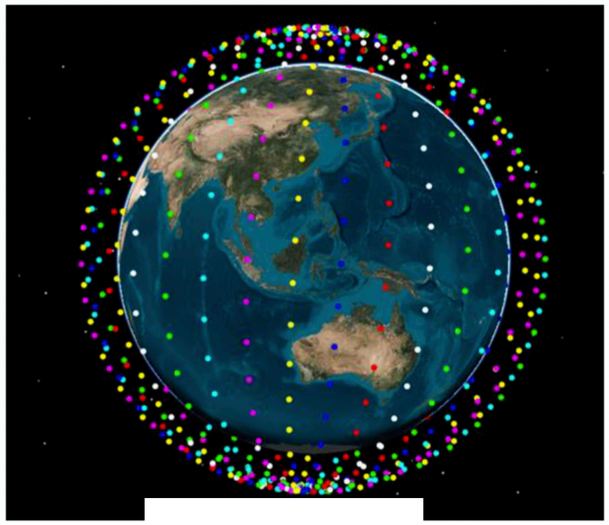

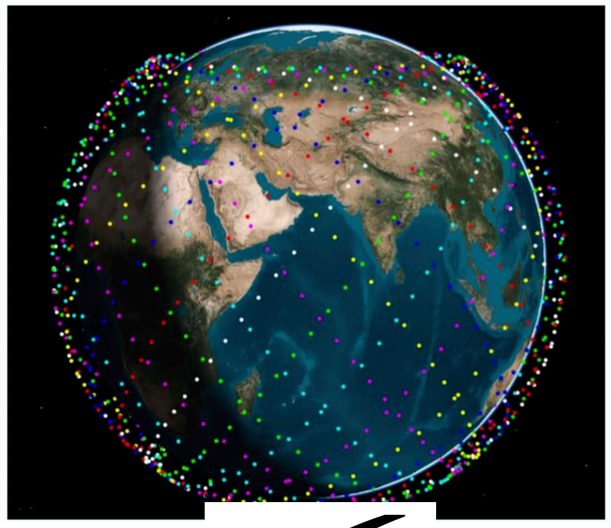

OneWeb

STARLINK

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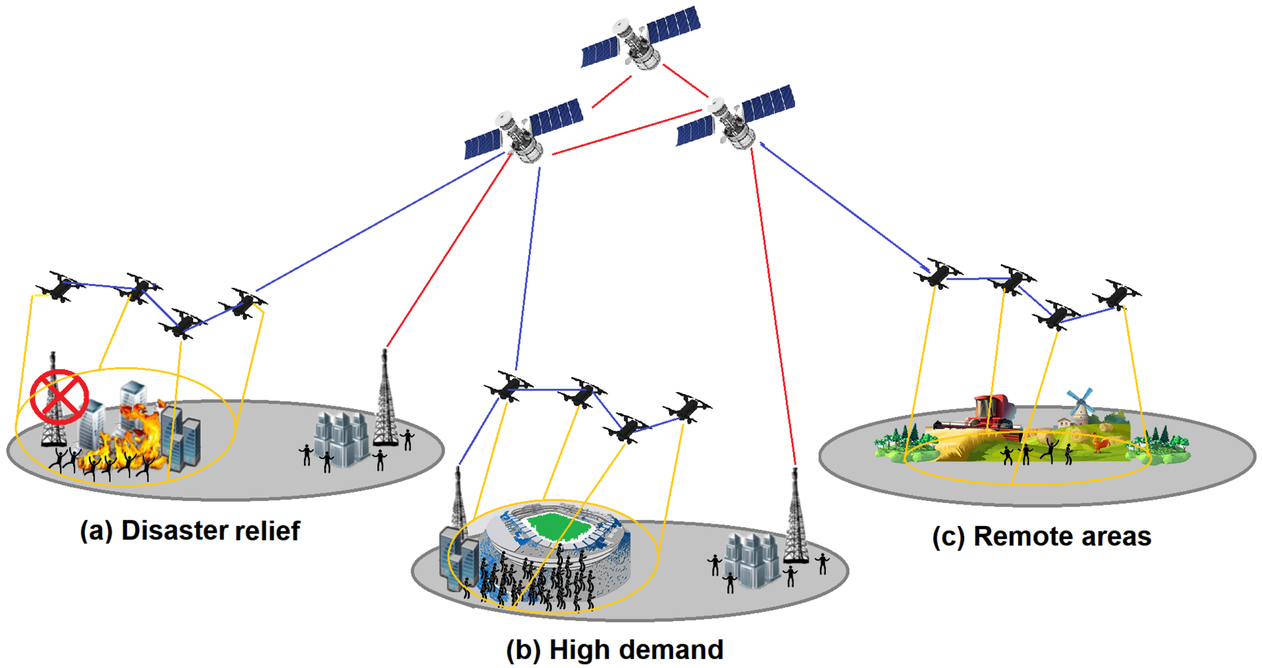
LEO Satellite Networks Surface Novel Research Directions

LEO mobility is unique relative to existing mobile networks

Compared to other mobile networks (e.g., cellular, drones)

- Core networking infrastructure is mobile
- Mobility is (theoretically) predictable
- Velocities are higher
- Distances are longer



Gholami, Anousheh, Usman A. Fiaz, and John S. Baras. "Drone-assisted communications for remote areas and disaster relief." *arXiv preprint arXiv:1909.02150* (2019).

Prior work has started to investigate different facets of LEO networks:

- How frequently do users experience outages or long latencies due to unavailable LEO satellites?
- What is the most effective way to route traffic across LEO constellations?
- How vulnerable are LEO constellations to congestion?
- How does network performance compare across different LEO constellation topologies?

Existing Techniques to Measure LEO Satellite Networks Are Restrictive

Existing Methodologies to Understand LEO Satellite Networks Are Restrictive

Option 1. Deploy Physical Hardware

Financial and Coverage Barrier

Fig. 17. A Gen-1 dish secured on the roof of a minivan.

Existing Methodologies to Understand LEO Satellite Networks Are Restrictive

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Fig. 17. A Gen-1 dish secured on the roof of a minivan.

Option 2. Recruit Existing Hardware

Labor Consuming and Coverage Barrier

Existing Methodologies to Understand LEO Satellite Networks Are Restrictive

Option 1. Deploy Physical Hardware

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Fig. 17. A Gen-1 dish secured on the roof of a minivan.

Option 2. Recruit Existing Hardware

Labor Consuming and Coverage Barrier

Option 3. Theoretical Models based on Physics

Not Validated and Slow

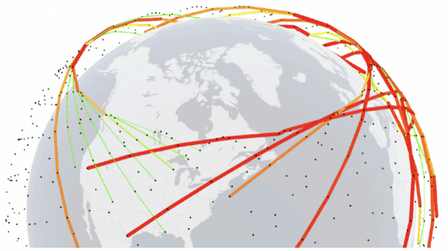


Fig. 15: *Constellation-wide utilization.* *On Kuiper, the trans-atlantic paths are highly congested for our tested traffic matrix. The red / thick ISLs are heavily utilized, while green / thin ISLs have minimal traffic. ISLs with no traffic are excluded.*

Democratizing LEO Satellite Network Measurement

Liz Izhikevich
Manda Tran, Katherine Izhikevich, Gautam Akiwate, Zakir Durumeric

LEO-HitchHiking is a new system that…

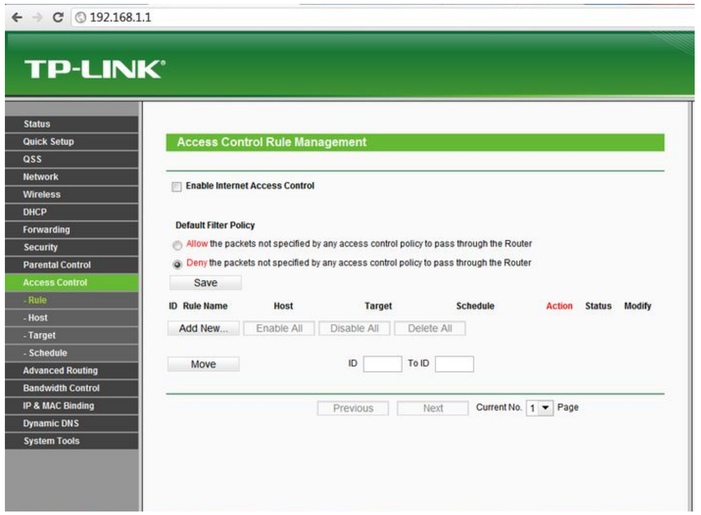
- Requires no special hardware or recruitment
- Accurately measures performance
- Can measure wherever satellite clients are already located across the globe

HitchHiking's *key observation* is publicly exposed satellite-routed devices can reveal satellite network architecture and performance

Thousands of LEO Customers Expose Services

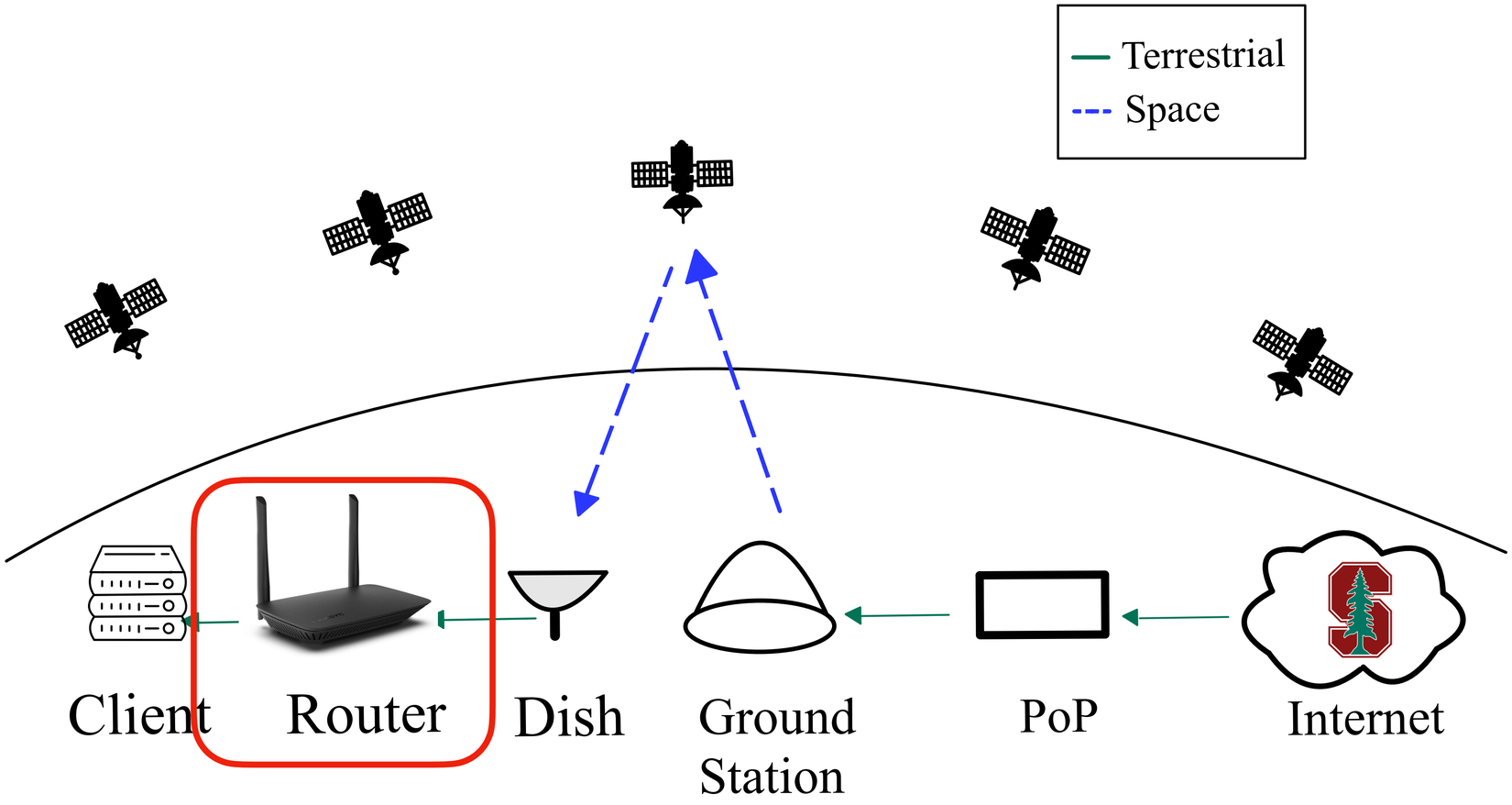
STARLINK

OneWeb

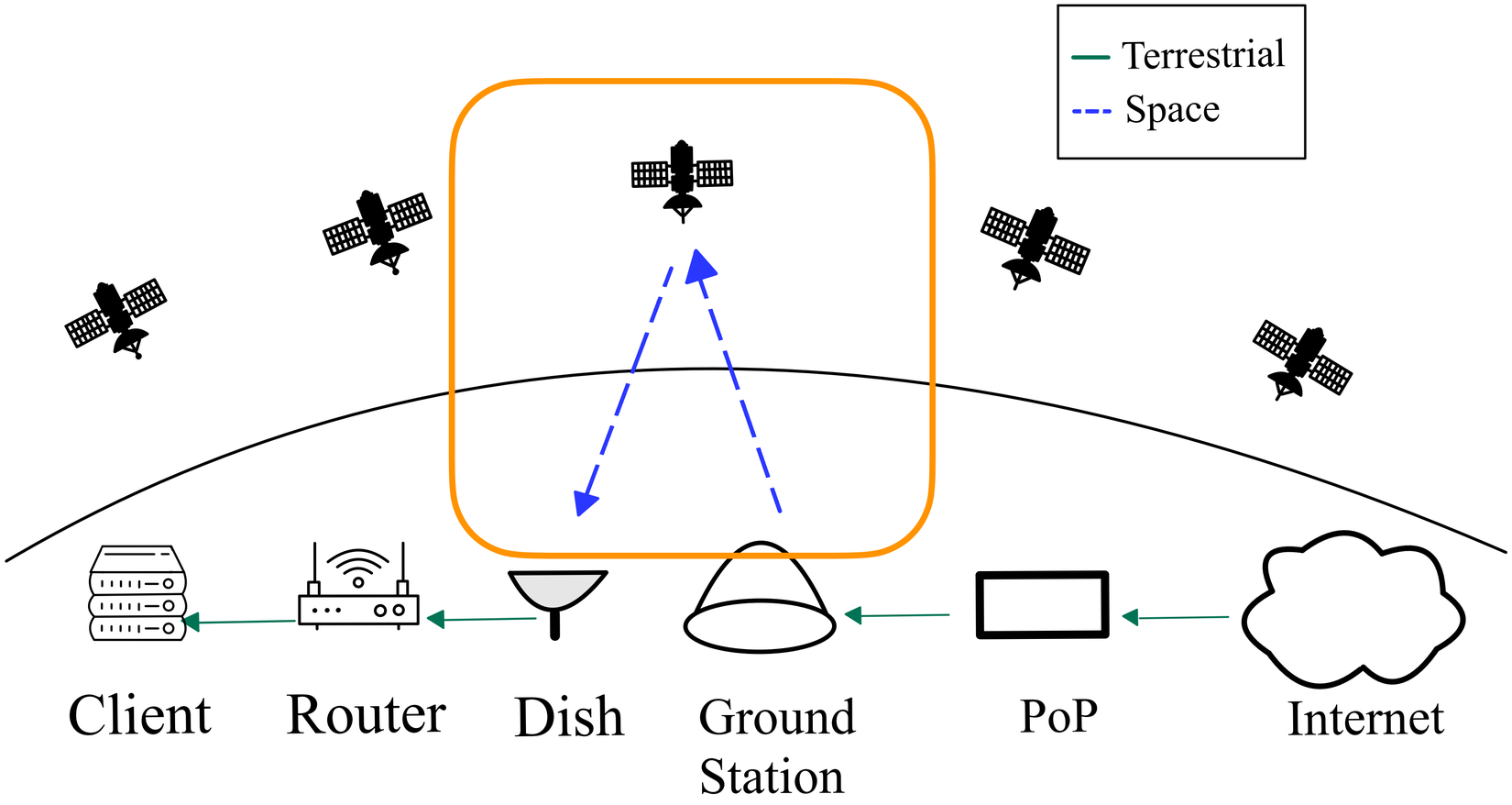


HTTP / Port 22000

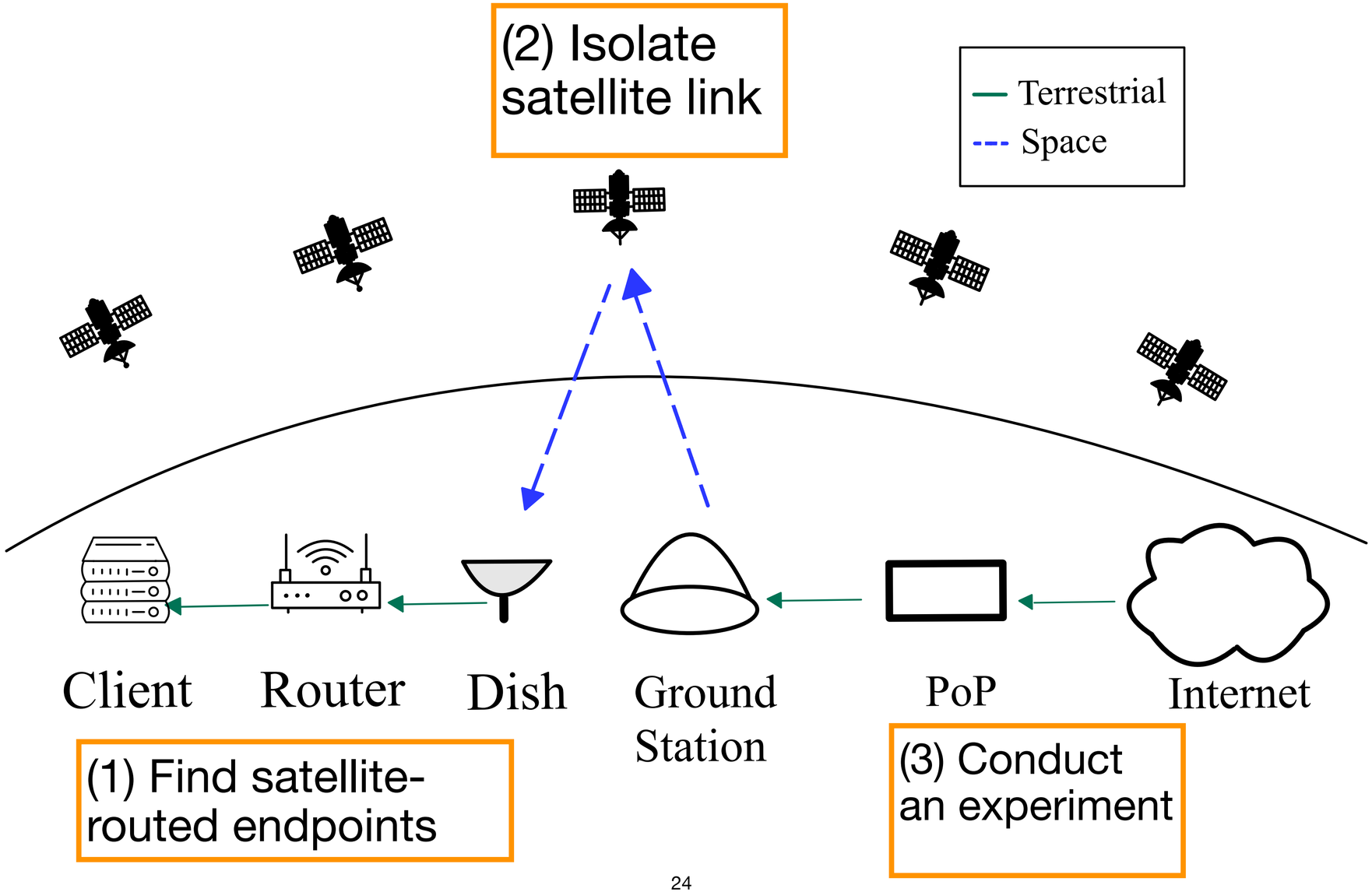
Exposed services allow us to use LEO satellite connectivity



HitchHiking's goal is to analyze the performance of the satellite link



HitchHiking must use an “outside-in” methodology

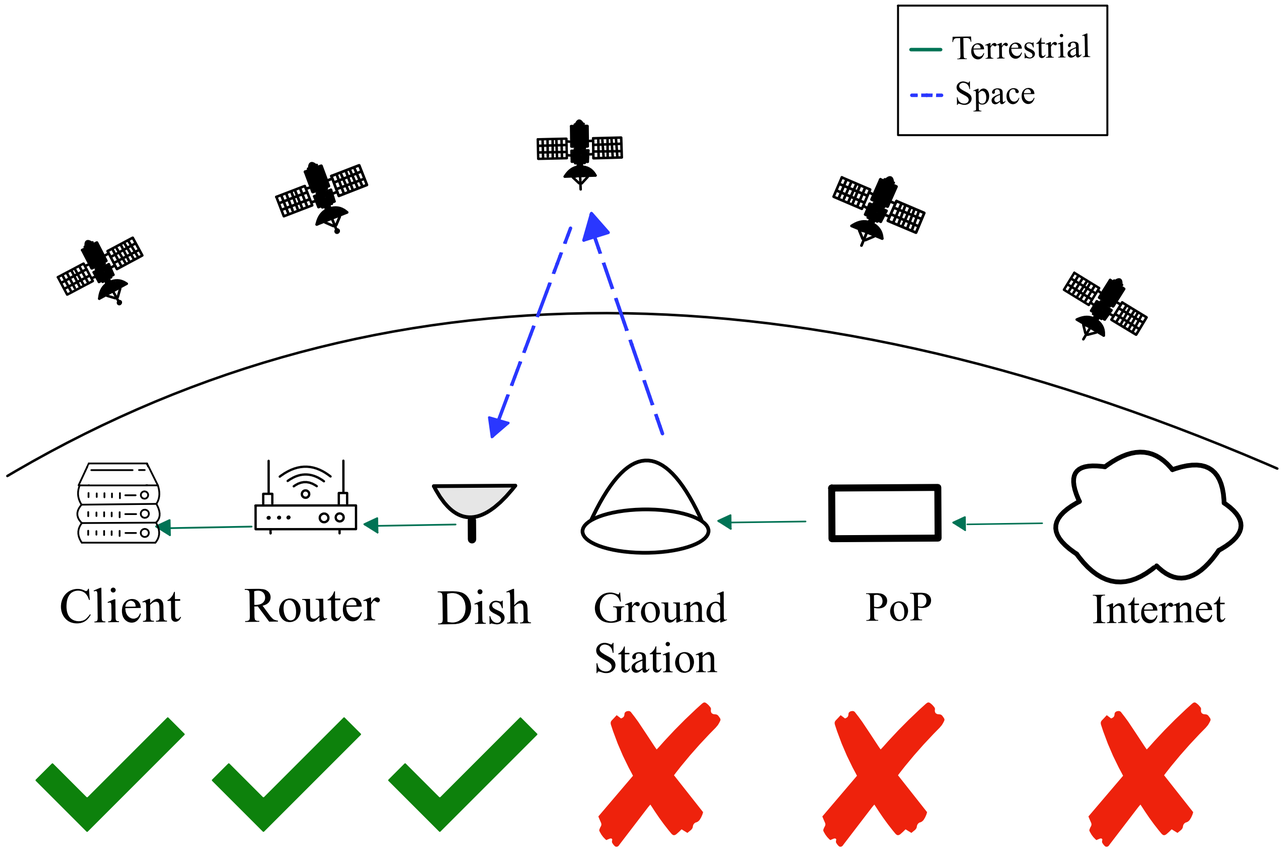


Step 1. Find Satellite Routed Endpoints

A. Identify Networks that house LEO-routed services

Step 1. Find Satellite Routed Endpoints

B. Find all *satellite-routed* services hosted in LEO networks



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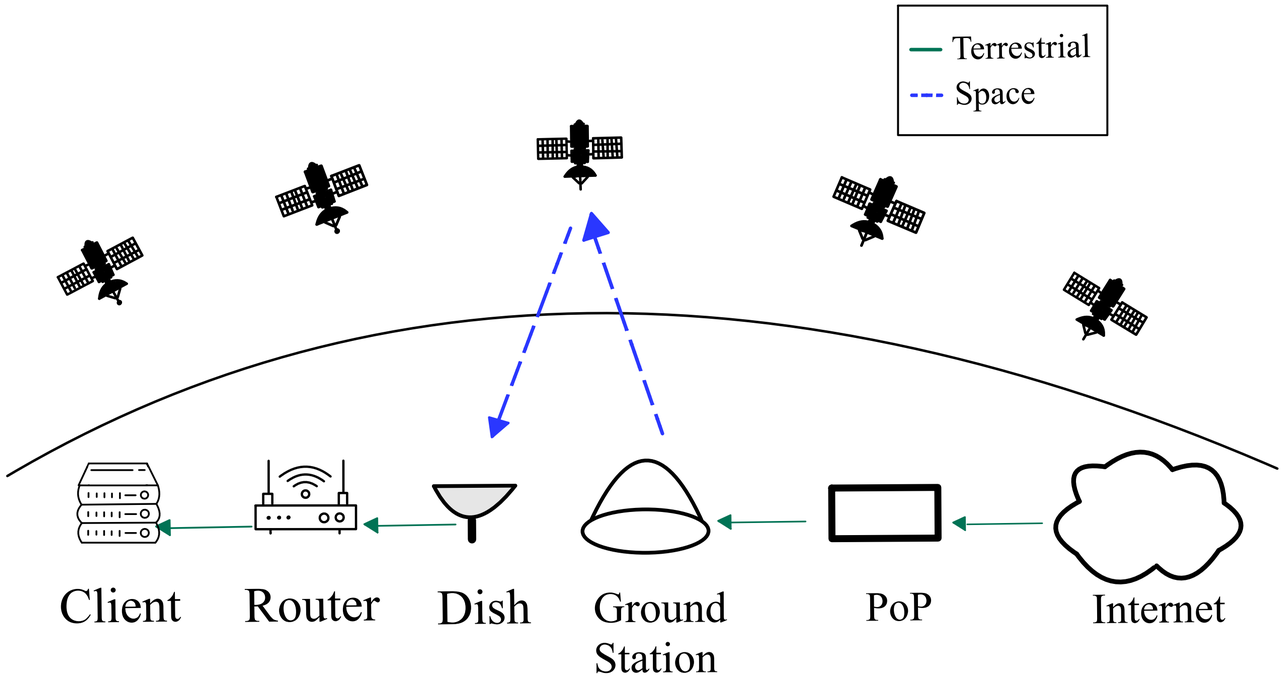


SHODAN

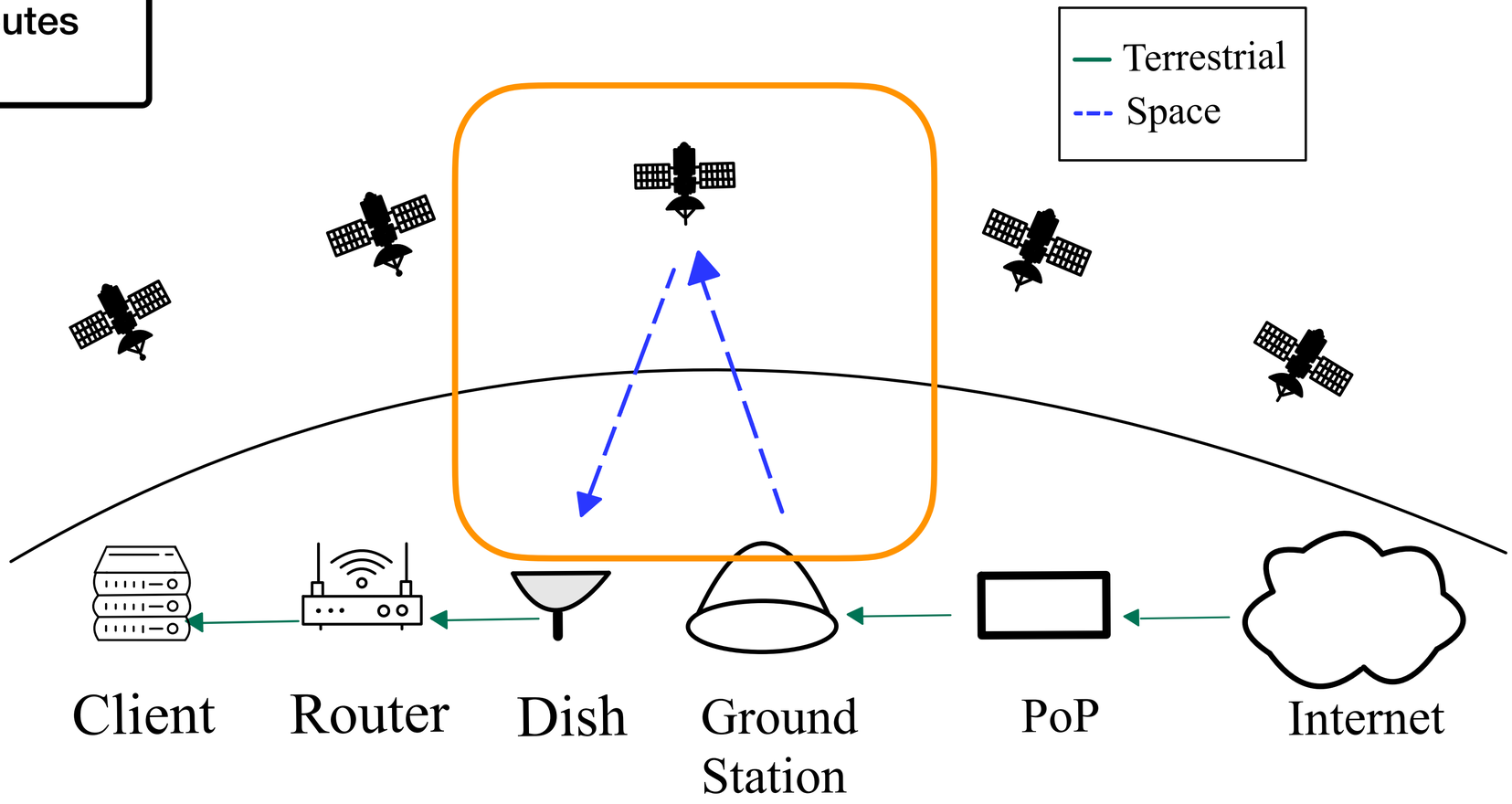
censys

Publicly available Internet service search engine reveal

Customer Services

Step 2. Isolate Satellite Link

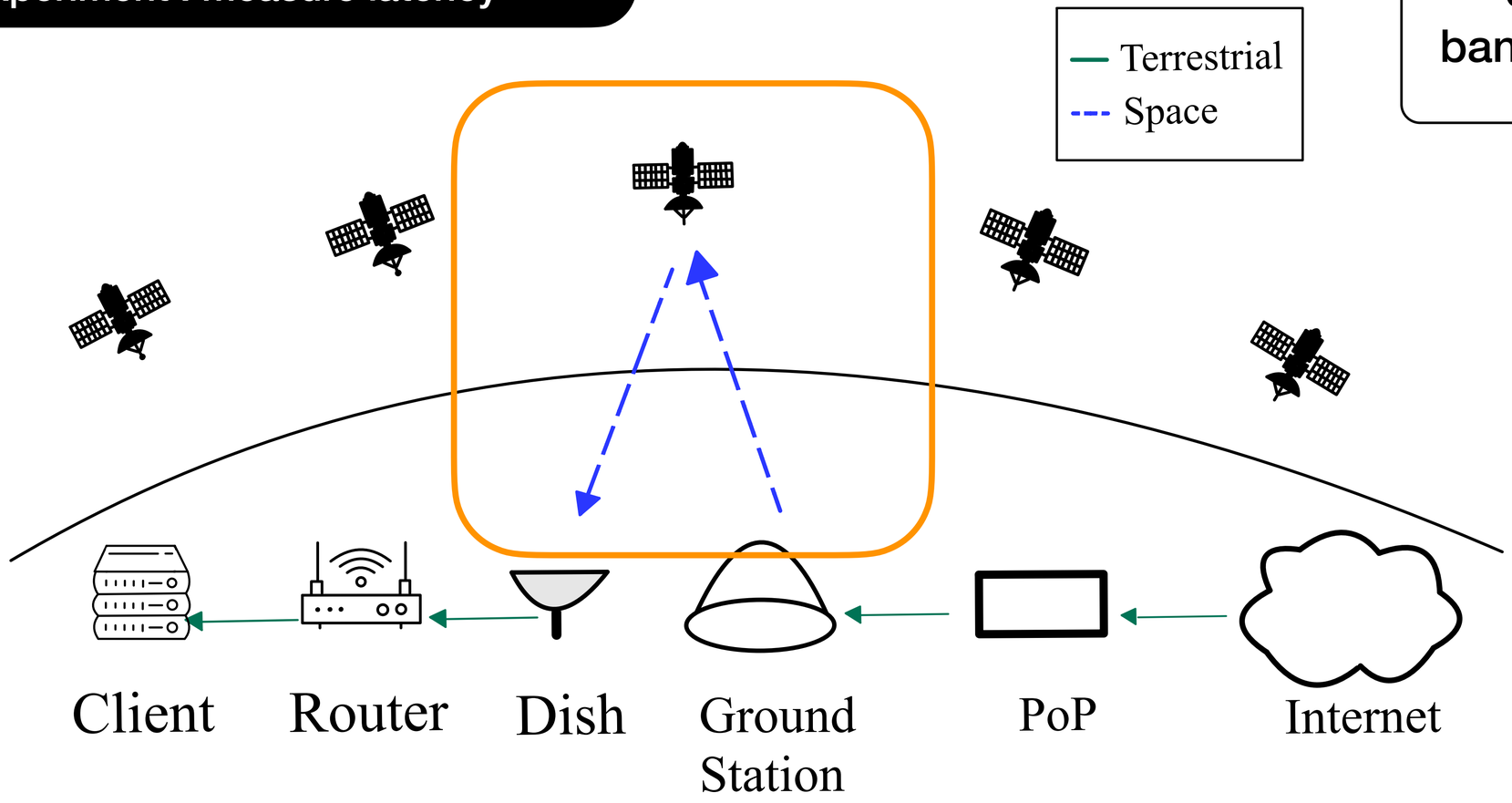
Custom traceroutes



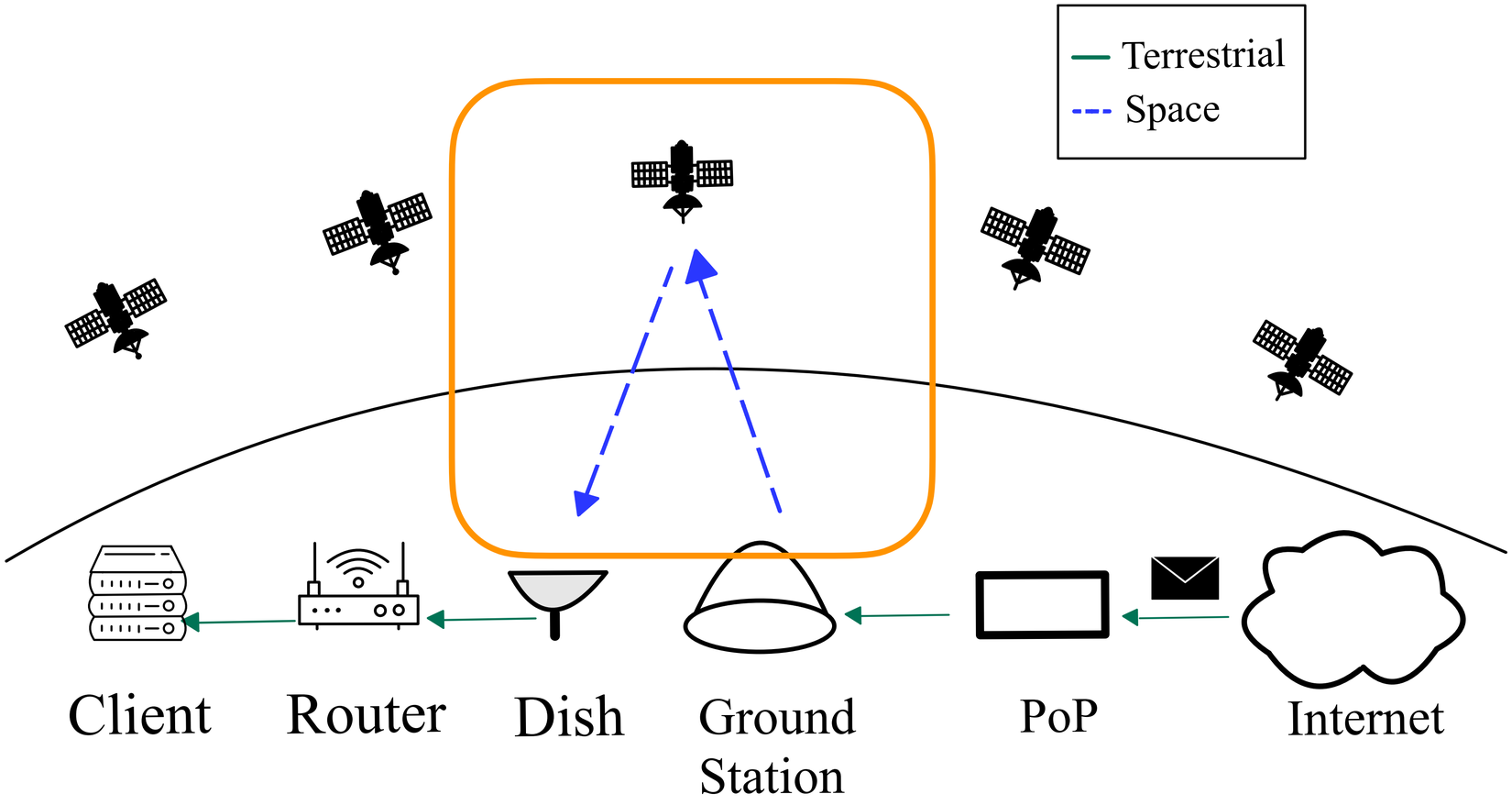
Step 3. Conduct an Experiment

HitchHiking can adapt to measure outages, bandwidth, etc

Example experiment : measure latency



Using HitchHiking To Measure Latency



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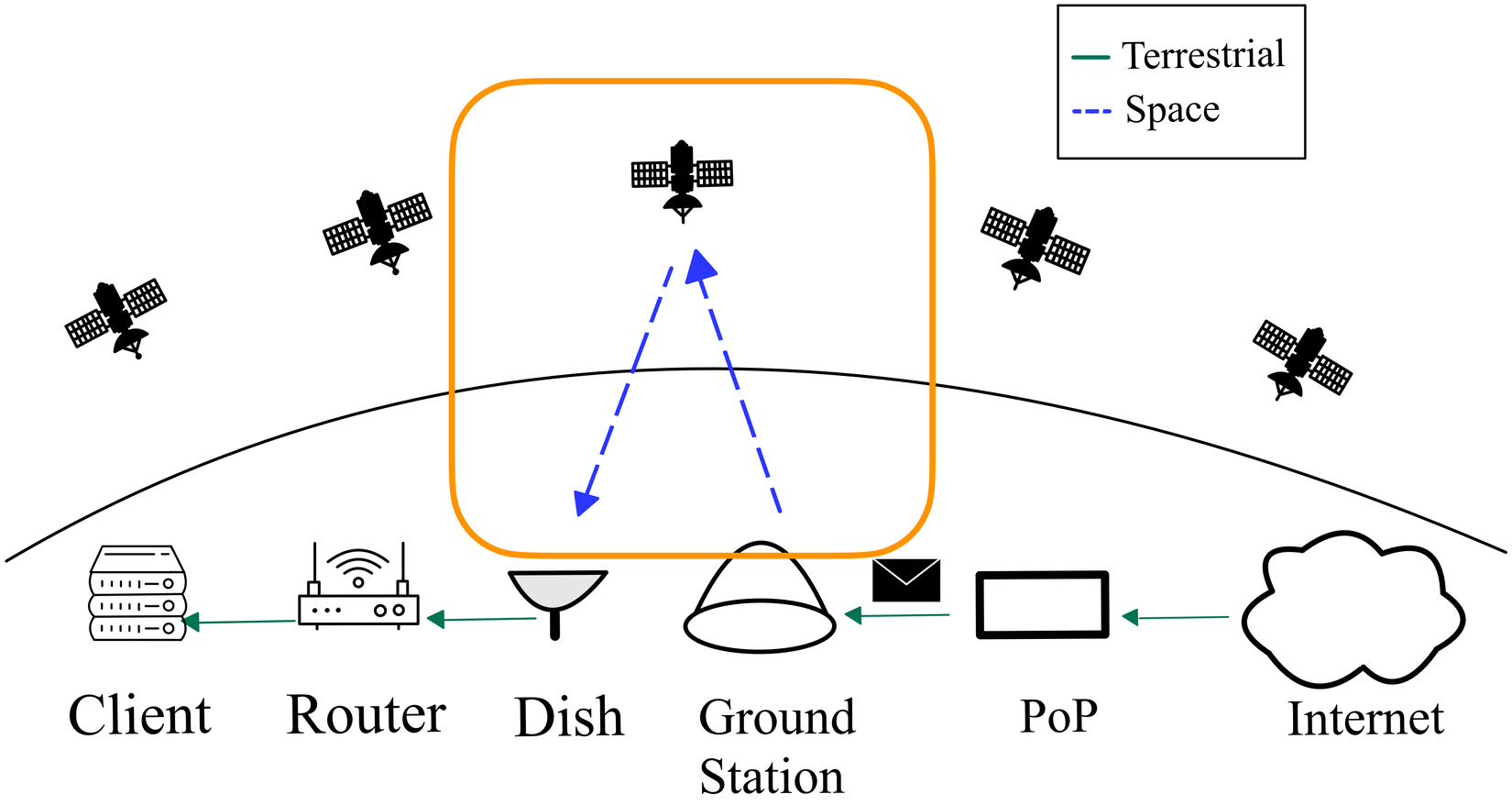

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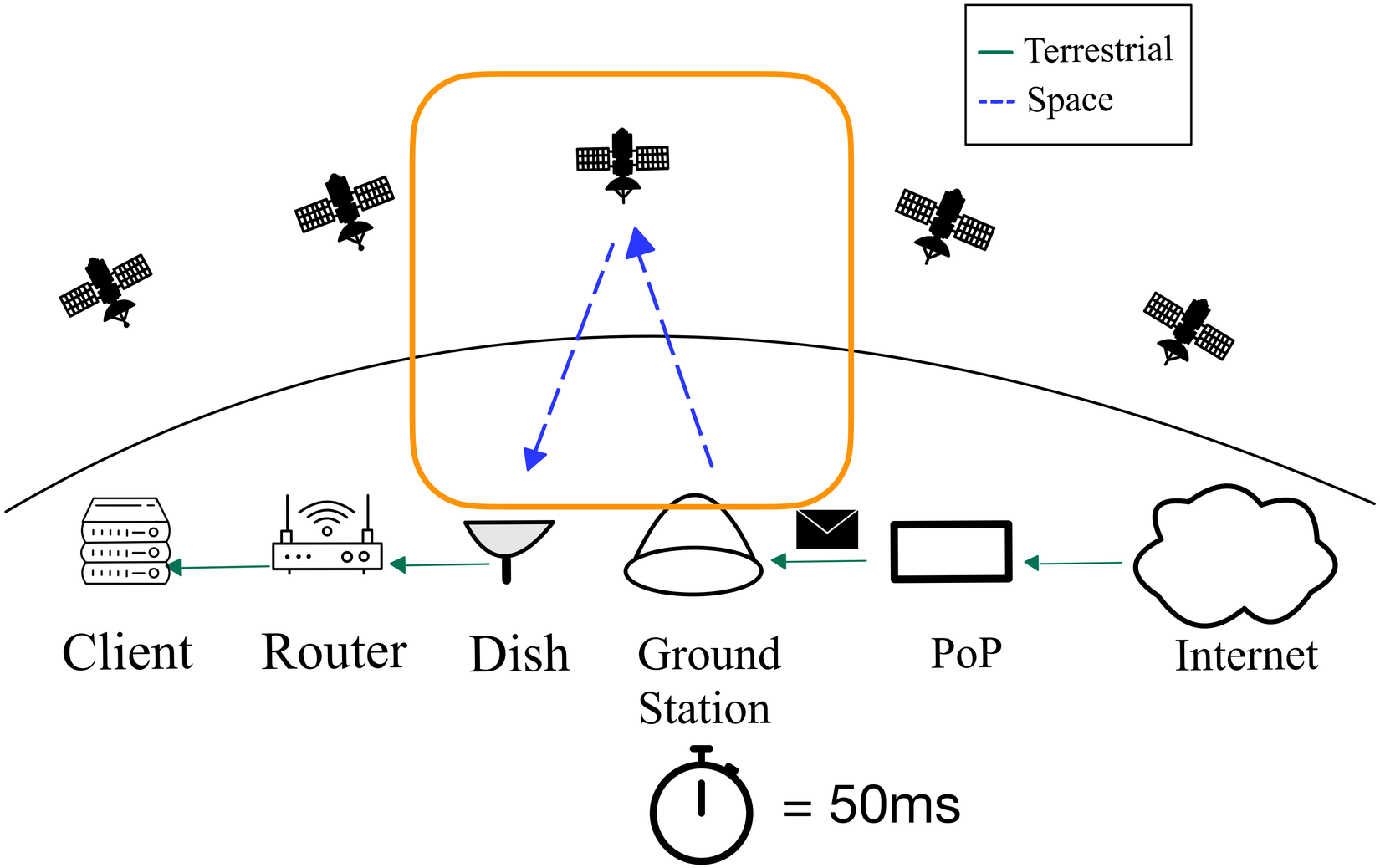

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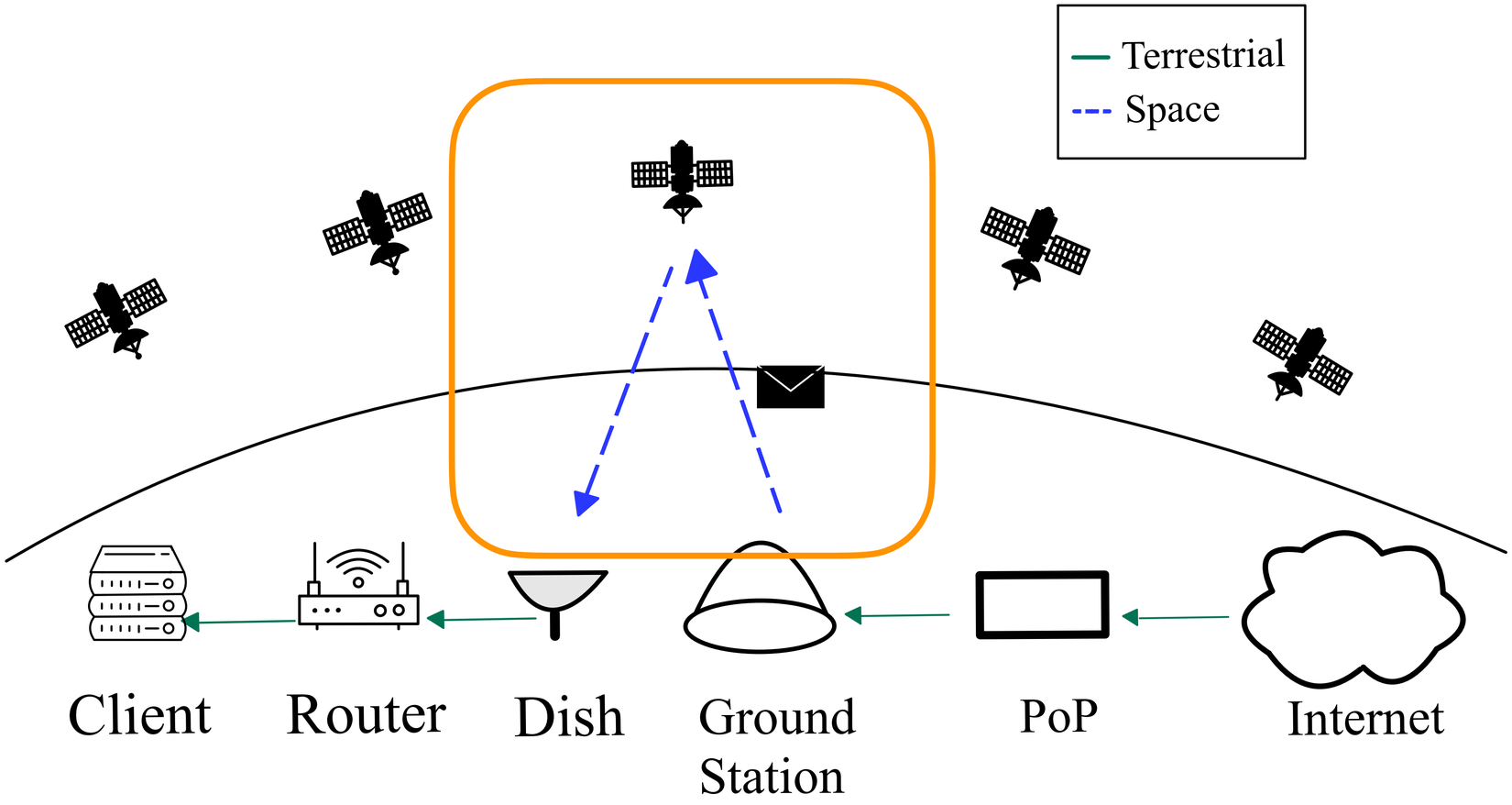

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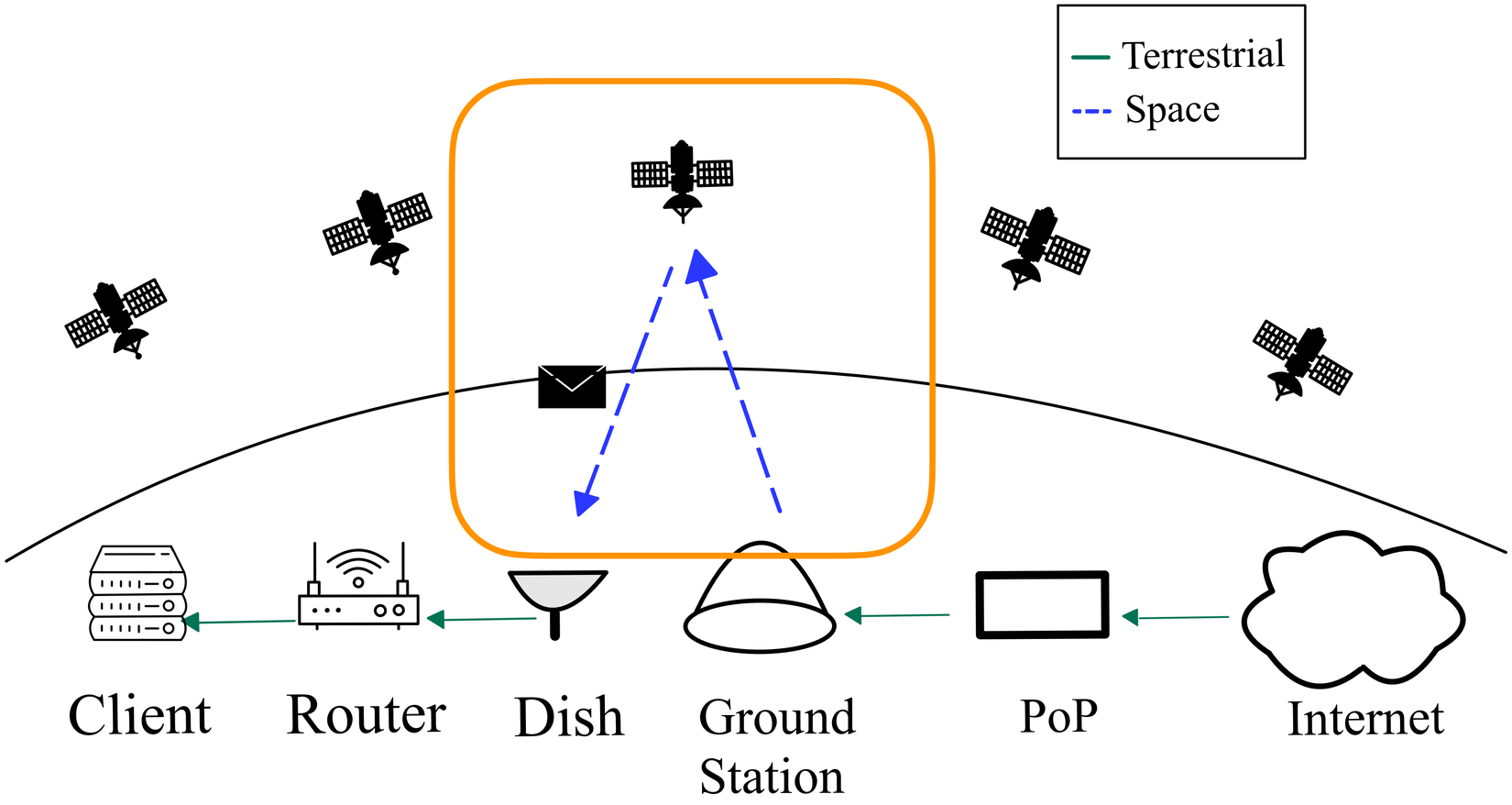

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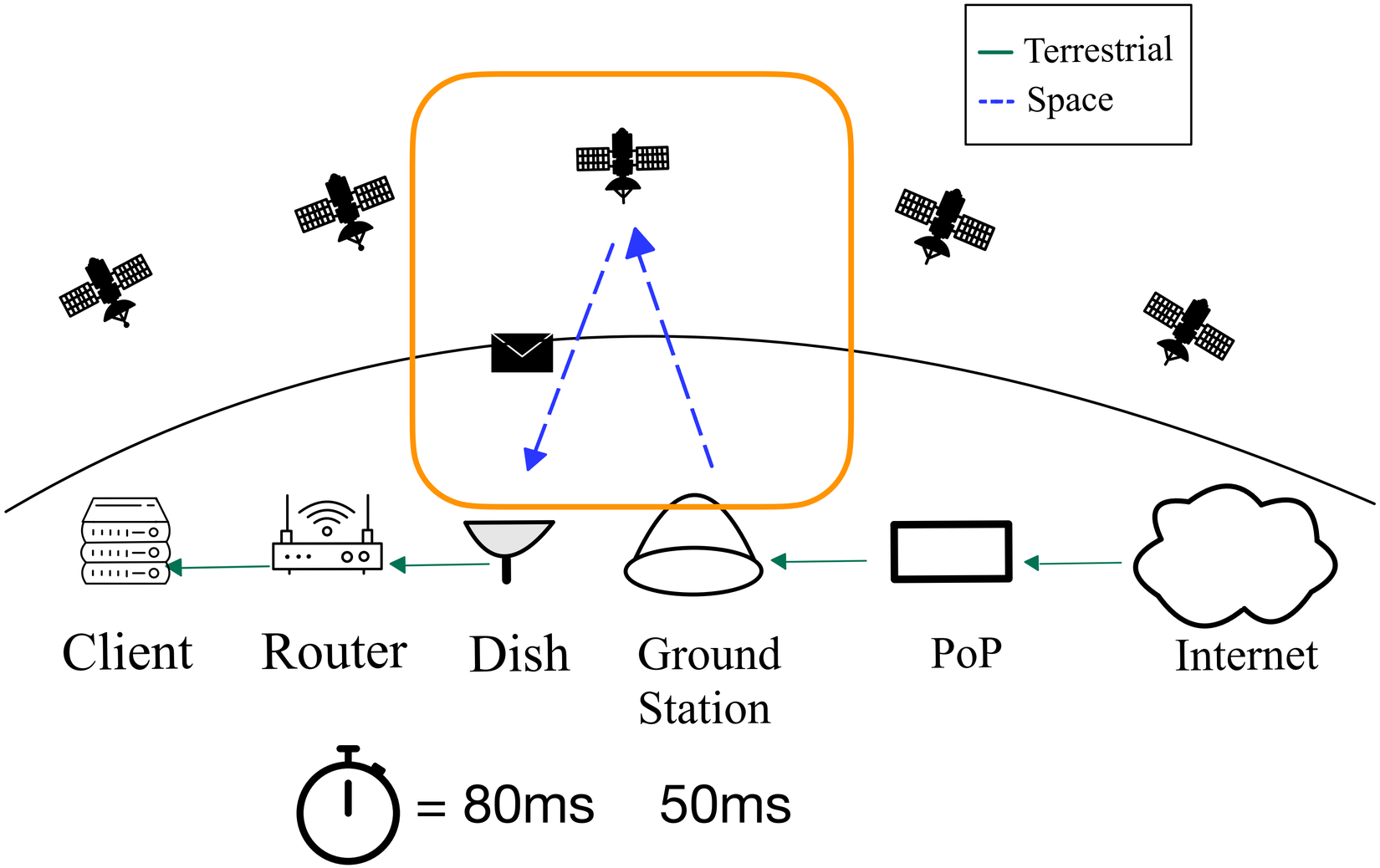

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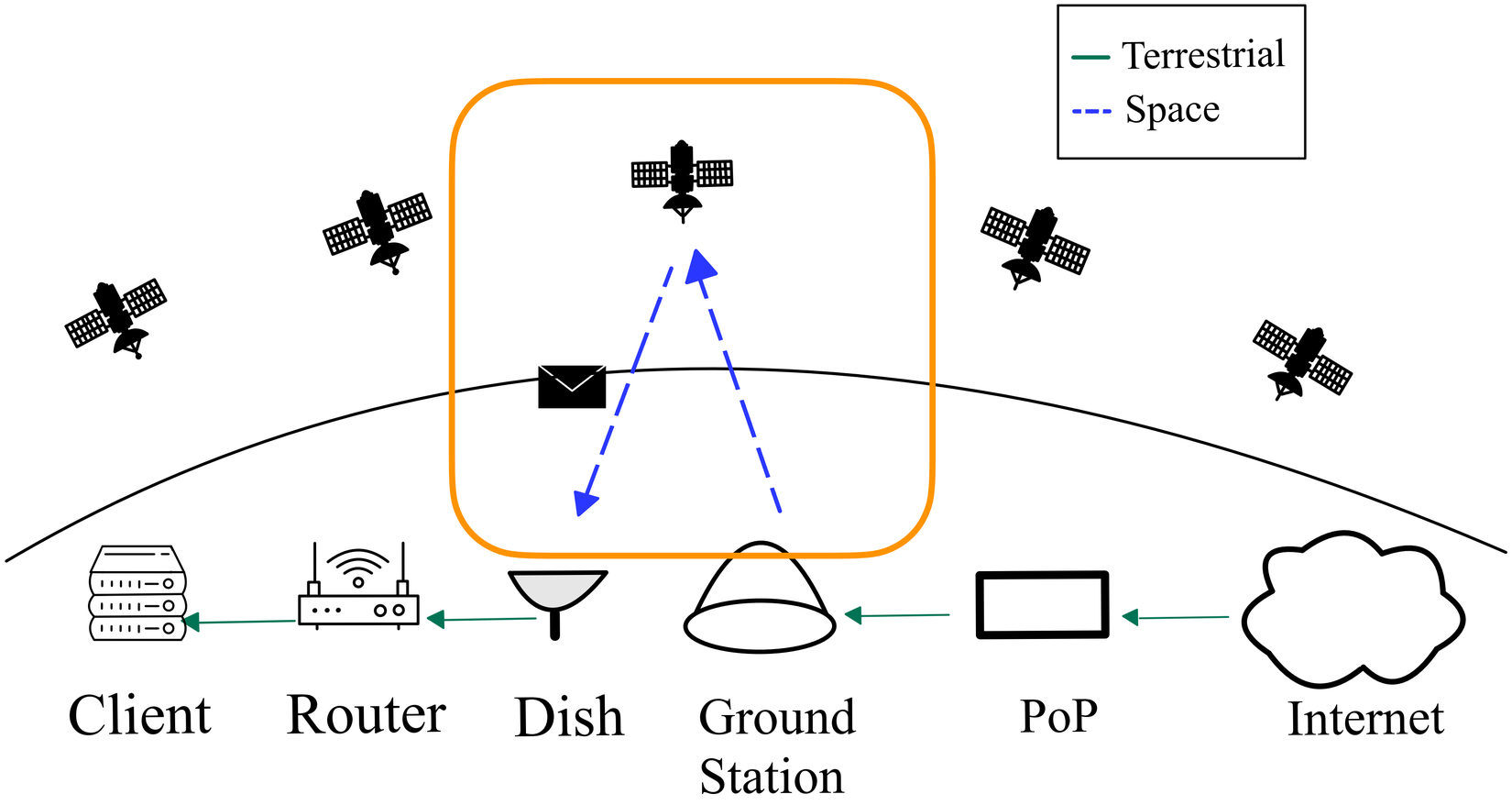
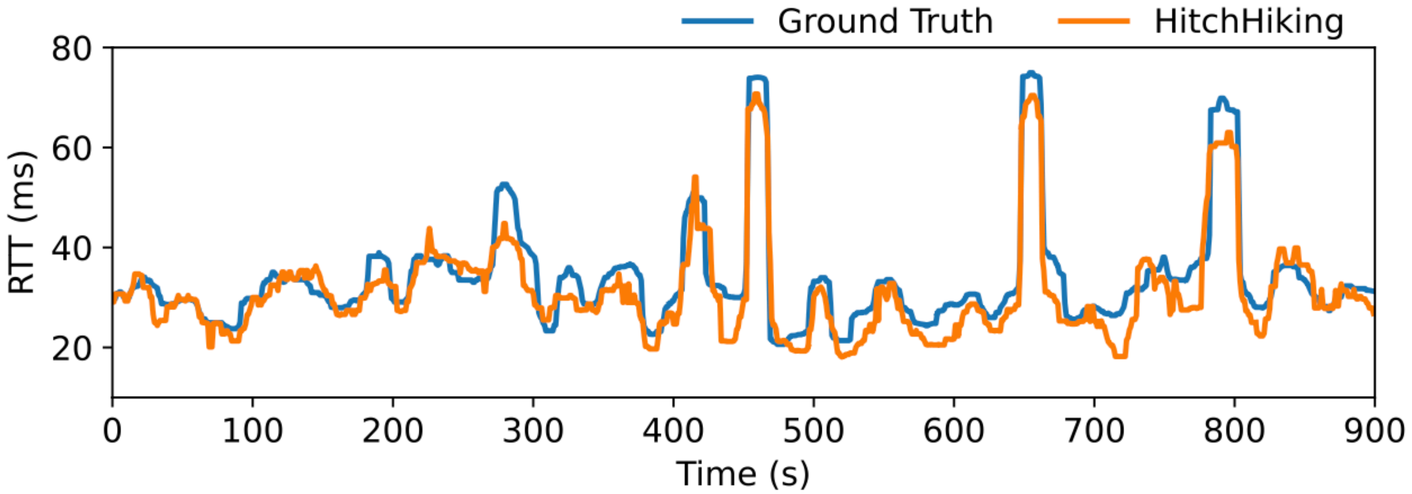


80ms - 50ms = 30ms latency

HitchHiking accurately estimates ground truth



HitchHiking

HitchHiking measures all over the world

Location	# Customers
Seattle, Washington	353
Frankfurt, Germany	261
Chicago, Illinois	251
Atlanta, Georgia	243
Dallas, Texas	242
New York City, New York	223
Los Angeles, California	222
Sydney, Australia	204
Denver, Colorado	141
Heathrow, England	118
Madrid, Spain	52
Santiago, Chile	32
Perth, Australia	29
Lagos, Nigeria	20
Mexico City, Mexico	20
Tokyo, Japan	15
Auckland, New Zealand	15
San Paulo, Brazil	12
Bogota, Colombia	10
Lima, Peru	7
Manila, Philippines	3
Total	2473

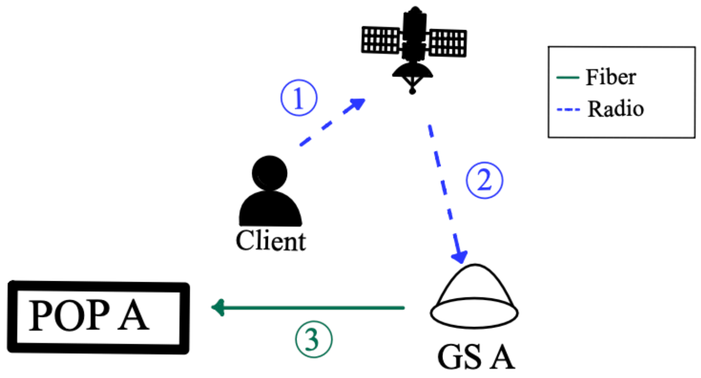
STARLINK

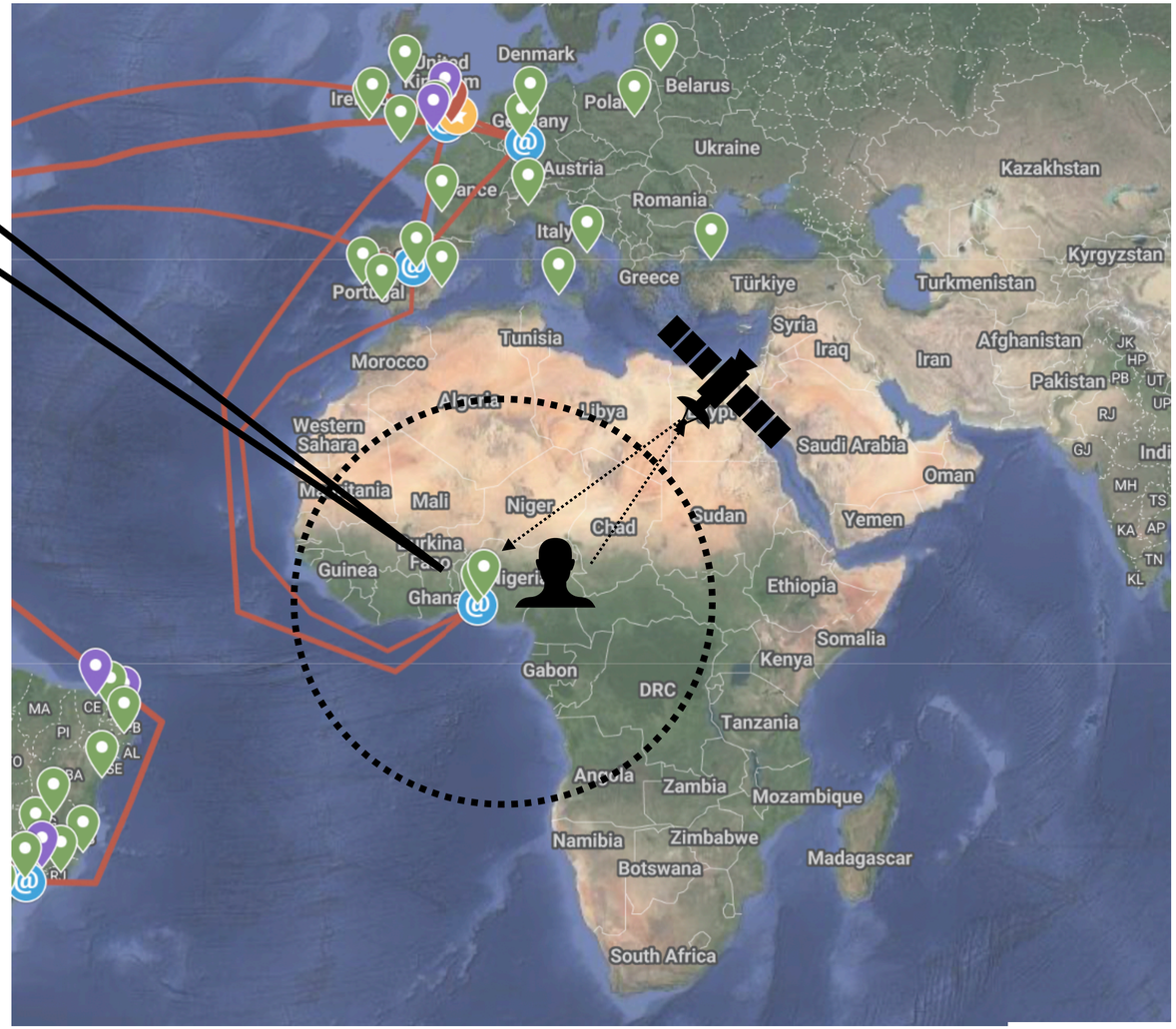
2023 >2K
2025 >30K

A World-Wide Perspective on Starlink Latencies

HitchHiking allows us to study customers anywhere in the world

We study Nigerian customers, which have minimal variables that influence packet routing



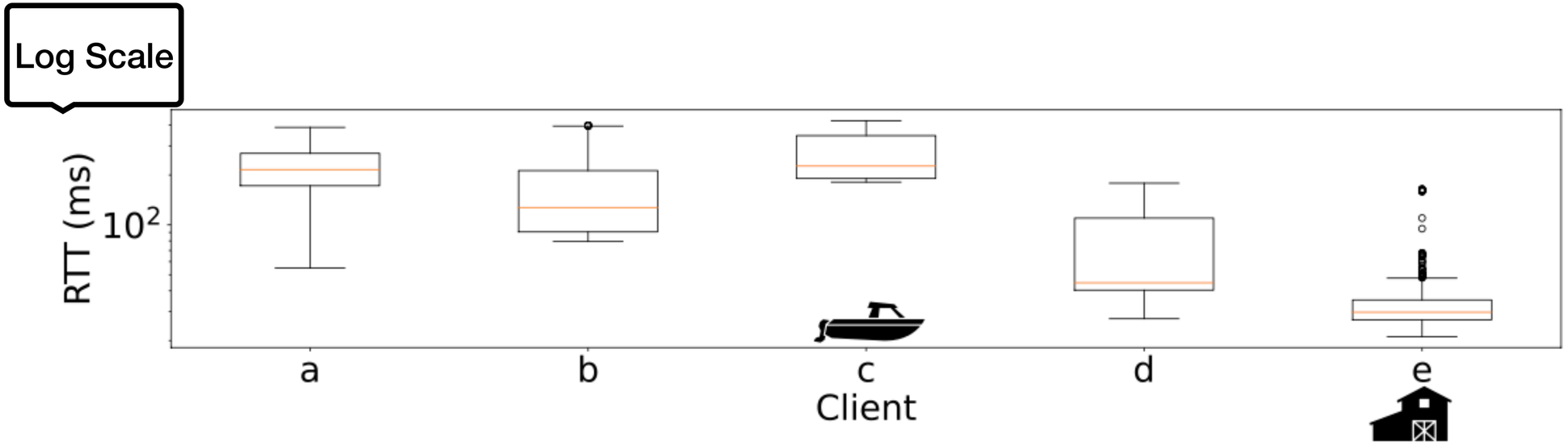


@ POP

Ground Station

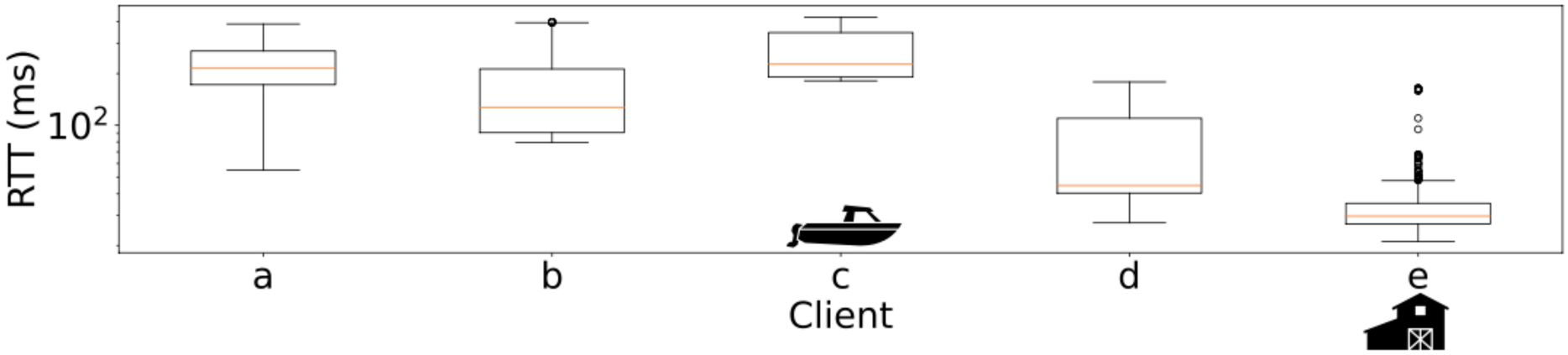
STARLINK

Minimum customer latency is correlated with their distance to POP



(a) Nigeria POP Per-Client Latency

Minimum customer latency is correlated with their distance to POP

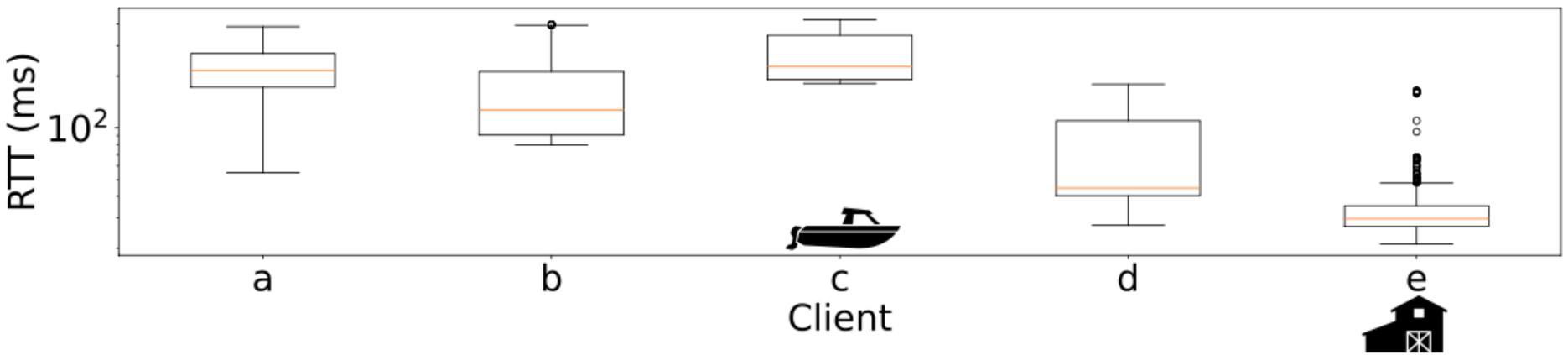


(a) Nigeria POP Per-Client Latency

TLS certificate fingerprints to a Nigerian Palm Oil Farm

Minimum customer latency is correlated with their distance to POP

TLS certificate fingerprints to a sports fisher yacht, which MarineTraffic.com locates to the Seychelles Islands



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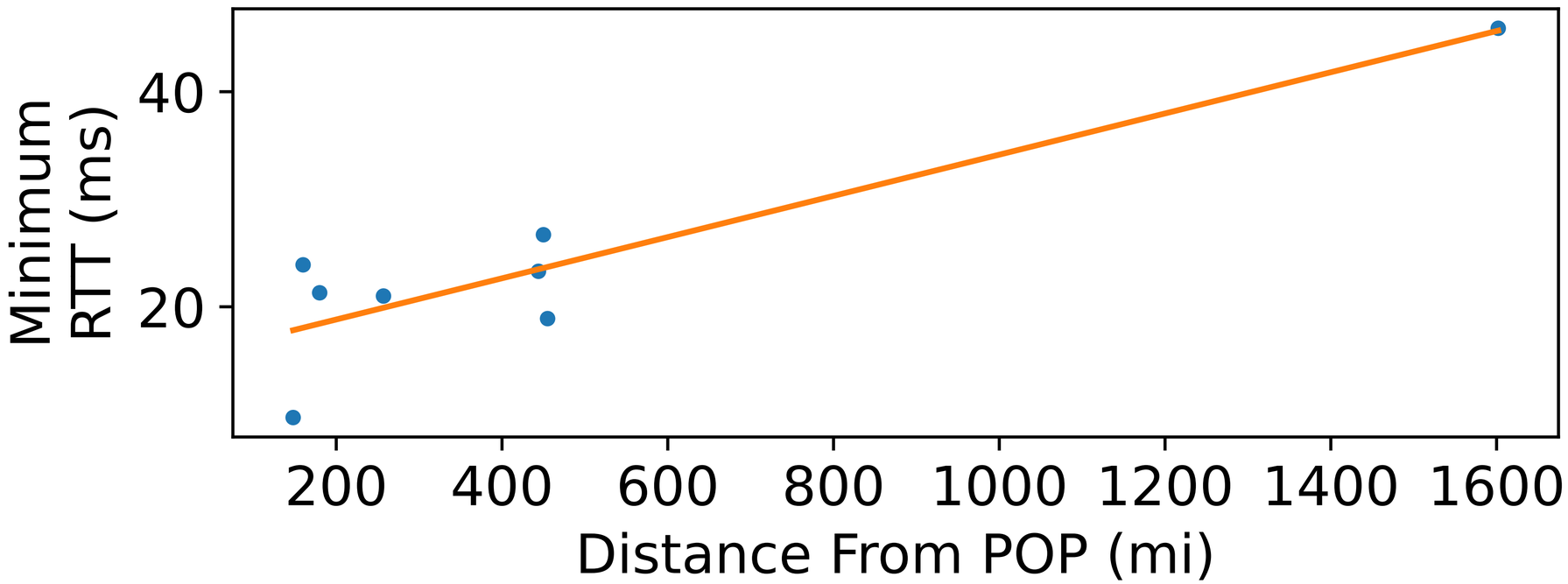
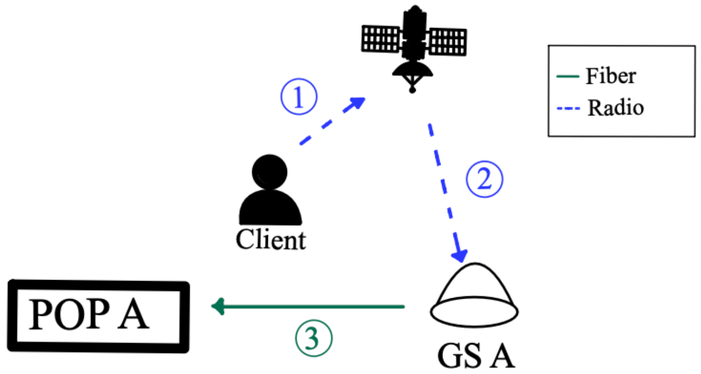
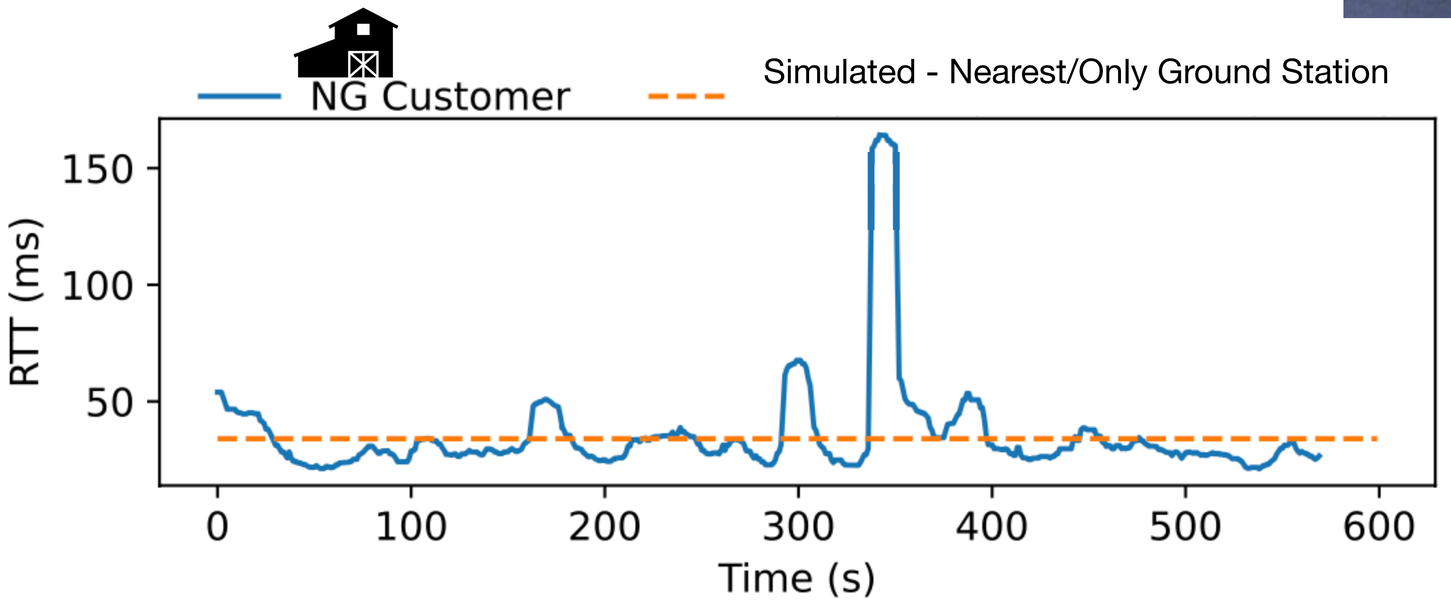
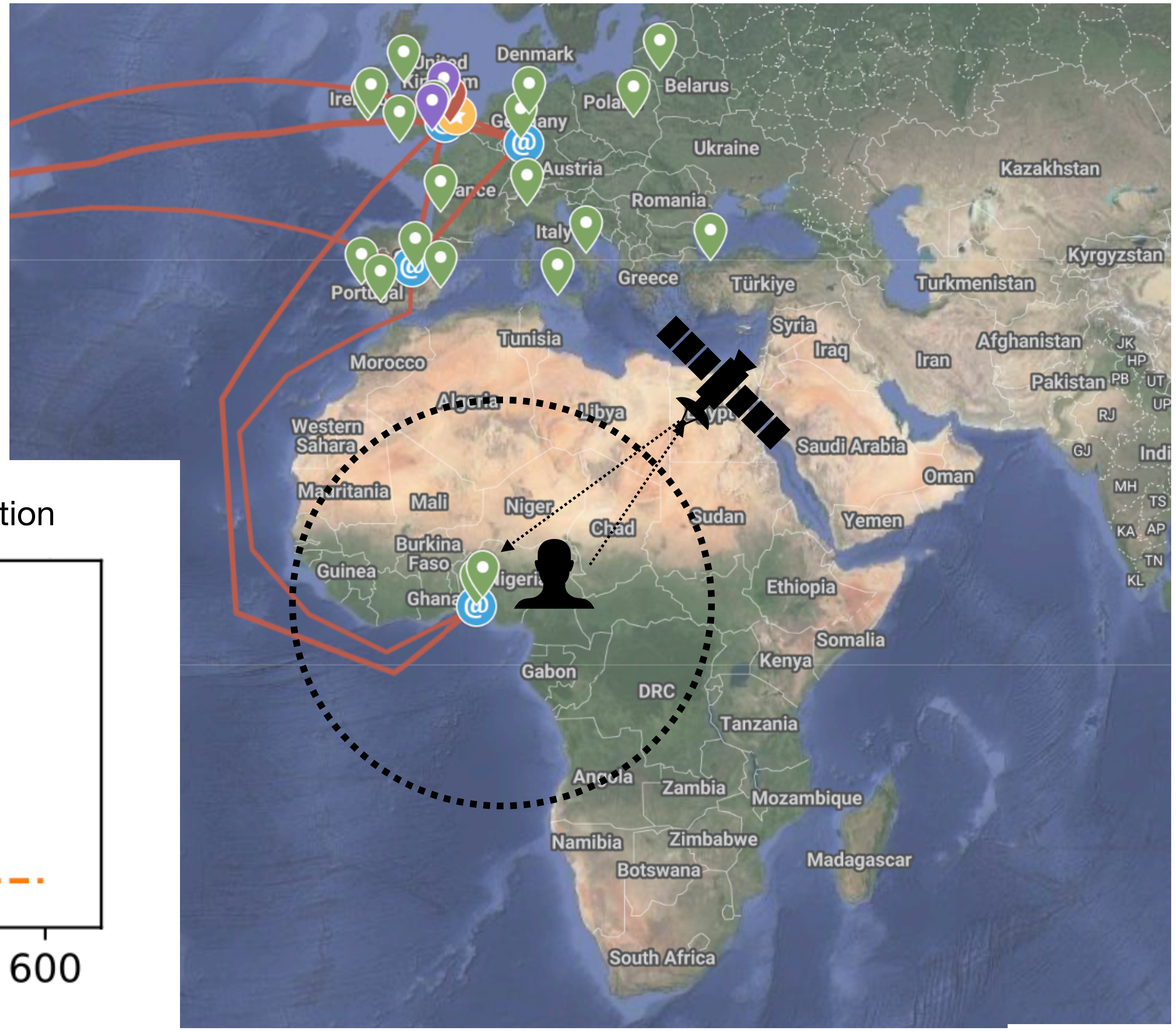


Customers experience unexpected sustained latency spikes

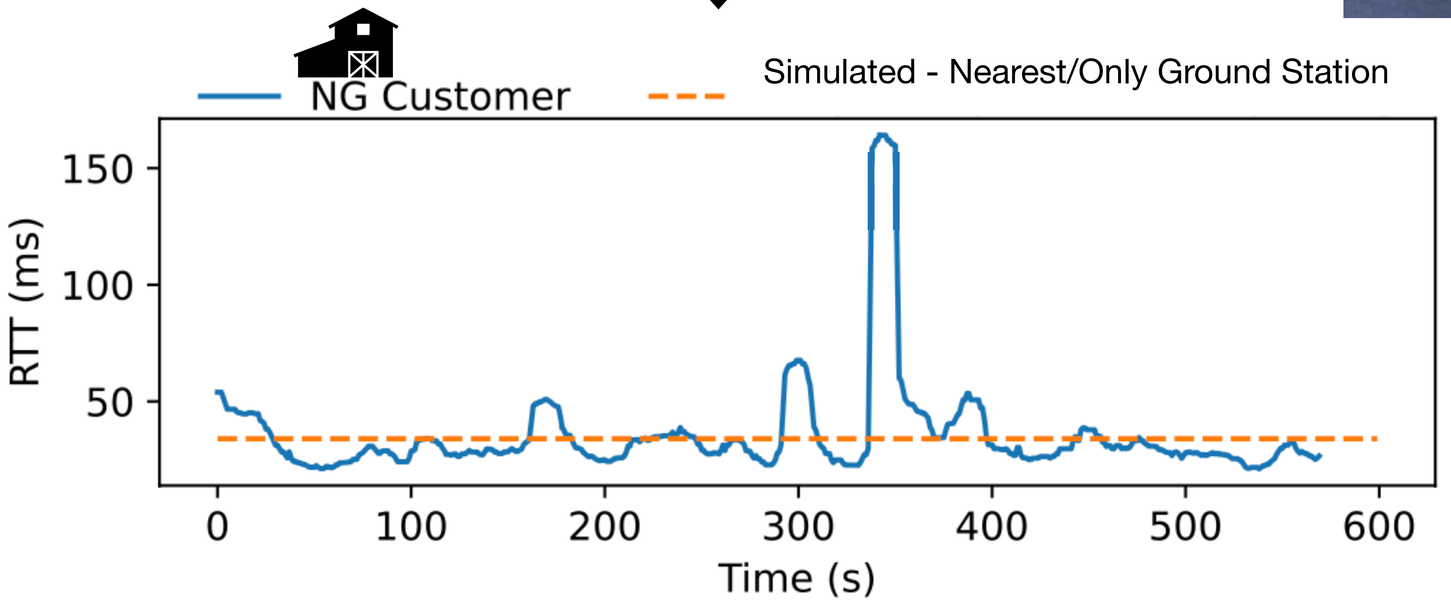


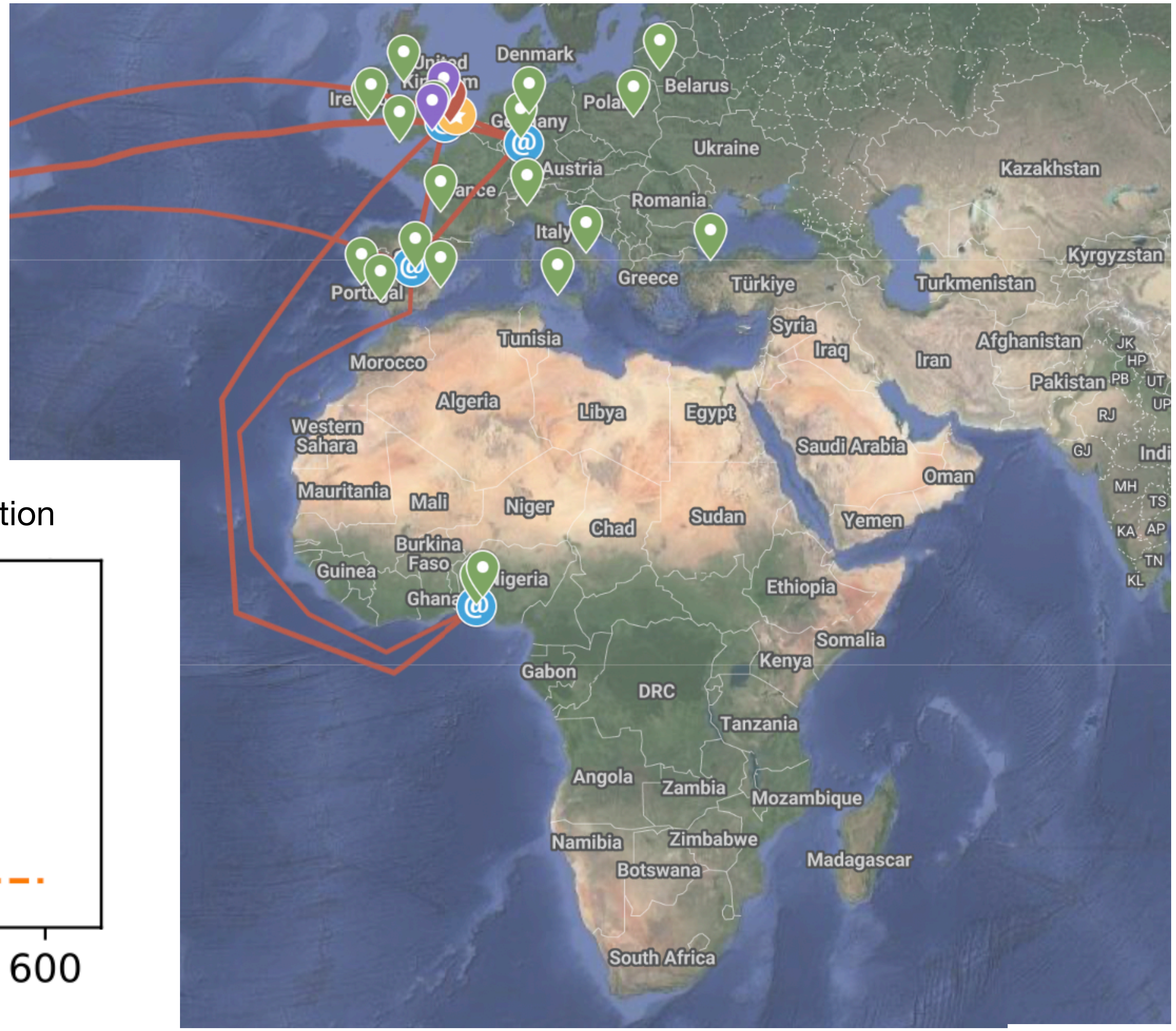




Customers experience unexpected sustained latency spikes

Over 70% of global customers experience sustained latency spikes



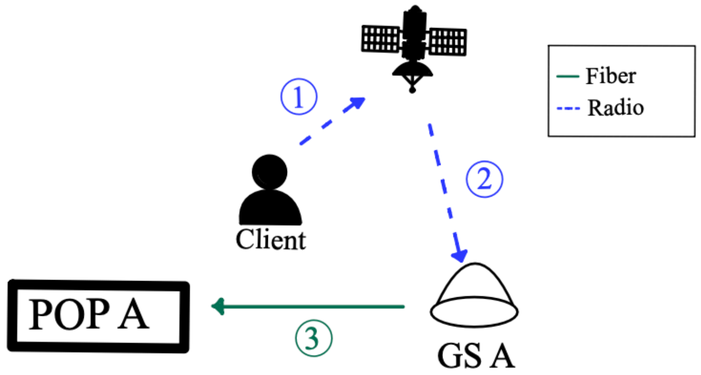


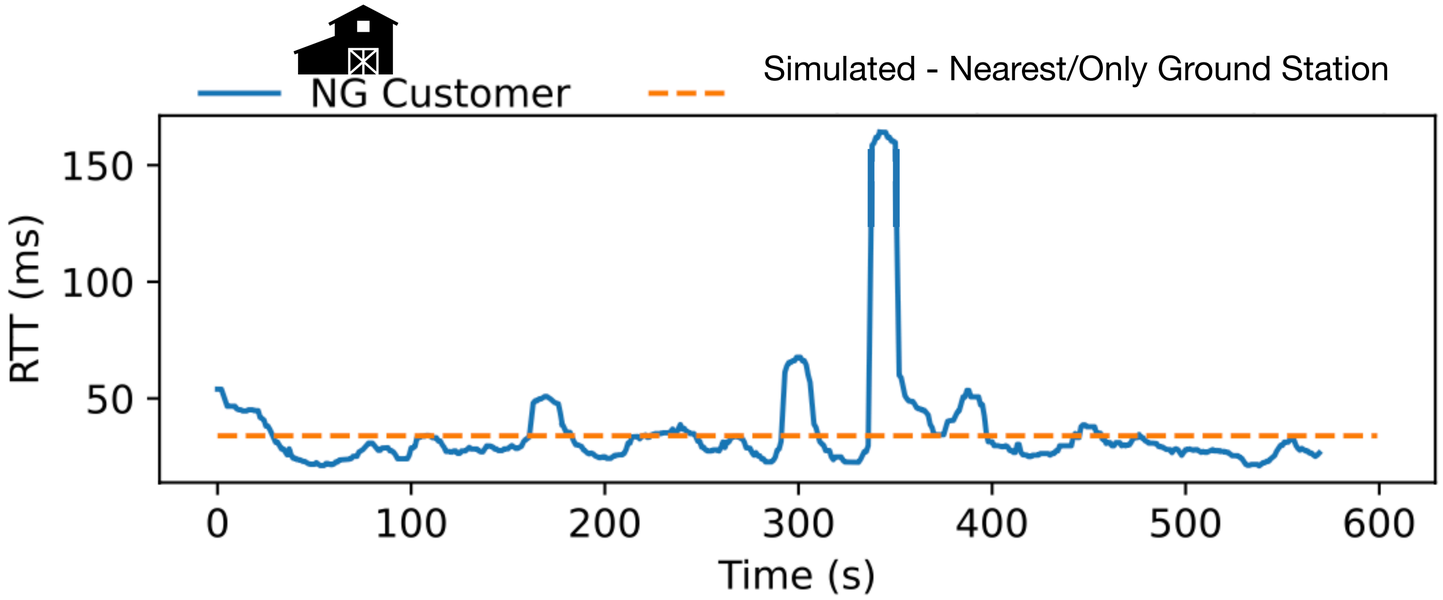
@ POP

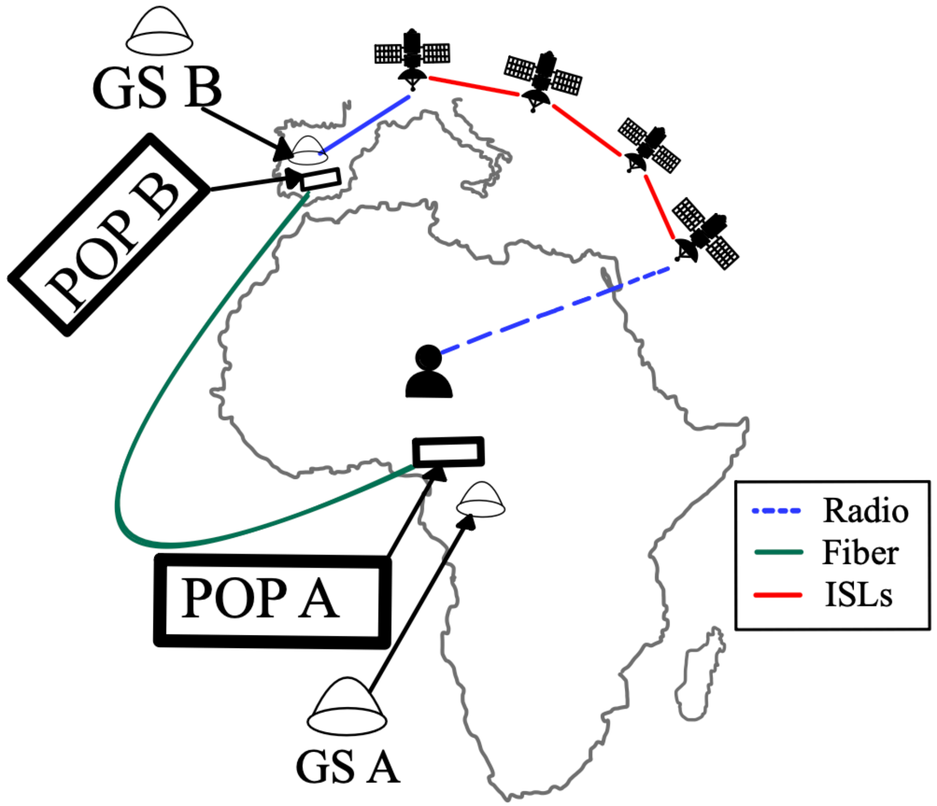
Ground Station

STARLINK

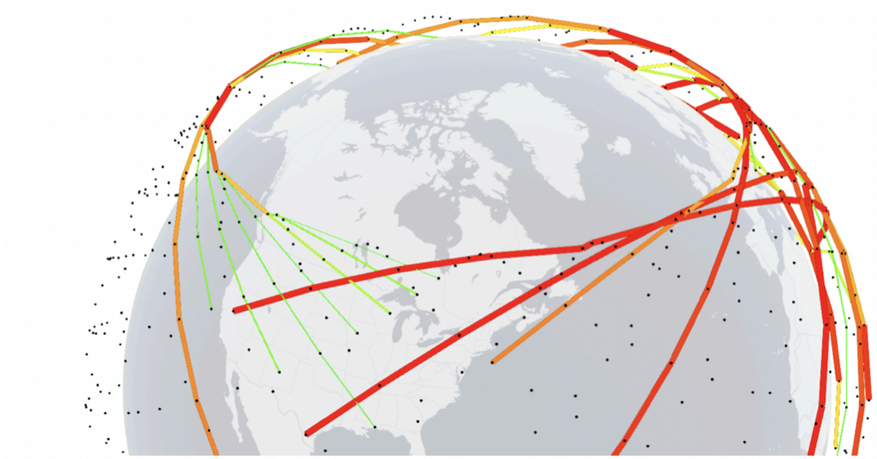
Customers are not always using the nearest ground station

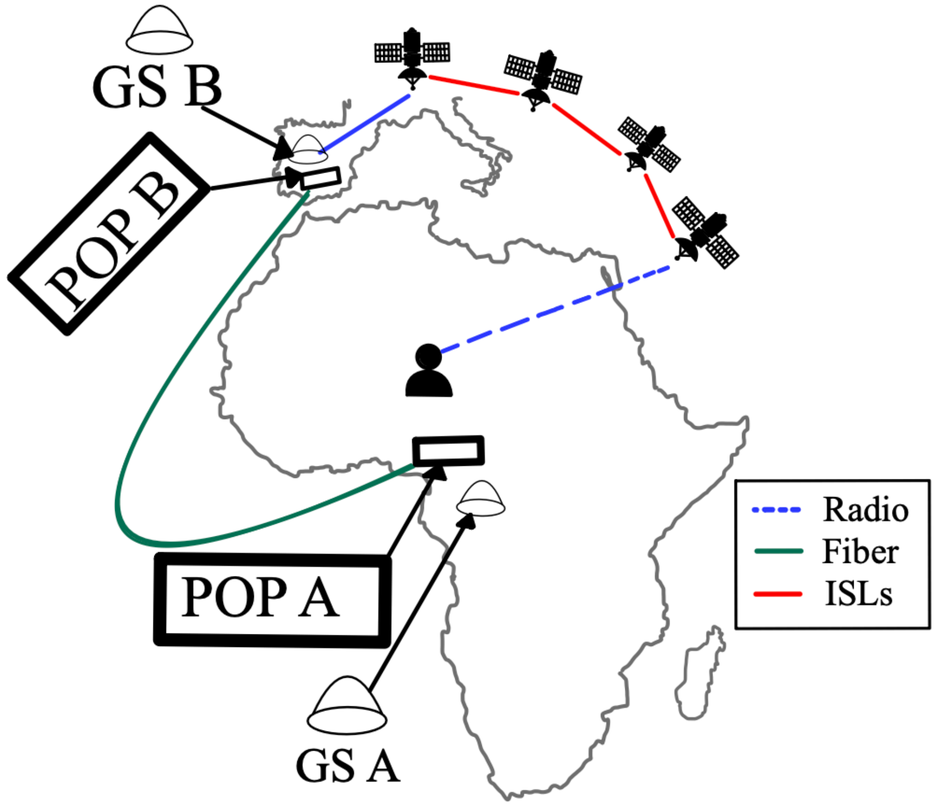






“Laser links” were (incorrectly) thought to improve performance





World Detours Are Prevalent Beyond Starlink

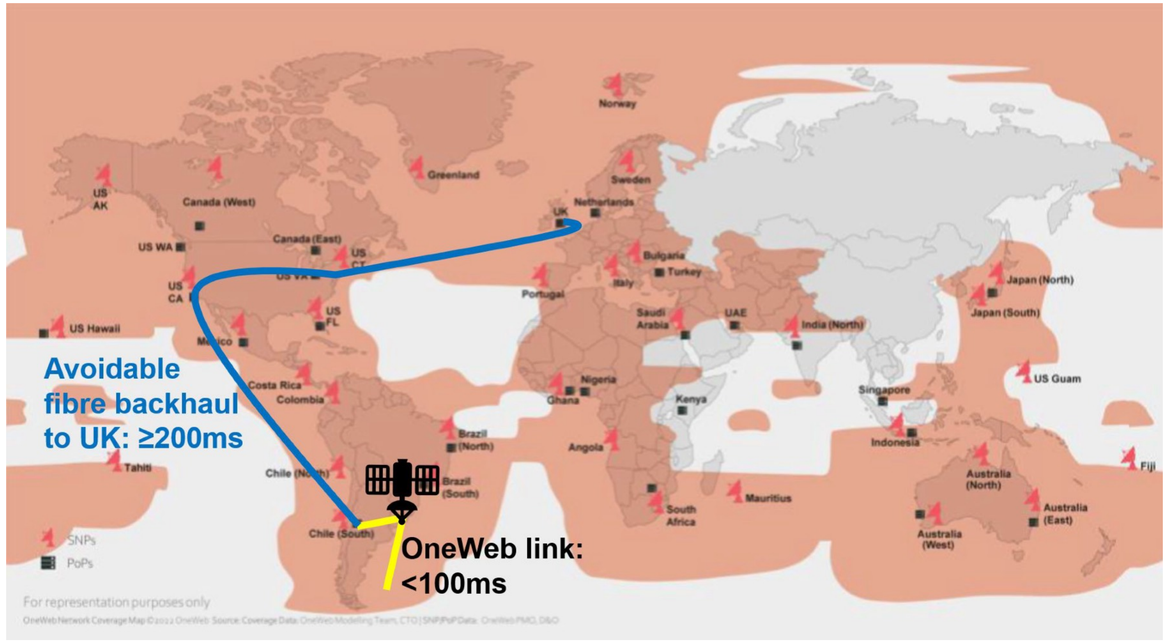
Government in talks with Sure over no LEO

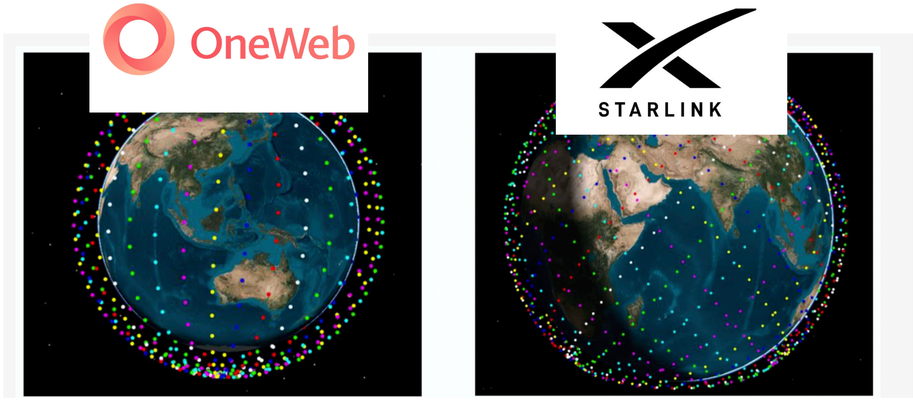
GOVERNMENT is currently in commercial discussions with Sure to understand the failure to introduce Low Earth Orbital (LEO) services to the Falklands, Member of Legislative Assembly Mark Pollard stated in the House on Thursday.

tion of this important improvement in service over a year later in January 2025 c[illegible]n the Hon Mark Pollard advise[illegible] how FIG will be compensated for the failure to deliver what was clearly an agreed obligation in return for financial support and what steps FIG are

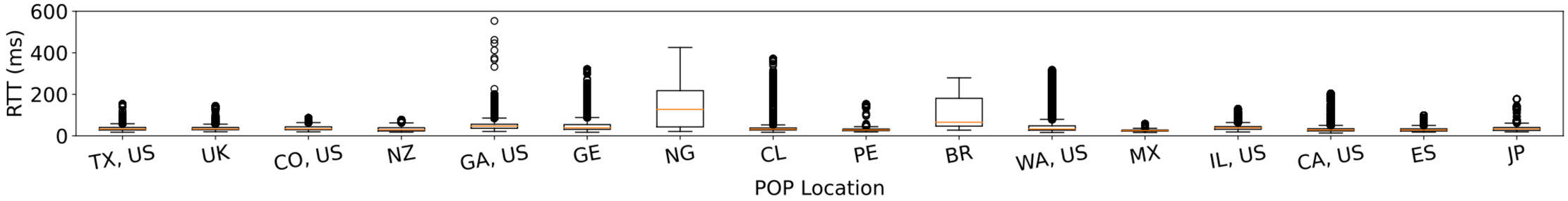
provide these services, which are now over a year late. If no commercial agreement is reached, legal solutions will be considered."

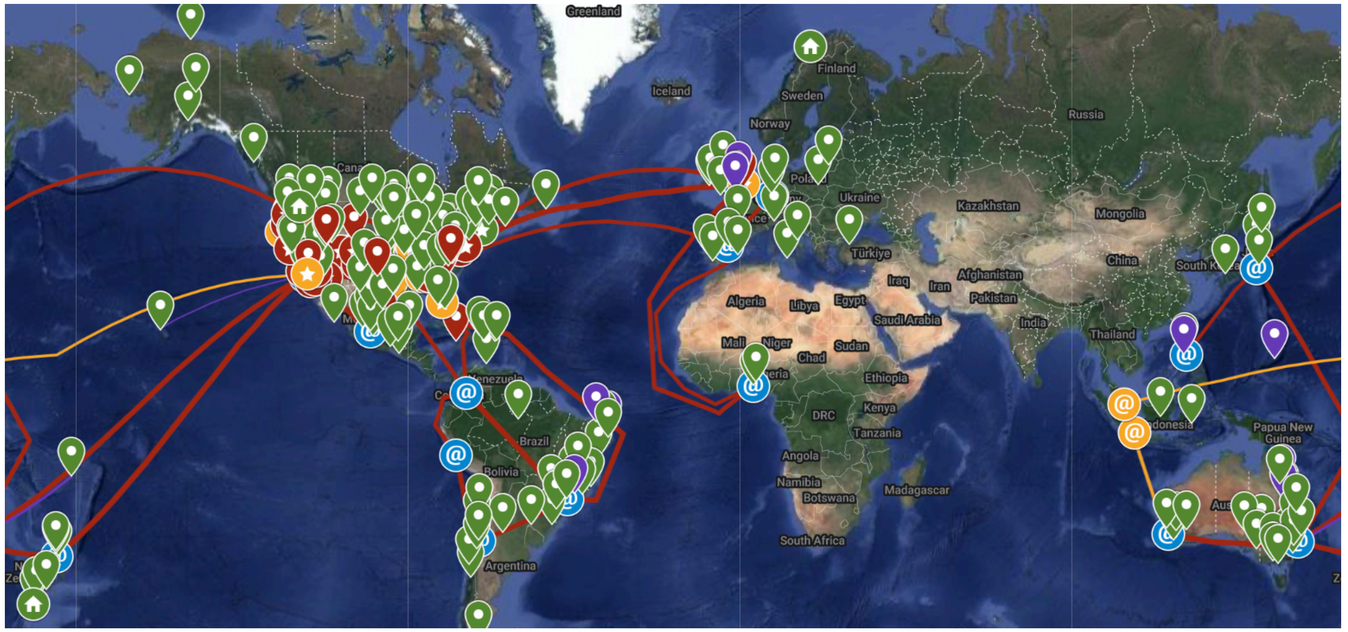
MLA Spink then responded: "Wouldn't he then agree that we have a solution which many people have turned to which is





Nigeria and Brazil POP-assigned customers experience the worst latencies





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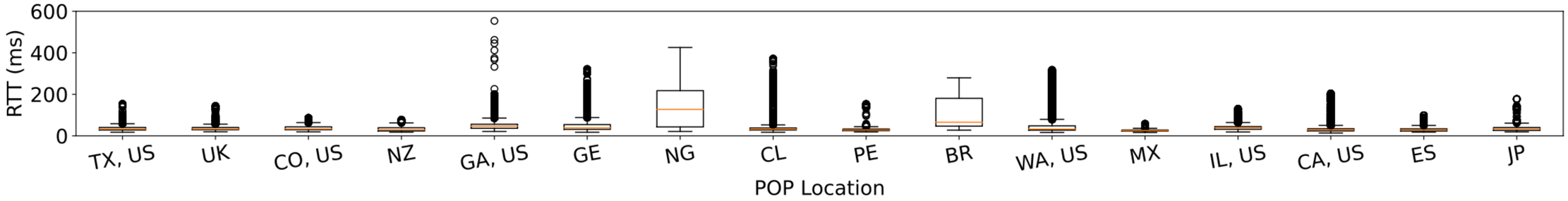


Open Questions:

- How do Starlink latencies compare to regional alternatives?
- How does latency impact real applications…like video streaming?

A Global Perspective on the Past, Present, and Future of Video Streaming Over Starlink

Liz Izhikevich
Reese Enghardt, Te-Yuan Huang, Renata Teixeira

How does LEO affect video streaming?

- What is **LEO’s role** in video delivery?

Video streaming over LEO is rapidly rising in popularity, especially in Africa

- What is **LEO's role** in video delivery?

- What is the **quality of experience** when streaming video over LEO?

- What is **LEO's role** in video delivery?

- What is the **quality of experience** when streaming video over LEO?

Often equivalent or better than terrestrial connections…but increased bitrate switches and rebuffers

Disproportionately more in Africa

- What is **LEO's role** in video delivery?

- What is the **quality of experience** when streaming video over LEO?

- How can we improve **bitrate switches** and **network rebuffers** for video streaming over LEO?

- What is **LEO's role** in video delivery?
- What is the **quality of experience** when streaming video over LEO?
- How can we improve **bitrate switches** and **network rebuffers** for video streaming over LEO?

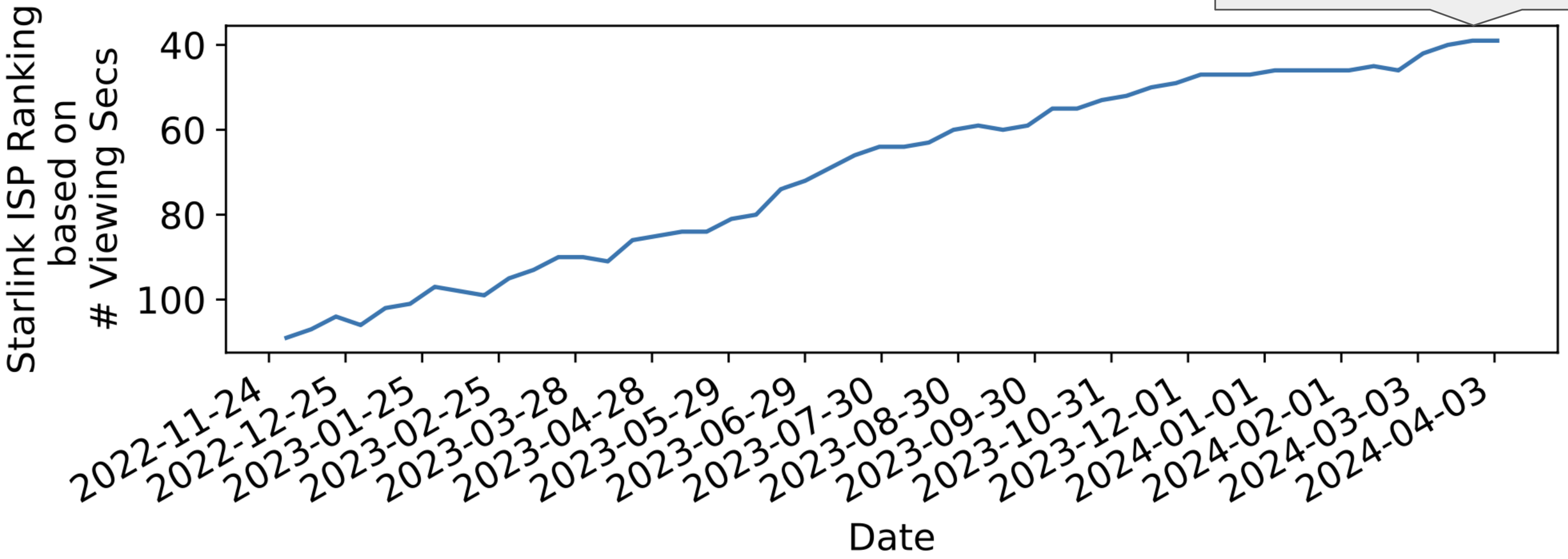
Existing **congestion control** & **adaptive bitrate** design principles can partially help, but are not sufficient

What is LEO’s role in video delivery?

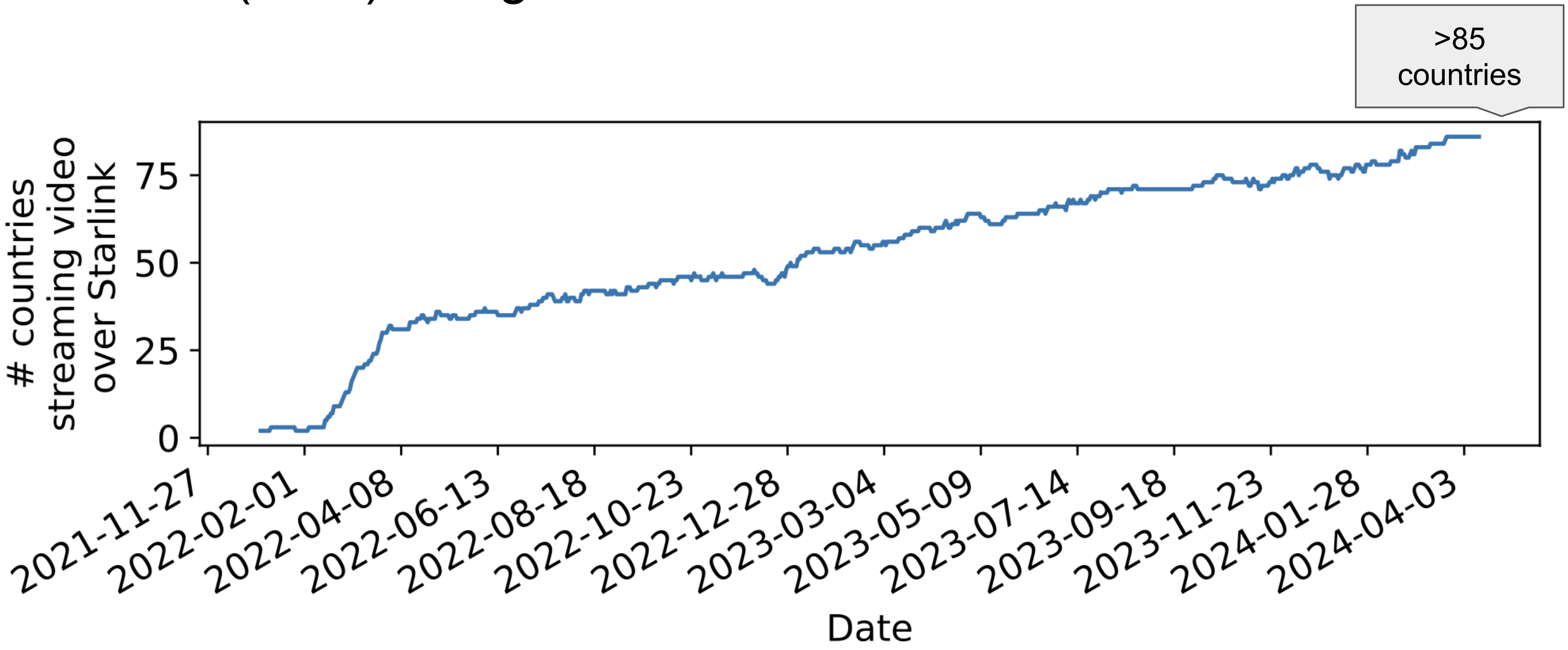
Starlink is the only major LEO provider from which Netflix users stream from today

Starlink (LEO) is growing in popularity

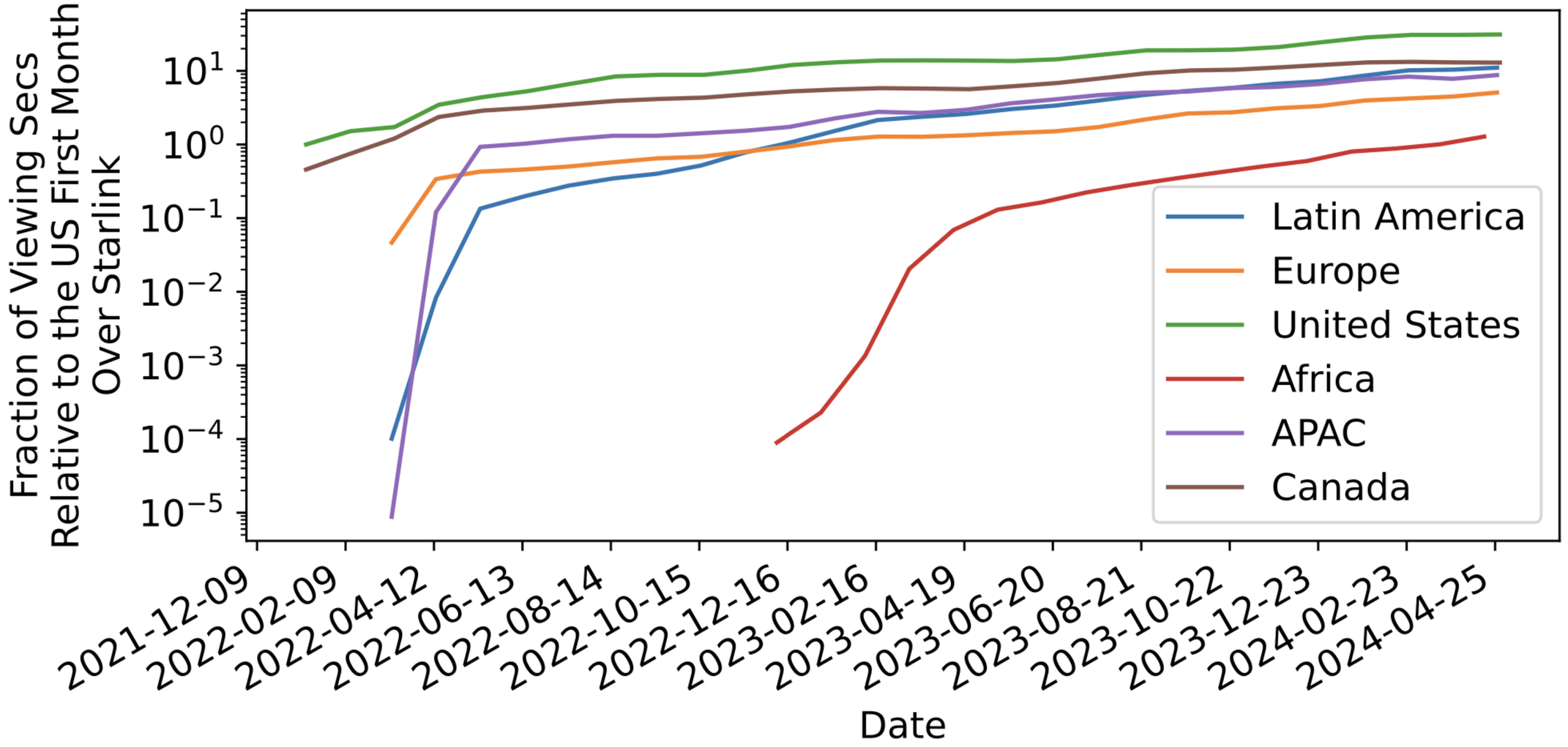
Starlink is 38/20K most popular ISP



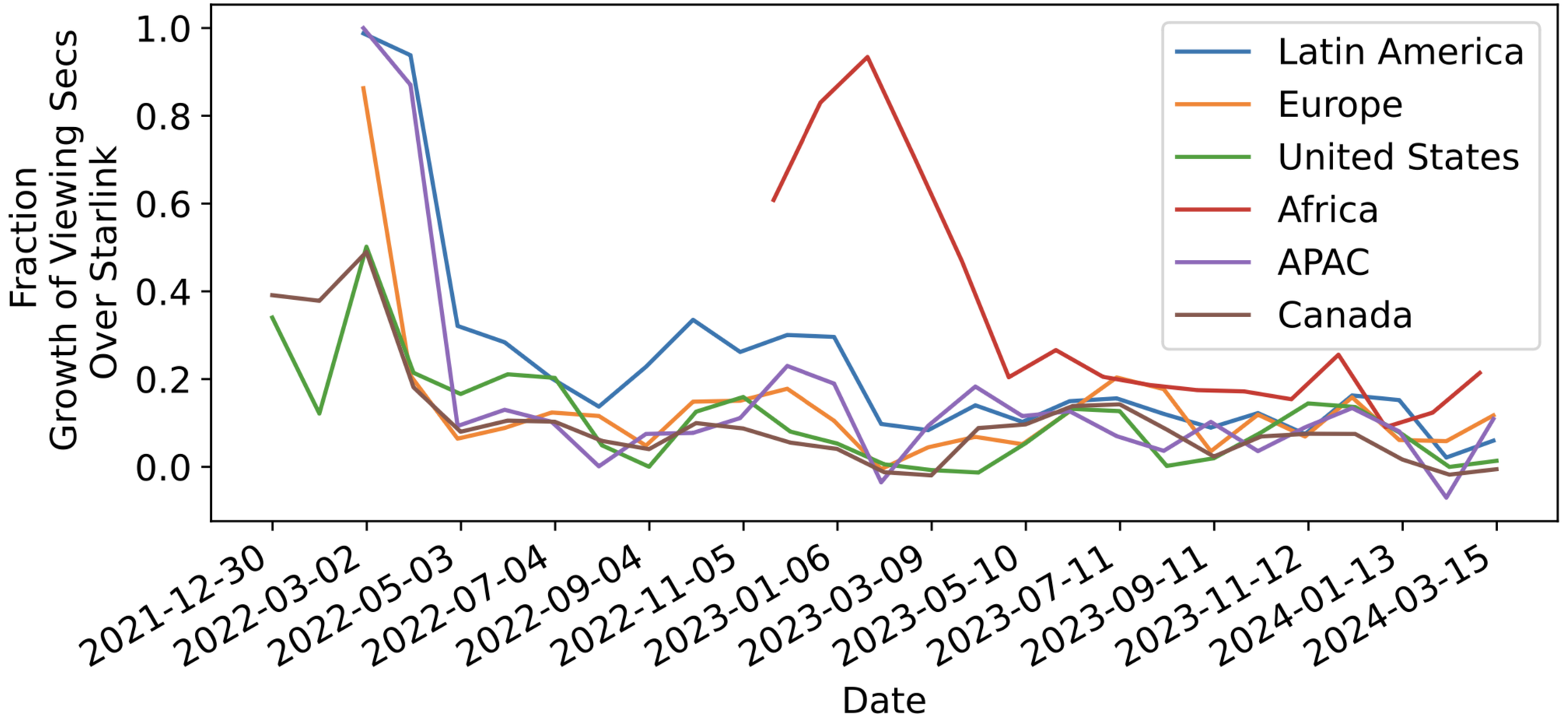
Starlink (LEO) is a *global* ISP



The US streams the most over Starlink



Africa is the fastest growing region for video streaming over Starlink



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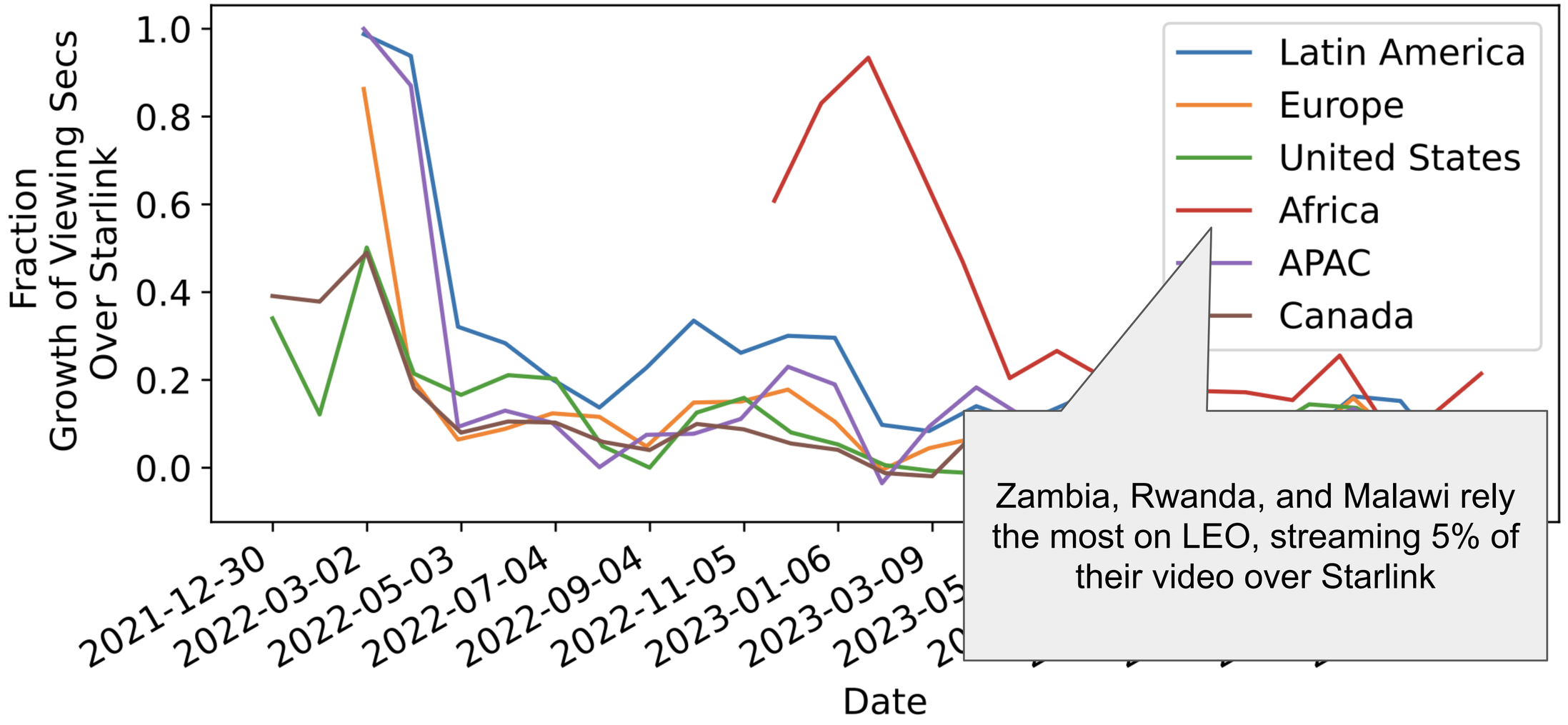


What is the QoE when streaming over Starlink?

What is the QoE when streaming over Starlink?

- Overall Perceptual Video Quality
- Play Delay
- Bitrate Switches
- Network Rebuffers

Filtering Methodology

We filter for video streaming sessions that are

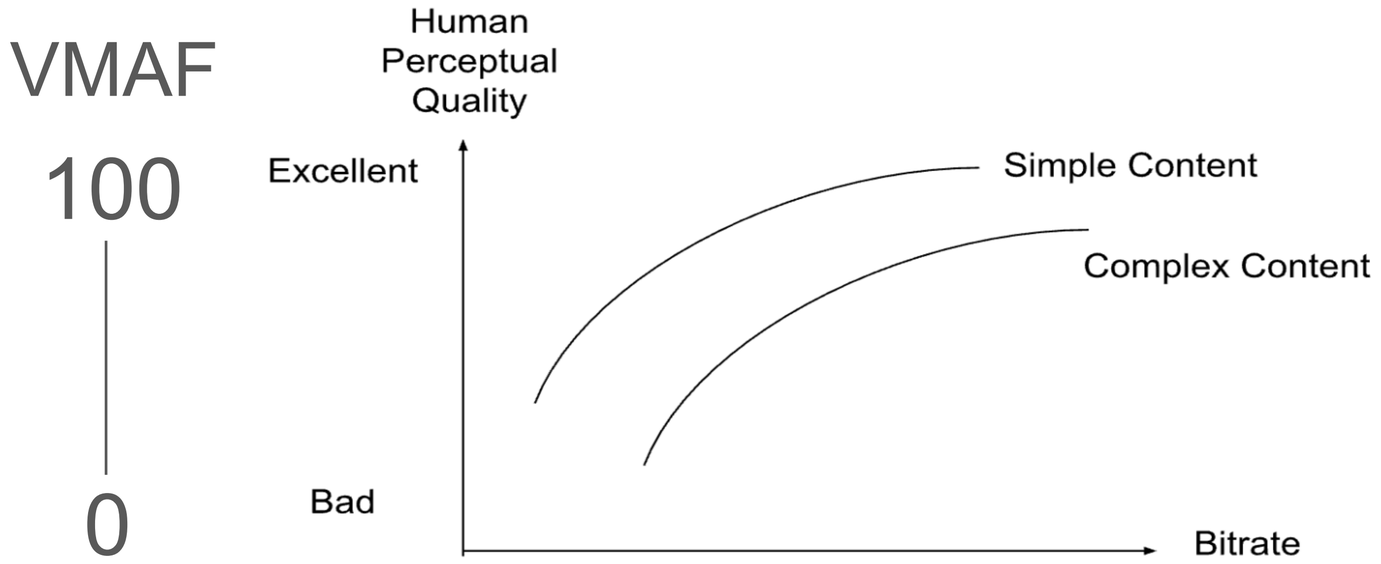
(1) theoretically capable to stream at least at a 720p high definition
(2) at least 5 minutes long
(3) destined towards TVs
(4) streamed during the first week of April 2024

Millions of streaming sessions for Starlink alone!

Perceptual Video Quality

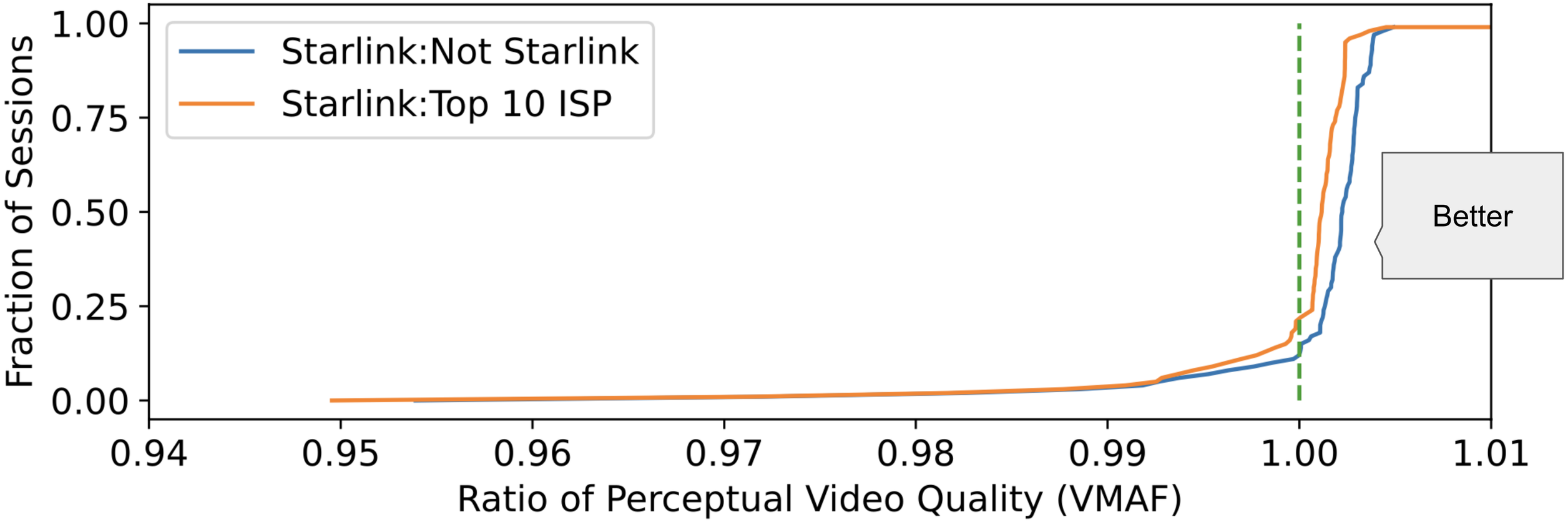
Quantifying Perceptual Video Quality Using Video Multi-Method Assessment Fusion (VMAF)

- For each (video, bitrate), predicts how humans will perceive its quality

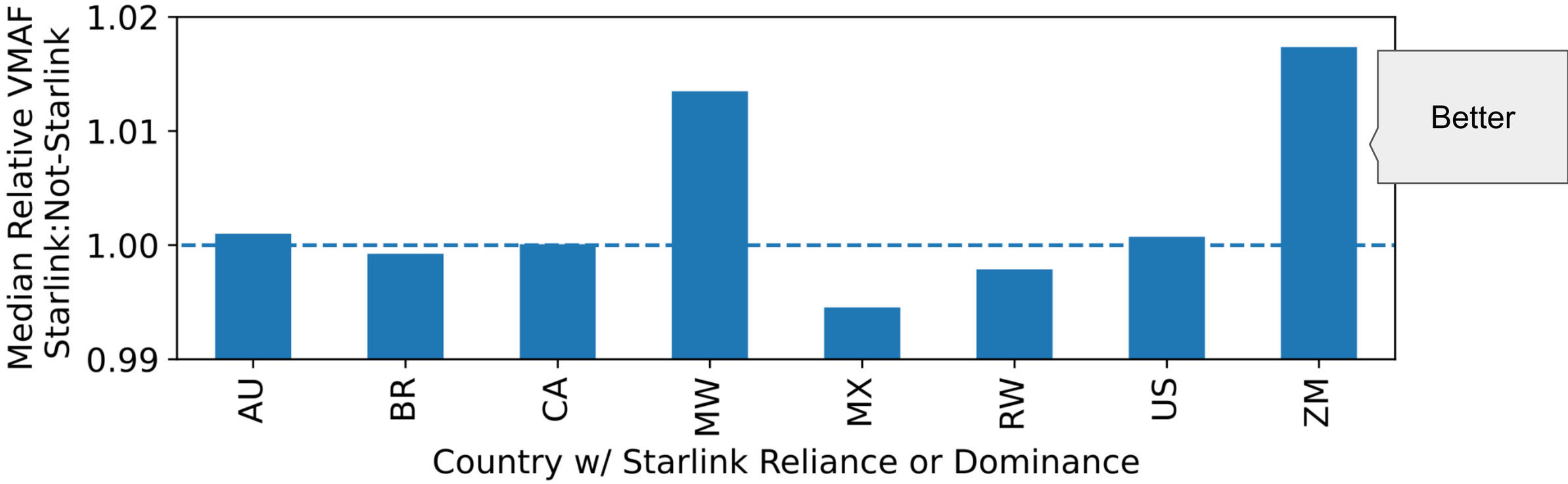


VMAF

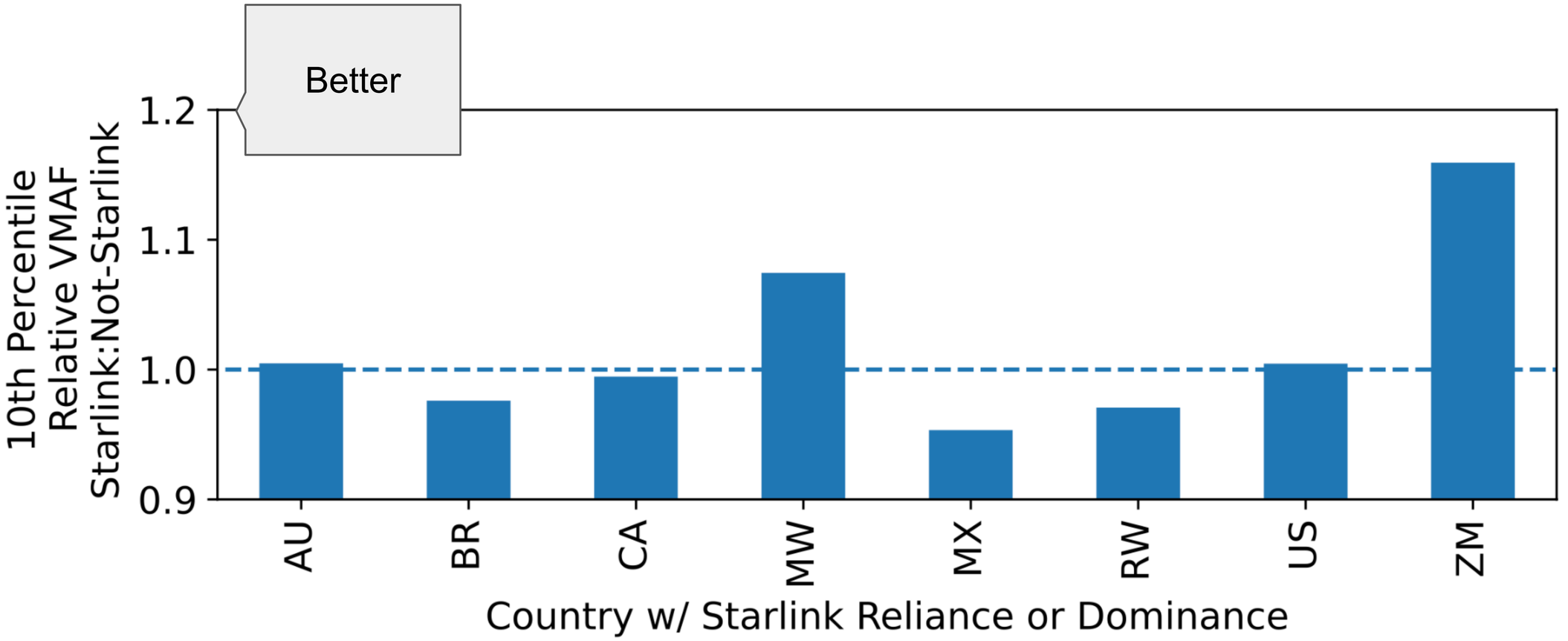
Starlink users often experience better perceptual video quality



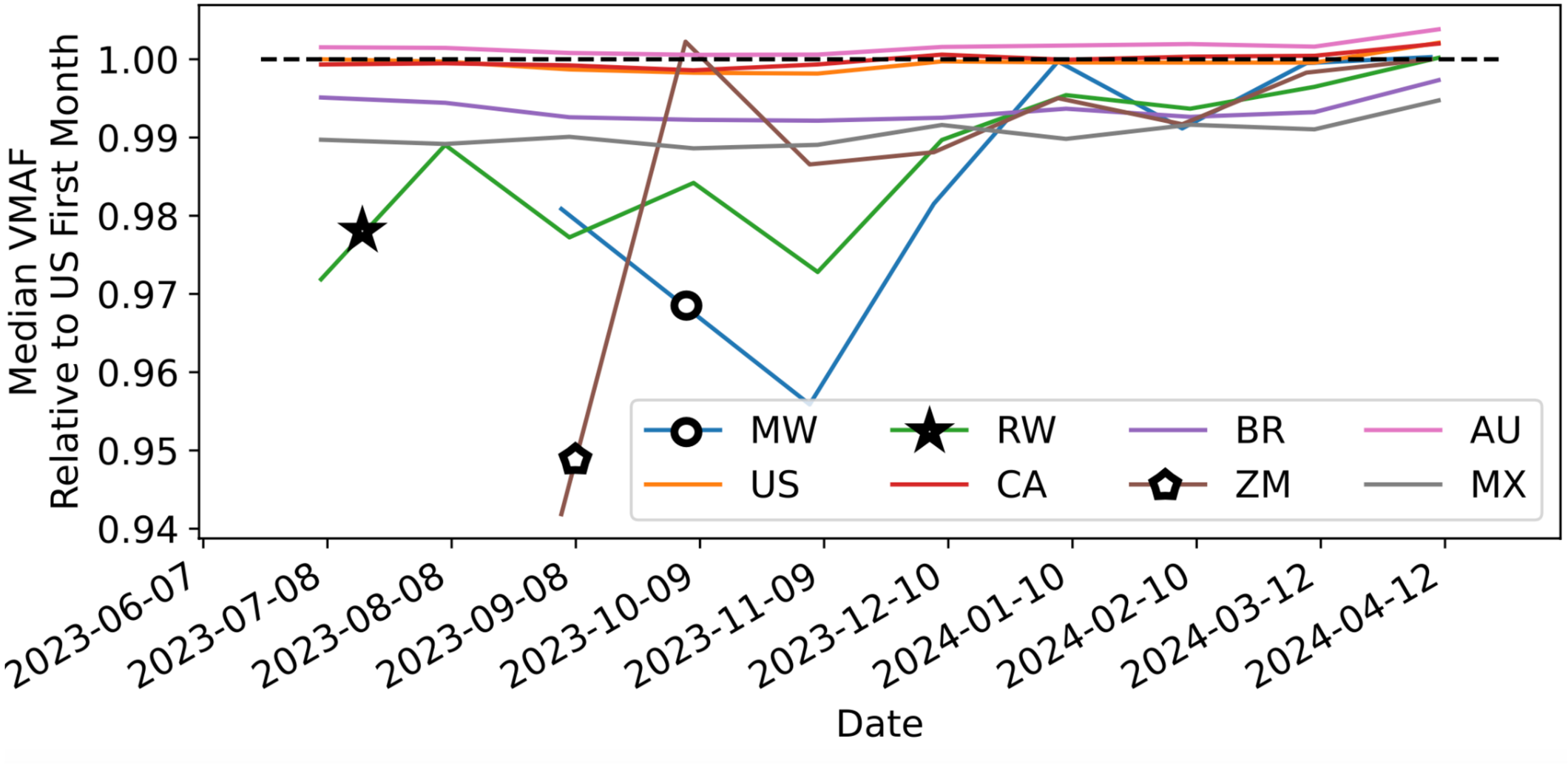
Malawi and Zambia experience better perceptual quality than local alternatives



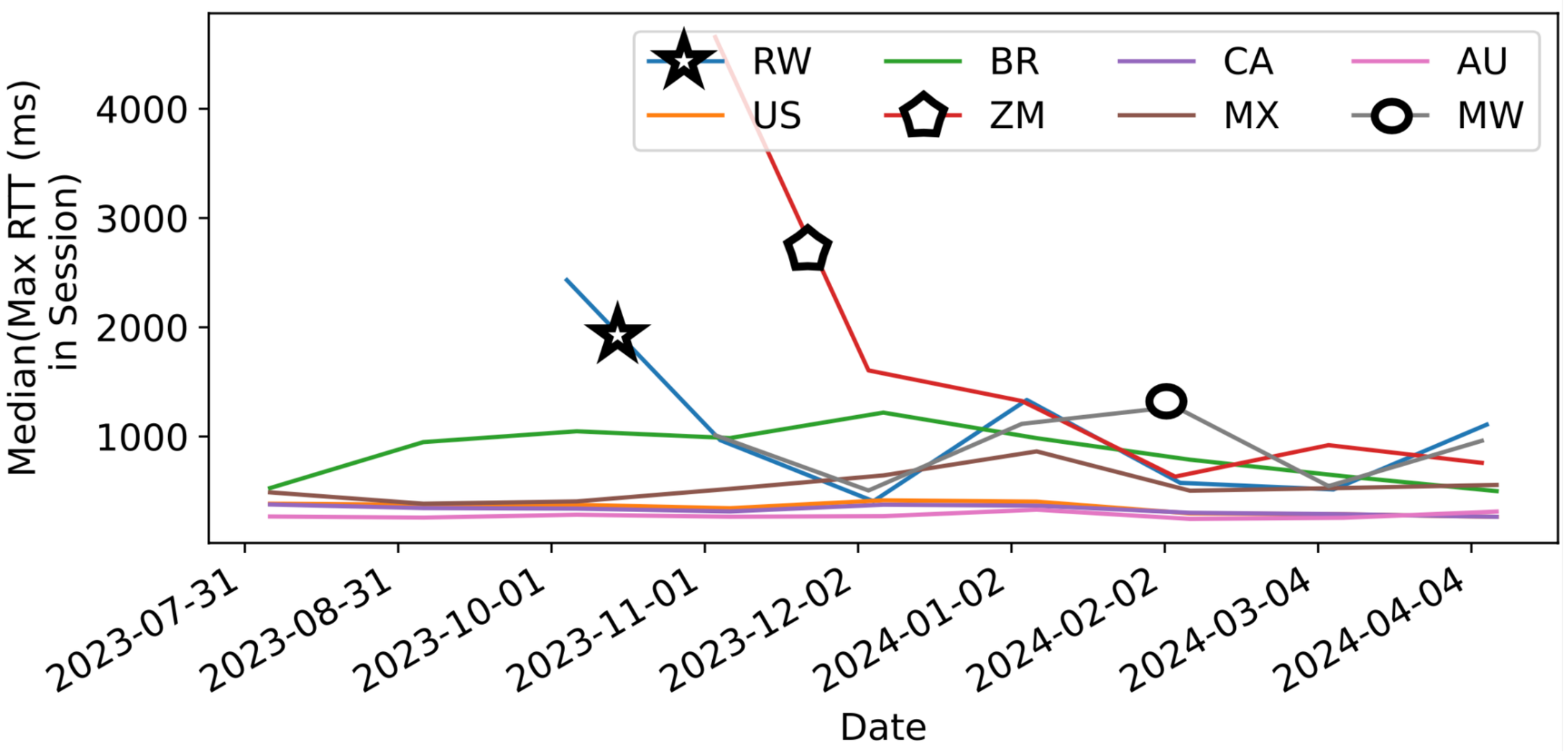
Malawi and Zambia experience better perceptual quality than local alternatives…especially in the long tail



Perceptual video quality over Starlink improves over time



Perceptual video quality over Starlink improves over time…which coincides with lower round trip times



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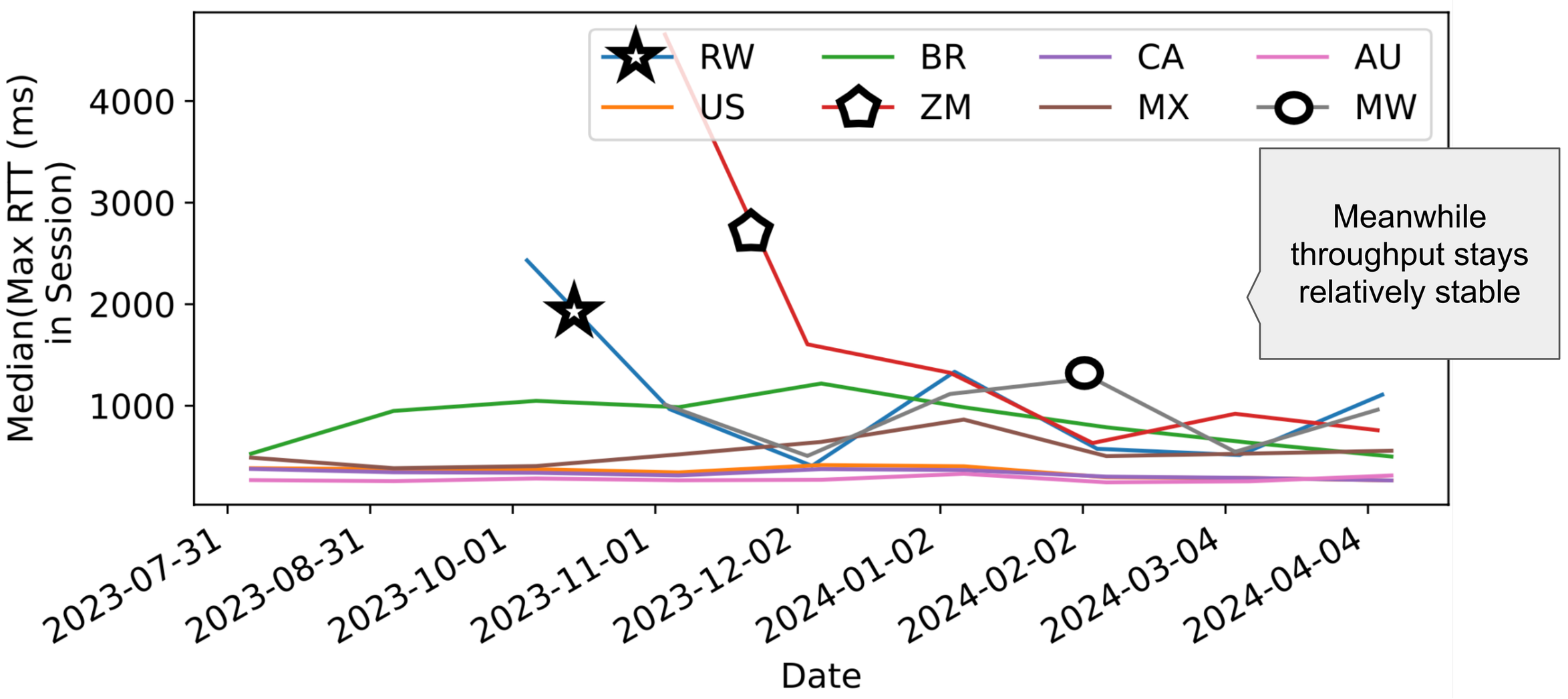
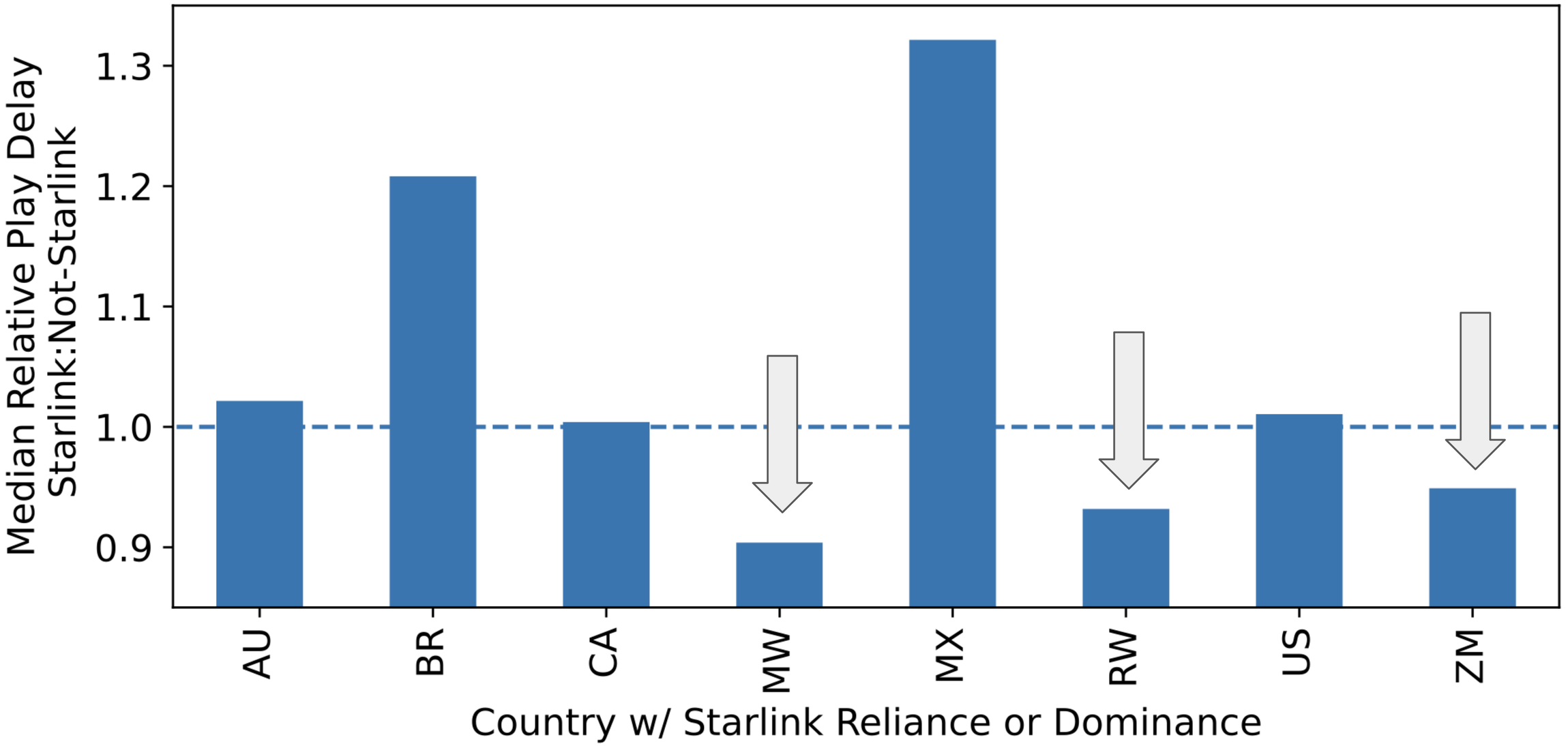
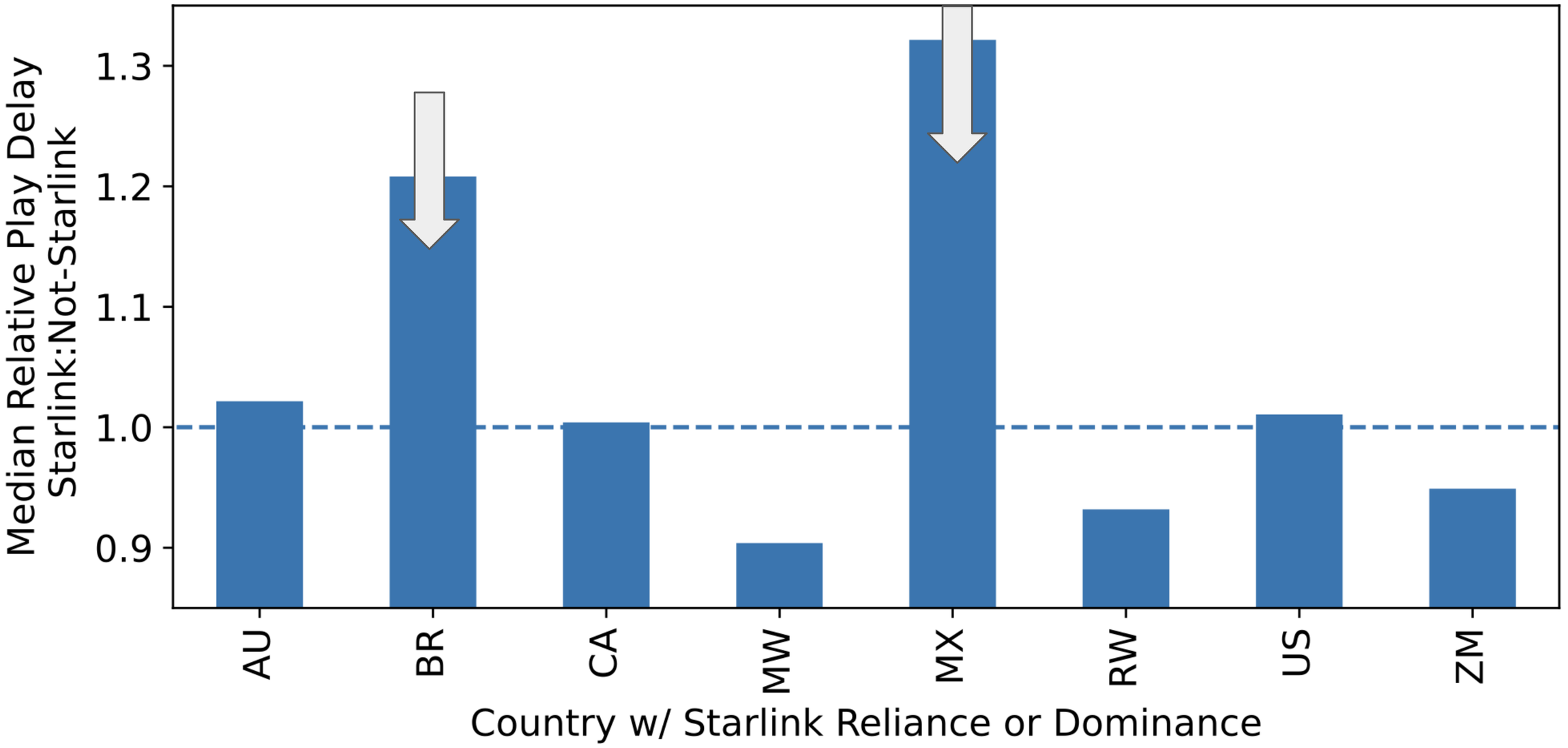


Play Delay

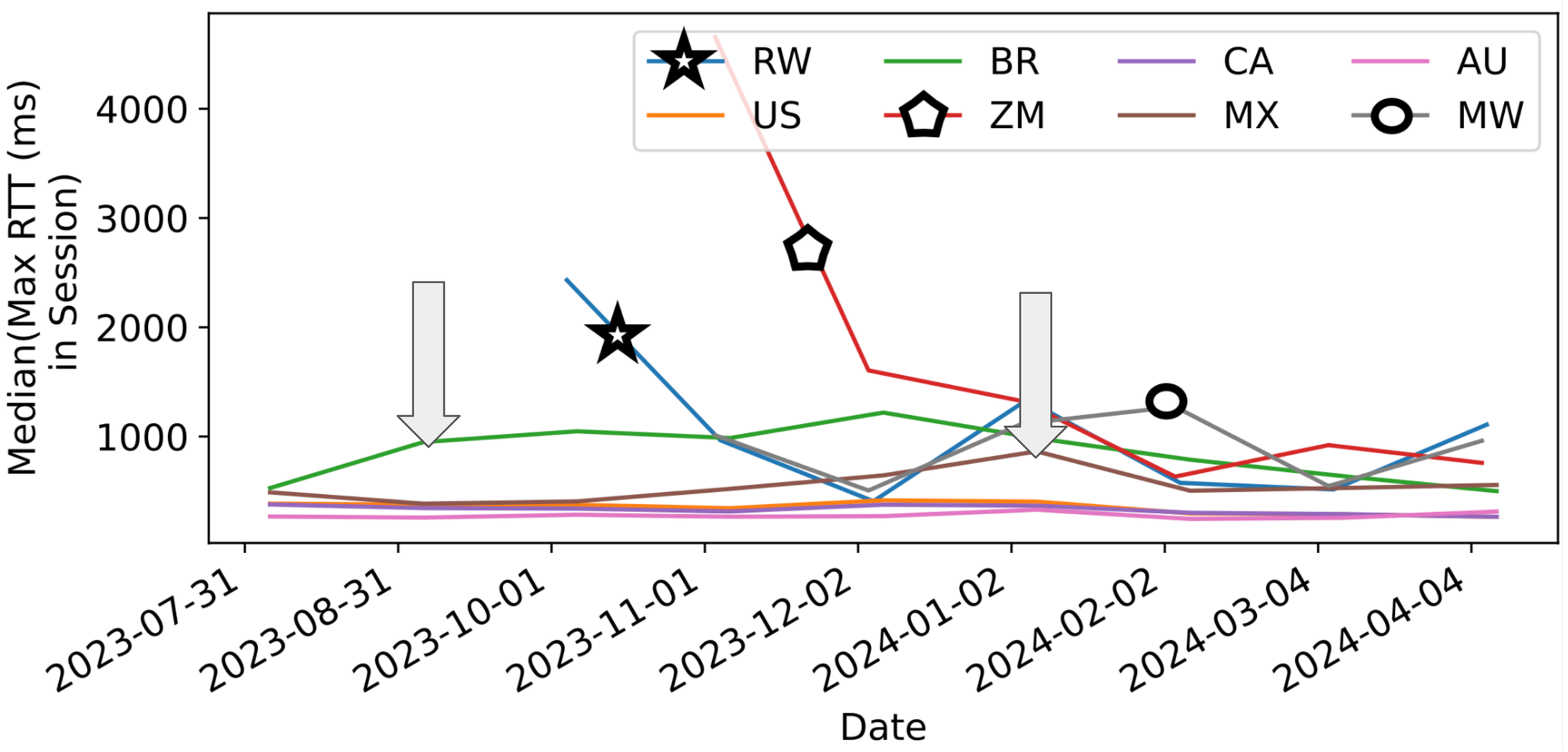
Play delay over Starlink in Africa is better than local alternatives



Play delay over Starlink in Brazil/Mexico is worse than local alternatives

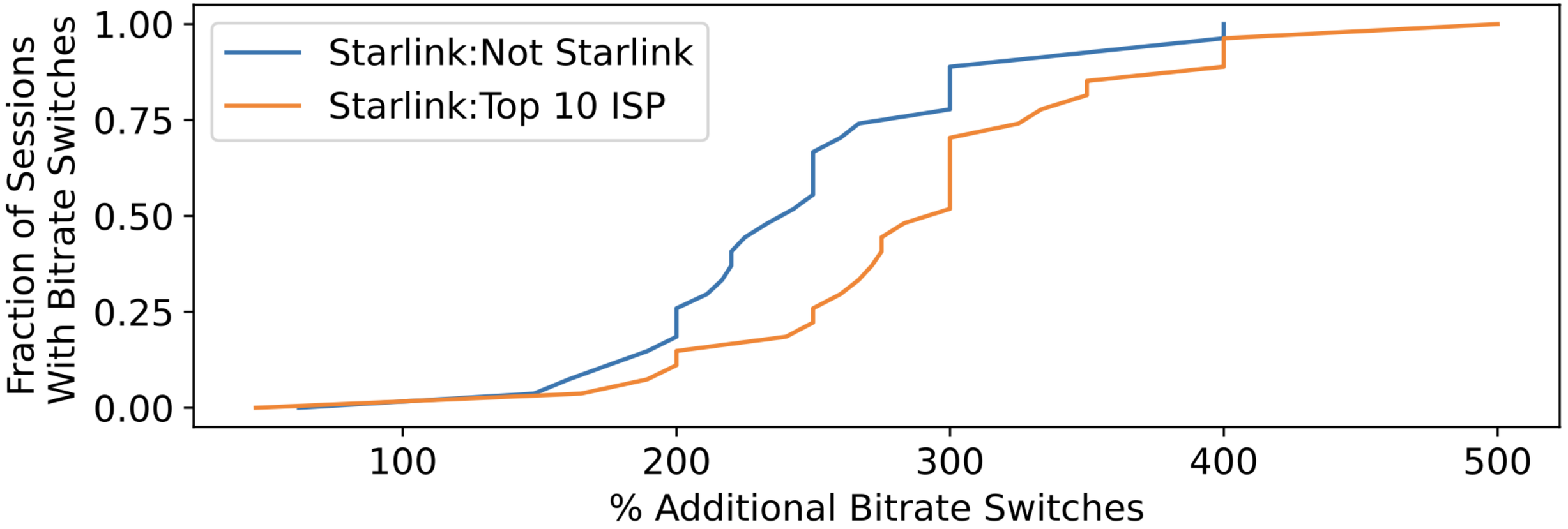


Mexico and Brazil experience marginally larger RTT times over US/CA/AU



Bitrate Switches

Video streaming over Starlink suffers from increased bitrate switches



Video streaming over Starlink suffers from increased bitrate switches

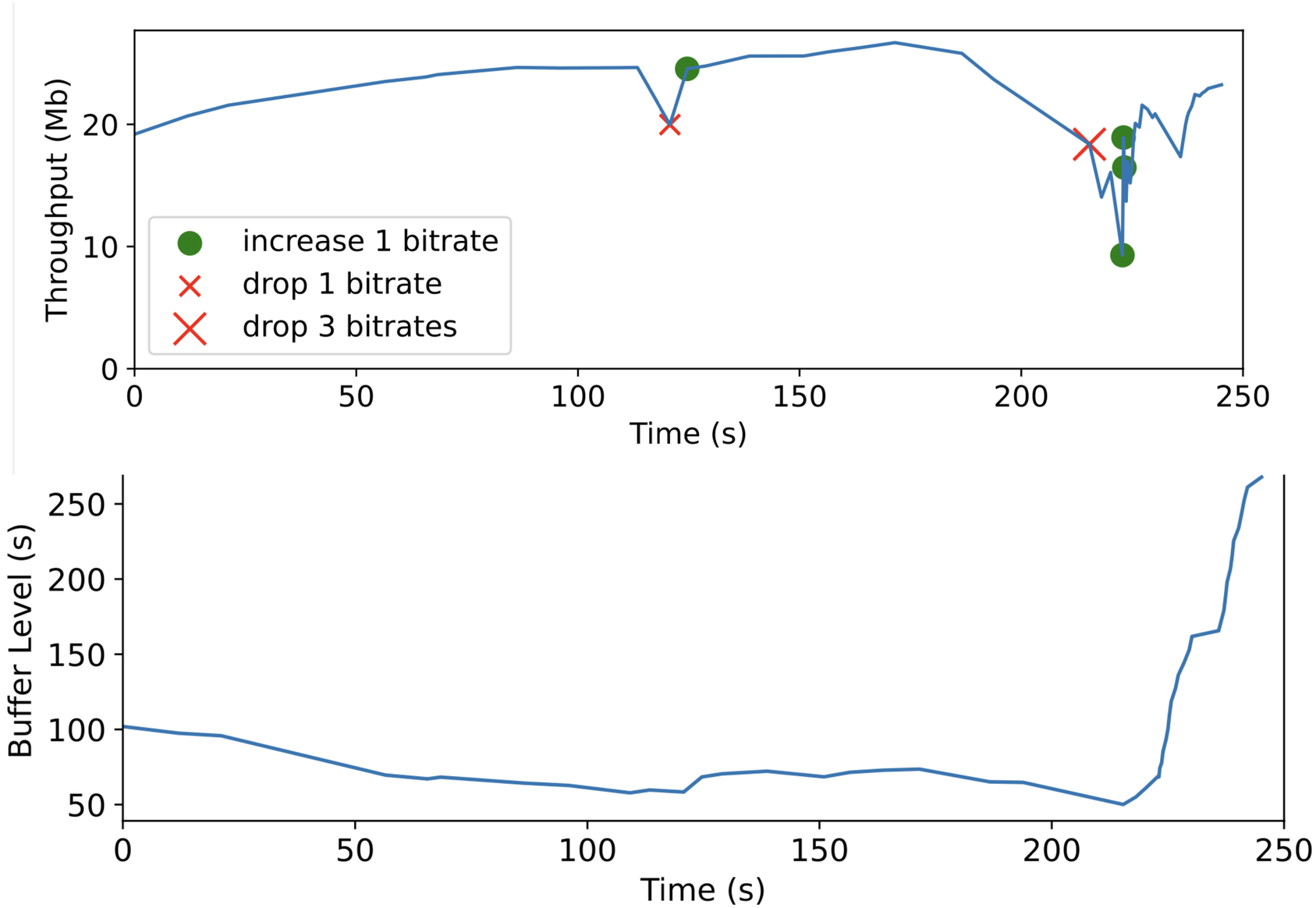
r/Starlink • 2 yr. ago
r00x

Anyone else struggle with poor quality on streaming services (Netflix/Amazon Prime mostly)?

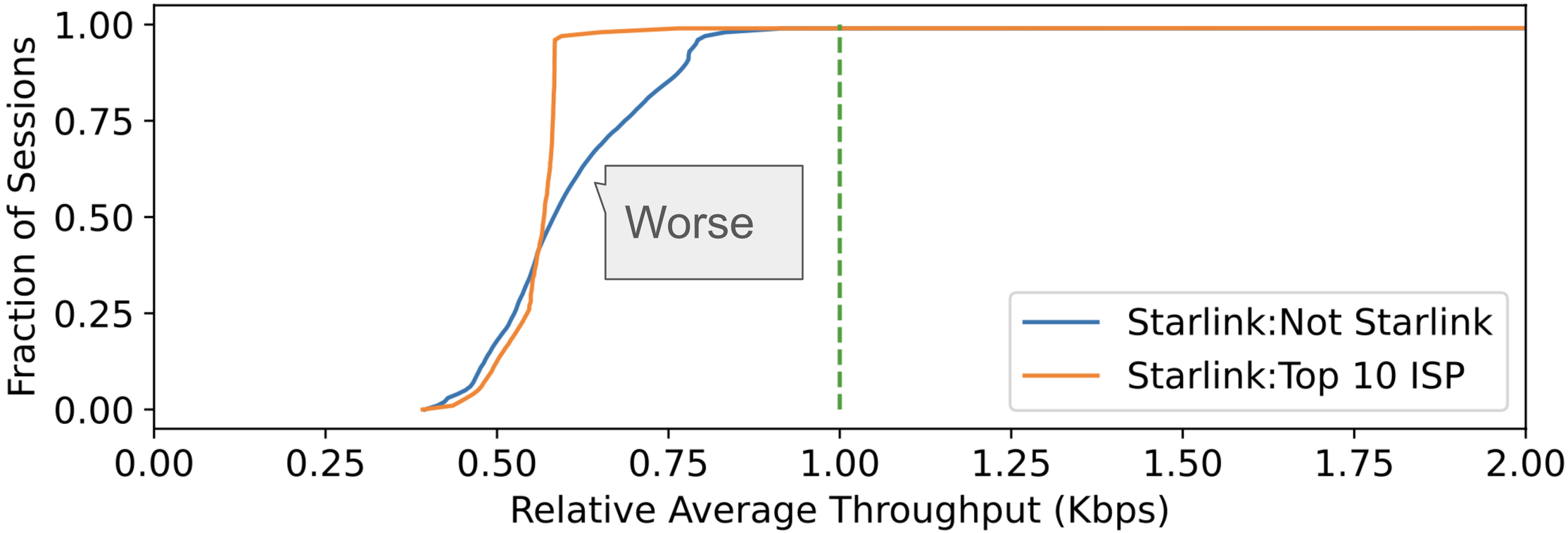
💻 Troubleshooting

Title. I've found Netflix and Amazon Prime are the worst offenders; regularly dropping stream quality from 4K UHD down to lower resolutions, all the way to unwatchable potato quality sometimes (Prime especially), despite the

Video streaming over Starlink suffers from increased bitrate switches



Starlink’s reduced throughput likely contributes to bitrate switches



Network Rebuffers

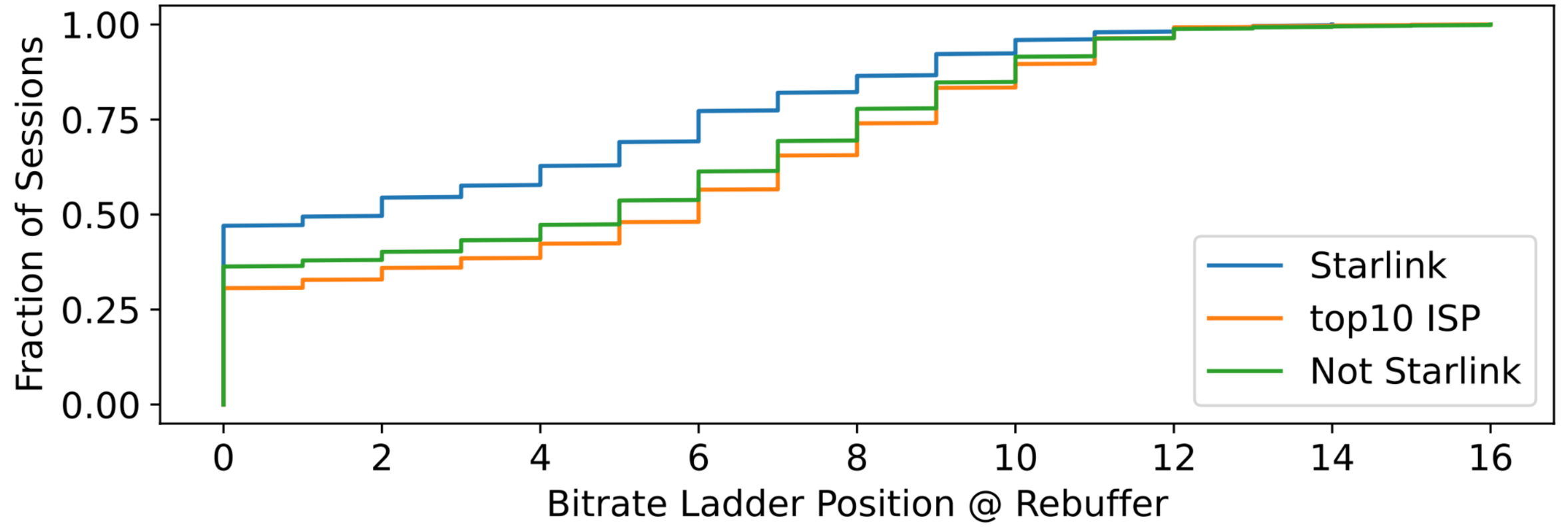
Network rebuffers (while rare) are more likely to occur over Starlink

- 216% more likely to occur over Starlink than a Top 10 ISP
- Starlink customers experience twice as many rebuffers as non-Starlink customers

Africa and Latin America are more likely to experience a rebuffer over Starlink

Region	Likelihood of >= 1 Rebuffer Relative to US
Canada	0.66x
Asia Pacific	0.9x
United States	1x
Europe	1.07x
Africa	2.7x
Latin America	3.7x

Starlink sessions are more likely to already be serving the lowest supported bitrate at the time of a rebuffer



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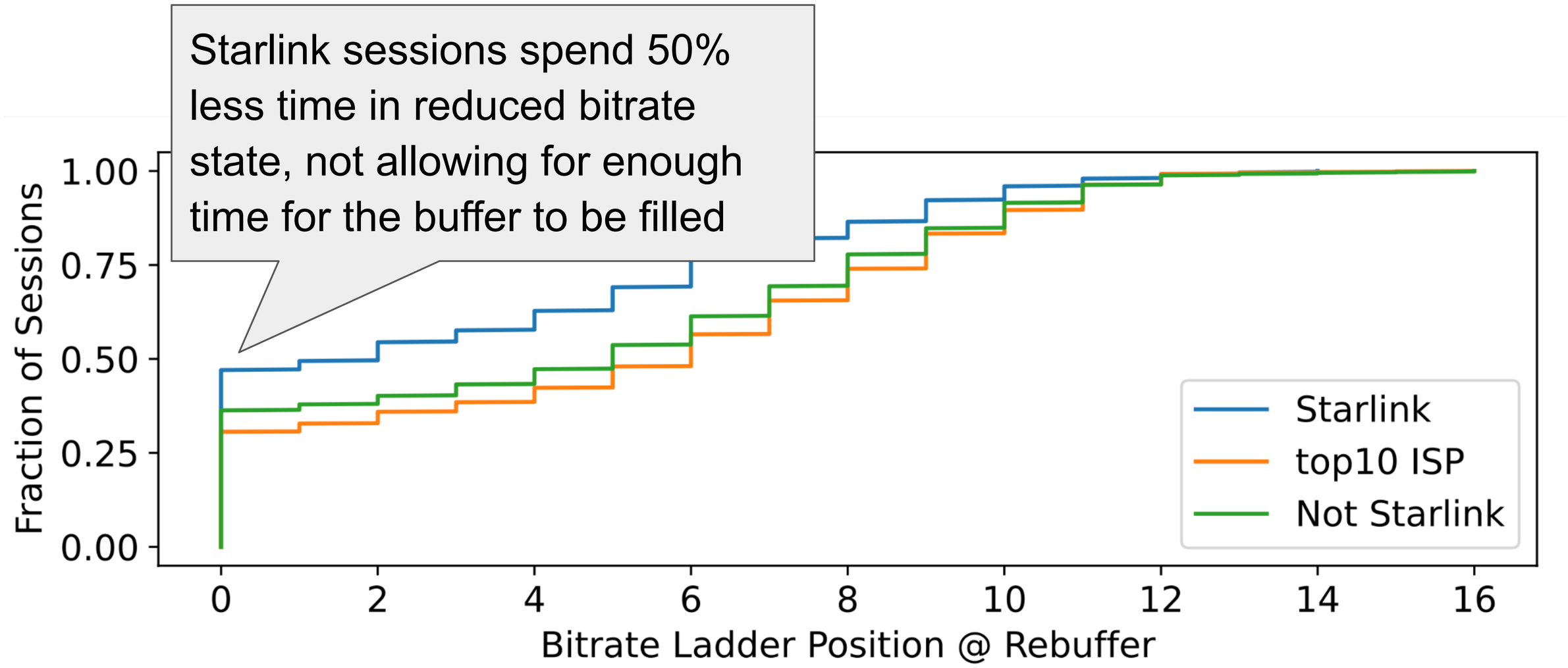


Improving Bitrate Switches Using Congestion Control

See paper

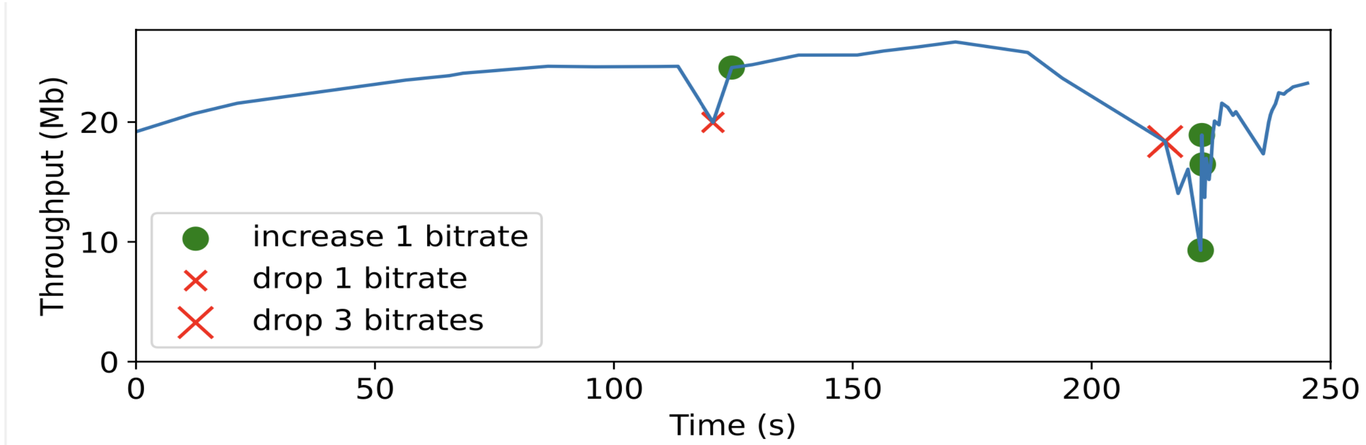
Improving Network Rebuffers Using Adaptive Bitrate

Hypothesis

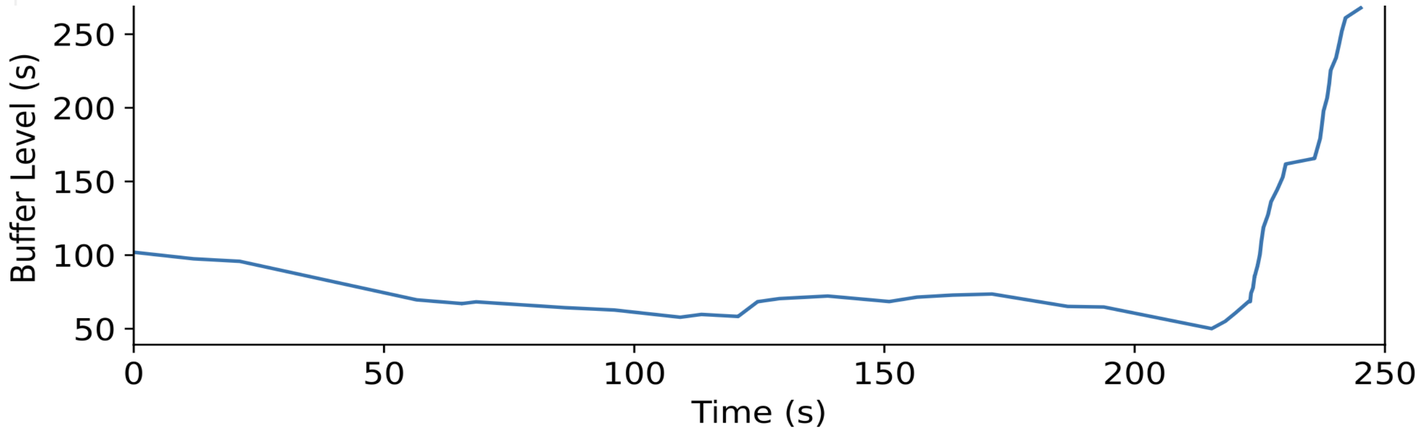
Fewer Network Rebuffers <- “Better” ABR <- Better ABR Parameters for Starlink

Adaptive Bitrate Design Parameters Today

- Throughput Discount
- Buffer Discount
- Throughput Smoothing



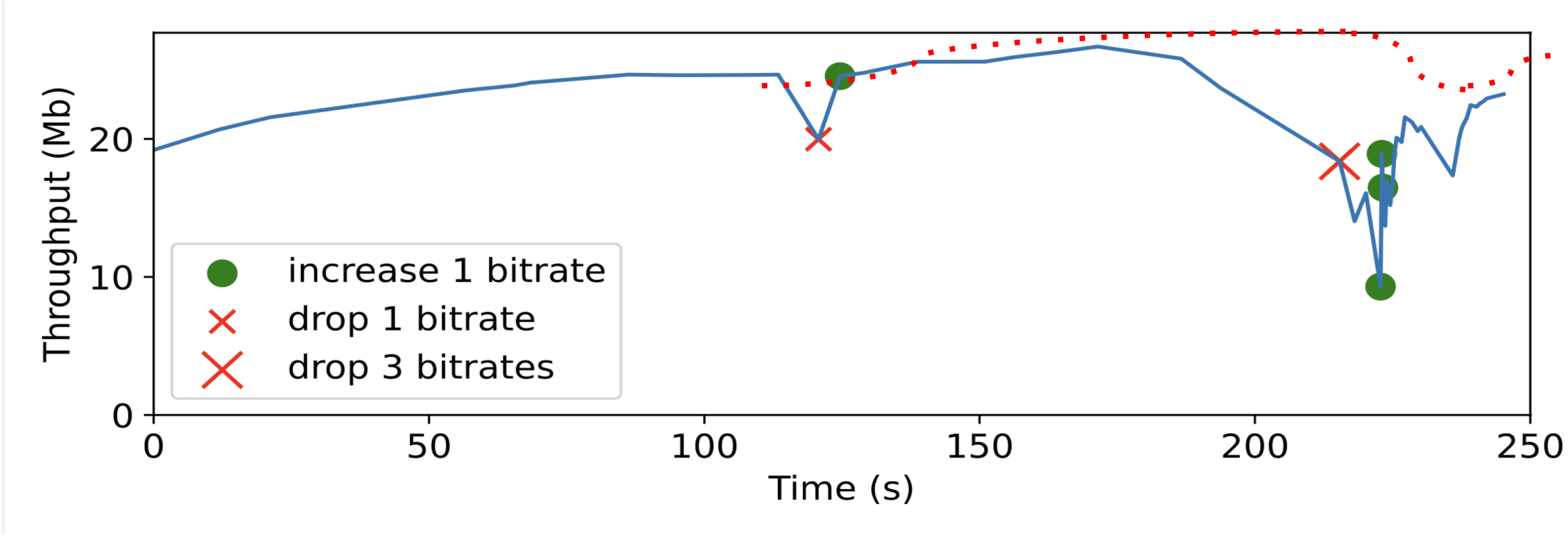
Imagine we want to increase buffer level..to avoid rebuffer…



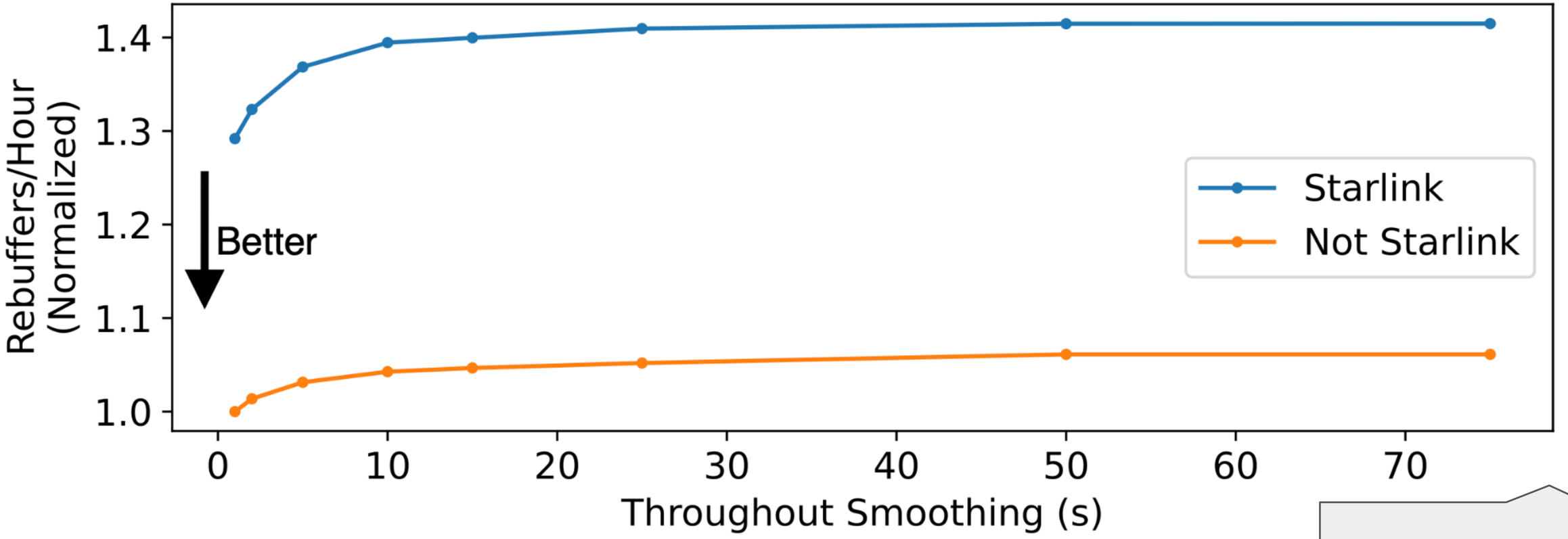
Simulation Methodology

- For 500K Starlink and 500K non-Starlink sessions
- Vary one value of one design (Throughput Discount, Buffer Level for Discount, Throughput Smoothing)
  - while holding the other two at a constant value.

Throughput smoothing is more likely (<10%) to overestimate Starlink's throughput

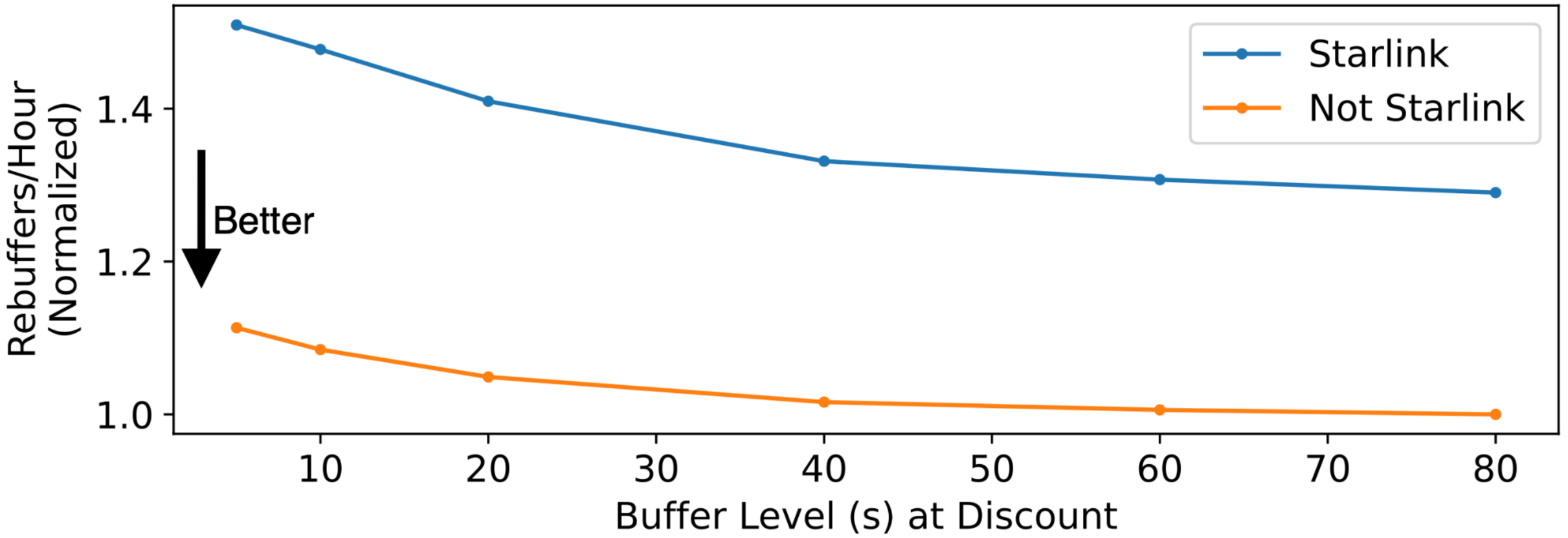


Throughput smoothing does not allow Starlink to catch up to other rebuffer rates



Verified with A/B Test

Buffer discount does not allow Starlink to catch up to other rebuffer rates



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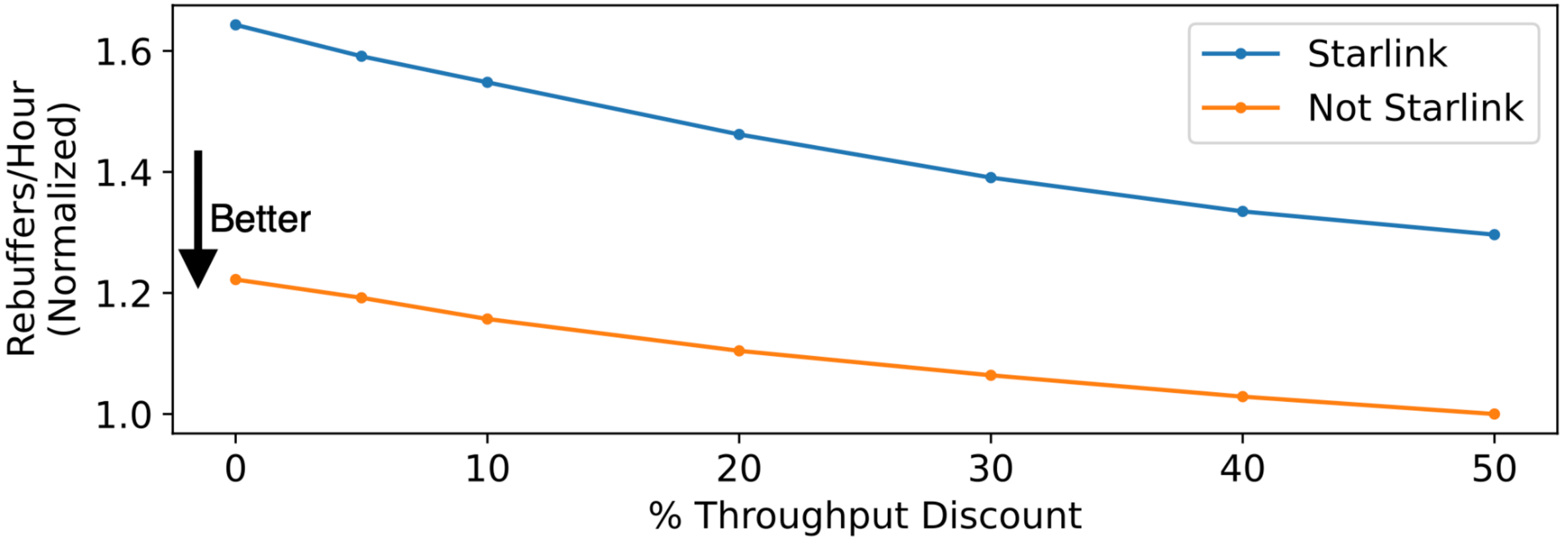


Hypothesis

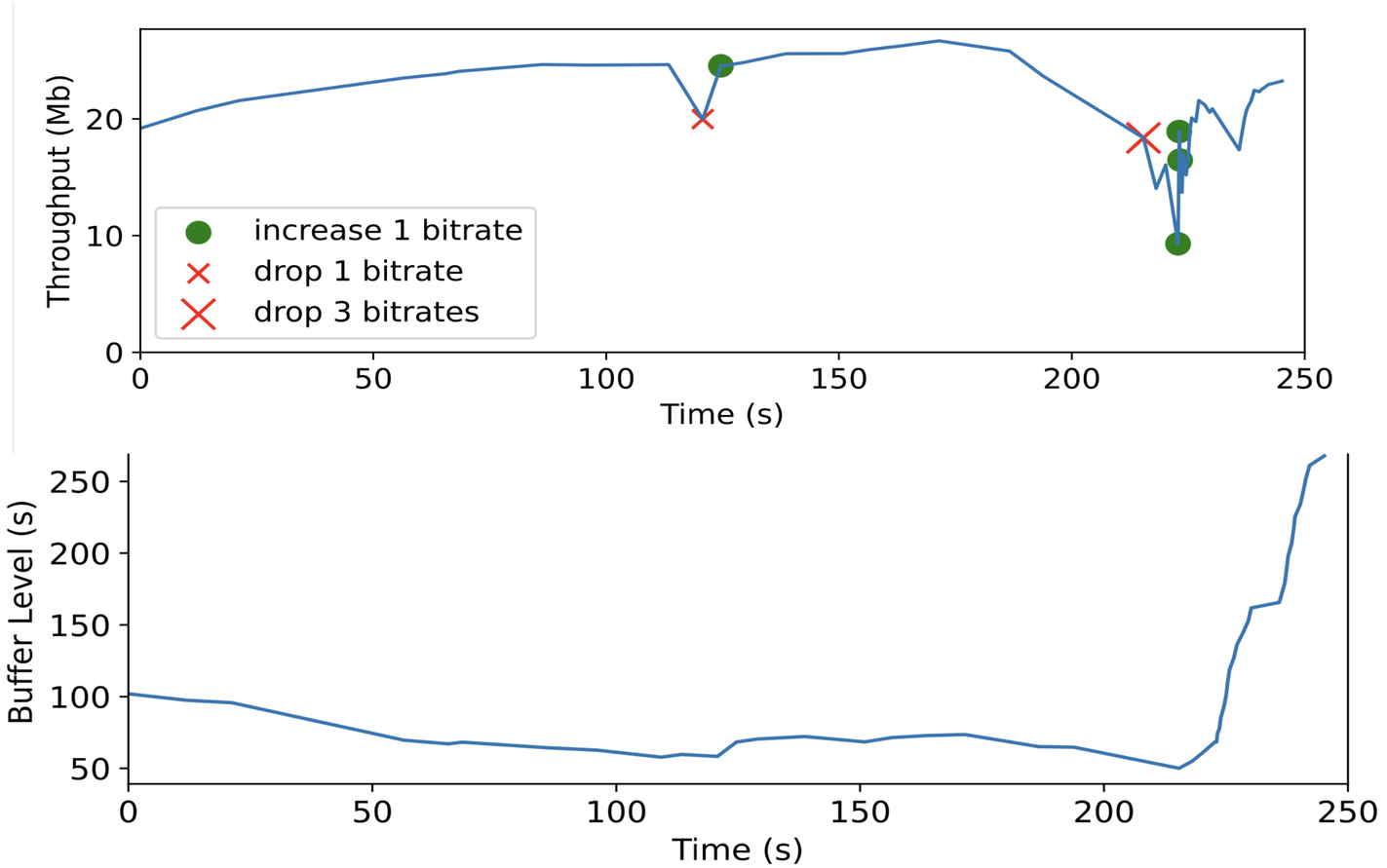
Fewer Network Rebuffers <- “Better” ABR <- Better ABR Parameters for Starlink

Hypothesis

Fewer Network Rebuffers <- “Better” ABR <- Better ABR Parameters for Starlink

Starlink can never catch up to non-Starlink rebuffer rates

Future of ABR: account for throughput variation



Summary

- HitchHiking is a methodology to measure satellite links without needing specialized hardware
- HitchHiking reveals that LEO network routing is more complex than previously understood
- Video streaming over LEO is rapidly rising in popularity
- Interesting applications for networking