Making Sense of Constellations

Methodologies for Understanding Starlink's Scheduling Algorithms

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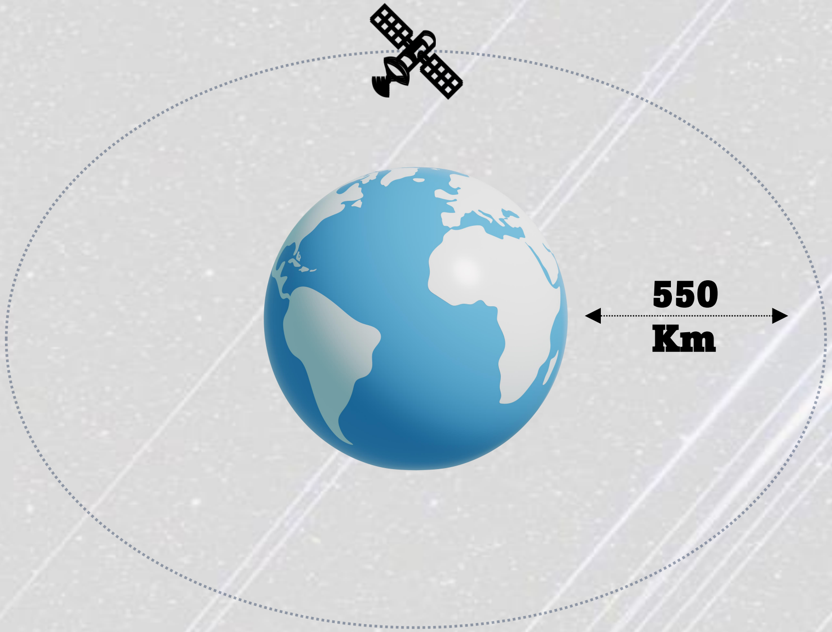
Antonio Bianchi, Rishab Nithyanand

GMI-AIMS-3

CoNEXT 2023

What is Starlink?

Low-earth orbit satellite constellation

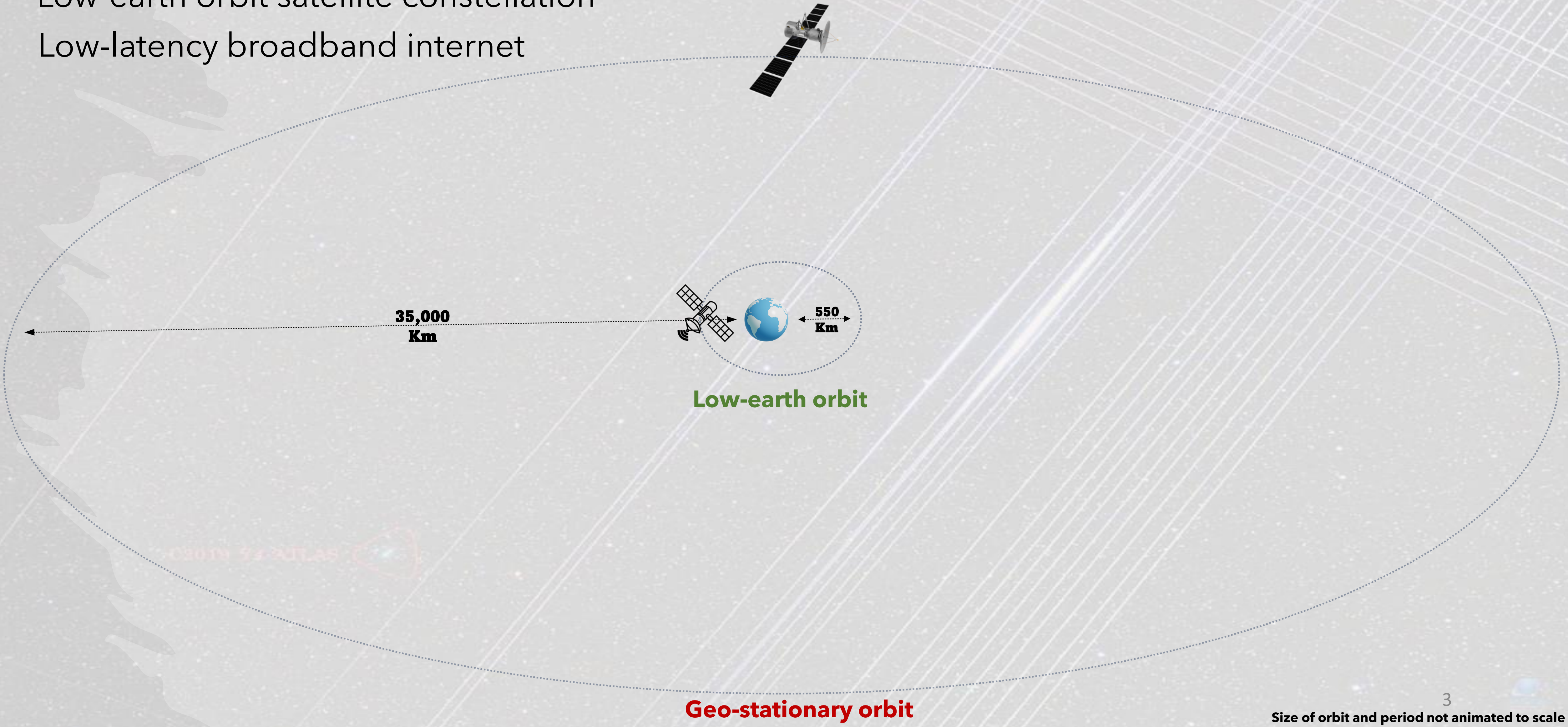


Size of orbit and period not animated to scale

What is Starlink?

Low-earth orbit satellite constellation

Low-latency broadband internet



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LEO constellation

Challenges

Faster orbital period
Smaller coverage area on Earth

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LEO constellation

Challenges

Fast orbit period
Smaller earth coverage area

Deploy 1000s of satellites on multiple orbital paths

Eliminates gaps between service times
Increases coverage

Size of orbit and period not animated to scale

How does Starlink work?

User terminal

Phased-array antennas installed at user's location to track and connect to satellites

Ground station

A set of phased-array antennas that receive traffic from satellites and send it through wired links to Starlink's PoPs

PoP
(Point of presence)

Physical network interfaces where user traffic is passed to the internet backbone

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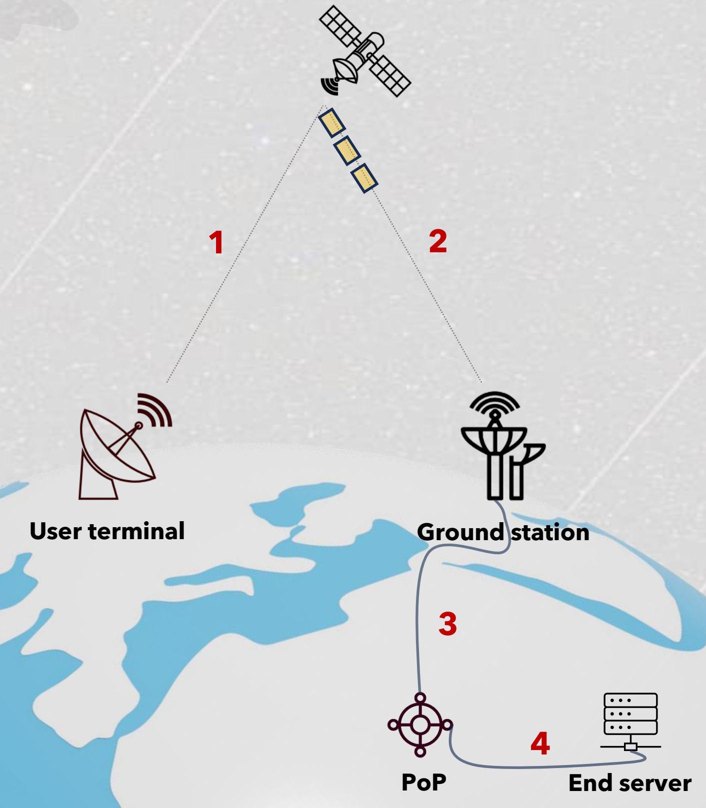

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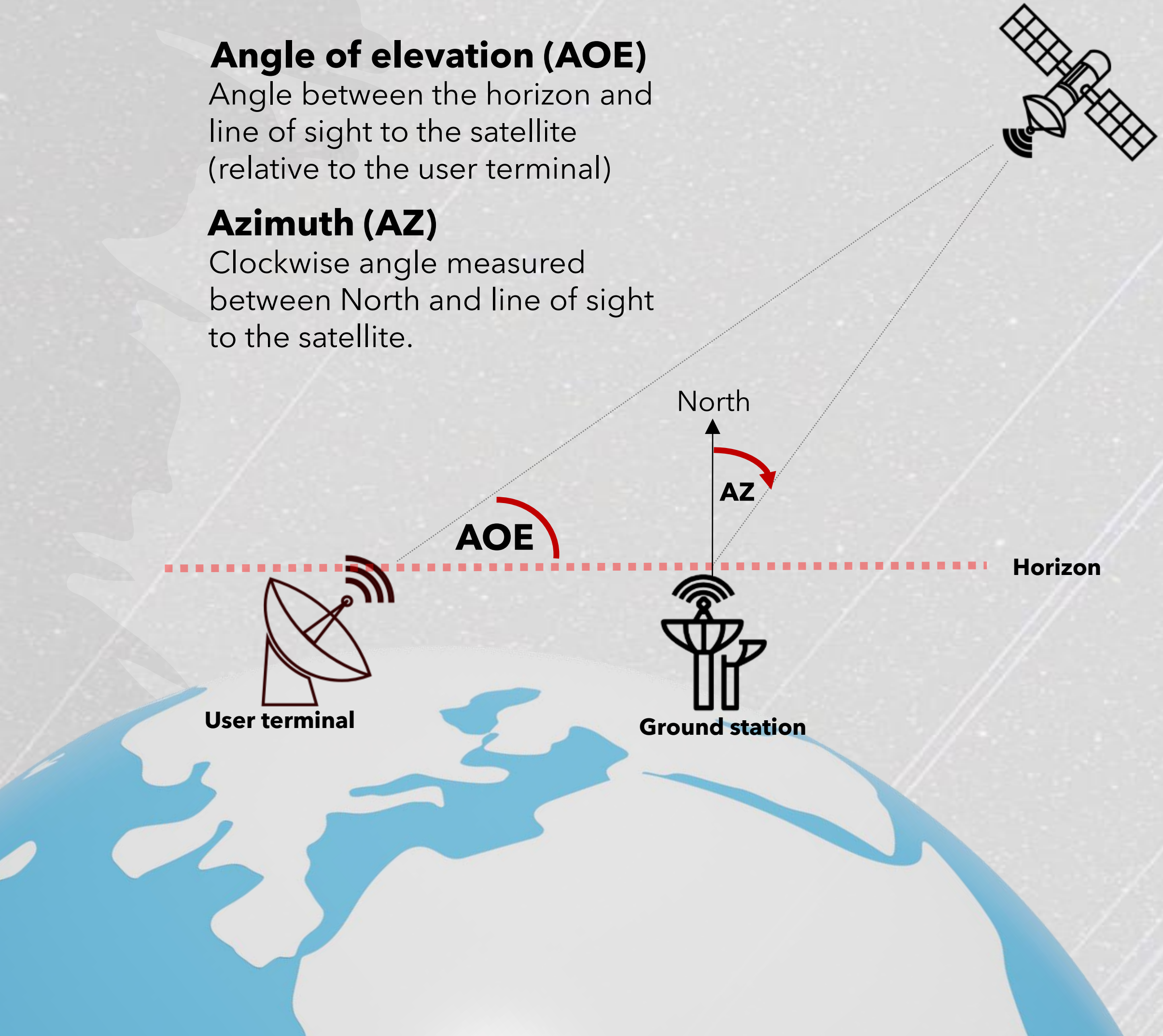
Connecting to a satellite

Angle of elevation (AOE)
Angle between the horizon and line of sight to the satellite (relative to the user terminal)

Azimuth (AZ)
Clockwise angle measured between North and line of sight to the satellite.



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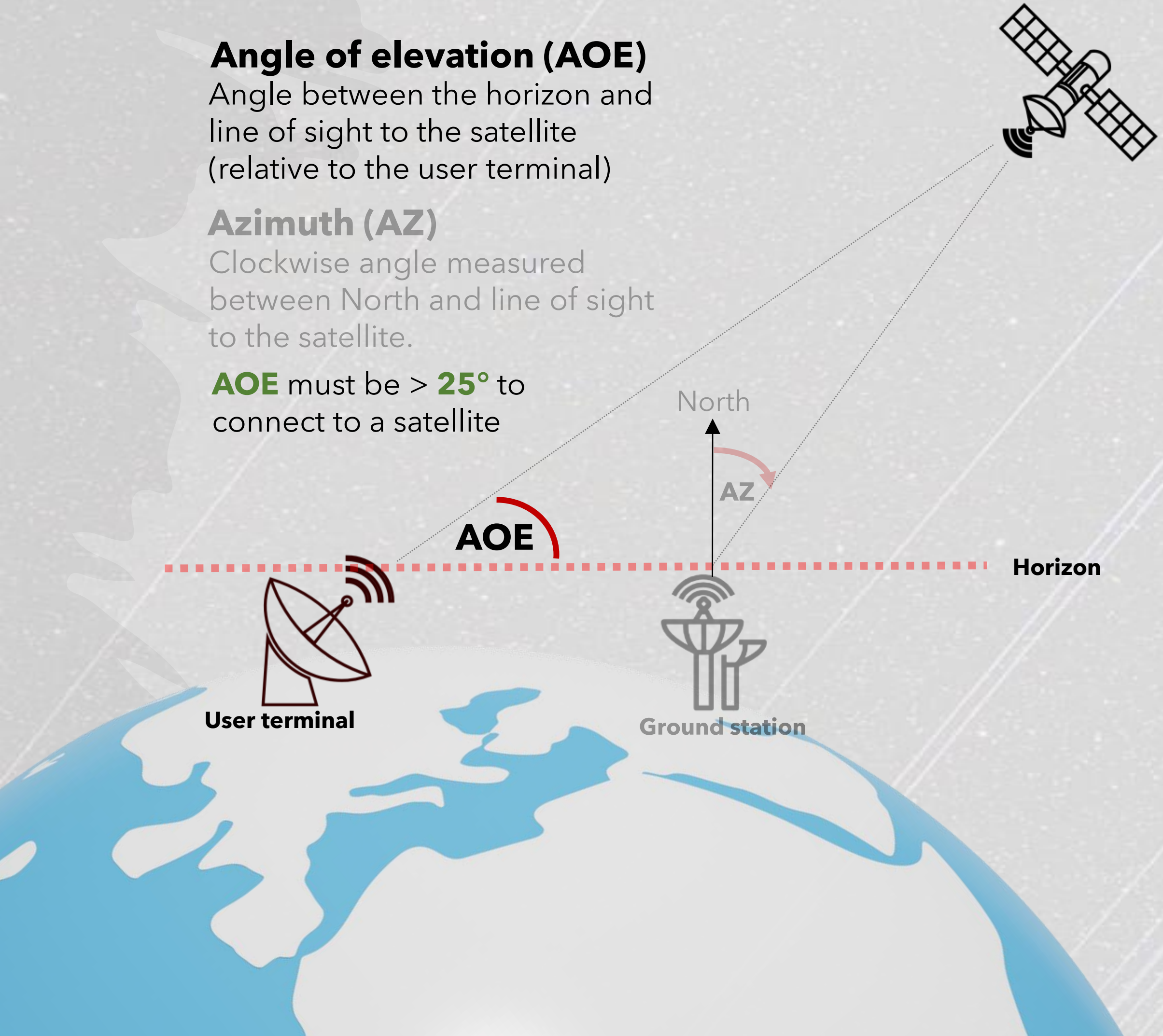
Clockwise angle measured between North and line of sight to the satellite.

AOE must be > **25°** to connect to a satellite



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Understanding Starlink's scheduling algorithms

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At any point in time, there are multiple satellites available for most user terminals that satisfy the **AOE** > **25°** condition.

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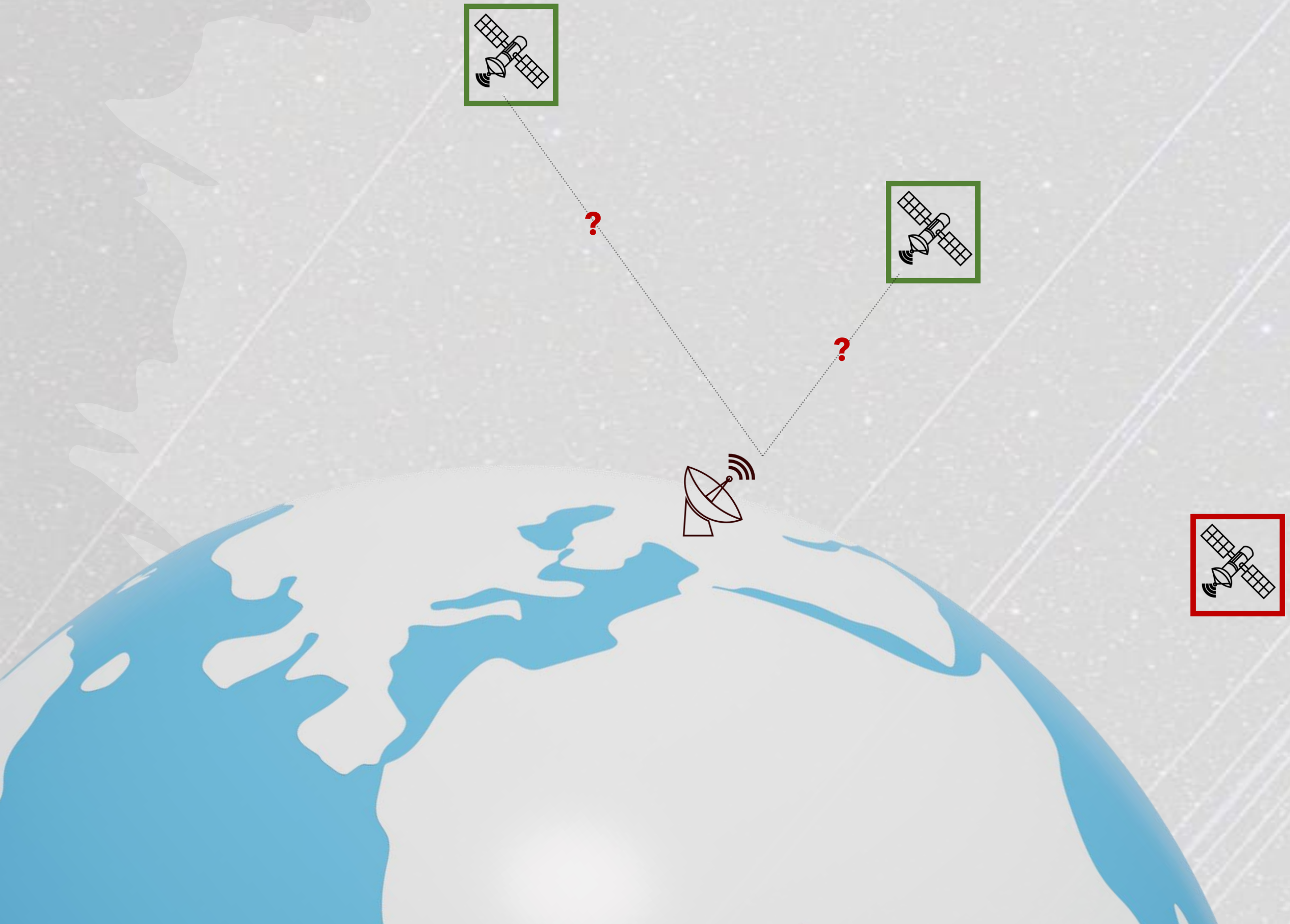

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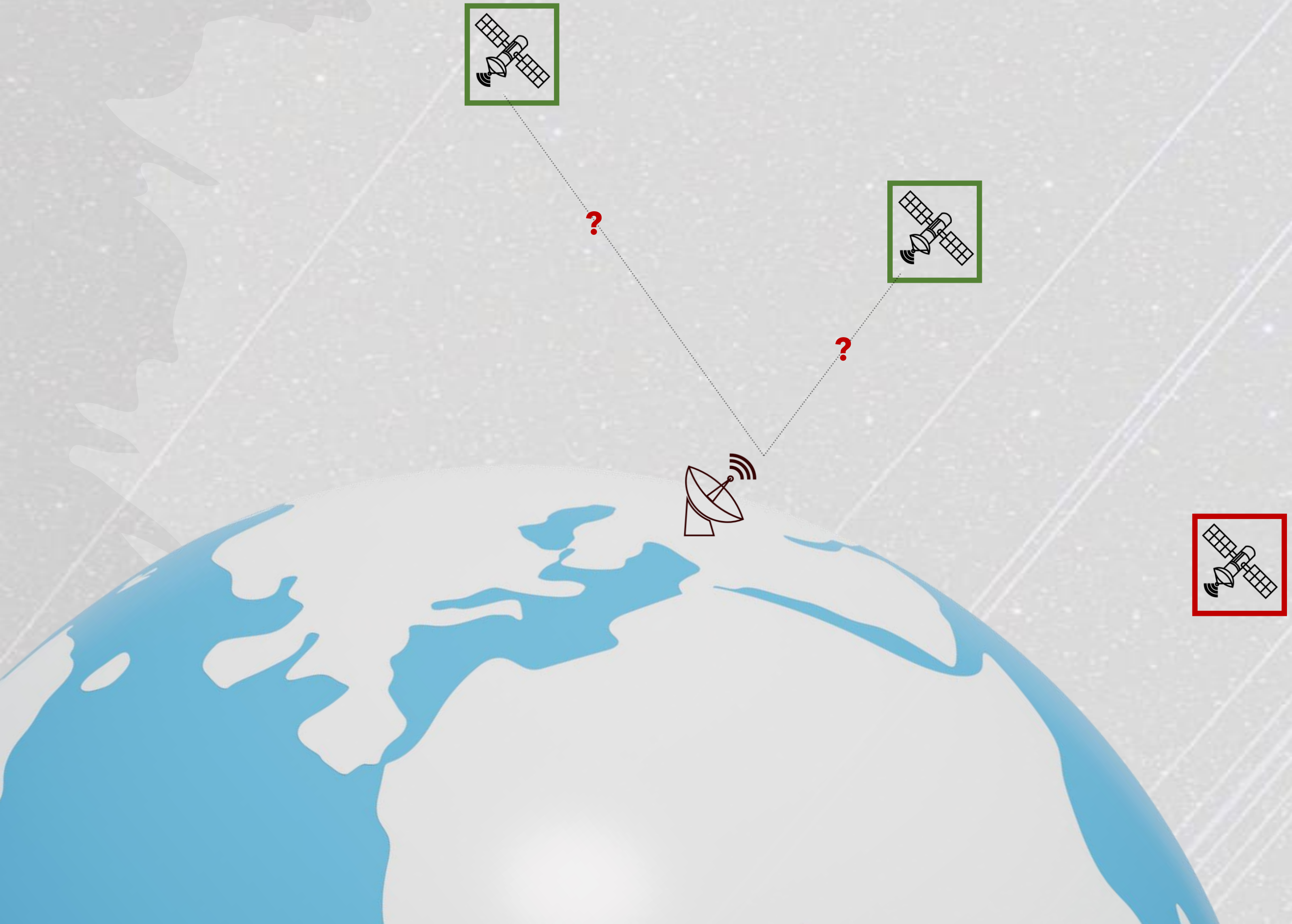

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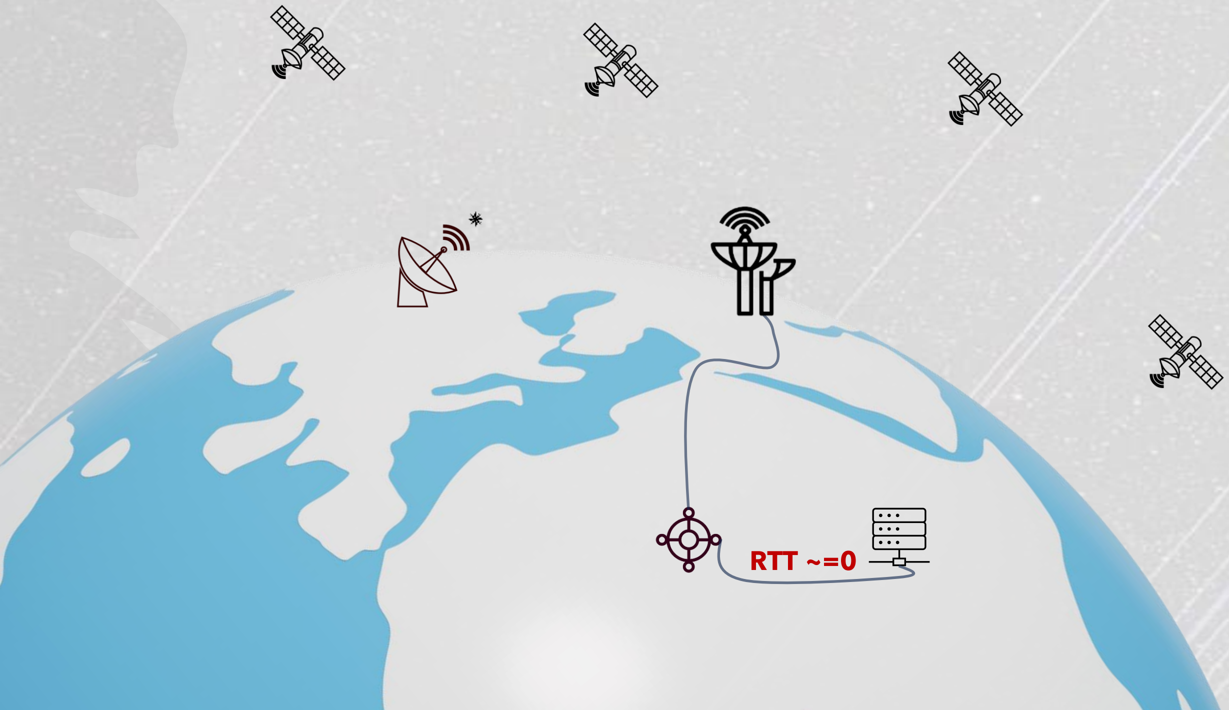
What factors influence the global scheduler's decision-making process when choosing one satellite out of the available set?

To answer this question, we first need to identify the satellite we are connected to during any given 15-second slot.

Understanding Starlink's scheduling algorithms

Experimental setup



Measurement vantage points

4 geographically distributed Starlink user terminals; 3 in the US, 1 in Europe.

Round-trip times

We conduct high fidelity round-trip measurements – once every 20ms – using iRTT.

Ground latency control

We co-locate our measurement servers with Starlink's PoPs thereby reducing the noise in RTT measurements introduced by fiber networks.

Image does not represent actual locations

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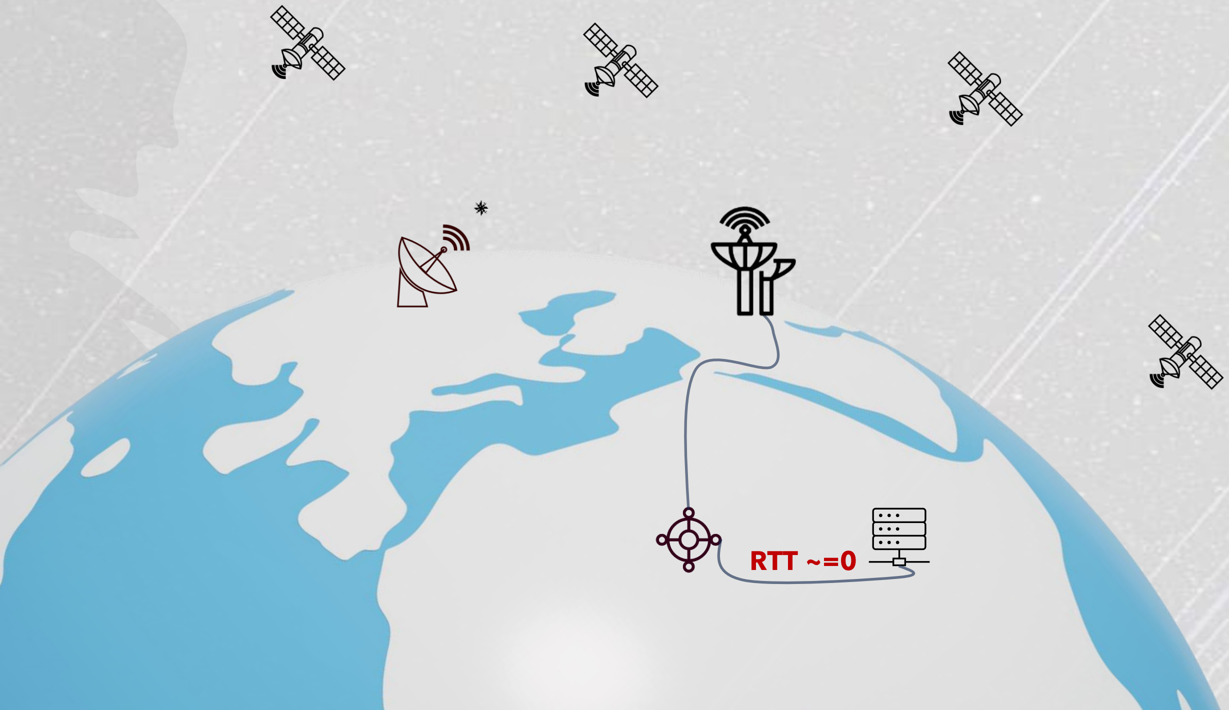

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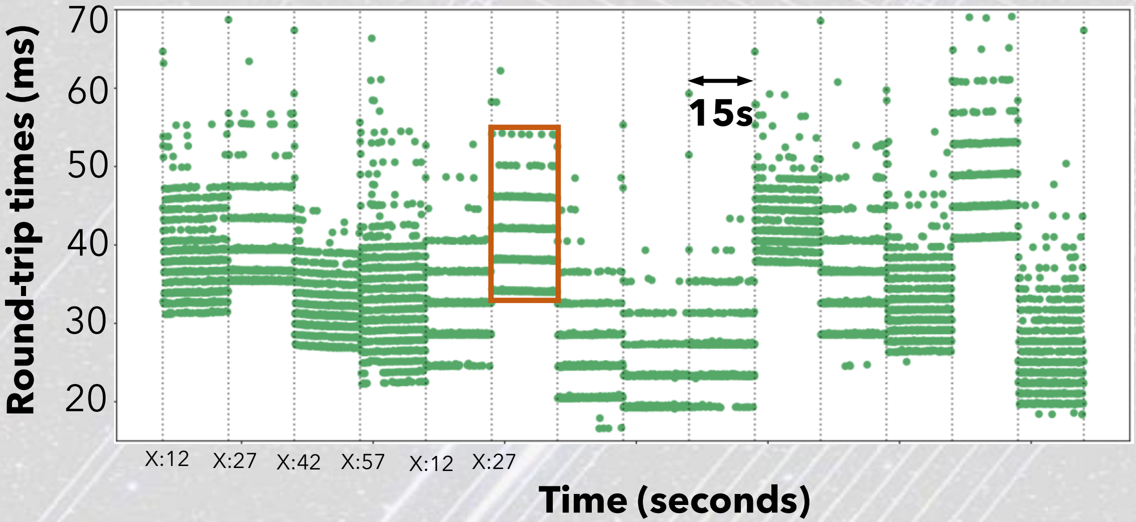

Formation of parallel bands

We observe the formation of parallel bands few milliseconds apart in all locations; reflects evidence for a round-robin on-satellite medium access controller mentioned in a SpaceX FCC filing.

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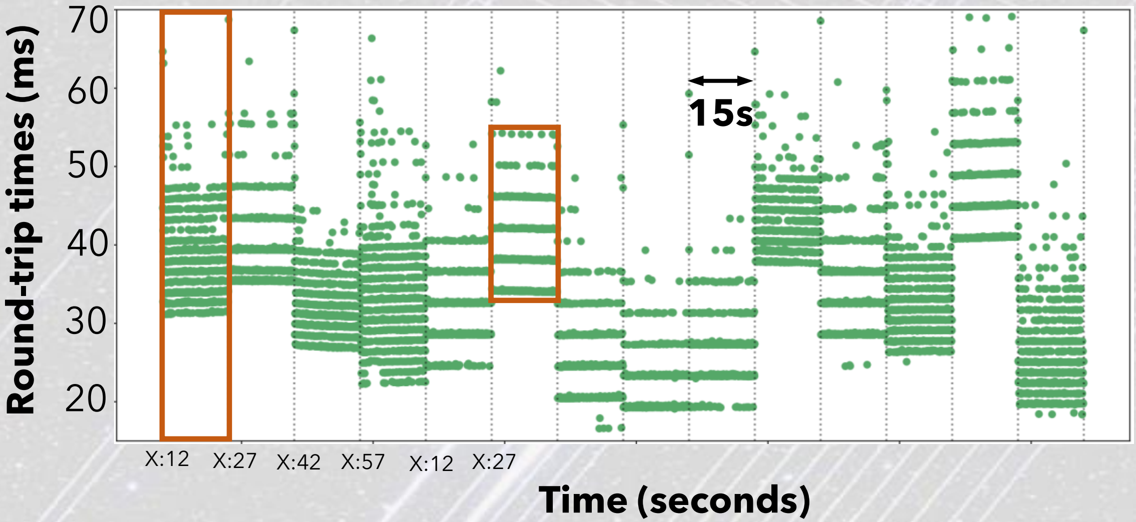

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Synchronized changes in RTT
Significant change in latency characteristics observed 12, 27, 42 and 57 seconds after every minute. There changes were simultaneously observed at every vantage point. Evidence for a global scheduler outlined in an FCC filing.

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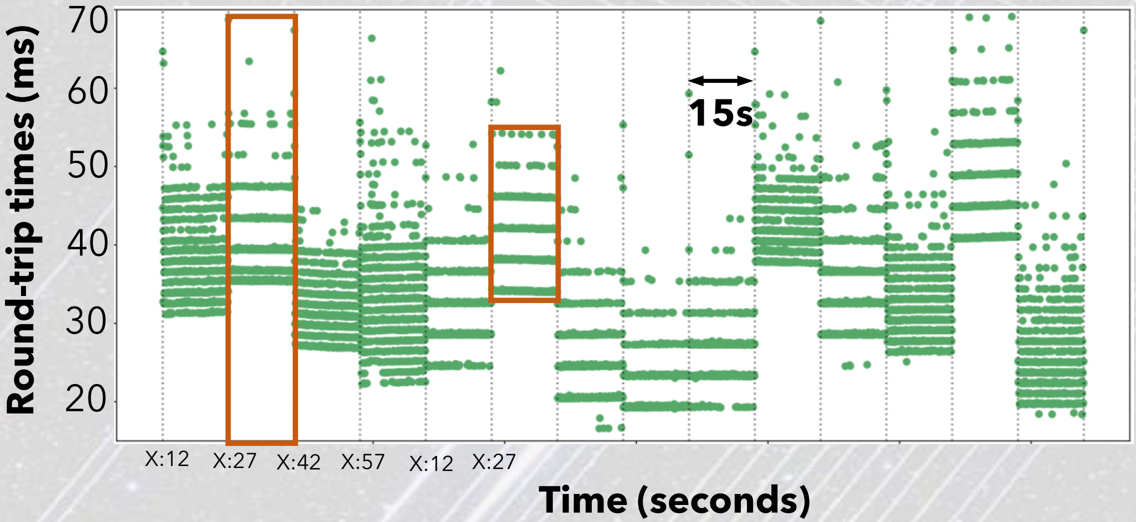

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Identifying current connected satellite

Two-line element set file

Publicly available snapshots of satellites position in their orbit.

```
STARLINK-64
1 44275U 19029AS  19322.78559003  .00000401  00000-0  46912-4 0  9998
2 44275  53.0018  89.6274 0006823   0.9672 359.1327 15.05482543 27051
```

Satellite position propagation

SGP4 algorithm to calculate satellite's position every second during its orbit.

Starlink obstruction images

2-D image showing the trajectories of satellites the user terminal connects to.

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S_3	P_{S3T1}, P_{S3T2}, P_{S3T3}...
S_4	P_{S4T1}, P_{S4T2}, P_{S4T3}...
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Starlink obstruction images

O_{T1}

O_{T2}

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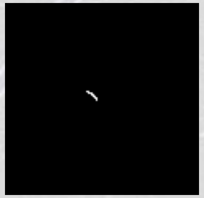
$\oplus$ XOR →



Isolated satellite trajectory

Extract → **positions**

P_{SxT1}, P_{SxT2}, P_{SxT3}...

Compare → **Edit distance**

S3 Current connected satellite

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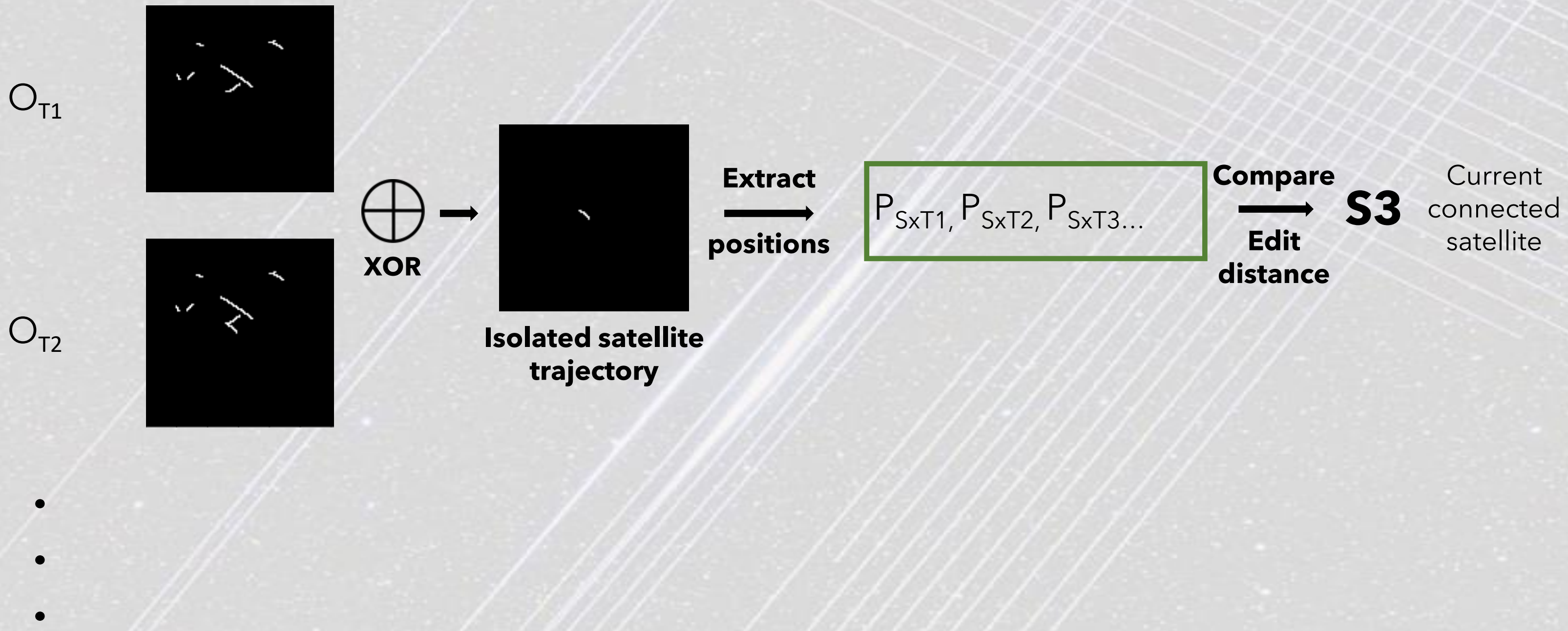

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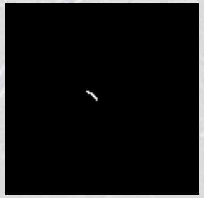

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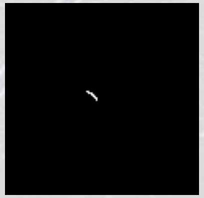

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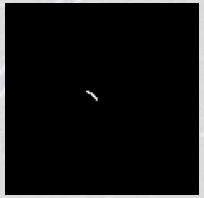

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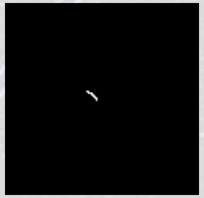

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Understanding Starlink's scheduling algorithms

Factors influencing global scheduler decisions

Satellite positions

Satellite launch dates

Satellite sunlit

Understanding Starlink's scheduling algorithms

Factors influencing global scheduler decisions

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Comparison of angle of elevations and azimuths of available vs. selected satellites

Takeaway: Satellites higher-up in the sky towards the north of the user-terminal are preferred.
Rationale: Allows more efficient communication due to less power loss

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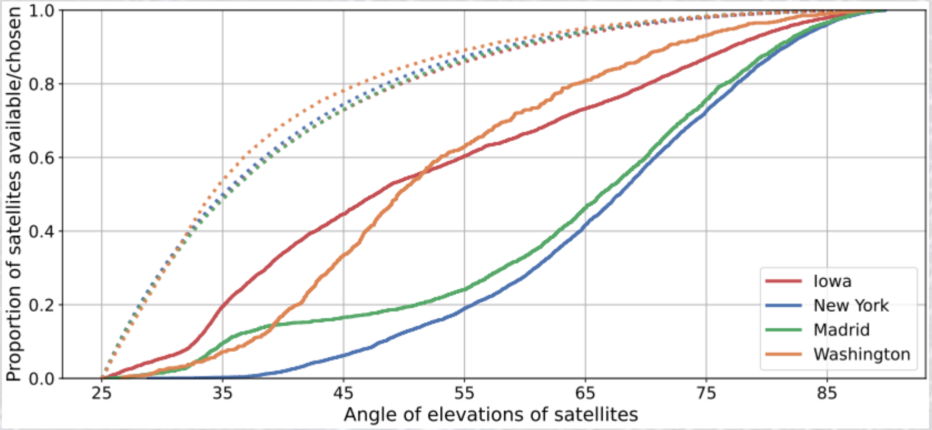

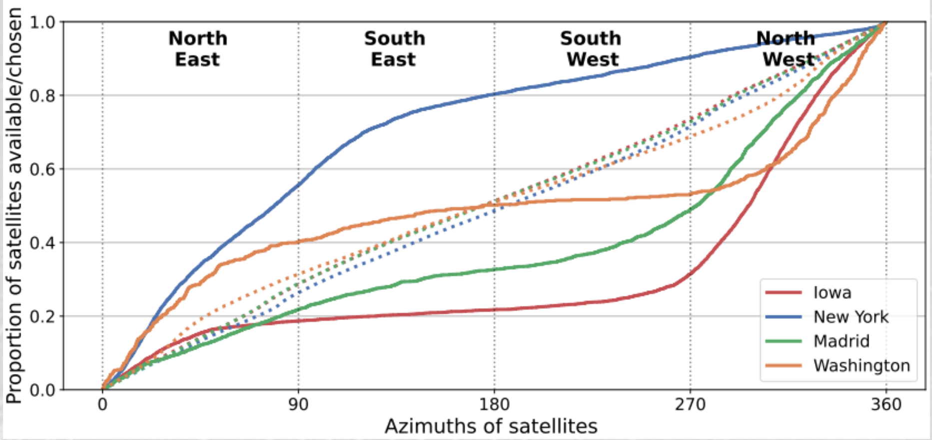

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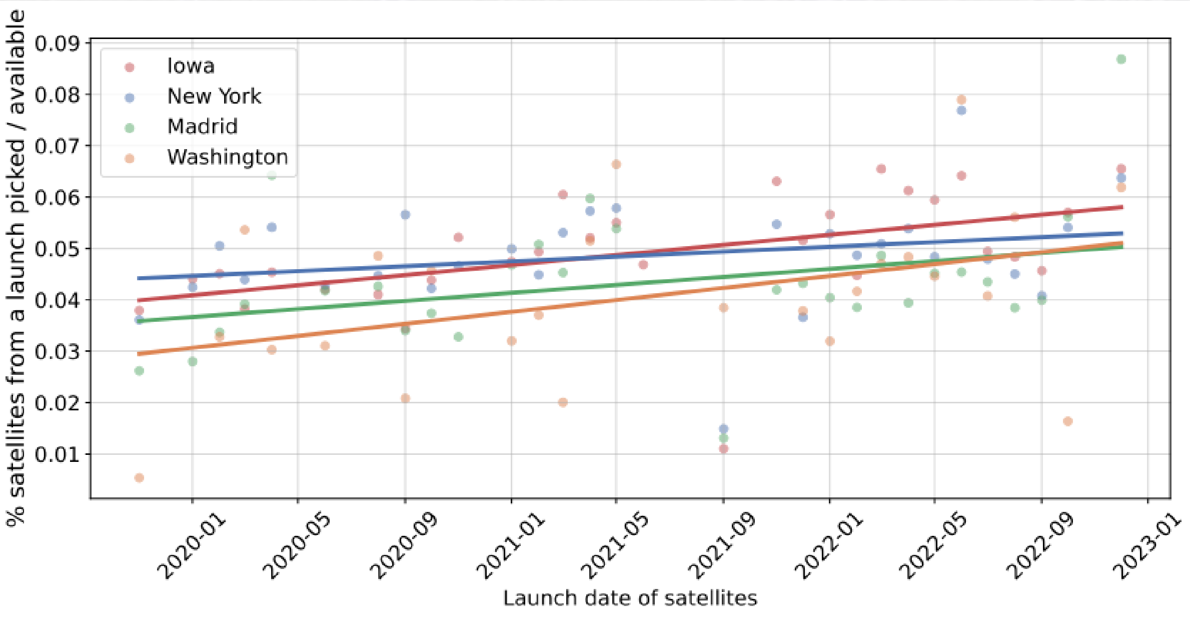

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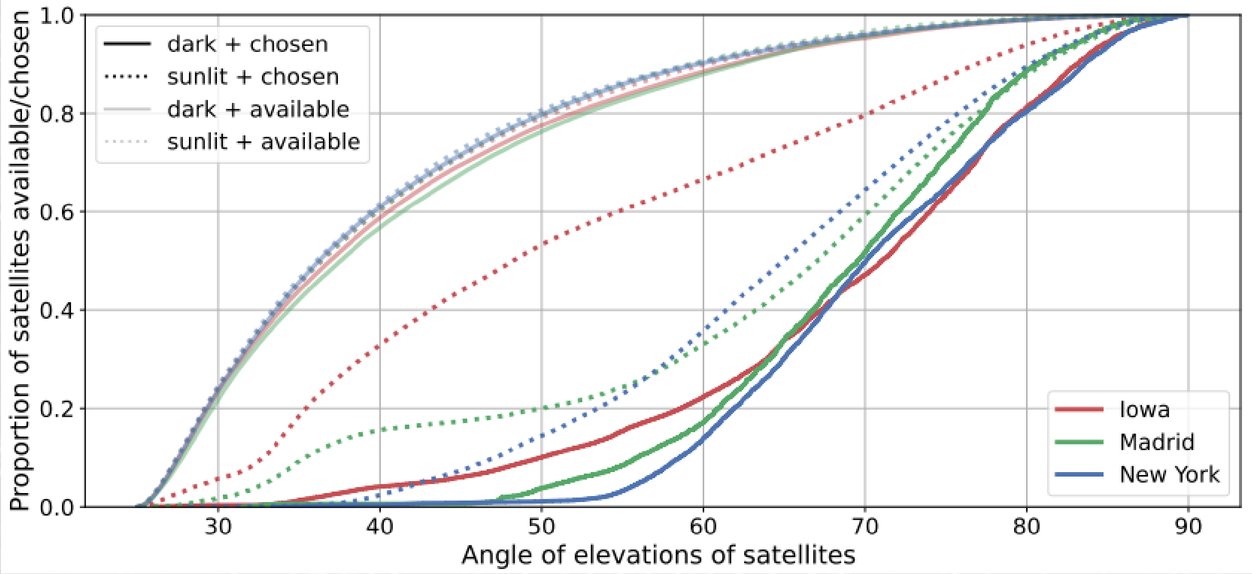
Satellite sunlit

Takeaway: Sunlit and high-elevation dark satellites are preferred.
Rationale: As satellites can only charge when sunlit, this preference allows efficient communication and energy preservation.



Understanding Starlink’s scheduling algorithms

Modeling the global scheduler

Batch-aware modelling

For each available in a 15-second slot satellite,
we extract the following parameters:

(θ) - azimuth
(ϕ) - angle of elevation
(a) - age
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Cluster

$$\left(\frac{\theta s - \mu(\theta)}{\sigma(\theta)}, \frac{\phi s - \mu(\phi)}{\sigma(\phi)}, \frac{as - \mu(a)}{\sigma(a)}, \epsilon \right)$$

where:
μ(x) – mean of feature x
σ(x) – std. dev of feature x

clusters satellites by how many standard deviations away from the group mean each of their parameters are

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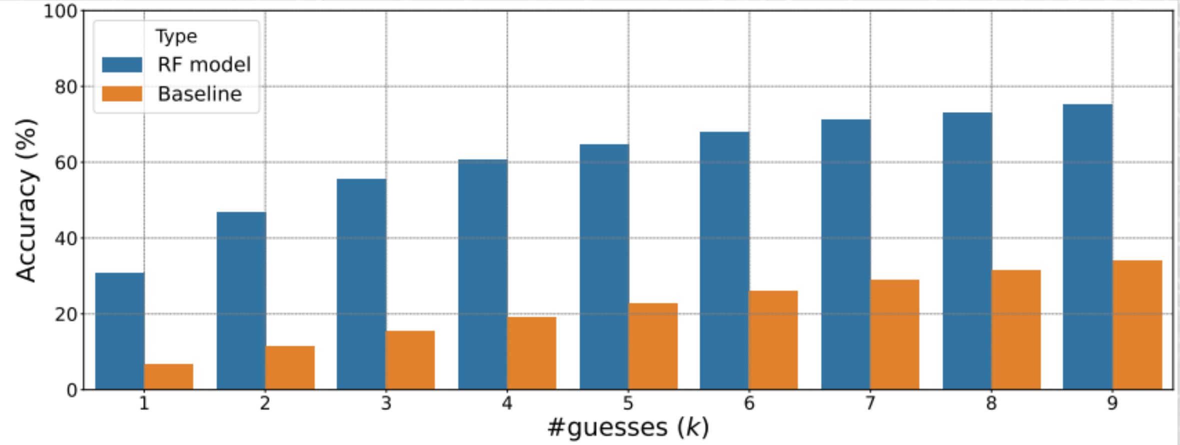
top-k-accuracy



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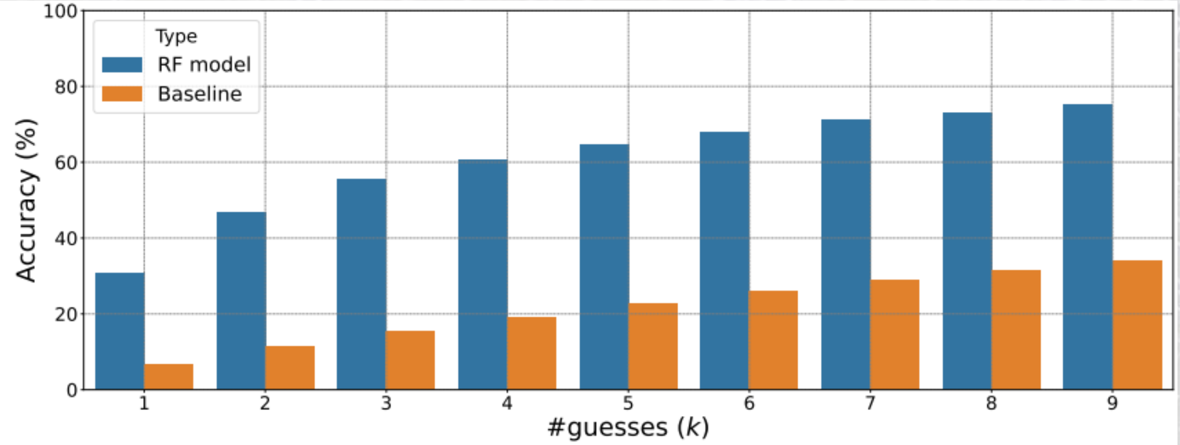

Important features

(x, 2, y, z) – preference for satellites higher in the sky

(x,y,-1,1) – preference for newer sunlit satellites

Conclusion

We perform high-fidelity RTT measurements to identify evidence for the presence of an on-satellite MAC scheduler

We develop a novel methodology to identify the current satellite a user terminal is connected to

We uncover the behavior of Starlink's "global scheduler".

Making Sense of Constellations

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University of Iowa

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Cornell University

Antonio Bianchi
Purdue University

Rishab Nithyanand
University of Iowa

For further questions and discussions

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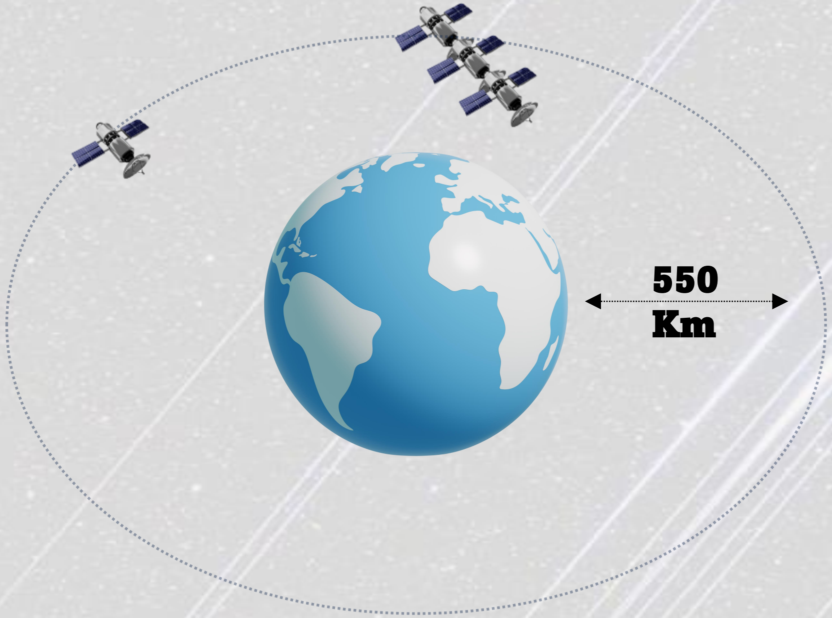
Backup slides

What is Starlink?

Low-earth orbit satellite constellation



Size of orbit and period not animated to scale

How does Starlink work?

Understanding Starlink's scheduling algorithms

Satellite bandwidth constraints

Each Starlink satellite receives network traffic from multiple user terminals; how do satellites schedule traffic given limited bandwidth capacity?

Satellite to user terminal mapping

What factors go into the decision-making process of assigning user terminals to satellites (given multiple choices).

LEO constellation

Challenges

Fast orbit period

Smaller earth coverage area

Deploy 1000s of satellites on multiple orbital paths

Eliminates gaps between service times

Increases coverage

Size of orbit and period not animated to scale

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