A Deep Dive into LEO Satellite Topology Design Parameters

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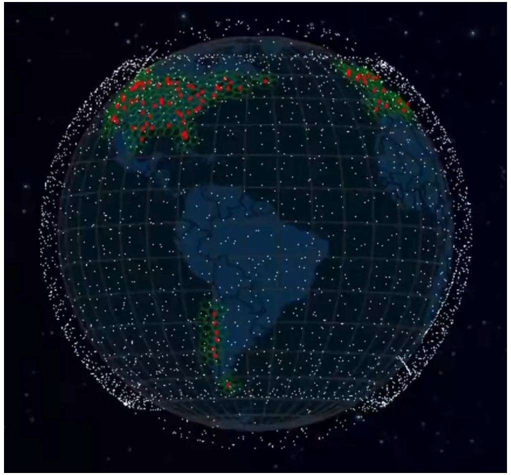
LEO Constellations are Rapidly Growing

Thousands of fast-moving Low Earth Orbit (LEO) satellites.

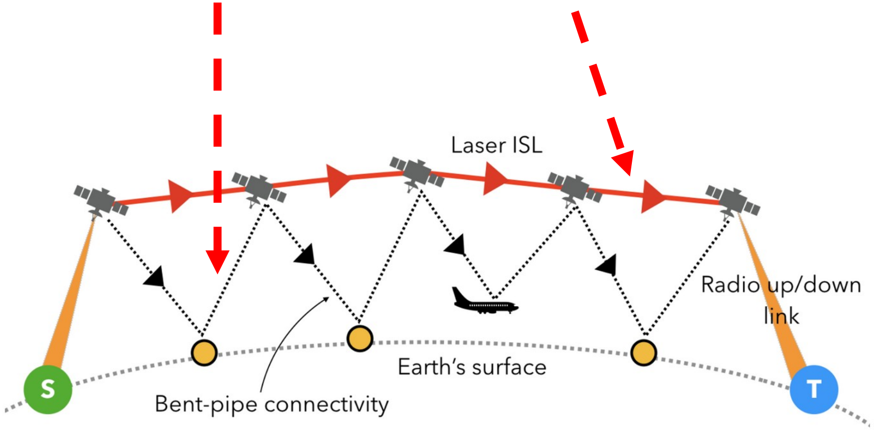


Benefits

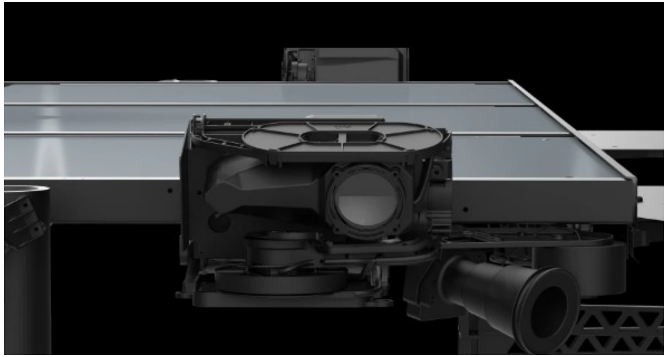
- High global coverage (especially for remote/marine/aviation users)
- Reasonable speeds (25-220 Mbps per user)
- Low latency & Cost-effective
- Advanced communication technology → Laser-based Inter Satellite Links (ISLs)

Inter-Satellite Links (ISLs)

“Bent Pipe” vs “Inter-satellite Links”



Our paper considers the ISL-based topology

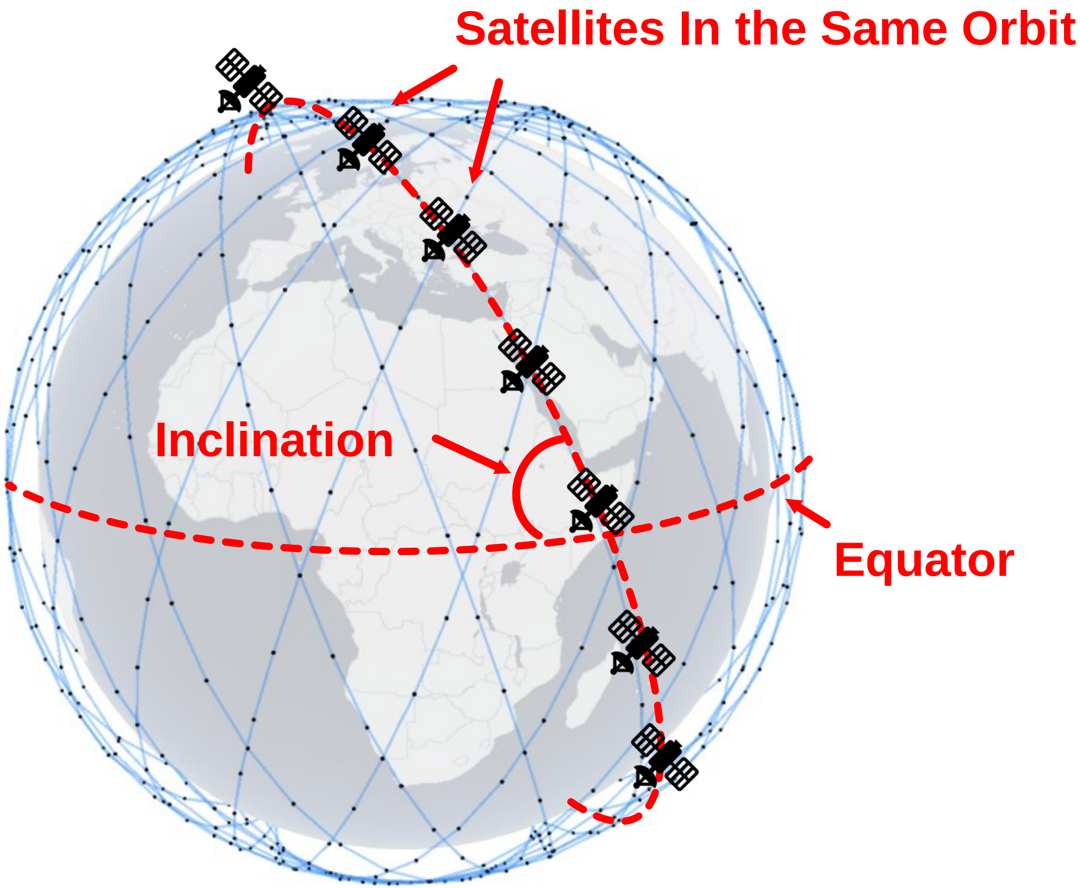


Laser port of Starlink

LEO constellations parameters

Key Parameters

- **Altitude**
- **Number of Orbits**
- **Number of satellites per orbit**
- **Inclination**



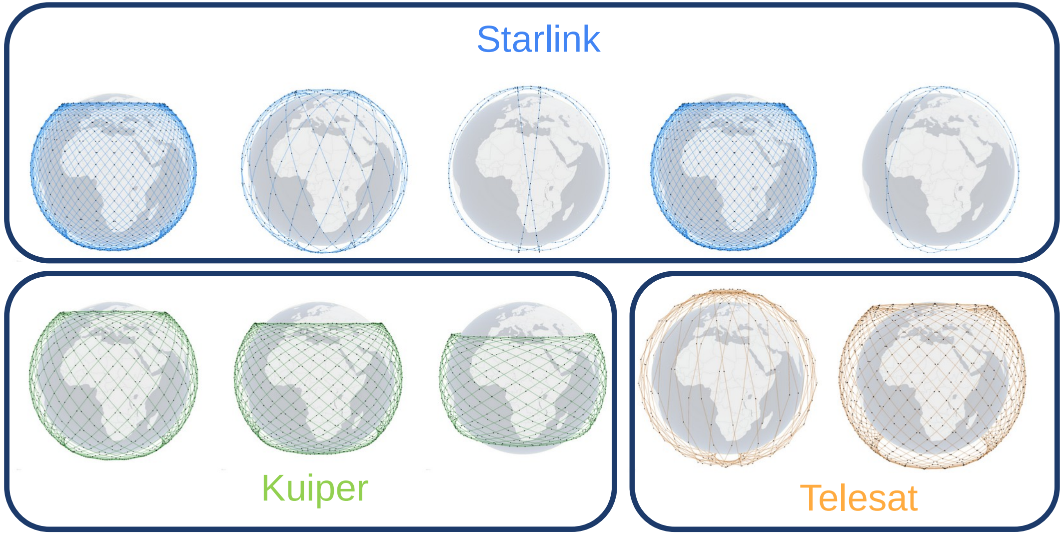
Why are LEO constellations parameters important?

Primary parameters for
different shells of LEO constellations

Name	H (km)	Orb.	Sats/Orb	Total Sats	Incl.
S1	550	72	22	1584	53.0°
S2	570	36	20	720	70.0°
S3	560	6	58	348	97.6°
S4	540	72	22	1584	53.2°
S5	560	4	43	172	97.6°
K1	630	34	34	1156	51.9°
K2	610	36	36	1296	42°
K3	590	28	28	784	33°
T1	1015	27	13	351	98.98°
T2	1325	40	33	1320	50.88°

Table 1: Shell configurations for Starlink's first phase (S1-S5), Kuiper (K1-K3), and Telesat (T1-T2).

Visualization of LEO Constellations

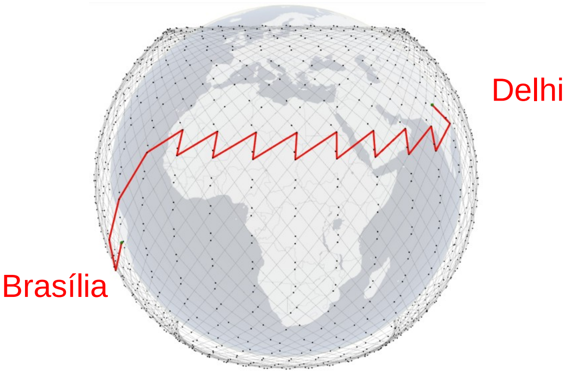


What is the impact of LEO shell configuration parameters on network performance?

Experiment Setup

- We utilize the open-source LEO satellite network analysis platform, Hypatia [IMC' 20].
- +Grid topology for ISLs. (One satellite connected with four satellites closest to it)
- The user traffic is end-to-end traffic between 100 ground stations.
- Each experiment runs for 400 seconds and we capture snapshots of satellite position every 1 second.

100 Ground Stations on earth.



Shortest path between Delhi and Brasília

Motivating Example

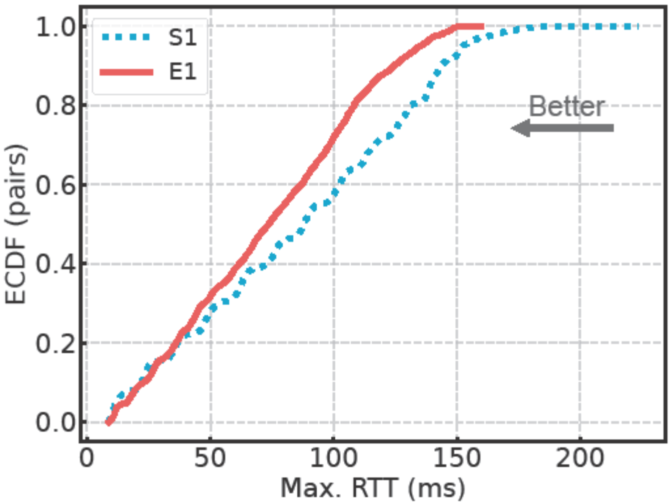
Starlink shell 1 (S1) : **1584** satellites

Custom-designed example shell (E1): 720 satellites.

Same altitude but differ in:

- Number of Orbits (**S1: 72** vs **E1: 20**)
- Number of Satellites per Orbit (**S1: 22** vs **E1: 36**)
- Inclination (**S1: 53°** vs **E1: 70°)**

E1 is better than **S1** ?!



Fewer satellites but **better** latency performance ？

Experiment Design Overview

Different shells of the existing LEO mega-constellations.:

- Starlink Phase 1 (5 shells)
- Kuiper (3 shells)
- Telesat (2 shells)

Experiments with Synthetic Configurations:

- Number of orbits (20, 33, 46, and 59)
- Number of satellites per orbit (20, 28, 36, and 44)
- Inclination (45°, 55°, 65°, and 75°)

Inclination & User Endpoints Experiment:

- Study the impact of alignment between satellite orbit **inclination** and **geographic angle** of user endpoints on latency performance

Experiment Design - Metrics

Round-Trip Time (RTT):

(a) *Max. (Min.) RTT*, which denotes the maximum (minimum) RTT observed between the sender and the receiver during a specified period
(b) *Max. RTT - Min. RTT*, is the difference between the maximum RTT and minimum RTT observed between the sender and the receiver during a specified period. This metric reflects the fluctuations in RTT experienced by a connection.

Path Changes :

The number of path changes between two endpoints over a specified period.

Experiment Design - Metrics

Geodesic Slowdown: slowdown relative to the optimal path.

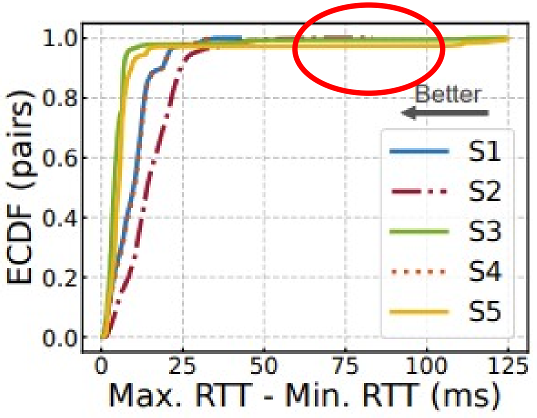
$max.RTT$: maximum Round Trip Time (RTT) between the sender and receiver during a specified period

$ideal.RTT$: RTT for direct data transmission between two endpoints over the shortest Euclidean distance on the Earth's surface

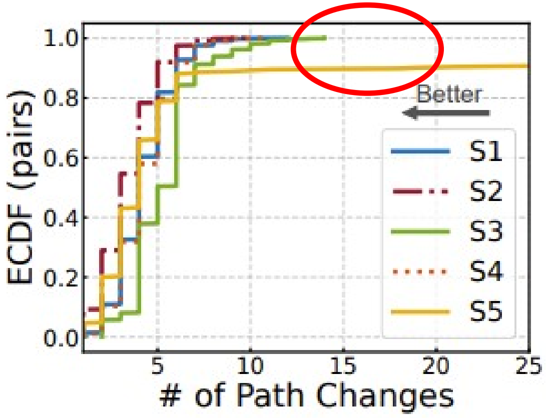
Average Hop Count:

average number of hops between a pair of endpoints during simulation.

Real-World LEO Constellations’ Performance



Starlink shell 1-5

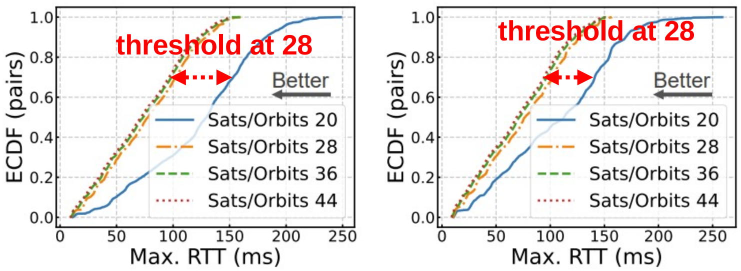


Starlink shell 1-5

- Sparse shells lead to high RTT variance and frequent path changes. (S3 and S5)
- Denser shells with more satellites and better coverage generally have lower RTT, lower geodesic slowdown, and more stable paths.
- S2, K2, and T2 offer the best performance in each of the three constellations, respectively.

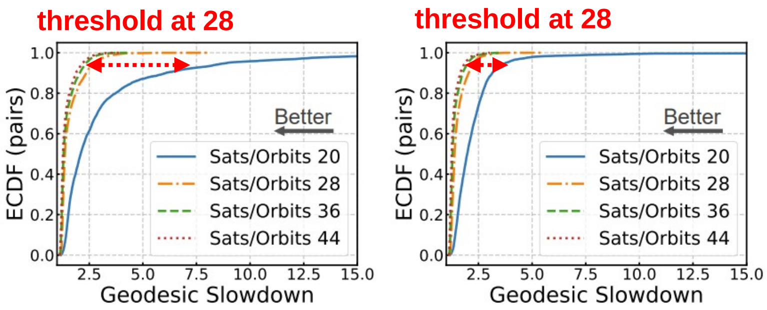
The Impact of the Number of Satellites per Orbit

Max. RTT



(a) 20 Orbits (b) 33 Orbits

Geodesic Slowdown

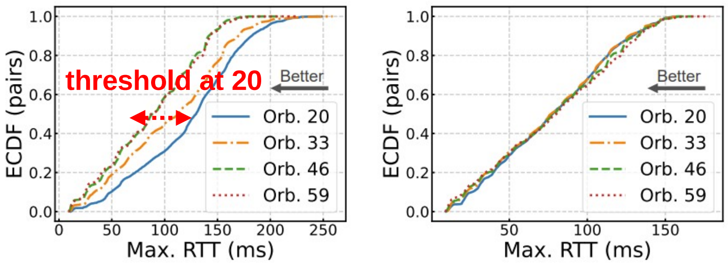


(a) 20 Orbits (b) 33 Orbits

- As the number of satellites per orbit increases, the latency and geodesic slowdown in the network decrease.
- We identify a threshold for the number of satellites per orbit, 28, below which the network performance degrades significantly.

The Impact of the Number of Orbits

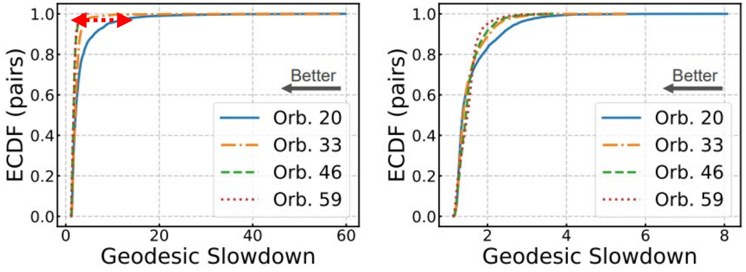
Max. RTT



(a) 20 Sats/Orbit (b) 28 Sats/Orbit

Geodesic Slowdown

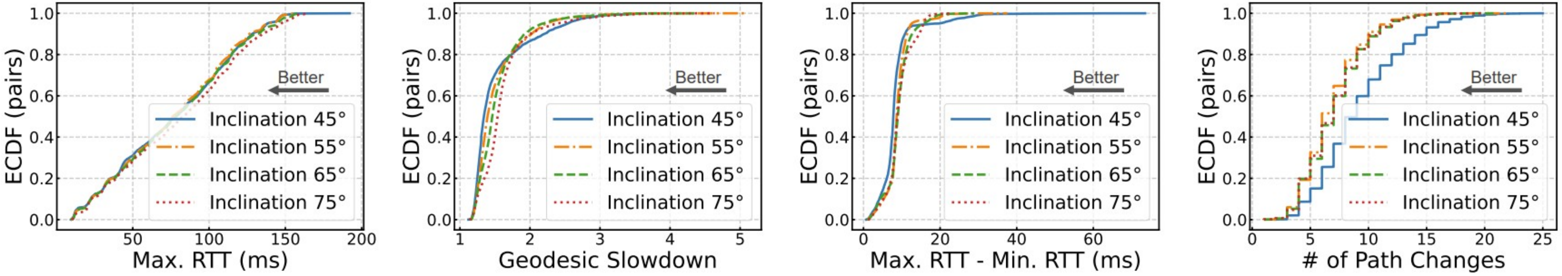
threshold at 20



(a) 20 Sats/Orbit (b) 28 Sats/Orbit

- As the number of orbits increases, the latency will generally decrease.
- Threshold: 20 orbits. Below this, network performance degrades significantly.
- Number of Orbits matter less than Number of Satellites per orbit, as seen in the small Max RTT improvement gap of 28 satellites per orbit.

The Impact of Orbit Inclination

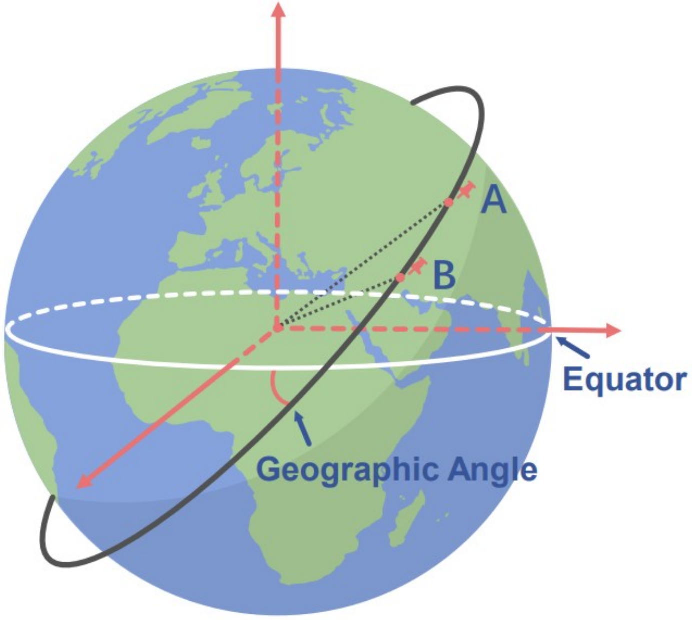


(a) Maximum RTT (b) Geodesic Slowdown (c) Max. RTT - Min. RTT (ms) (d) Number of path changes

Hard to tell which one is better.

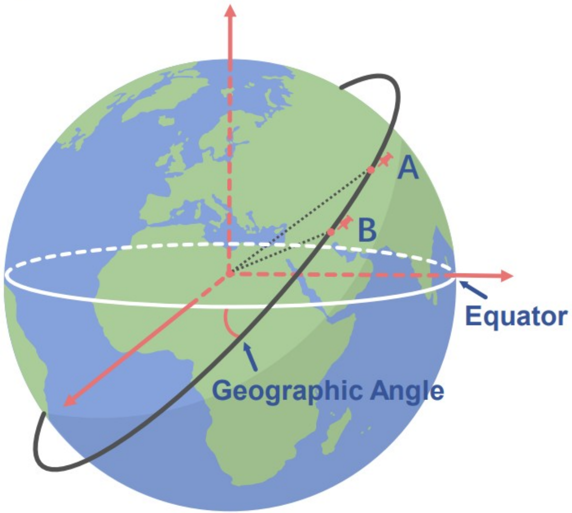
Geographic Angle of User Endpoints Pair

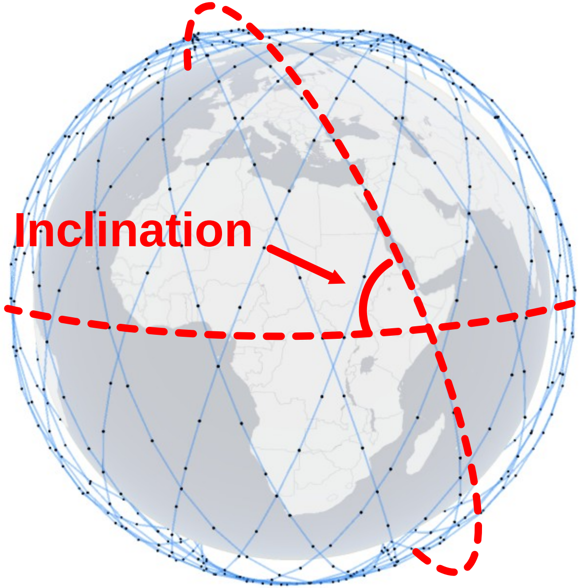
The angle between the Equator and the Plane contains the Earth Center, User Endpoint A, User Endpoint B.



Geographic Angle vs Inclination

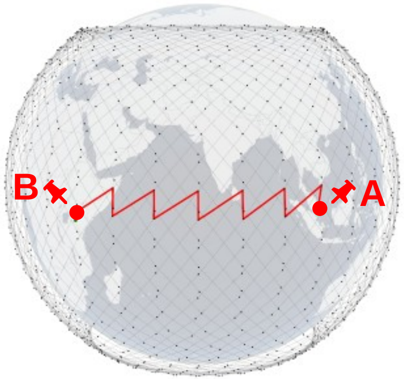
The **alignment** between satellite orbit **inclination** and **geographic angle** of user endpoints affects the path's latency performance.



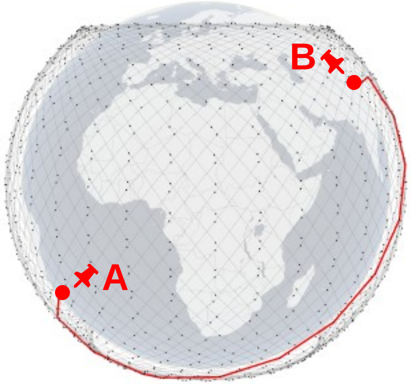


Geographic Angle vs Inclination

If the orbit inclination and geographic angle between endpoints A and B are not aligned, the path is more likely to follow a **zig-zag** pattern crossing multiple orbits.

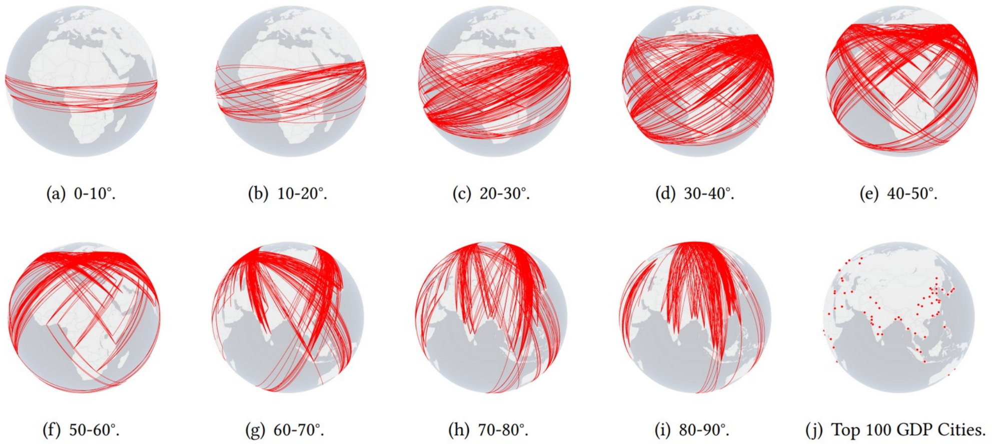


If the geographic angle of endpoints is close to the inclination of the orbits, the shortest path is more likely to follow a **single orbit** for most of the distance.

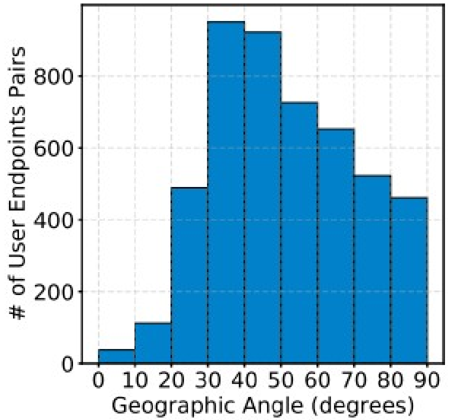


User Endpoints Traffic Distribution

- We categorize user traffic into **nine groups** (10° intervals from 0° to 90° based on geographic angle)
- We evaluate performance under different inclination values (**45°, 55°, 65°, and 75°**) for synthetic constellations.

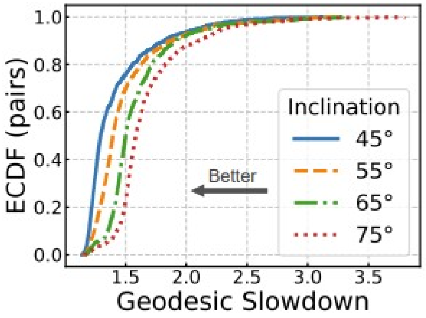


Nine groups user endpoint traffic based on their Geographic Angle

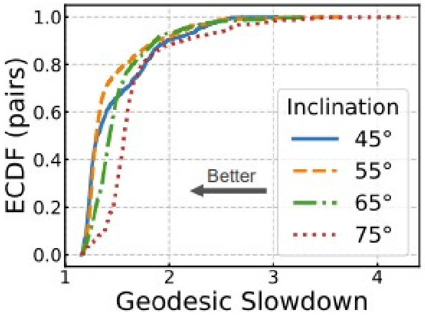


Number distribution of the user endpoint pairs

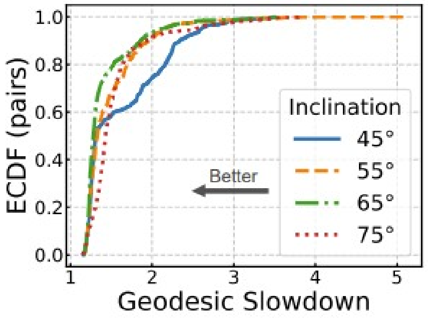
Evaluation - Inclination & User Endpoints



(e) 40-50° Endpoints pairs.



(f) 50-60° Endpoints pairs.



(g) 60-70° Endpoints pairs.

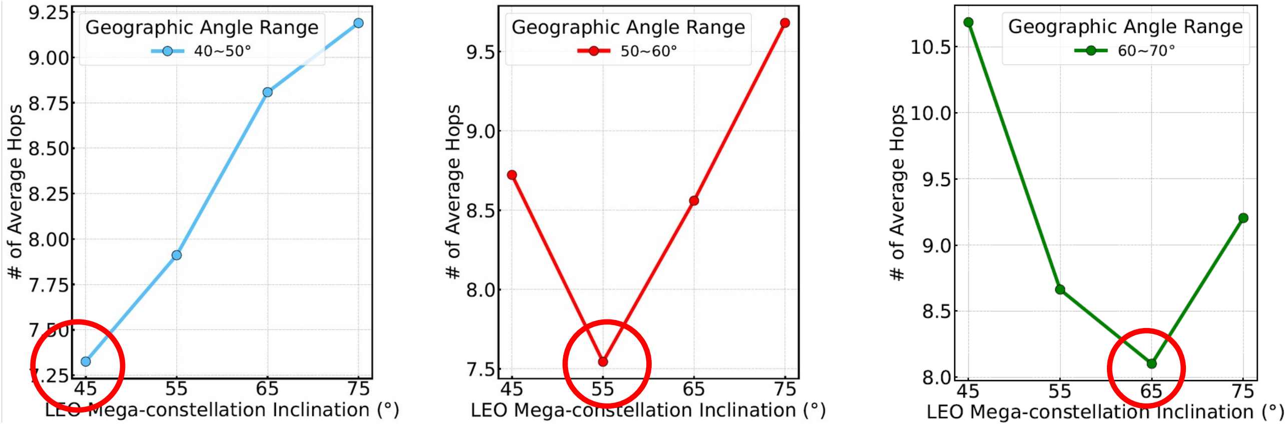
(e) 40-50°.

(f) 50-60°.

(g) 60-70°.

When the orbit inclination aligns with the endpoints' geographic angle, the latency performance is better.

Evaluation - Inclination & User Endpoints



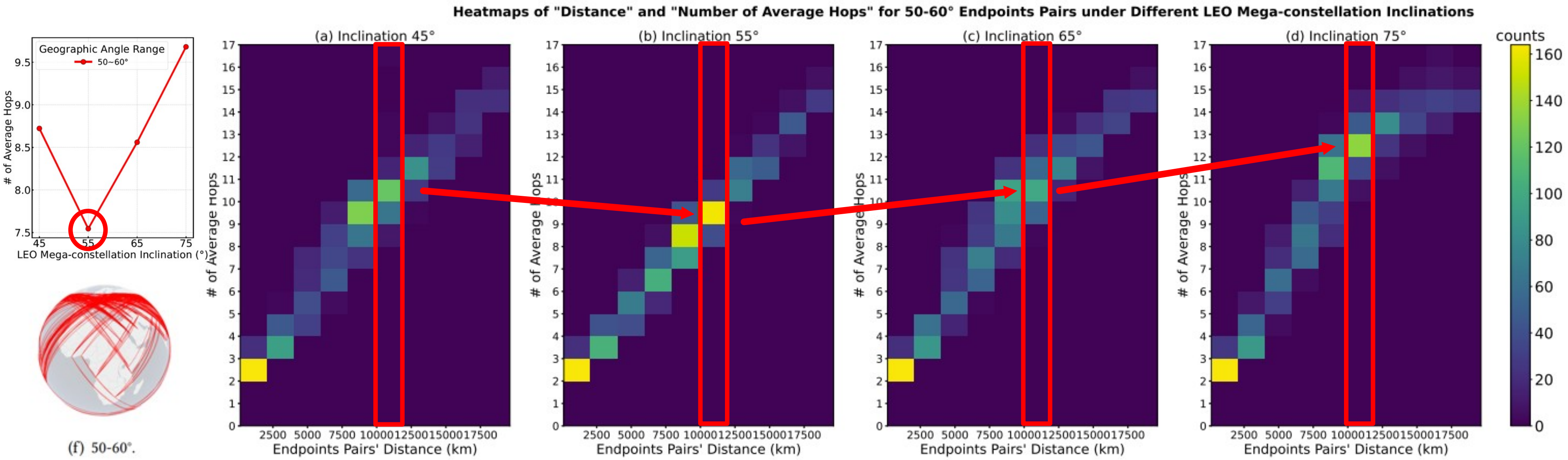
(e) 40-50°.

(f) 50-60°.

(g) 60-70°.

When the orbit inclination aligns with the endpoints' geographic angle, the average hop count performance is better.

Evaluation - Inclination & User Endpoints



When the orbit inclination aligns with the endpoints' geographic angle, the latency and average hop count performance is better.

Conclusion & Future work

Summary of Findings

- For the parameters number of orbits and number of satellites per orbit, there exist thresholds below which performance drops significantly.
- Beyond the threshold, there is marginal improvement in performance as satellite density increases.
- Alignment of satellite orbit inclination and user endpoints geographic angle can improve latency and hop count performance.
- Considering both delay and link stability, S2, K2, and T2 offer the best performance in each of the three constellations, respectively.

Future Work

- Alternative topologies with ISLs
- Multi-shell analysis.
- Incorporate real-world performance characteristics.