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Stable Hierarchical Routing for Operational LEO Networks

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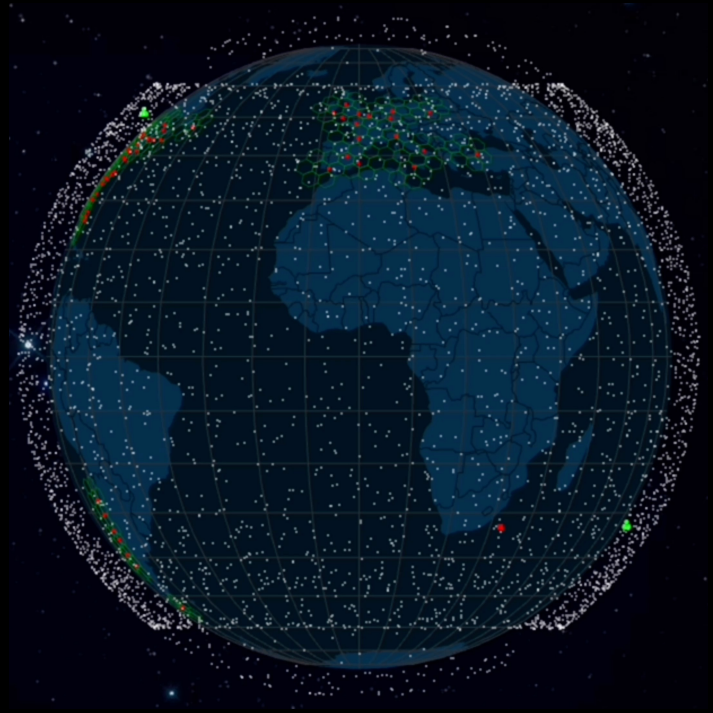
Jianping Wu, Qian Wu, Jun Liu, Zeqi Lai

*figure source: Geespace

Low Earth Orbit (LEO) Mega-Constellation

STARLINK

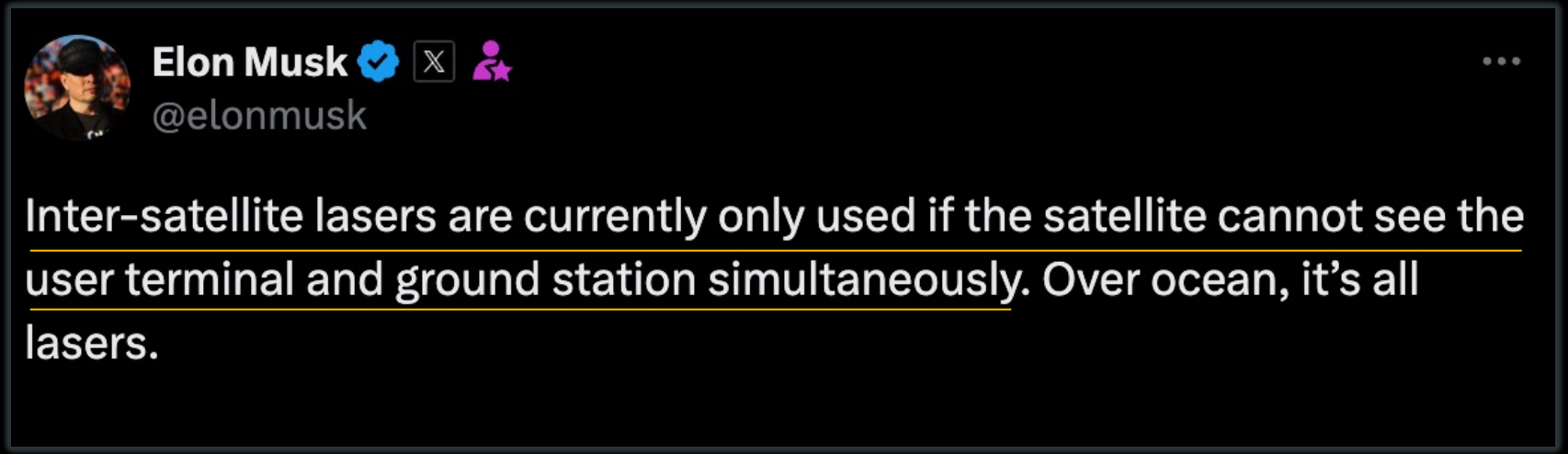


42,000
SATELLITES

8
SHELLS

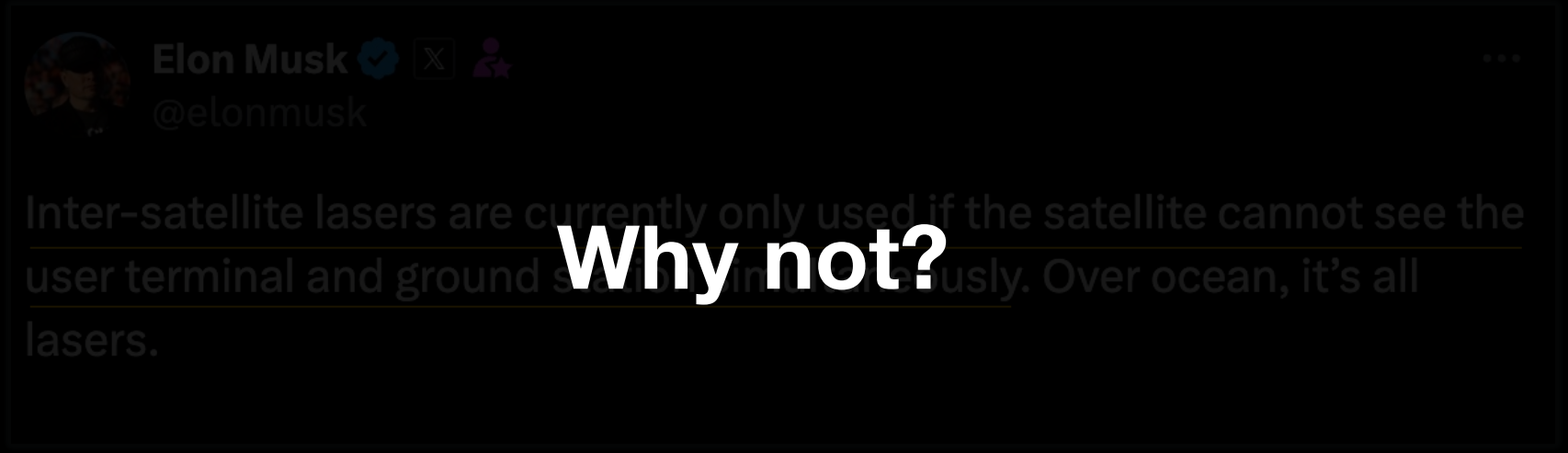
High-speed Internet for the “unconnected” 2.7B users

Are the LEO satellites networked?



Inter-satellite links (ISLs) are not activated at scale

Are the LEO satellites networked?



Why not?

Inter-satellite links (ISLs) are not activated at scale

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Why not networked satellites?

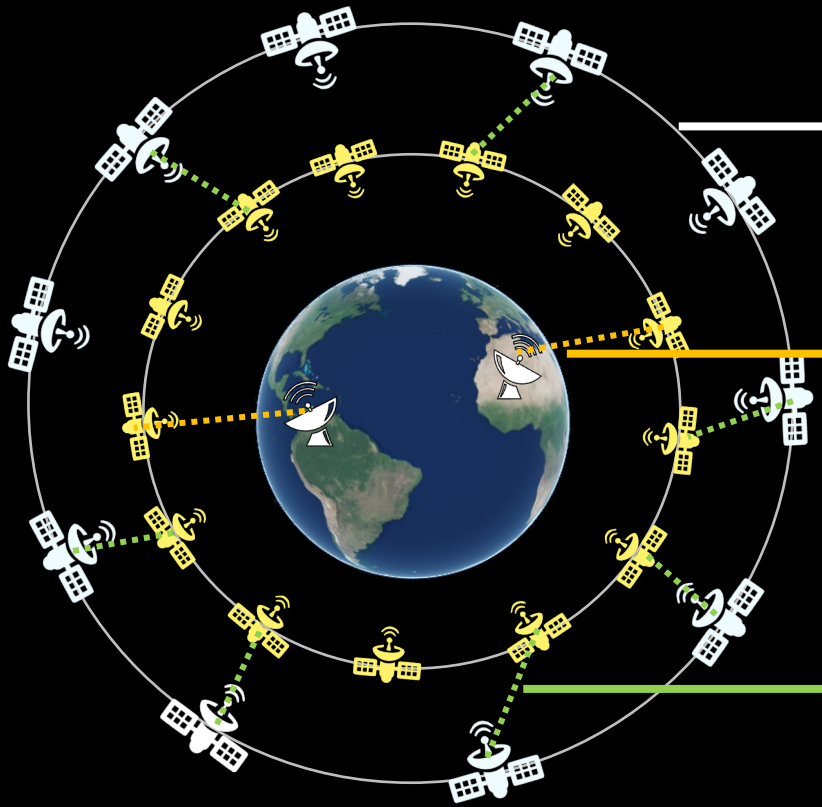
Chaotic and exhaustive network dynamics

Routing in space is unstable!

This work

- What does LEO network dynamics look like?
- How does dynamics affect satellite routing at scale?
- How to stabilize large-scale routing over dynamics?

Low-Earth-Orbit Dynamics



Intra-orbital-shell ISL

Ground-to-Space Link (GSL)

Inter-orbital-shell ISL

Ideal Low-Earth-Orbit Dynamics

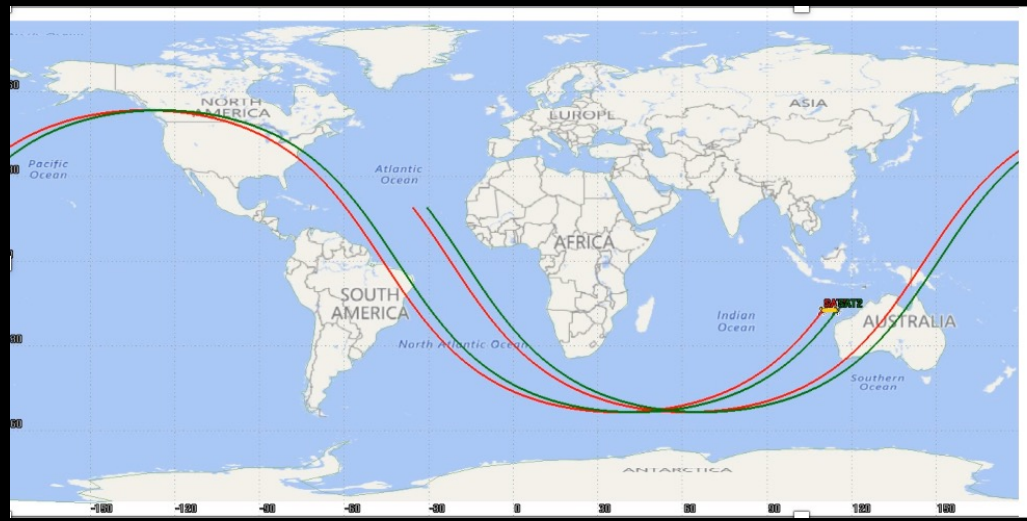
1. Space-Terrestrial Dynamics

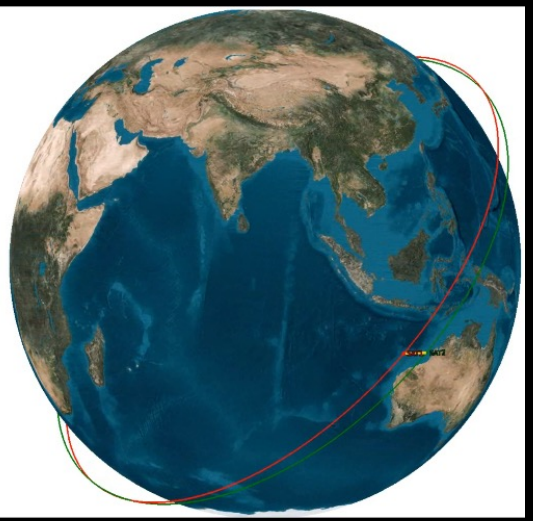
Asynchronous mobility between satellite and Earth → Frequent GSL churn

Ideal Low-Earth-Orbit Dynamics

2. Intra-Orbital-Shell Dynamics

Satellite in Orbit 1 — Satellite in Orbit 2 — Inter-satellite link





Homogeneous satellites → Mild ISL dynamics in **ideal** cases

Ideal Low-Earth-Orbit Dynamics

3. Inter-Orbital-Shell Dynamics

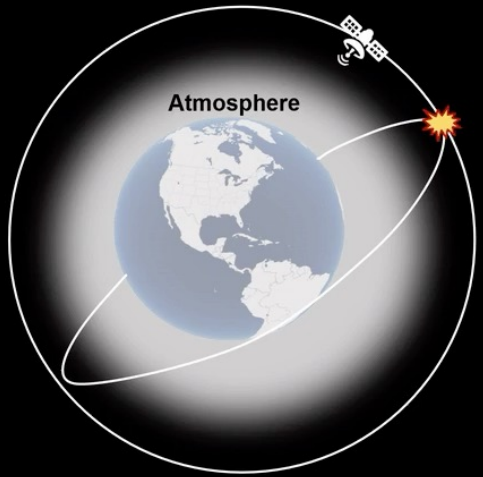
Satellite in Shell 1 Satellite in Shell 2 Inter-satellite link

Heterogeneous satellites → Chaotic ISL dynamics even in ideal cases

Real Low-Earth-Orbit Dynamics

Orbital imperfections

- Orbital drags
- Orbital maneuvers



"A Networking Perspective on Starlink's Self-Driving LEO Mega-Constellation", MobiCom 2023

Real Low-Earth-Orbit Dynamics

Orbital imperfections

- Orbital drags
- Orbital maneuvers
- Orbital failures

INVESTING IN SPACE

SpaceX to lose as many as 40 Starlink satellites due to space storm

PUBLISHED WED, FEB 9 2022•10:53 AM EST | UPDATED WED, FEB 9 2022•6:42 PM EST

Michael Sheetz
@THESHEETZTWEETZ

SHARE

SpaceX rocket accident leaves the company's Starlink satellites in the wrong orbit

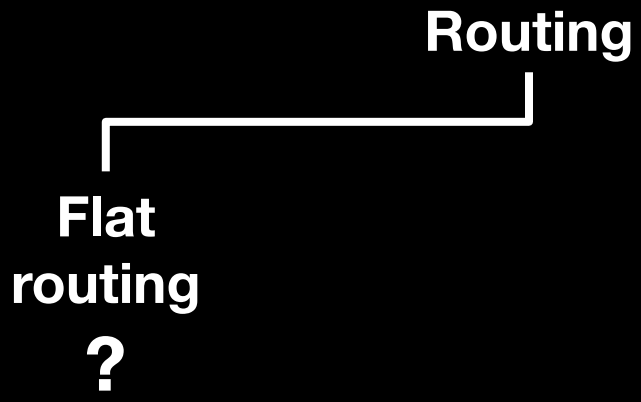
JULY 13, 2024 · 3:27 AM ET

Partial deployments

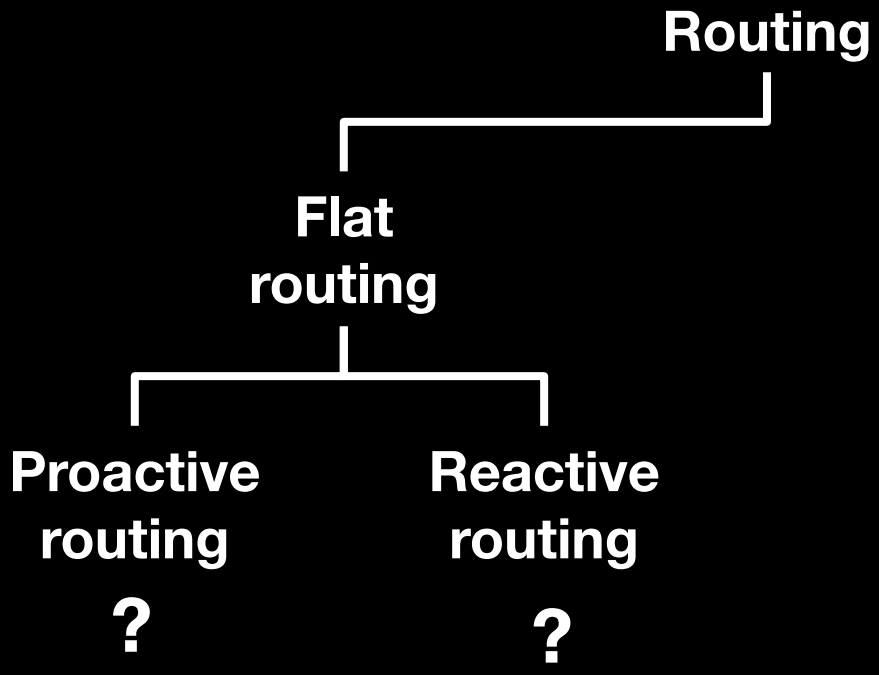
Starlink Shell 3

"A Networking Perspective on Starlink's Self-Driving LEO Mega-Constellation", MobiCom 2023

Implications for Routing



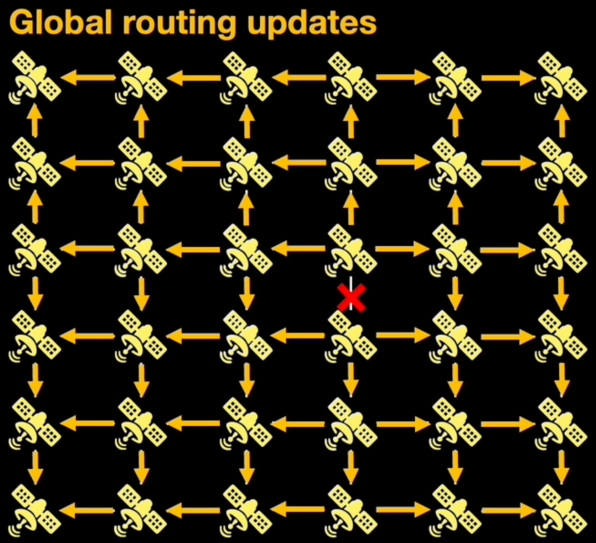
Implications for Routing



Flat routing?

Proactive routing

Link state/Distance vector, SDN

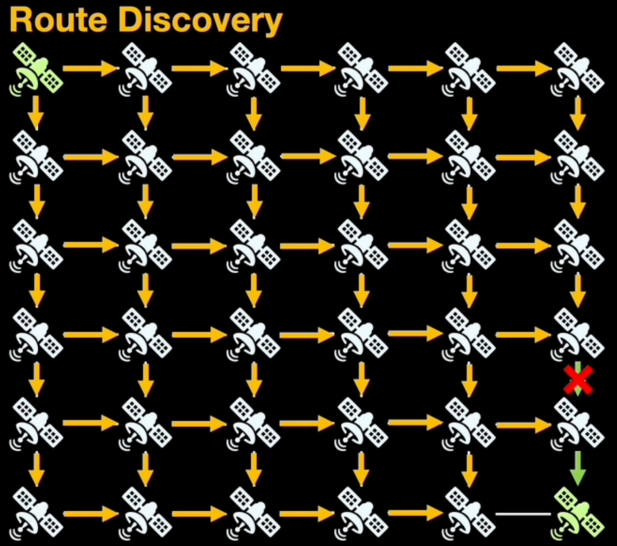


Excessive global route exchanges ☹

Transient routing inconsistencies ☹

Reactive routing

AODV, DSR



Exhaustive route request flooding ☹

Frequent route cache expiry ☹

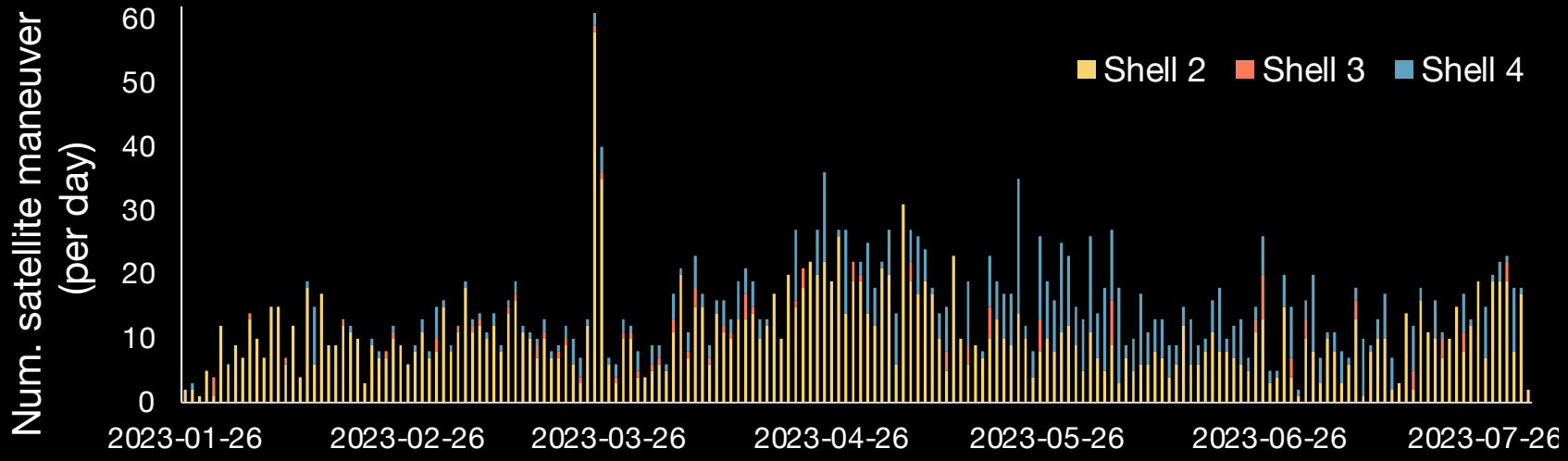
SOTA: introducing predictability in routing

Satellite trajectories are predictable

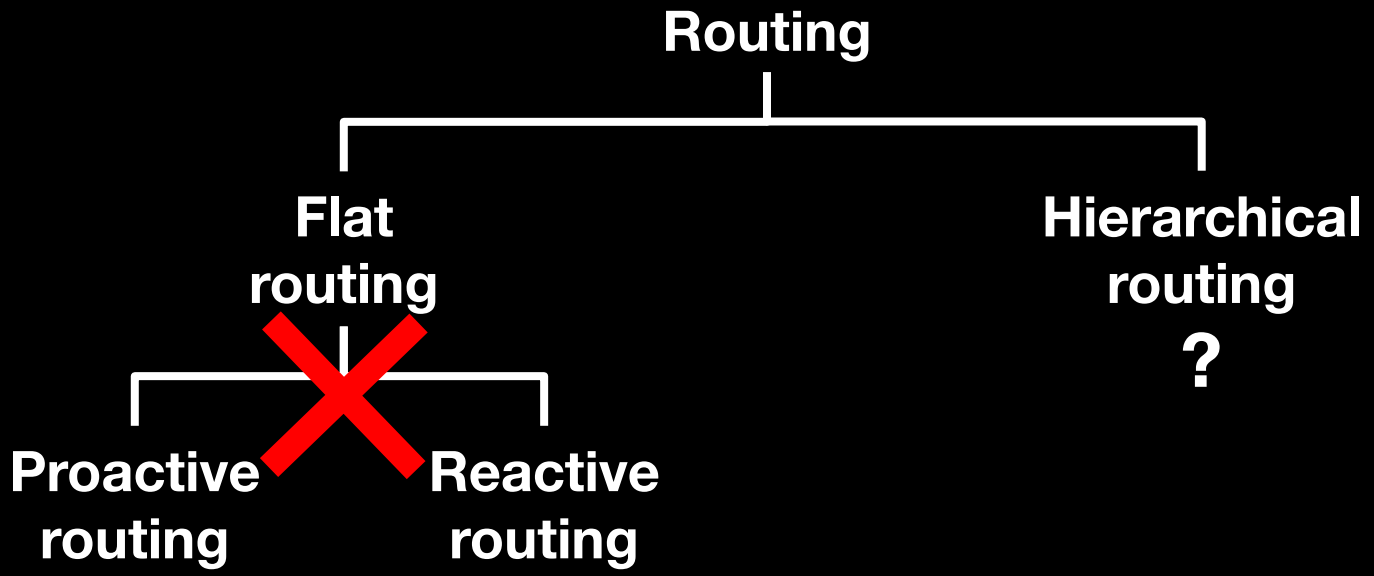
Is it enough for optional LEO networks?

Flat predictive routing?

Unpredictable and random orbital imperfections ☹

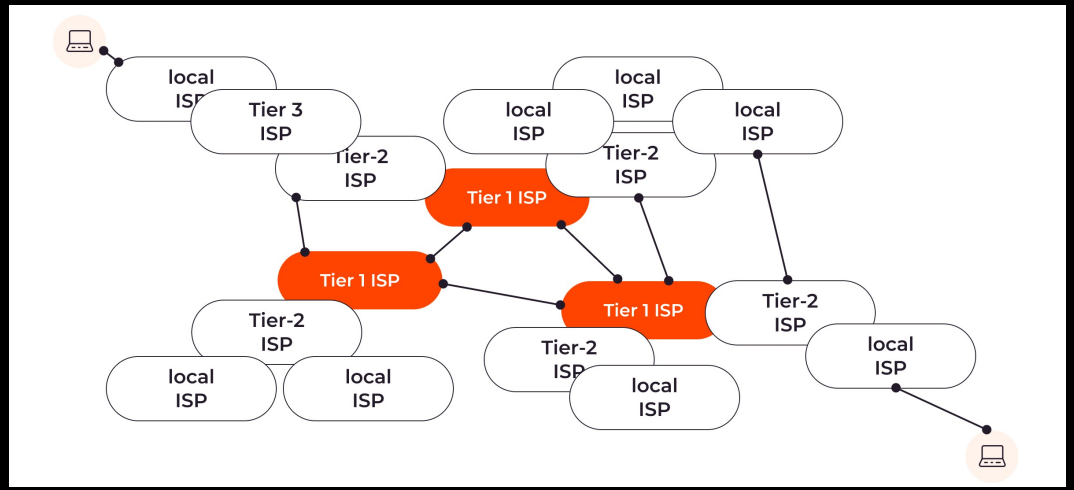


Implications for Routing



Hierarchical routing?

- Prerequisite: **well-defined**, **stable** routing domains
- Not readily available in **extremely mobile** LEO networks ☹



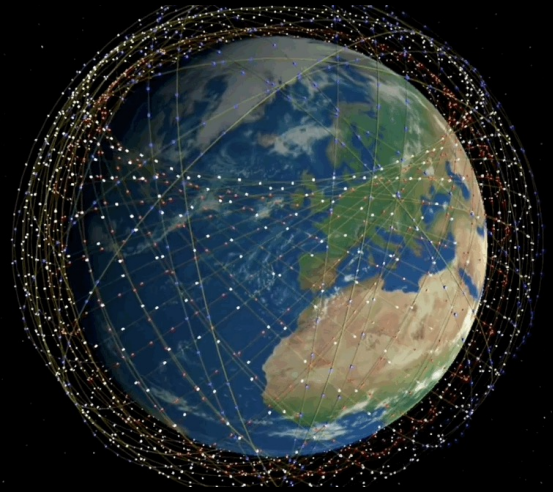
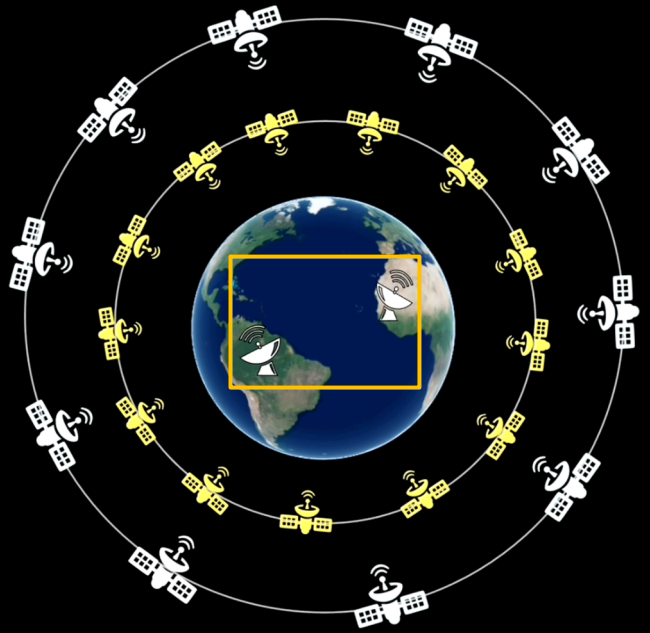


*figure source: GCORE，Mark Handley

How to stabilize hierarchical routing in dynamic LEO networks?

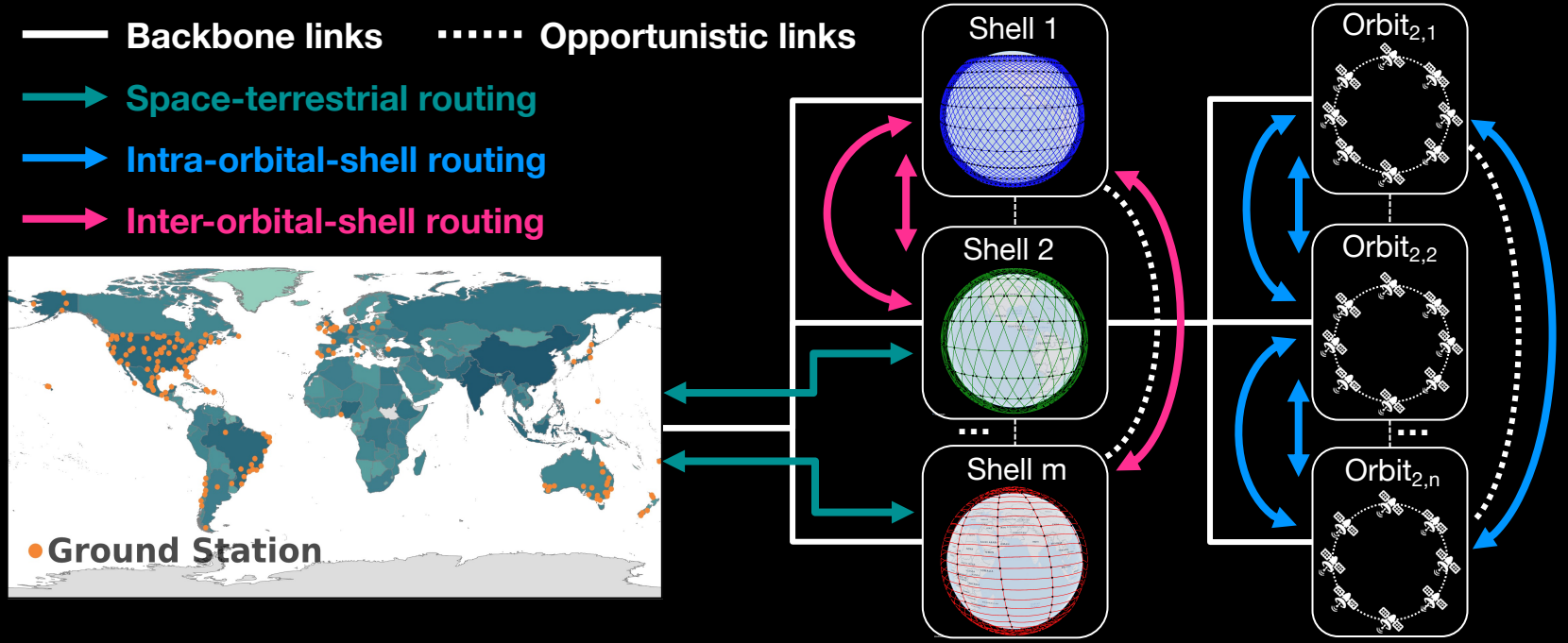
Our work: Earth-centric geographic paradigm

Earth's geographic locations are invariant of extreme satellite mobility



An Earth-Centric Stable LEO Routing Hierarchy

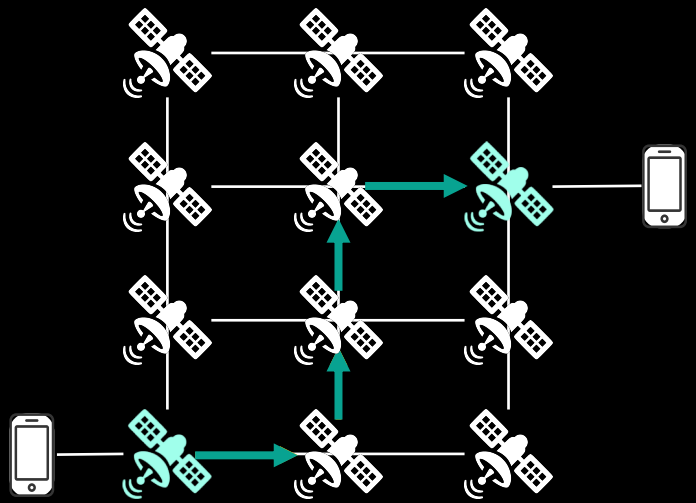
Decouple, localize, and mask LEO dynamics hierarchically



Stabilizing Space-Terrestrial Routing

- Use geographic routing to decouple from fast-changing satellites

Logical routing



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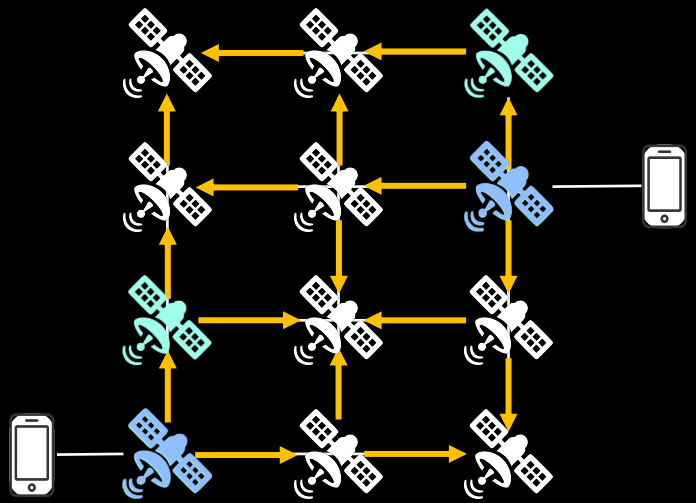

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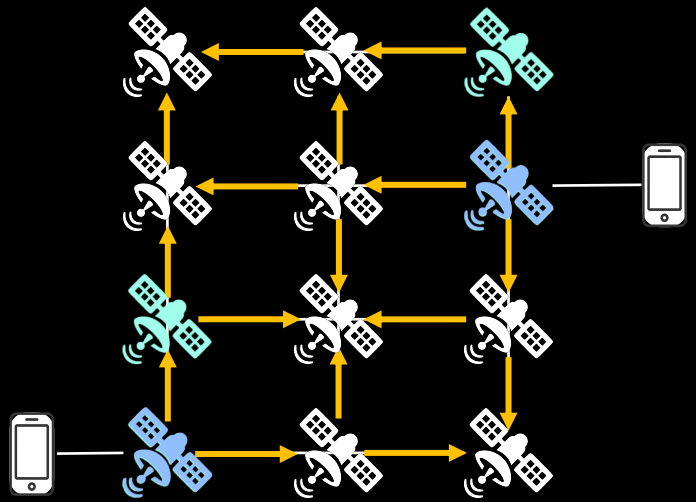
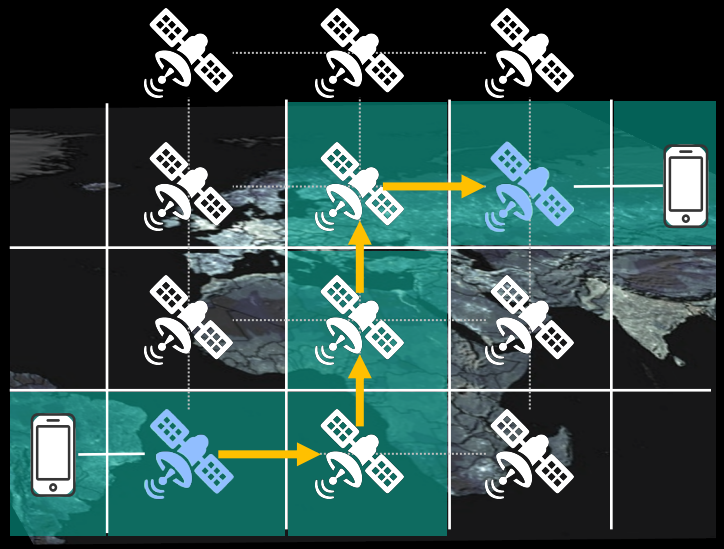


Geographic routing



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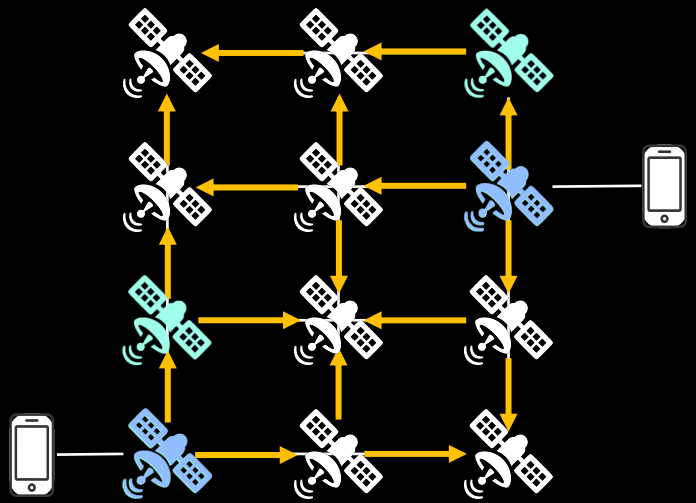
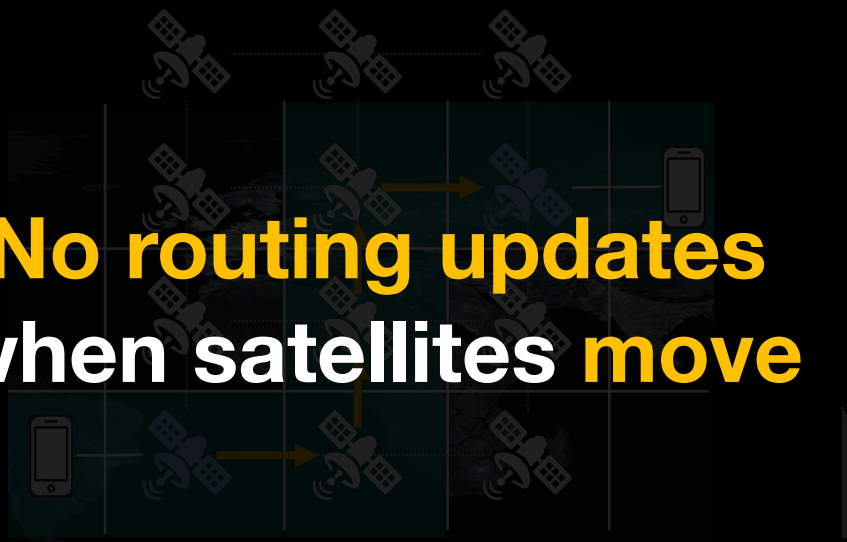


Geographic routing

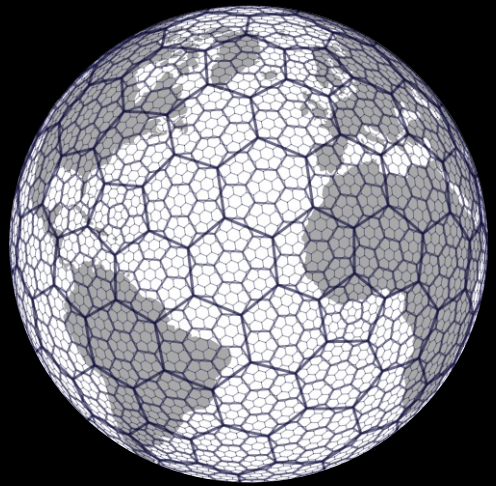


No routing updates when satellites move

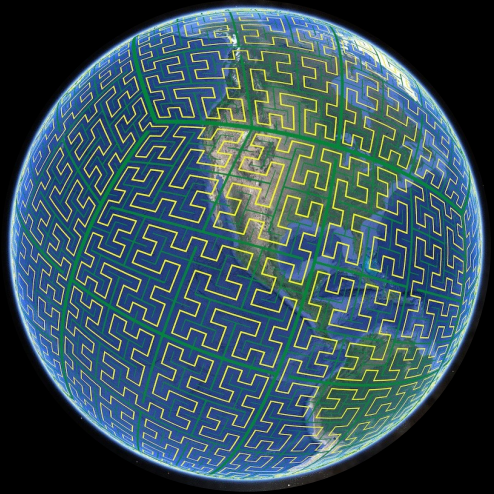
Stabilizing Space-Terrestrial Routing

- How to lay out the geographic service areas?

Latitude-longitude cells



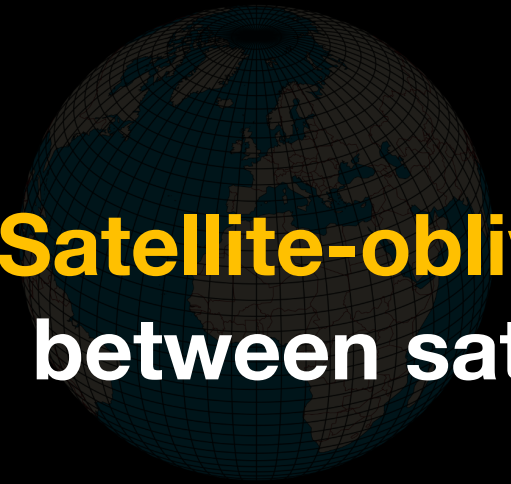
Hexagon cells (Uber H3)



Space-filling curve (Google S2)

Stabilizing Space-Terrestrial Routing

- How to lay out the geographic service areas?



Satellite-oblivious and **complex** mapping between satellites and terrestrial users

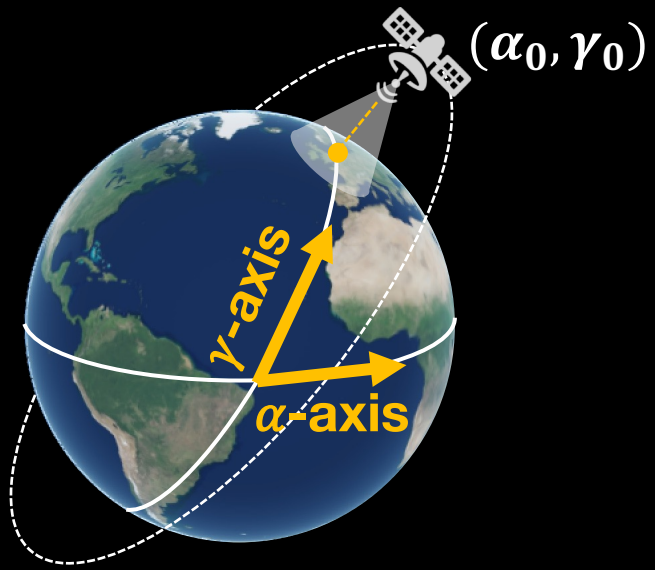
Latitude-longitude cells

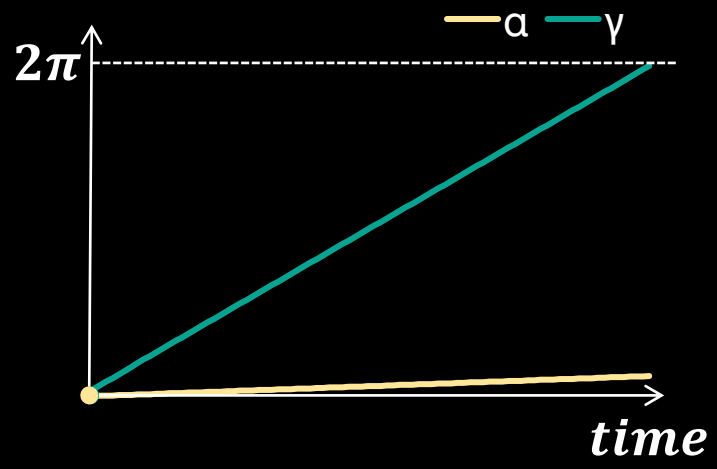
Hexagon cells (Uber H3)

Space-filling curve (Google S2)

Stabilizing Space-Terrestrial Routing

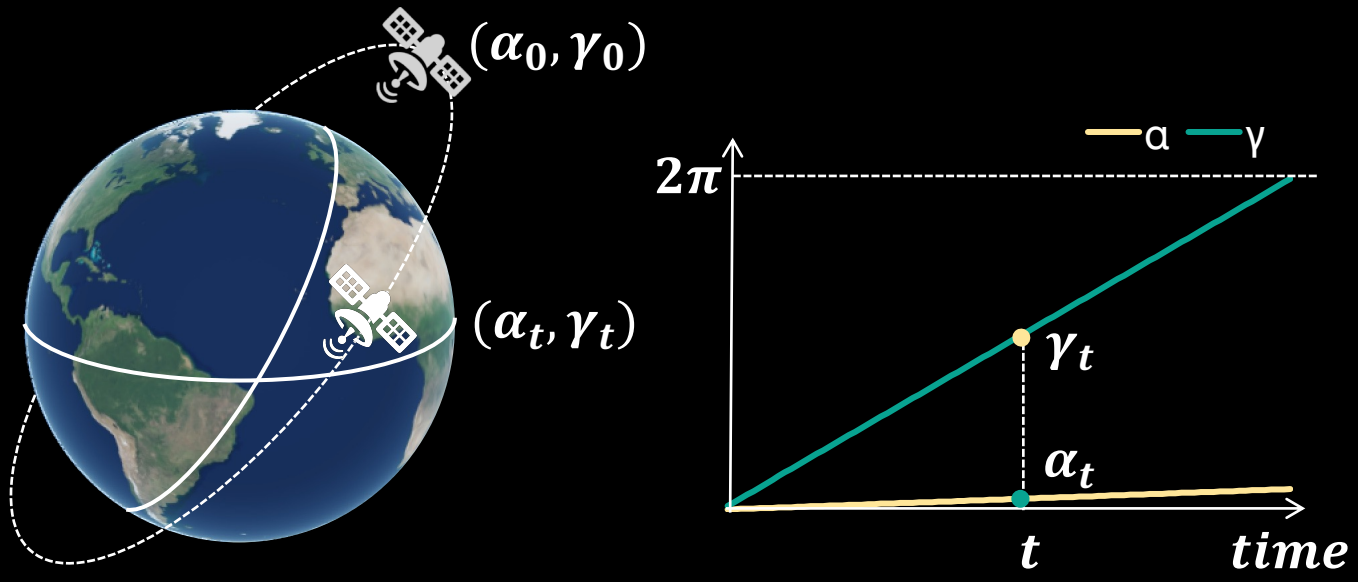
- **Simplify** satellite's runtime mapping





Stabilizing Space-Terrestrial Routing

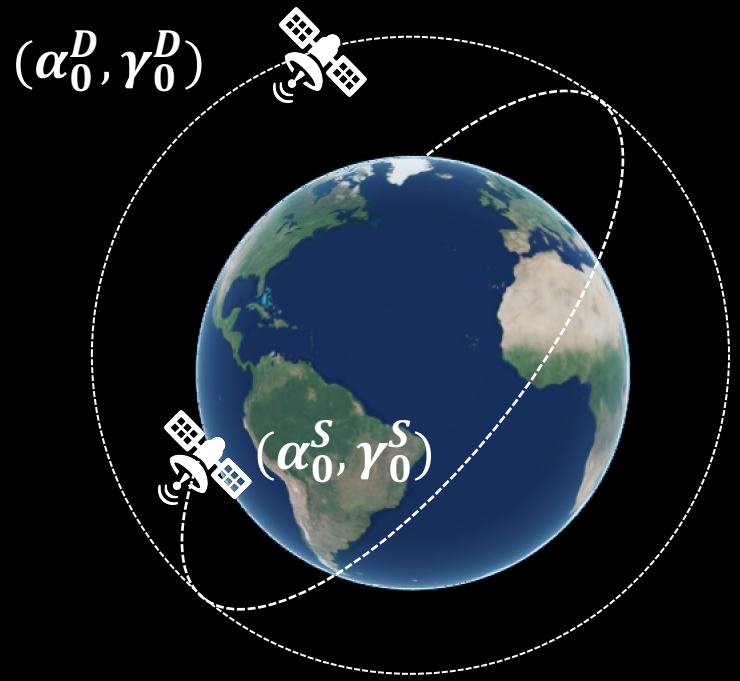
- **Simplify** satellite's runtime mapping



Satellite's runtime sub-point **linearly changes**

Stabilizing Space-Terrestrial Routing

- Stabilize routing distance between satellites



Stabilizing Space-Terrestrial Routing

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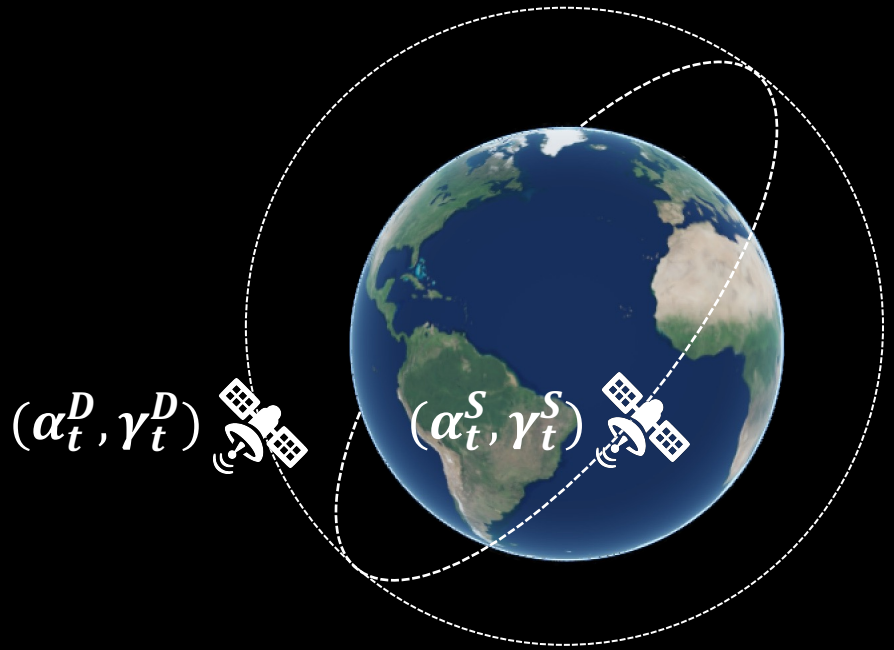


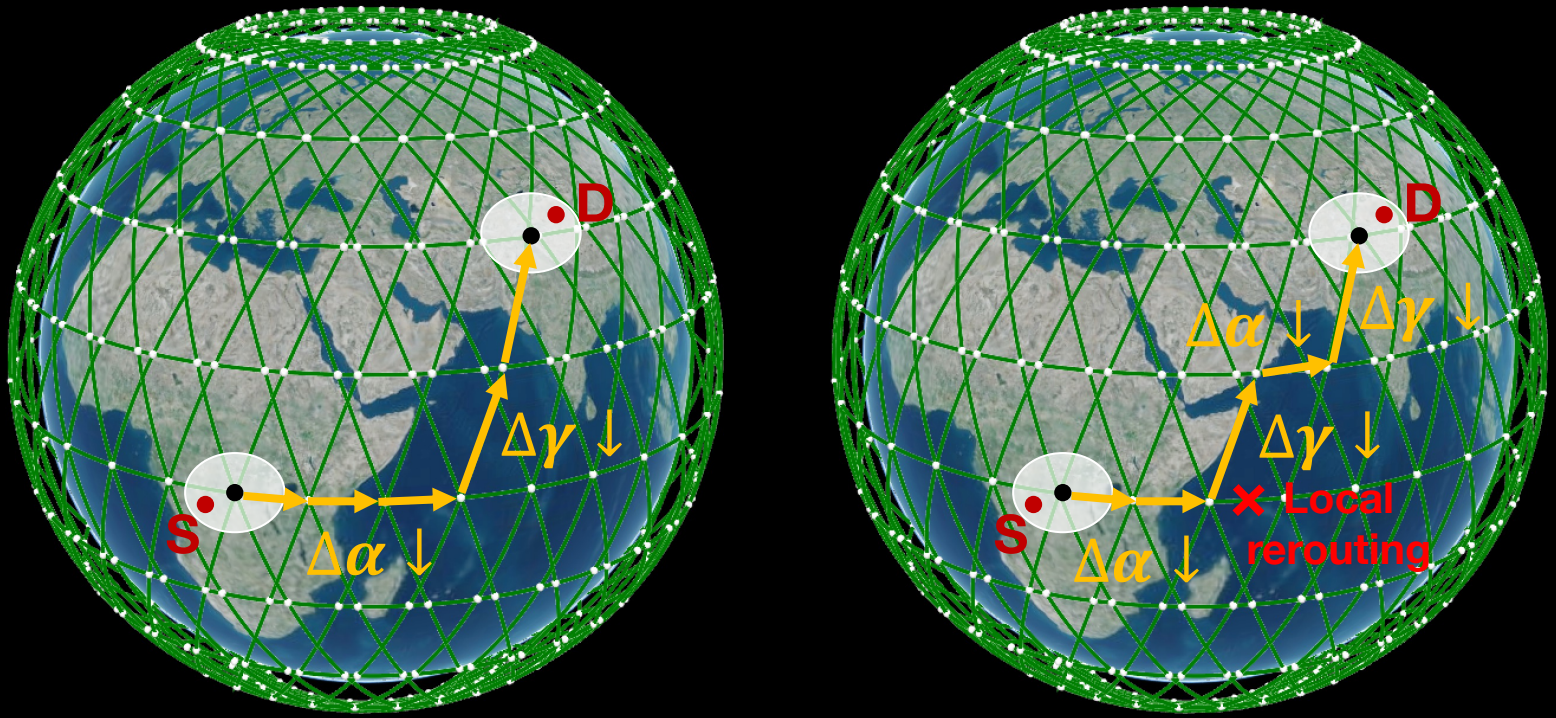
$$\Delta\alpha_t^{S,D} \equiv \Delta\alpha_0^{S,D} = \alpha_0^S - \alpha_0^D$$

$$\Delta\gamma_t^{S,D} \equiv \Delta\gamma_0^{S,D} = \gamma_0^S - \gamma_0^D$$

Time-invariant coordinate distance enable stable routing

Intra-Orbital-Shell Routing for Earth

- **Stable** and **ISL churn resilient** geographic routing



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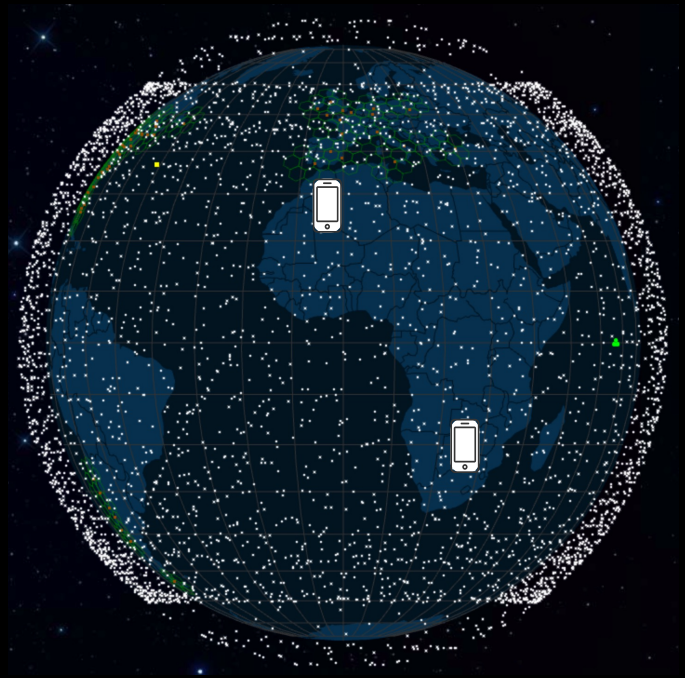
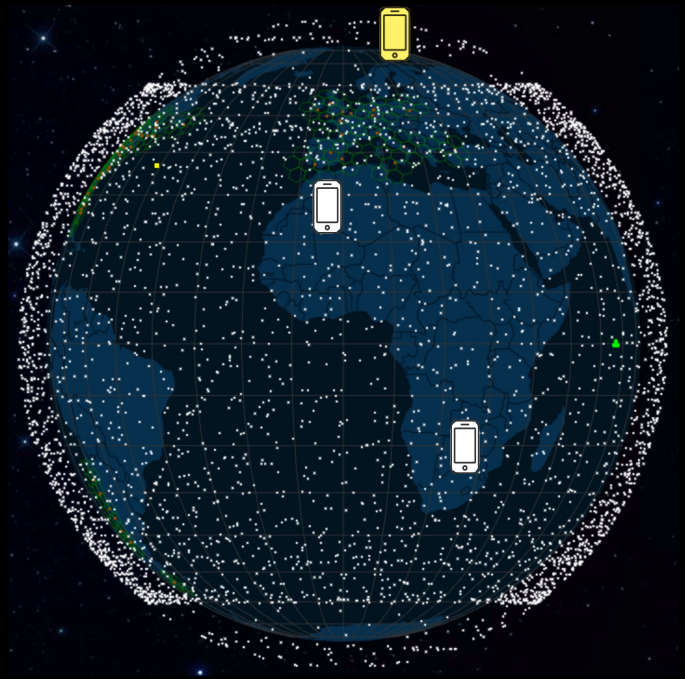
Inter-Orbital-Shell Routing for Earth

When will we need it?



Inter-Orbital-Shell Routing for Earth

- Only when the nodes can not be covered by one shell
  - Source or destination in high-latitude areas (rare in reality)



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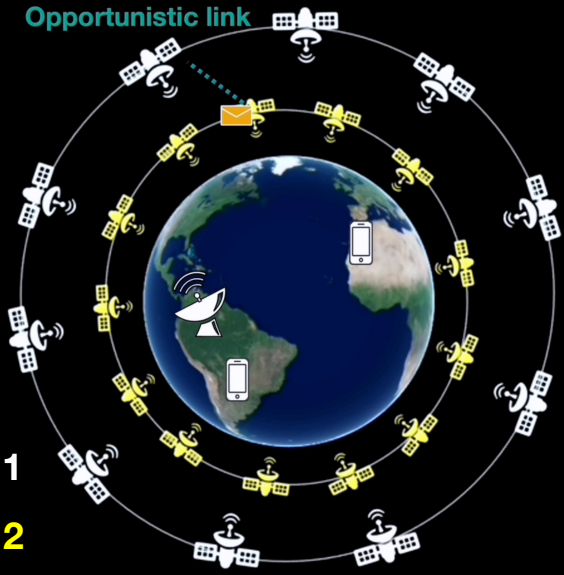


Orbital shell 1

Orbital shell 2

Earth as the anchor

Opportunistic shortcuts

Practical Deployment

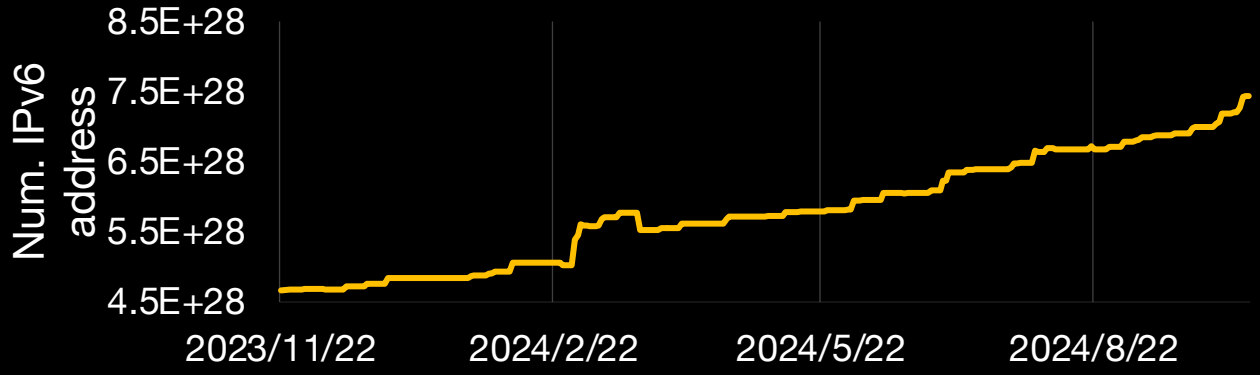
- Take IPv6 as an example

What IP address does Starlink provide?

public IPv4 Addresses. Starlink supports native IPv6 across all Starlink routers, kit versions, and service plans. All IPv6 compatible Starlink router clients are assigned IPv6 addresses.

Practical Deployment

- Take IPv6 as an example



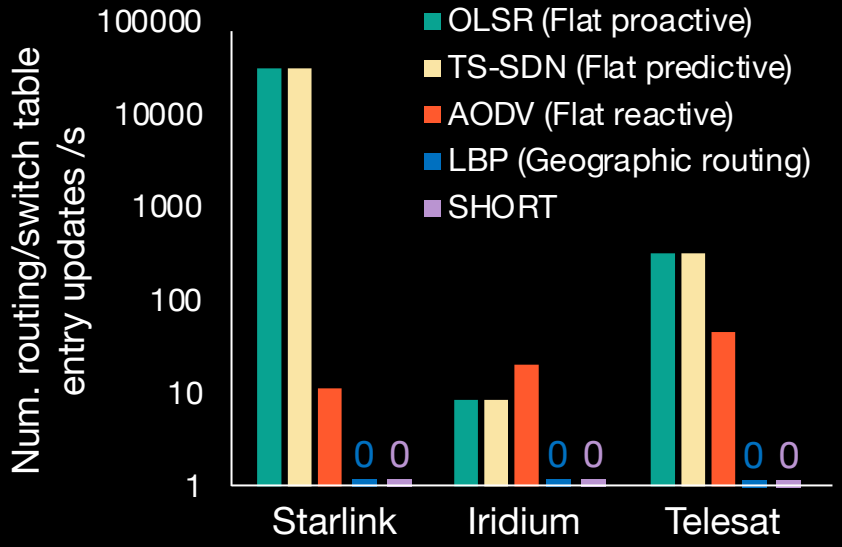
IPv6 Header

Version	Traffic class	Flow Label
Payload Length	Next Header	Hop Limit
Source Address		
Destination Address		

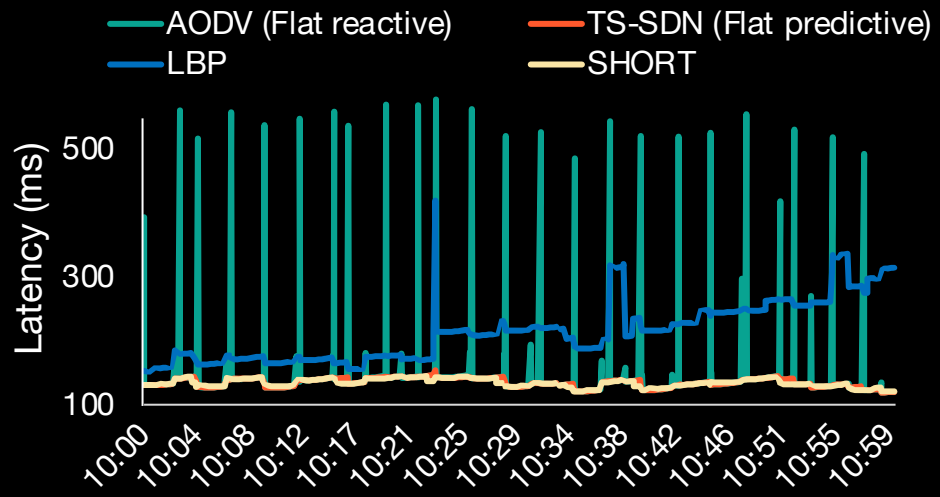
Network prefix	Orbital shell ID	Col (α)	Row (γ)	Terrestrial node ID
Routing to the external Internet	Inter-shell routing	Intra-shell routing		Unique identifier in its geographic cell

Evaluation Highlights

81-1489x routing updates ↓

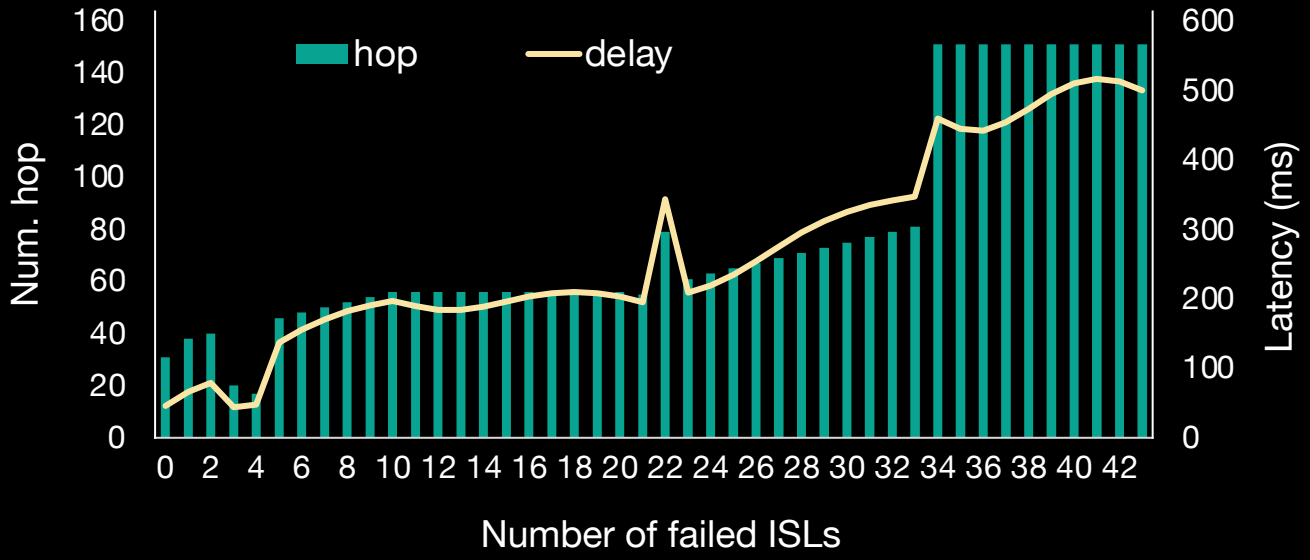


Near optimal routing



Evaluation Highlights

Resilient to ISL failures



Conclusion

- Multi-dimensional and exhaustive LEO dynamics in reality
  - New challenges that terrestrial routing never encounter
- **SHORT**: Stable hierarchical geographic routing
  - Earth as the anchor to decouple from fast-moving LEO satellites
- Operational complexities and imperfections matter for satellite networking
  - More practical solutions needed toward Internet from space at scale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