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Stable Hierarchical Addressing and Routing for Operational Satellite Networks

Presenter: Lixin Liu

Joint work with Yuanjie Li, Hewu Li, Wei Liu, Yimei Chen, Jianping Wu, Qian Wu, Jun Liu, Zeqi Lai

draft-li-istn-addressing-requirement-04

*figure source: Geespace

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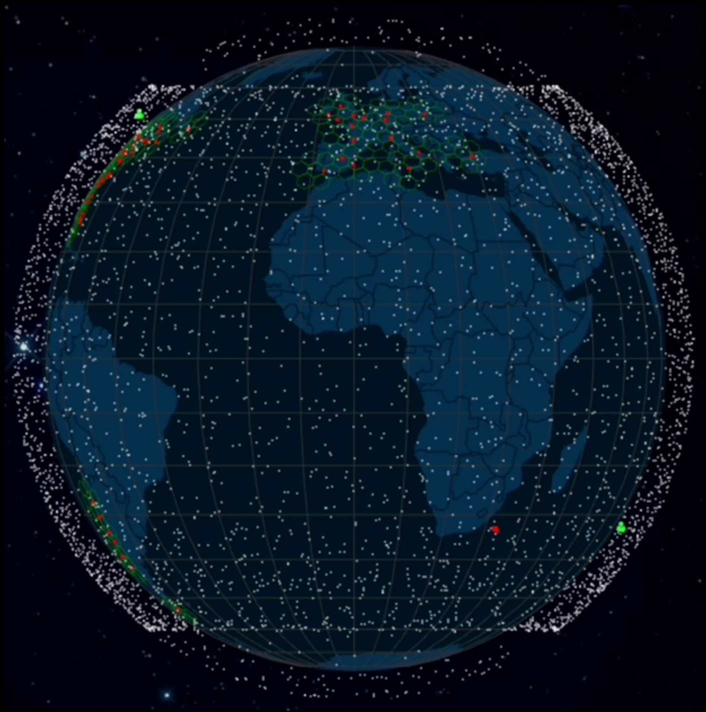
Low Earth Orbit (LEO) Mega-Constellation

STARLINK



42,000
SATELLITES

8
SHELLS

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

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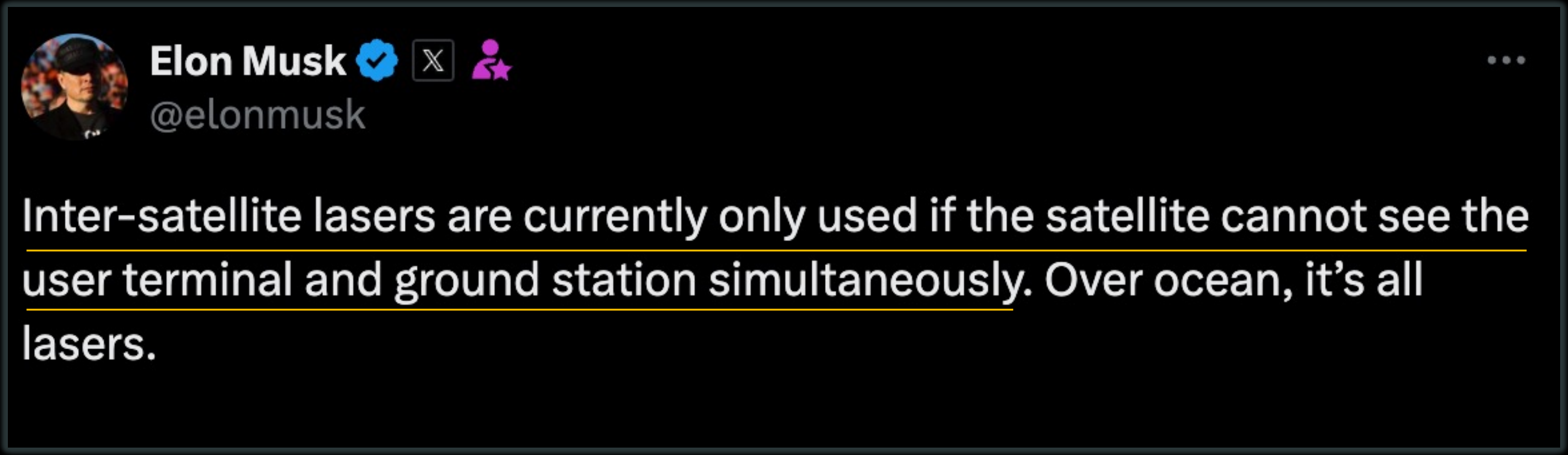
LEO Mega-Constellation in Reality


Elon Musk
@elonmusk

Inter-satellite lasers are currently only used if the satellite cannot see the user terminal and ground station simultaneously. Over ocean, it’s all lasers.

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

LEO Mega-Constellation in Reality

Why not?

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

LEO Mega-Constellation in Reality

Chaotic and exhaustive network dynamics

Addressing and Routing are Unstable!

This talk

- What does LEO network dynamics look like?
- How does LEO dynamics affect satellite networking?
- How to renovate addressing & routing over dynamics?
- A case: Stable Hierarchical Addressing and Routing

Ideal Low-Earth-Orbit Dynamics

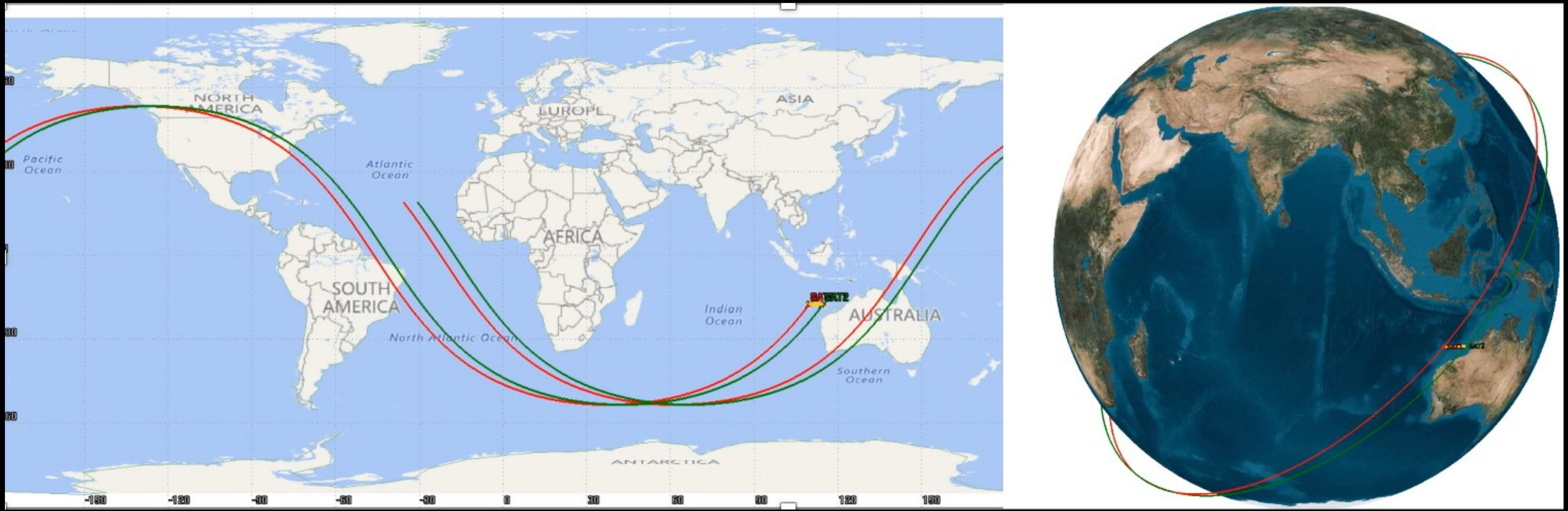
1. Space-Terrestrial Dynamics

Asynchronous mobility between the LEO satellite and Earth

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

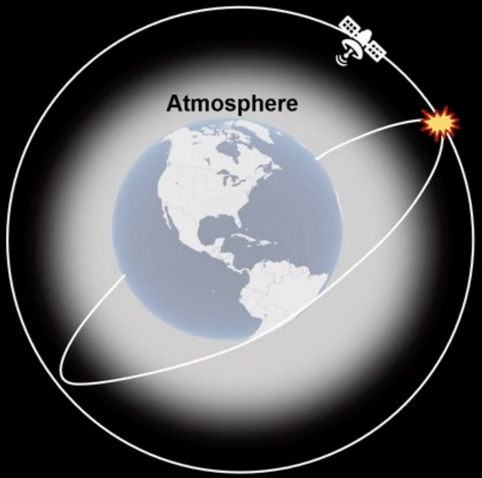
Satellite in Shell 1 — Satellite in Shell 2 — Inter-satellite link

Heterogeneous satellites → Chaotic ISL dynamics even in ideal cases

Real Low-Earth-Orbit Dynamics

Orbital imperfections

- Orbital drags
- Orbital maneuvers



Partial deployments

Starlink Shell 3

“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

Routing

Flat routing

?

Implications for Routing

Routing

Flat routing

Proactive routing

?

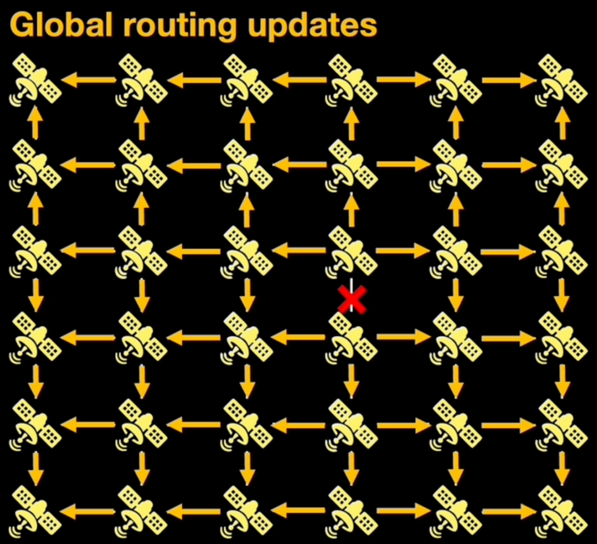
Reactive routing

?

Flat routing?

Proactive routing

Link state/Distance vector, SDN

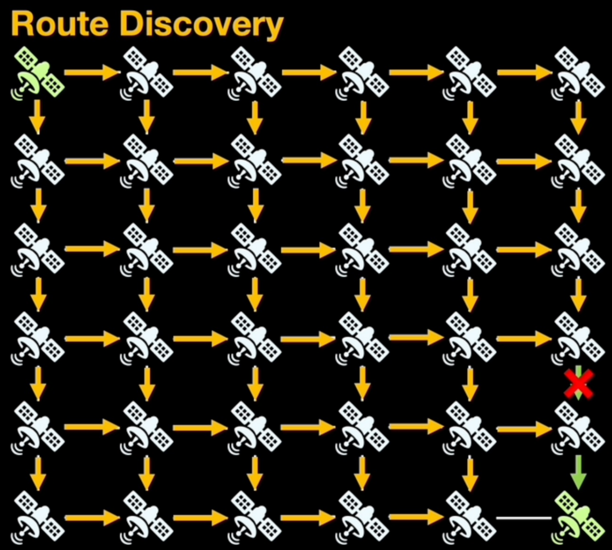


Excessive global route exchanges ☹

Transient routing inconsistencies ☹

Reactive routing

AODV, DSR

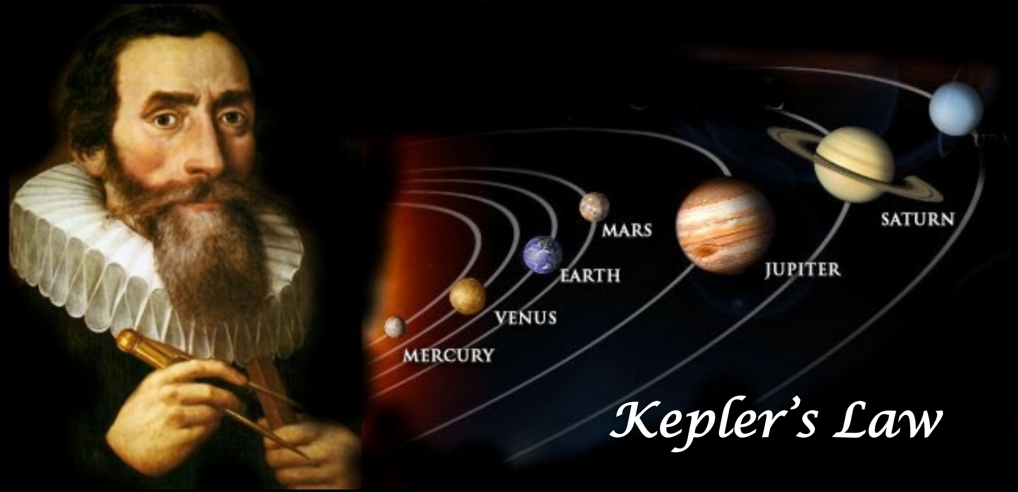


Exhaustive route request flooding ☹

Frequent route cache expiry ☹

SOTA: introducing predictability in routing

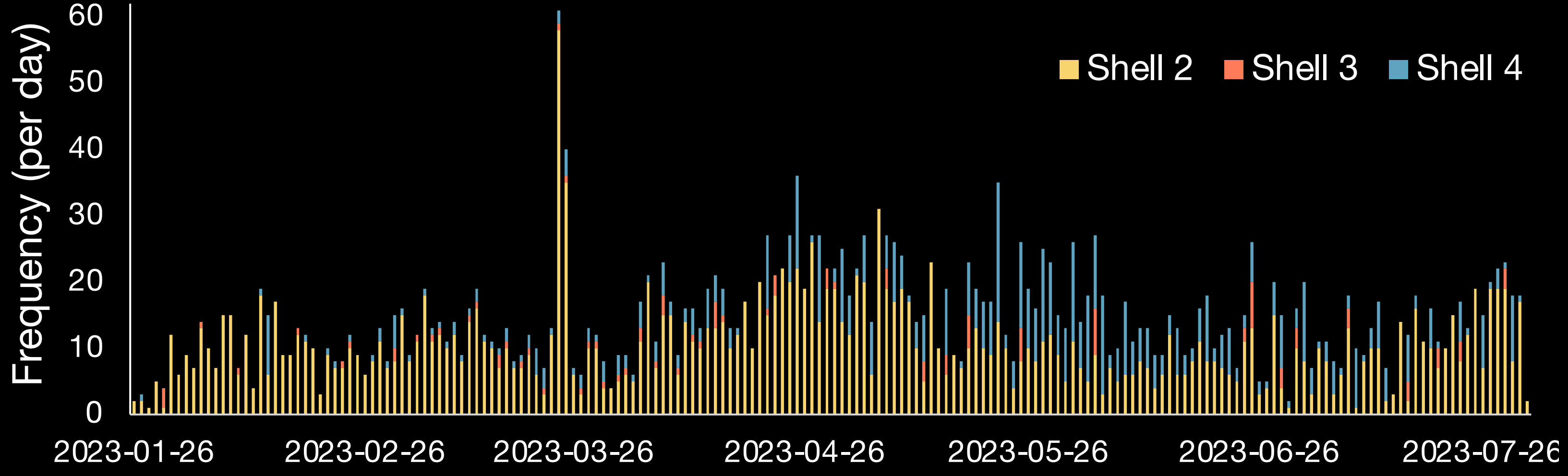
Satellite trajectories are **predictable**



Is it enough for optional LEO networks?

Flat predictive routing?

Unpredictable and random orbital dynamics ☹



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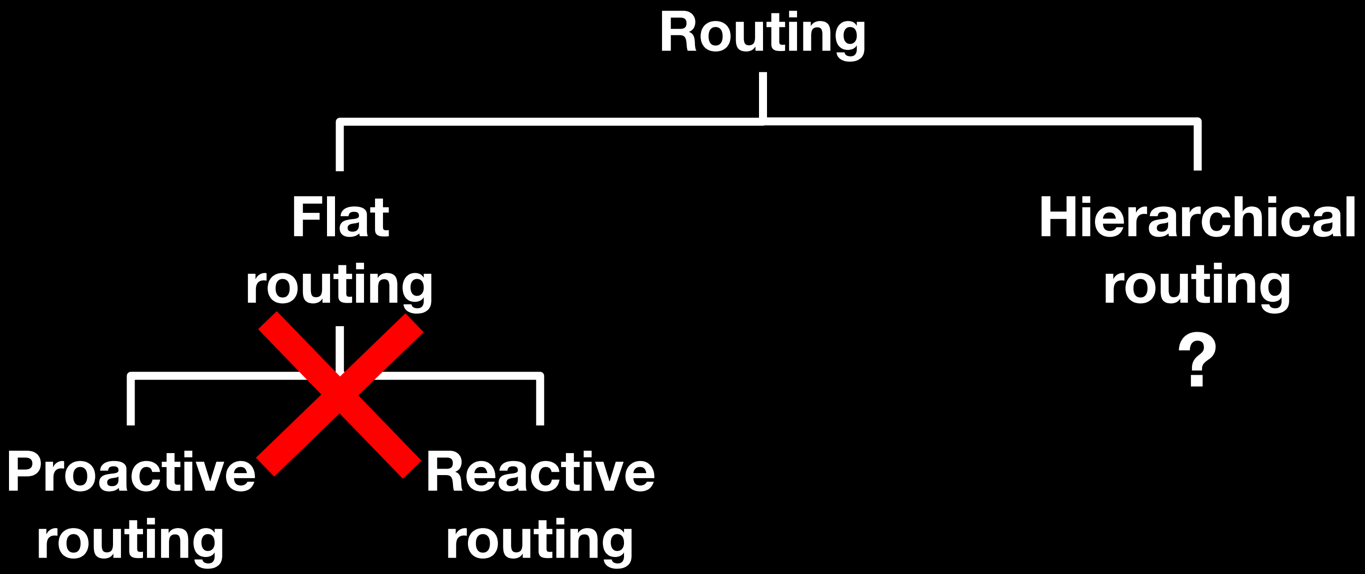
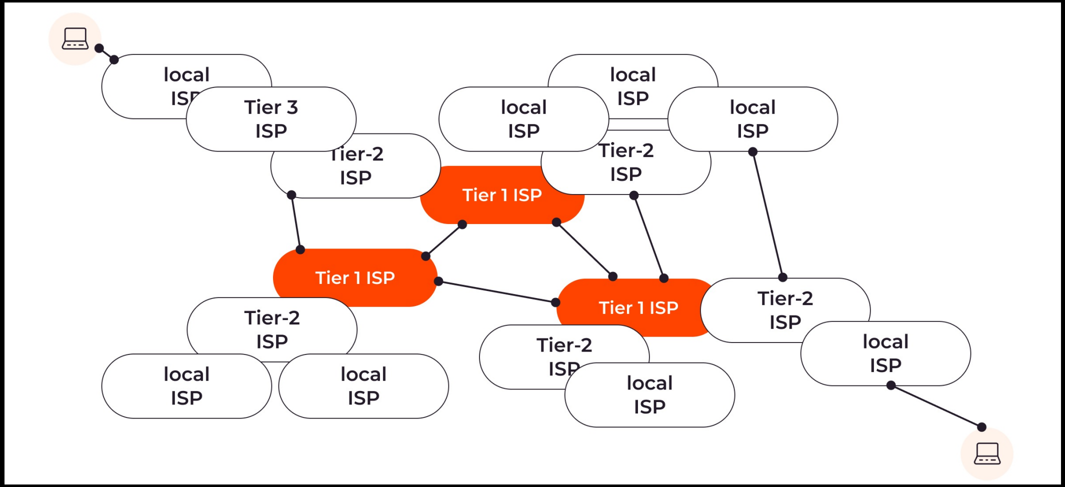
Implications for Routing



Hierarchical routing?

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



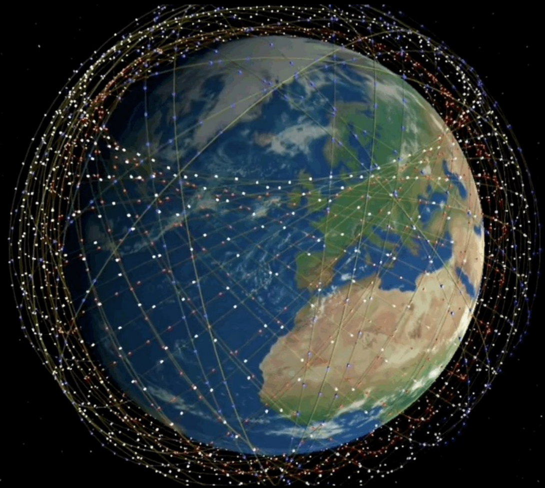


*figure source: GCORE，Mark Handley

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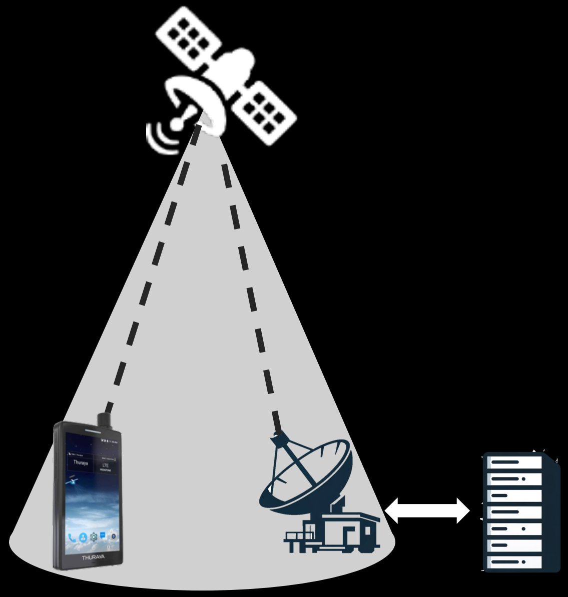
Implications for NTN Functions



Monopoly

SpaceX launches first satellites for T-Mobile’s direct-to-cell service

AT&T, Google join Vodafone in backing AST SpaceMobile

Satellite Network Operators (SNOs)

STARLINK, AST SpaceMobile, LYNK, iridium connected, Globalstar

Mobile Network Operators (MNOs)

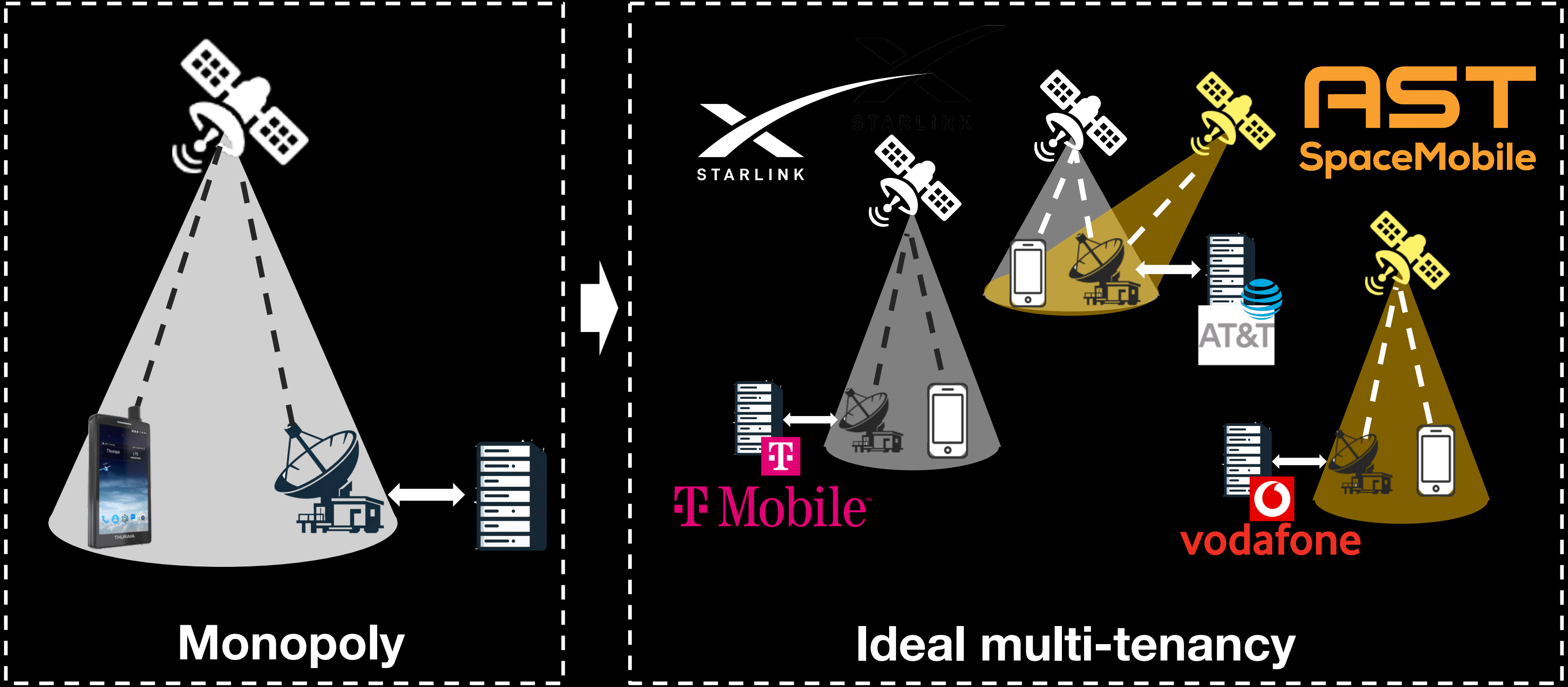
T Mobile, AT&T, vodafone, Salt, KDDI, ROGERS

Multi-tenancy

“Democratizing Direct-to-Cell Low Earth Orbit Satellite Networks”, NSDI 2024 Outstanding Paper Award

“ A Case for Stateless Mobile Core Network Functions in Space ”, SIGCOMM 2022

Implications for NTN Functions



"Democratizing Direct-to-Cell Low Earth Orbit Satellite Networks", NSDI 2024 **Outstanding Paper Award**

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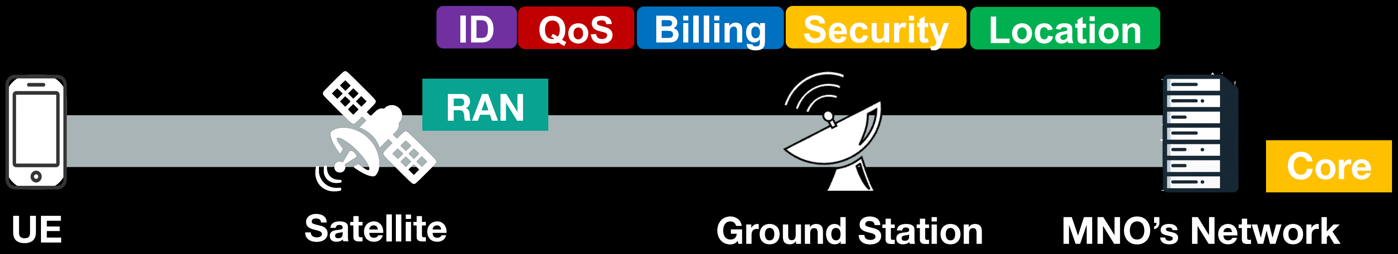
Implications for NTN Functions

Push network functions onboard for multi-tenancy



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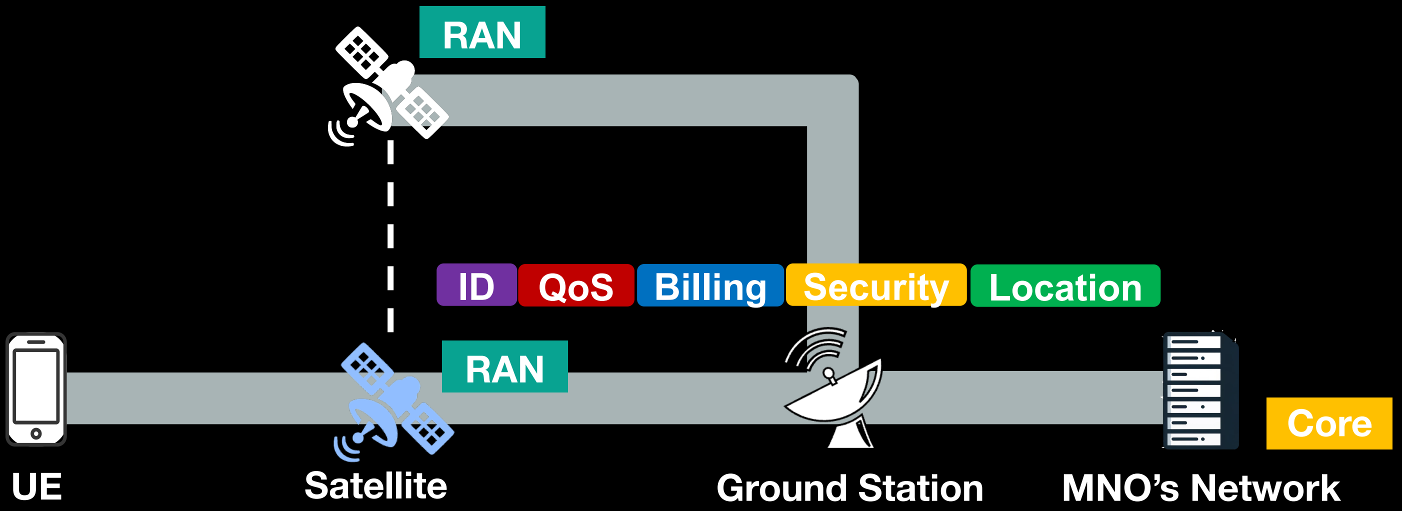

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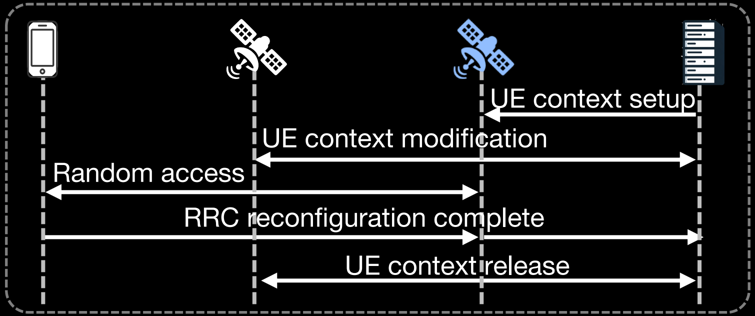
“ A Case for Stateless Mobile Core Network Functions in Space ”, SIGCOMM 2022

Implications for NTN Functions

Push network functions onboard for multi-tenancy

Each satellite can cover multiple MNOs (each having 1,000s of UEs)



Signaling storms

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How to stabilize hierarchical addressing and routing in dynamic LEO networks?

Requirements for Stable Hierarchical Networks

Addressing

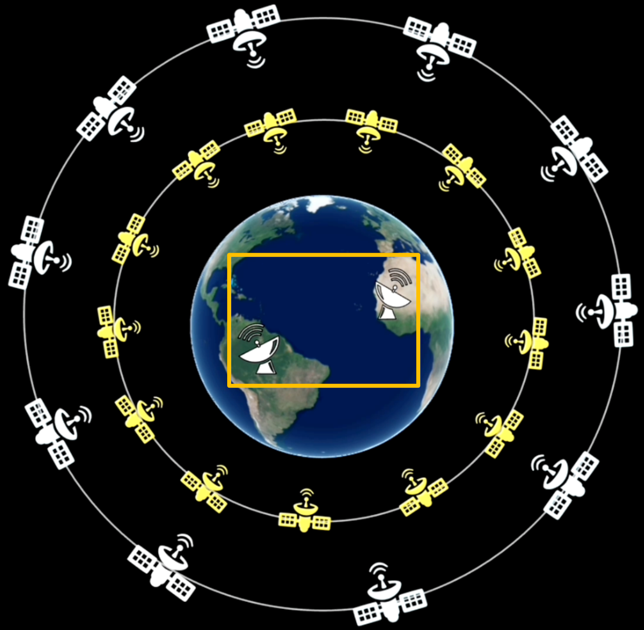
- Uniqueness
- Stability
- Locality
- Scalability
- Efficiency
- Backward compatibility
- Others?

Routing

- Well-defined and stable routing domains
- Stability
- Locality
- Scalability
- Efficiency
- Resiliency
- Backward compatibility
- Others?

A case: Earth-centric geographic paradigm

Earth's geographic locations are invariant of extreme satellite mobility



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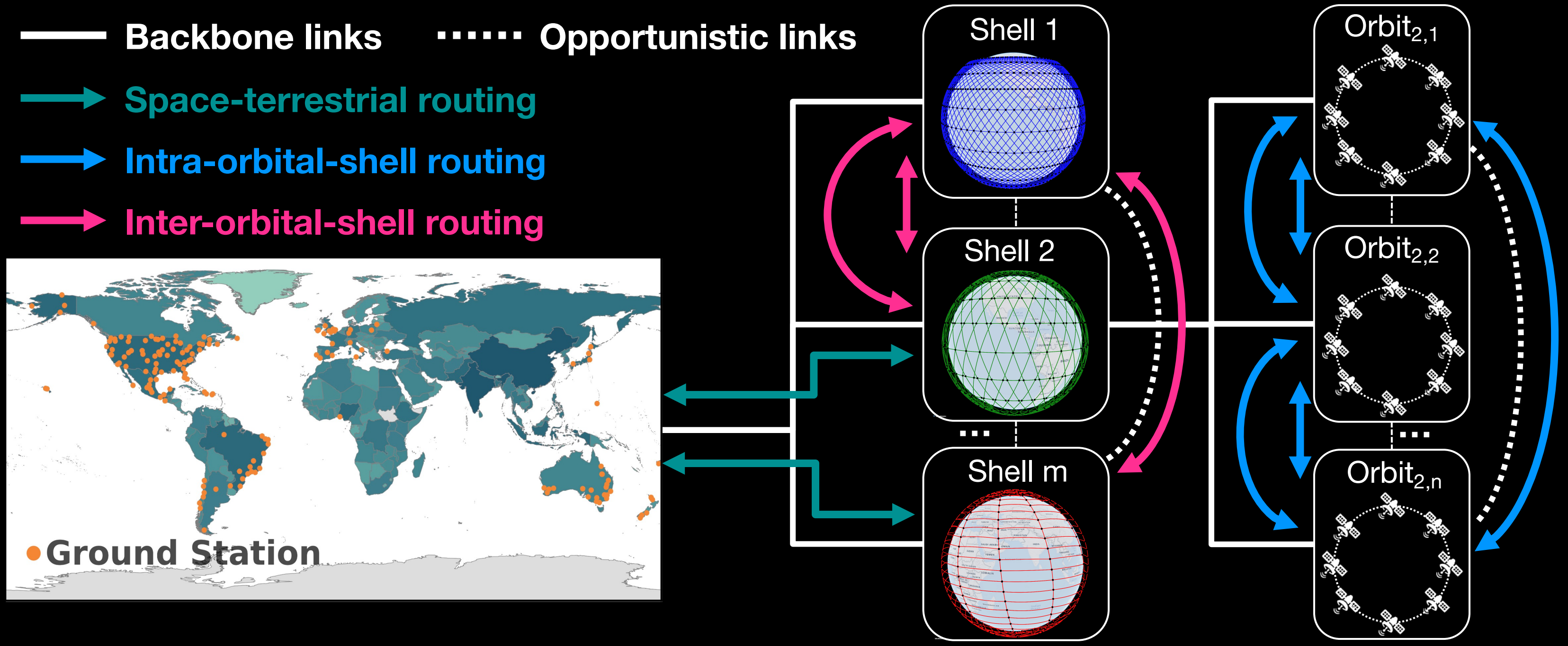
An Earth-Centric Stable LEO Routing Hierarchy

Decouple, localize, and mask LEO dynamics hierarchically



Tier 1: terrestrial network **Tier 2: orbital shells** **Tier 3: orbits**

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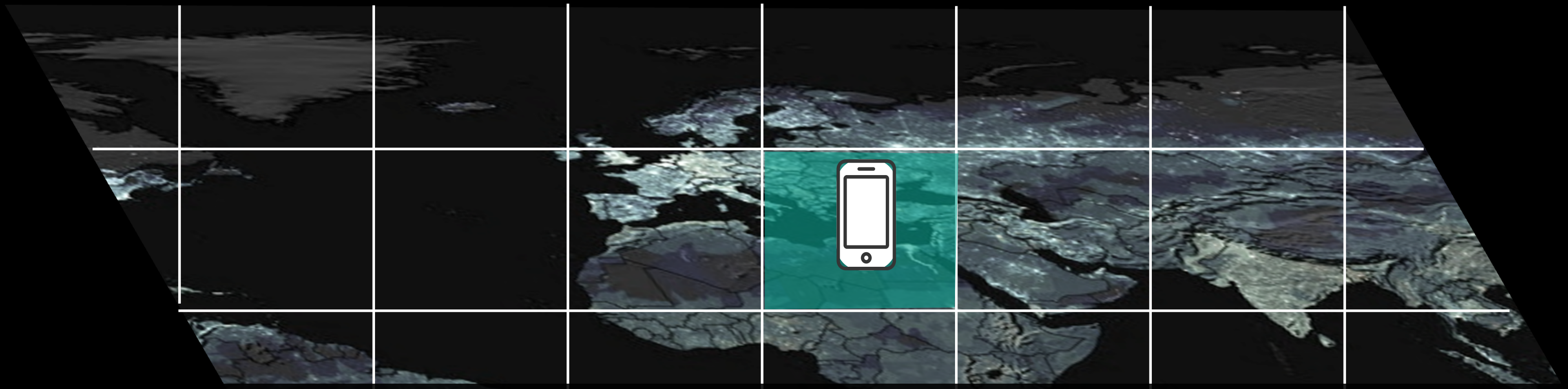
Stabilizing Addressing for Terrestrial Nodes

Decouple addressing from fast-changing serving satellites



Geographic addressing

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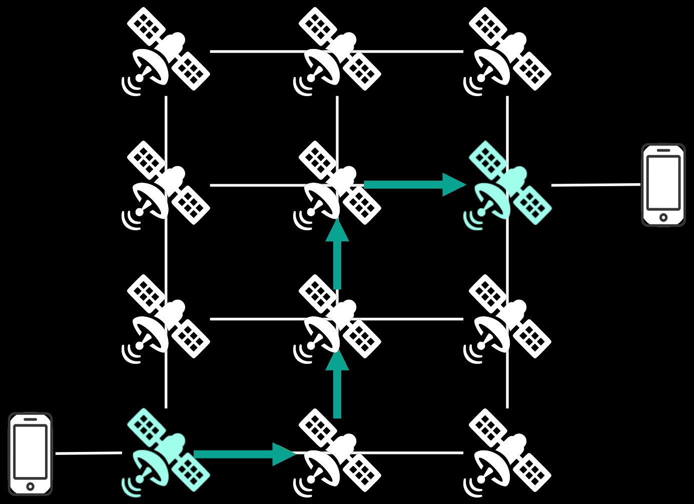
Stabilizing Space-Terrestrial Routing

Decouple routing for Earth from its fast-changing serving satellites

Logical routing



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Stabilizing Space-Terrestrial Routing

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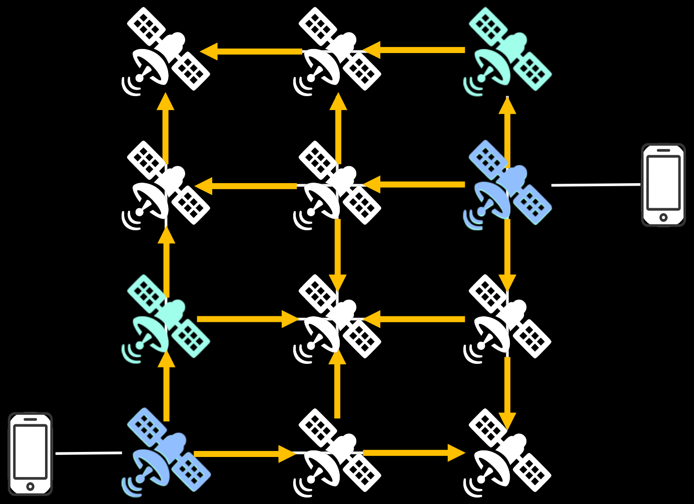

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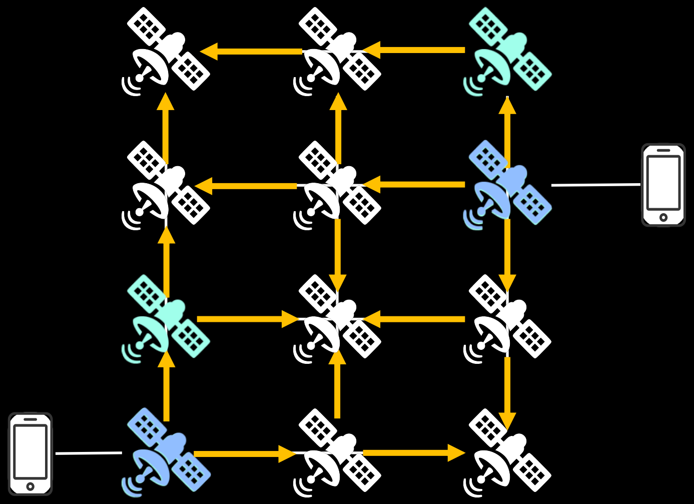

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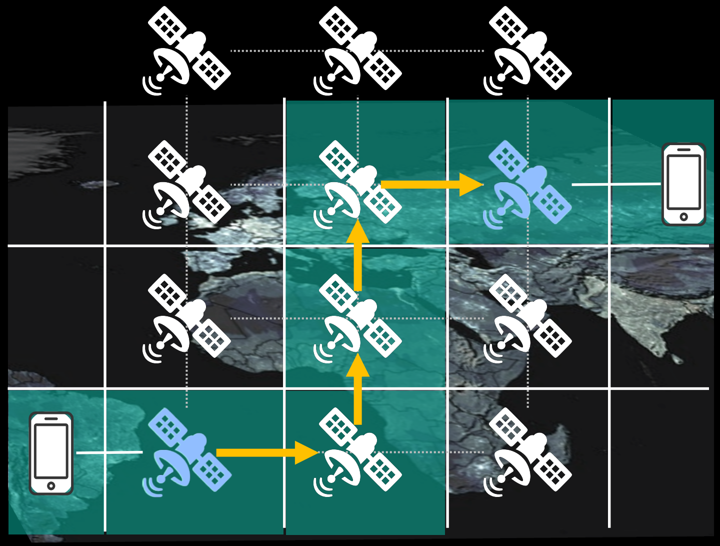

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Stabilizing Space-Terrestrial Routing

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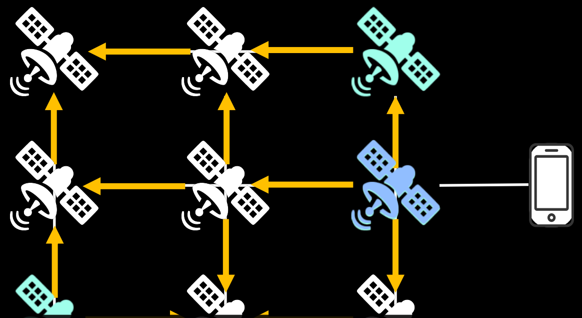
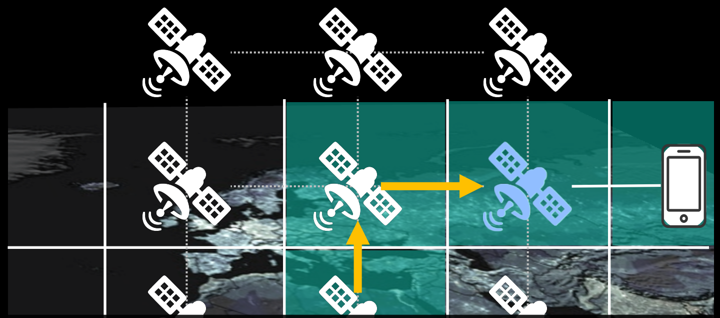


Geographic routing



No routing updates when satellites move

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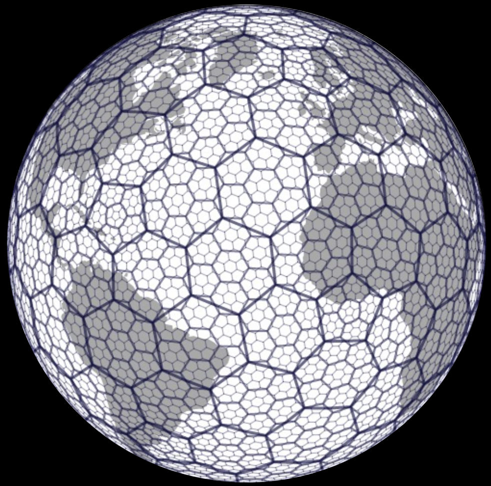
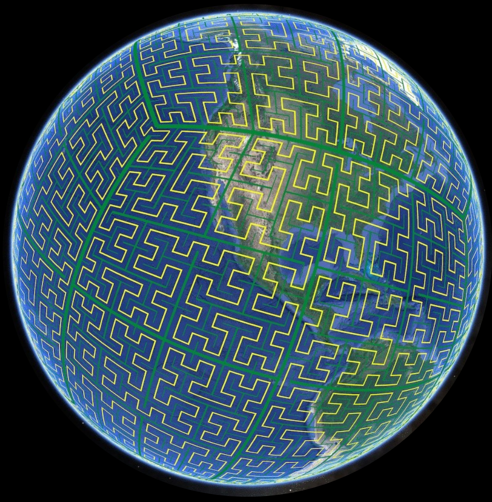
Stabilizing Space-Terrestrial Routing

- How to lay out the geospatial service areas?

Latitude-longitude cells



Hexagon cells (Uber H3)



Space-filling curve (Google S2)

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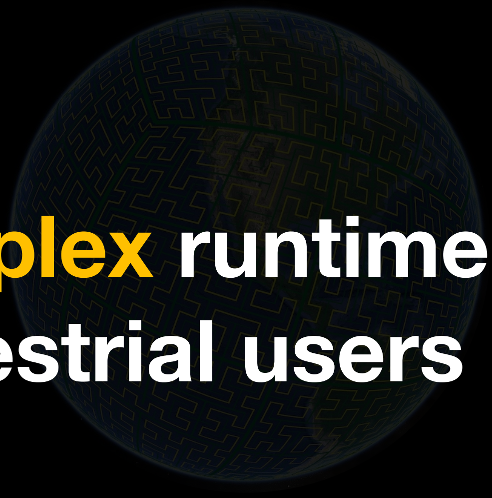
Stabilizing Space-Terrestrial Routing

- How to lay out the geospatial service areas?

Satellite-oblivious and **complex** runtime mapping from SATs to terrestrial users

Latitude-longitude cells

Hexagon cells (Uber H3)



Space-filling curve (Google S2)

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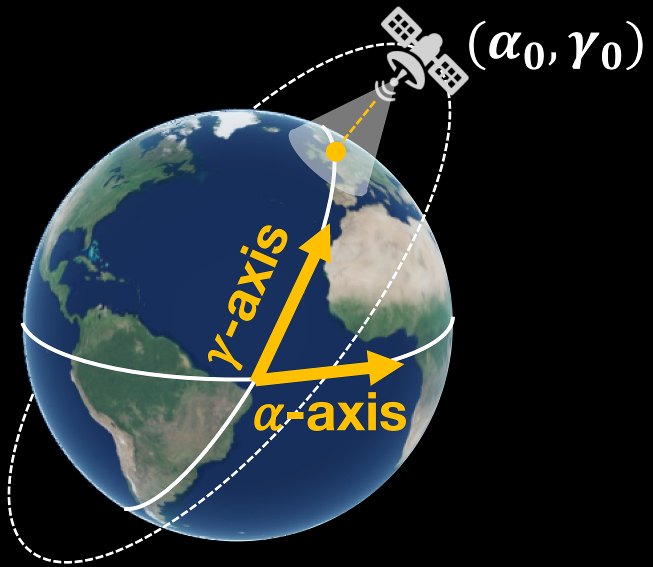
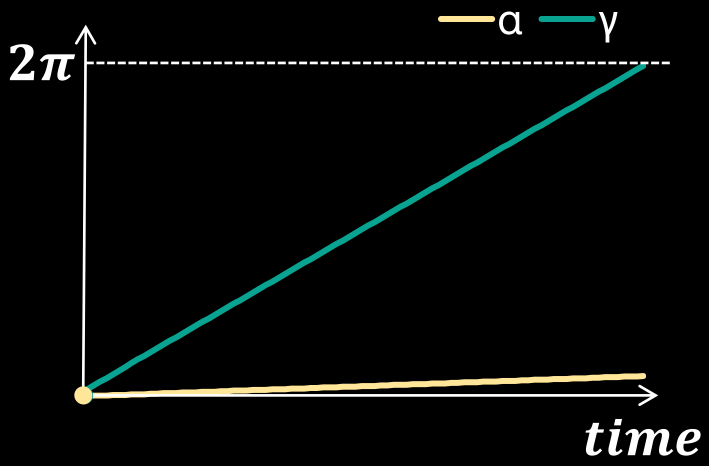
Stabilizing Space-Terrestrial Routing

- Our solution: **Align** geographic location with orbits





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Stabilizing Space-Terrestrial Routing

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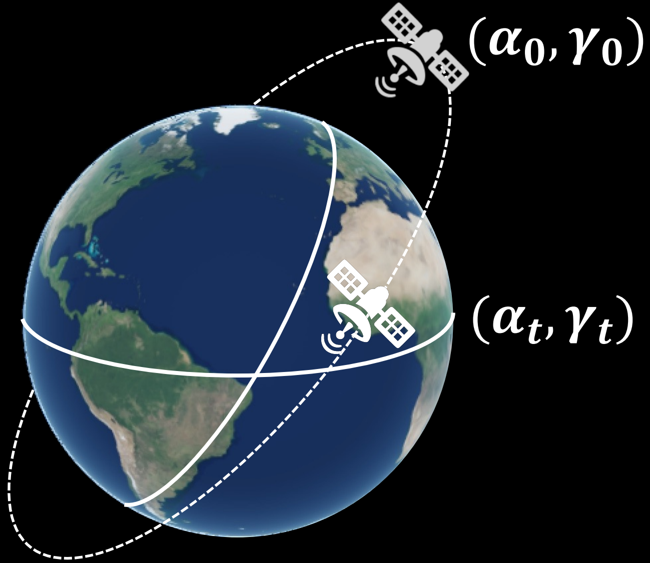

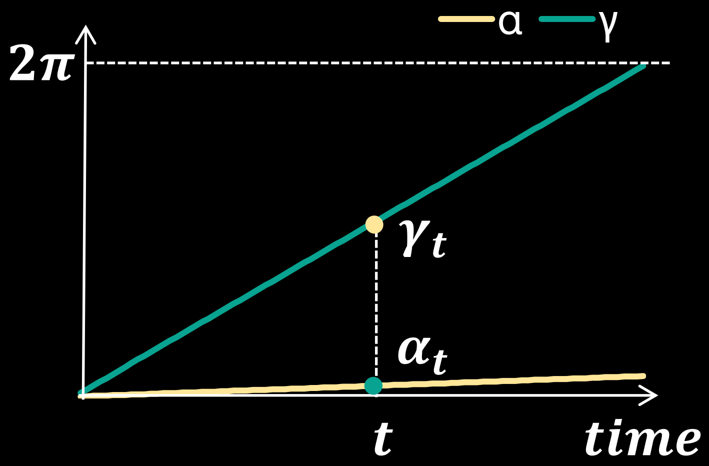

Satellite's runtime sub-point linearly changes

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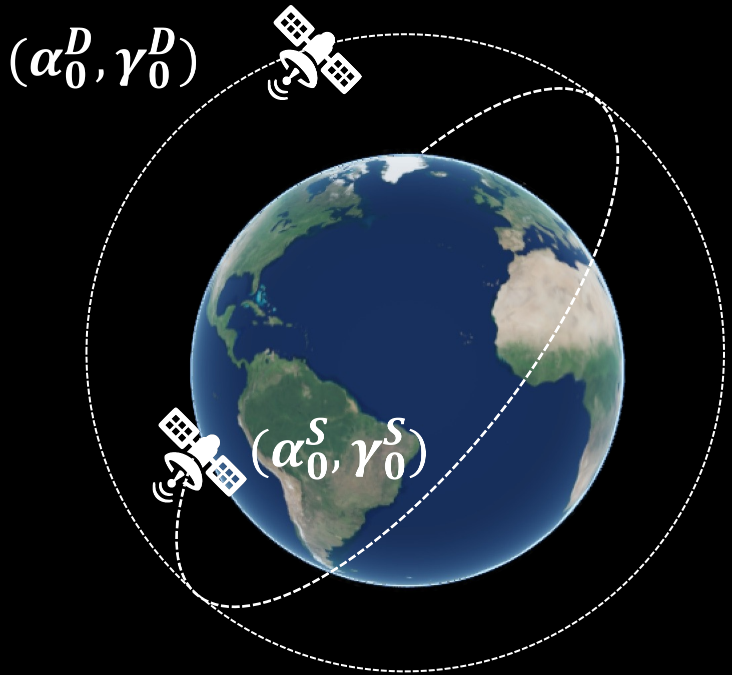
Stabilizing Space-Terrestrial Routing

- Our solution: **Align** geographic location with orbits



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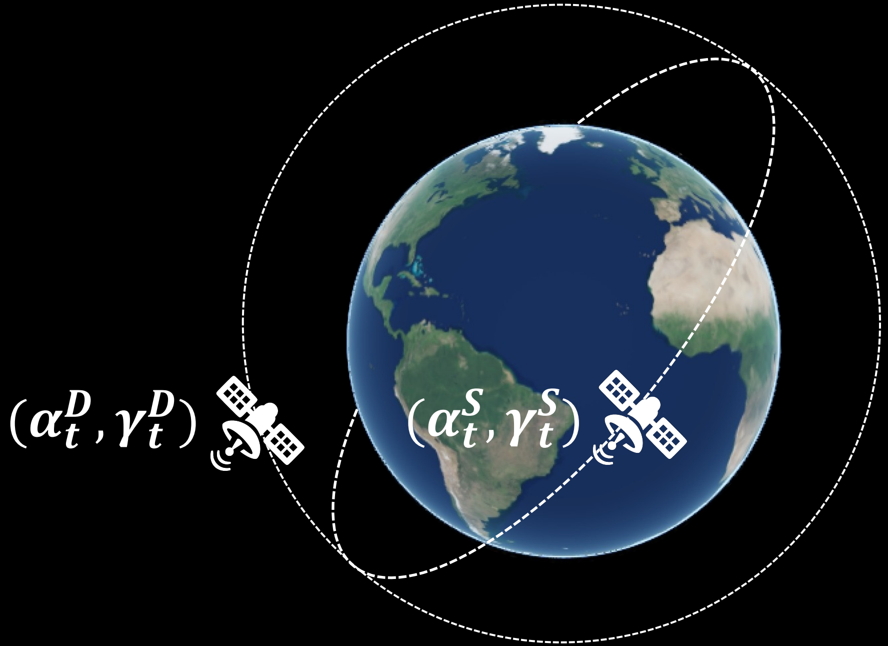
Stabilizing Space-Terrestrial Routing

- Our solution: **Align** geographic location with orbits



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

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

Time-invariant coordinate distance enable **stable routing**

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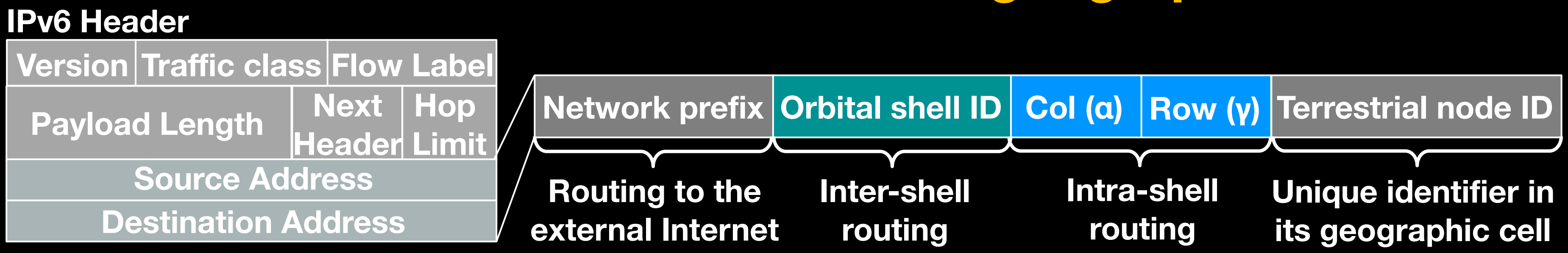
Stabilizing Space-Terrestrial Routing

- **Our solution: Stable Hierarchical geographic address**



- **Stable** address despite LEO satellite mobility and Earth's rotations
- **Local** address based on each terrestrial node's geographic location
- **Scalable** address based on hierarchical geographic cells
- **Unique** address for each terrestrial node
- **Backward compatible** with the legacy IP address
- **Efficient** address to support near-stateless geographic routing

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Stabilizing Space-Terrestrial Routing

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- **Our solution: Stable Hierarchical geographic address**

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

- **Stable** address despite LEO satellite mobility and Earth's rotations
- **Local** address based on each terrestrial node's geographic location
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No address update when satellite moves

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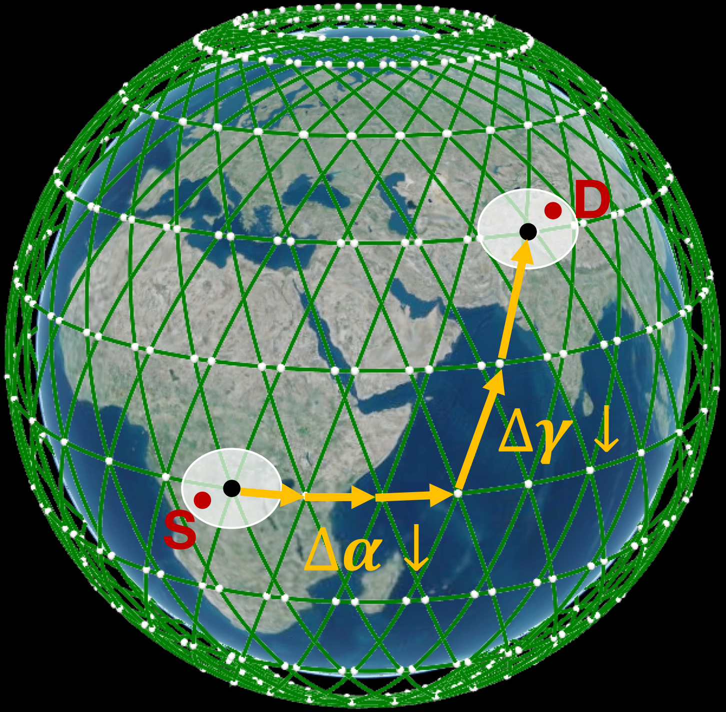
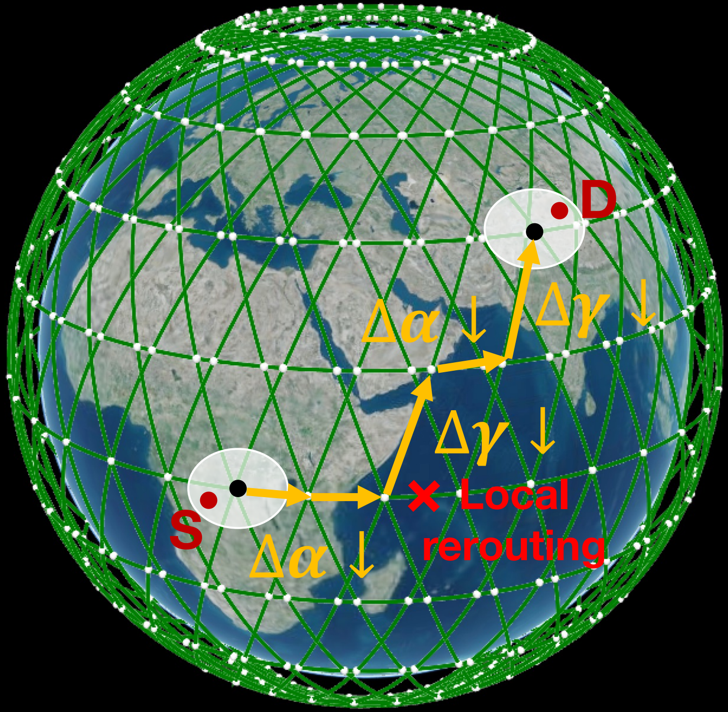
Intra-Orbital-Shell Routing for Earth

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





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Intra-Orbital-Shell Routing for Earth

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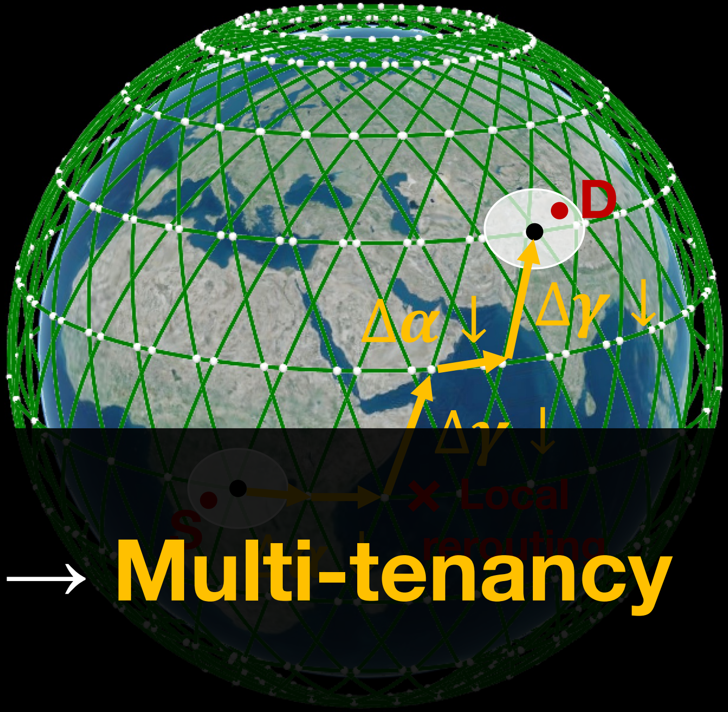

Operator-oblivious → Multi-tenancy

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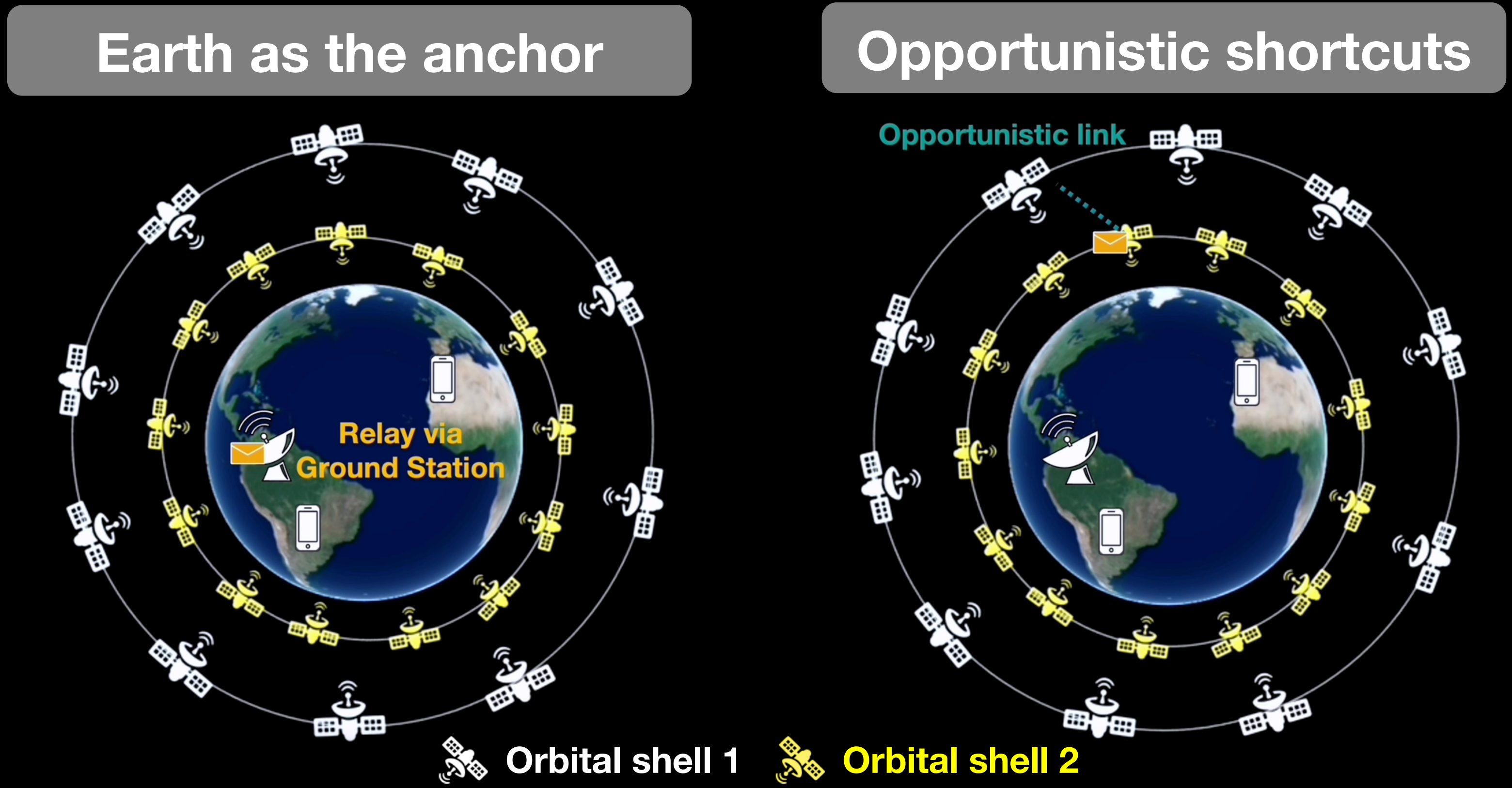
Inter-Orbital-Shell Routing for Earth



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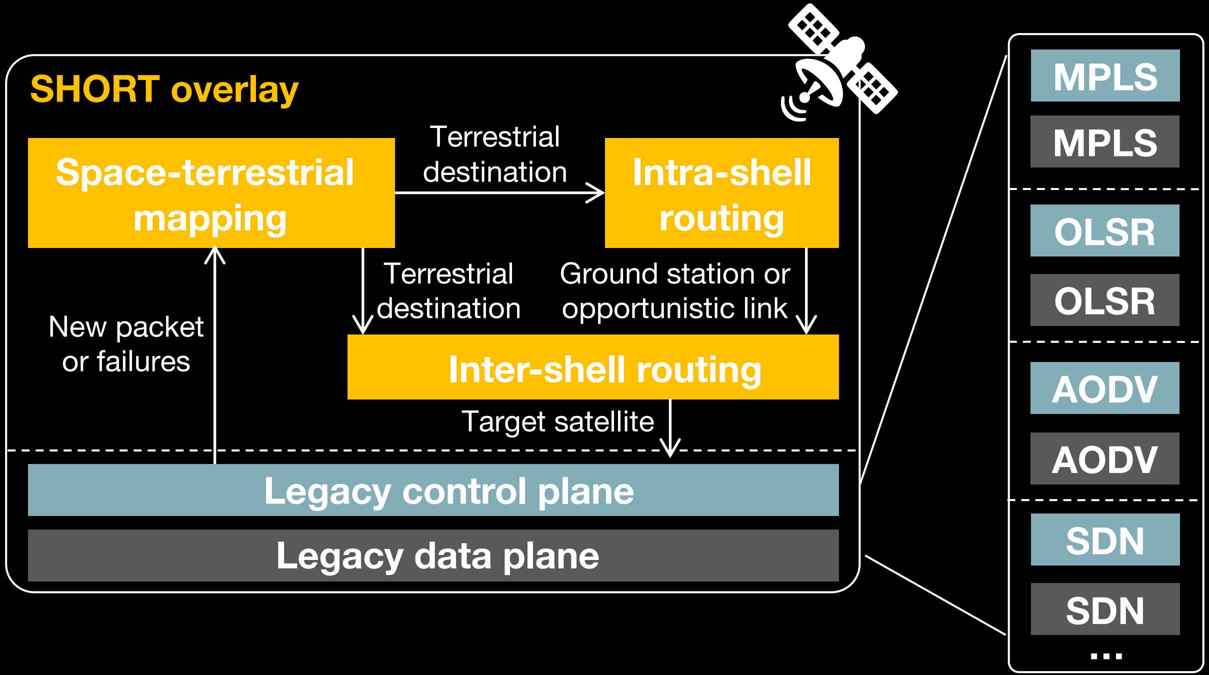
Practical Deployment

- As a **control-plane overlay**



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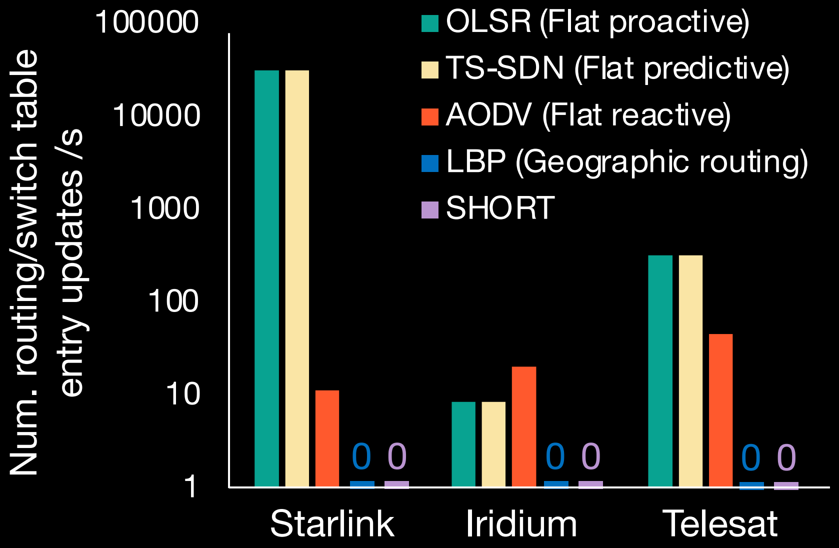
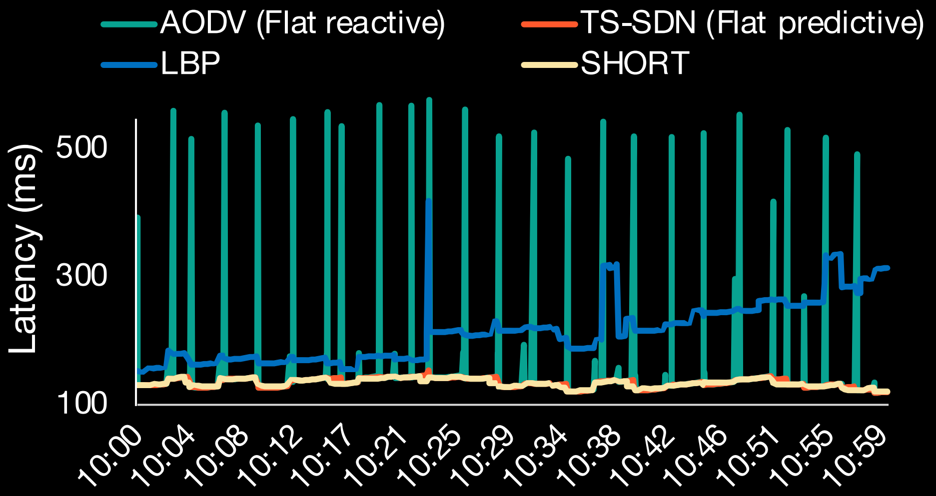
Preliminary Results

81-1489x routing updates ↓



Near optimal routing



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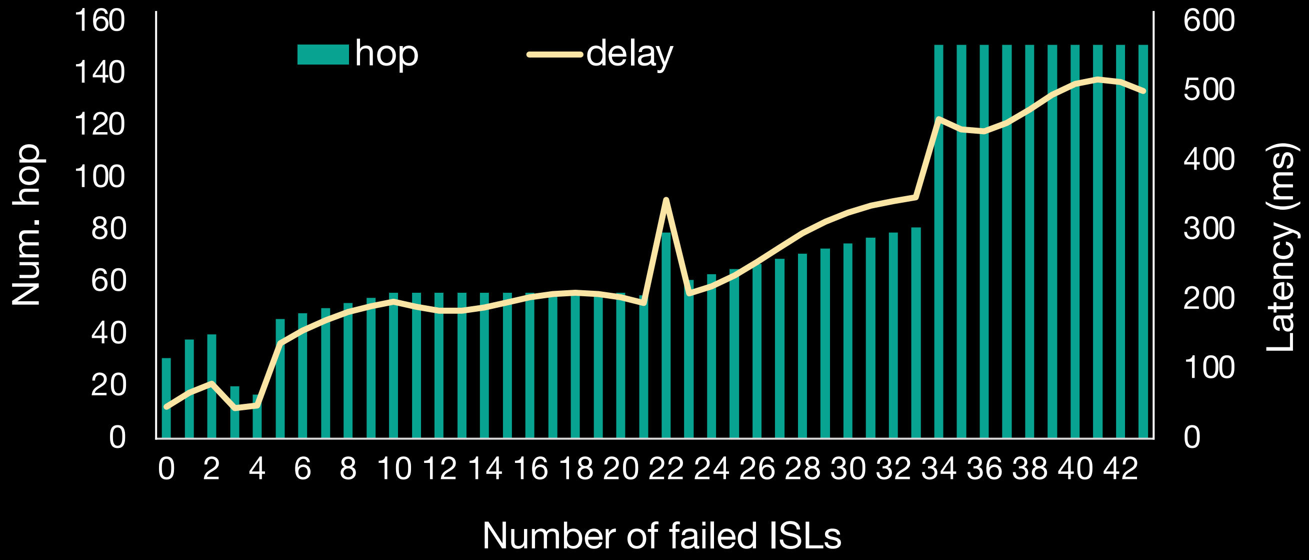
Preliminary Results

Resilient to ISL failures



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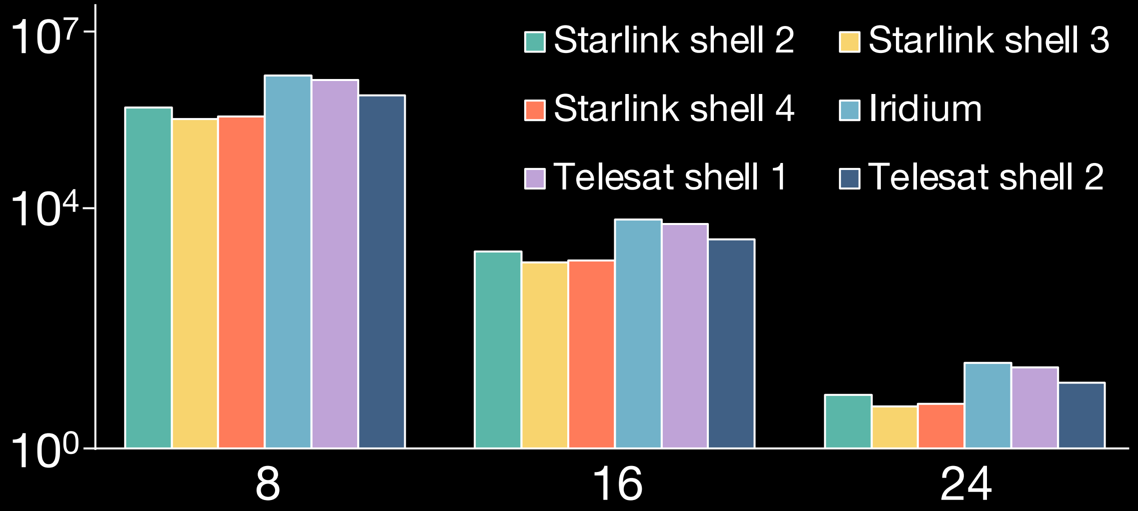
Preliminary Results

Cost-effective and scalable addressing

24-bit geographic cell index can address the full-fledged Starlink constellation with 42,000 satellites.



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Conclusion

- Multi-dimensional and exhaustive LEO dynamics in reality
  - New challenges that terrestrial networks never encounter
- A case for stable hierarchical addressing and routing
  - Decouple, localize, and mask LEO dynamics hierarchically
- IETF should play a more active role in this direction
  - Stable addressing and routing as the foundation for SatNet
  - Collaboration w/ 3GPP NTN standardization, academia & industry

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Thank you!

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*figure source: Geespace