

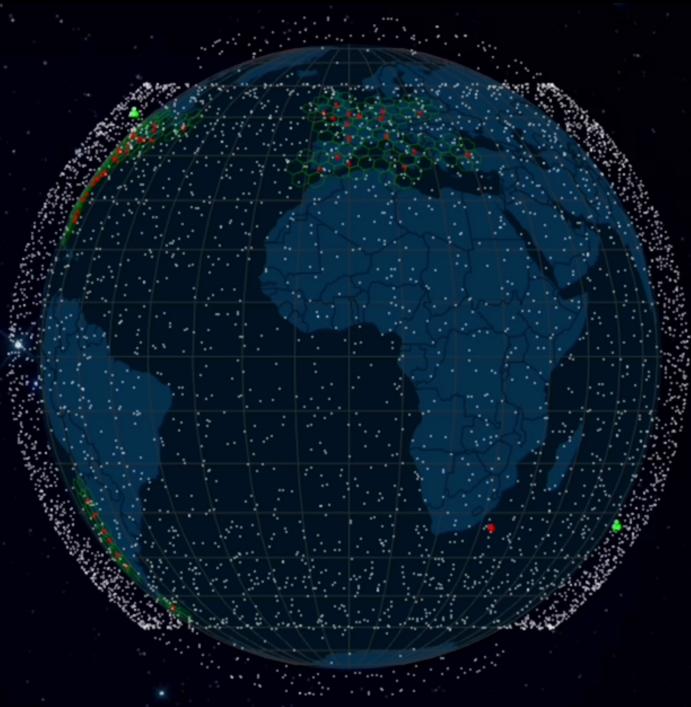


清华大学  
Tsinghua University

# Stable Hierarchical Routing for Operational LEO Networks

Yuanjie Li, **Lixin Liu**, Hewu Li, Wei Liu, Yimei Chen,  
Jianping Wu, Qian Wu, Jun Liu, Zeqi Lai

# Low Earth Orbit (LEO) Mega-Constellation



**42,000  
SATELLITES**

**8  
SHELLS**

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

# Are the LEO satellites networked?



Elon Musk  X   
@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

# Are the LEO satellites networked?



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

**Why not?**

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

# Why not networked satellites?

**Chaotic and exhaustive network dynamics**

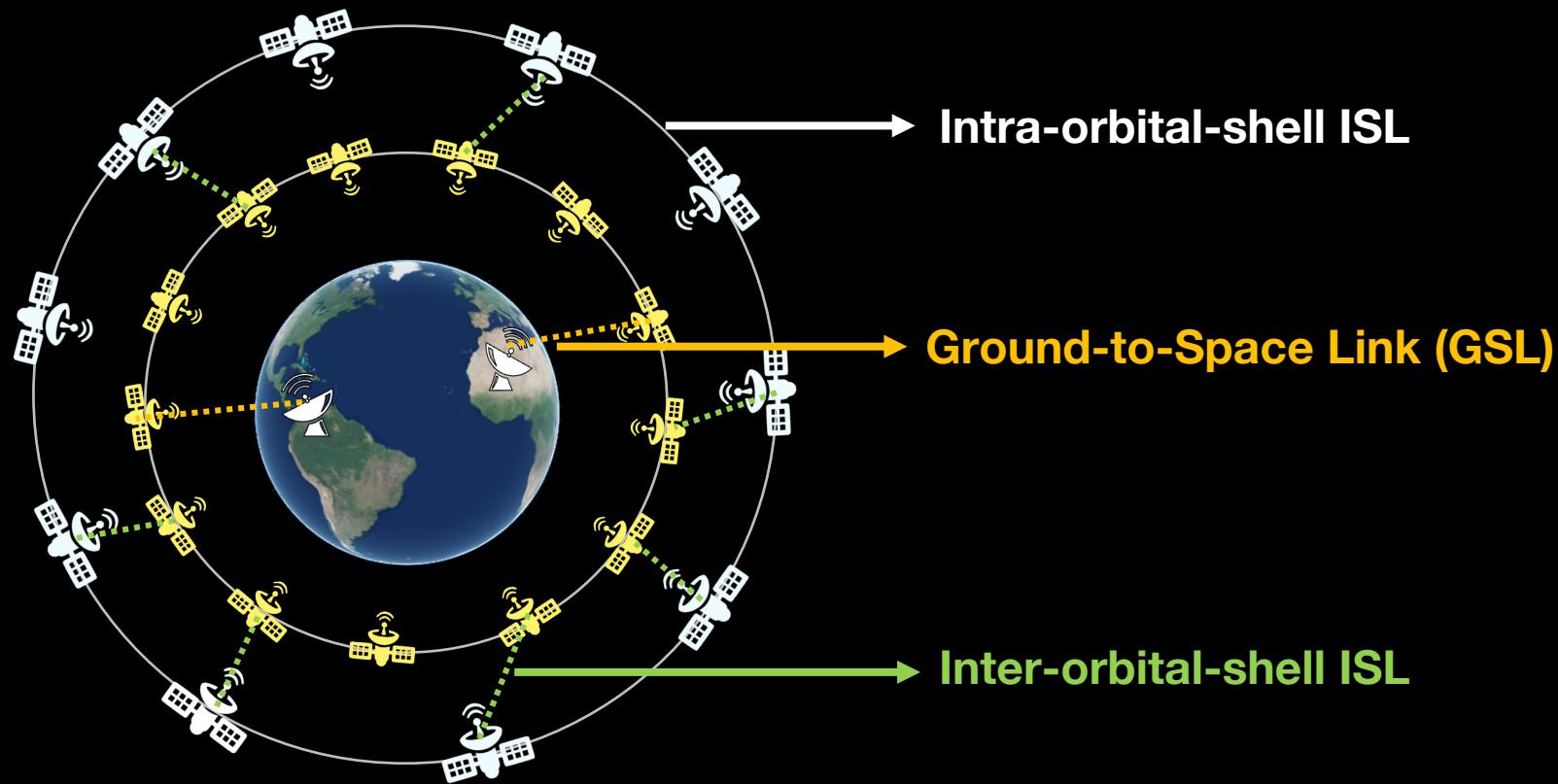
**Routing in space is unstable!**



# This work

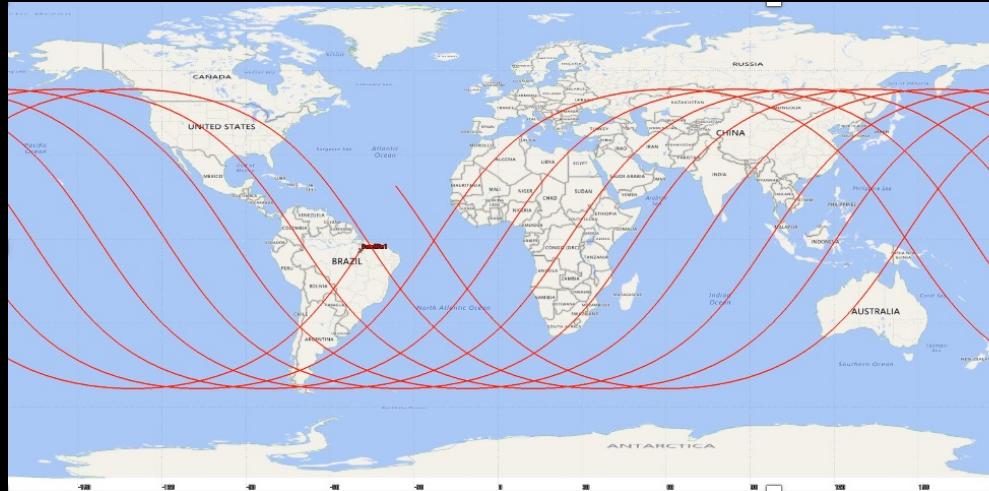
- **What does LEO network dynamics look like?**
- **How does dynamics affect satellite routing at scale?**
- **How to stabilize large-scale routing over dynamics?**

# Low-Earth-Orbit Dynamics



# Ideal Low-Earth-Orbit Dynamics

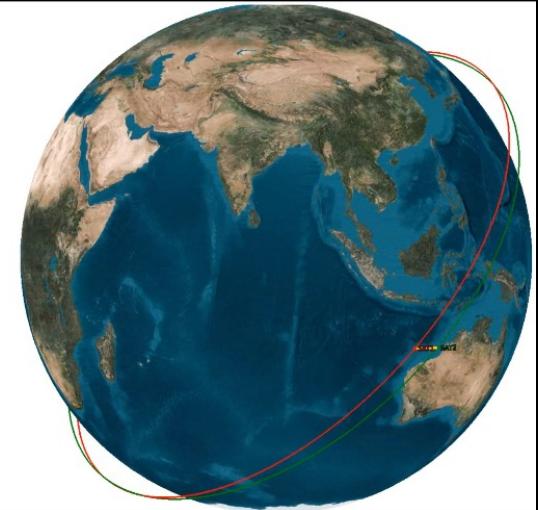
## 1. Space-Terrestrial Dynamics



**Asynchronous** mobility between satellite and Earth → Frequent GSL churn

# Ideal Low-Earth-Orbit Dynamics

## 2. Intra-Orbital-Shell Dynamics



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

# Ideal Low-Earth-Orbit Dynamics

## 3. Inter-Orbital-Shell Dynamics

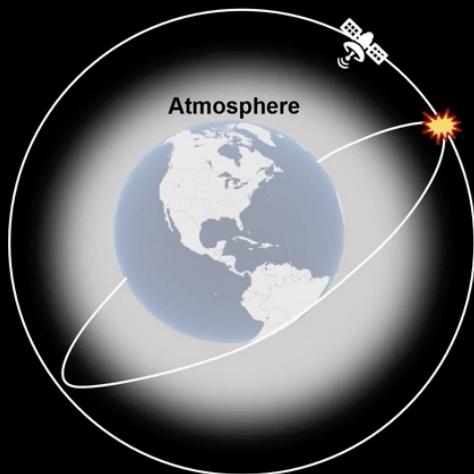


**Heterogeneous satellites → Chaotic ISL dynamics even in ideal cases**

# Real Low-Earth-Orbit Dynamics

## Orbital imperfections

- Orbital drags
- Orbital maneuvers



# Real Low-Earth-Orbit Dynamics

## Orbital imperfections

- Orbital drags
- Orbital maneuvers
- Orbital failures

## Partial deployments

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 f t in e

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

JULY 13, 2024 · 3:27 AM ET



Starlink Shell 3

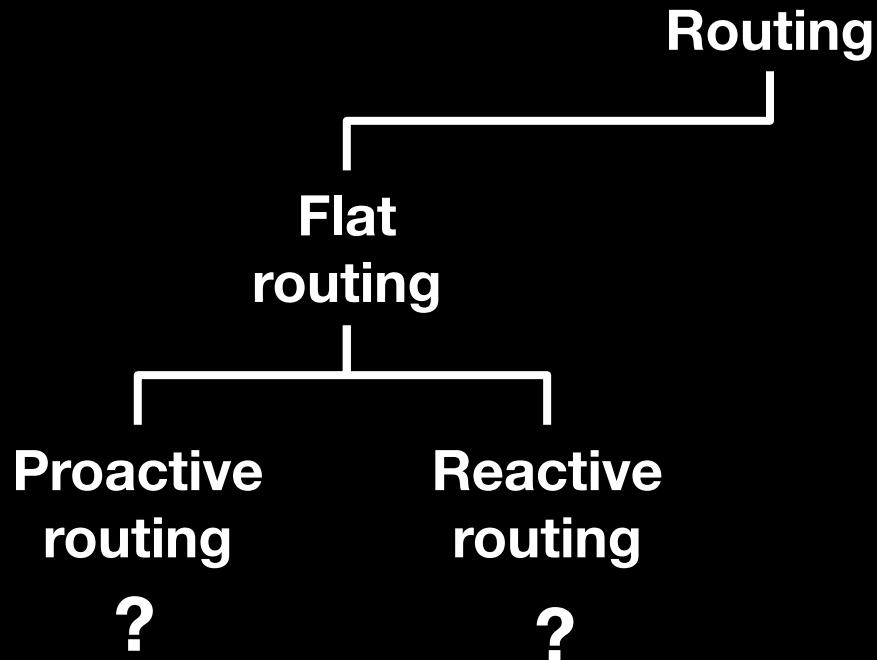
# Implications for Routing

Routing

Flat  
routing

?

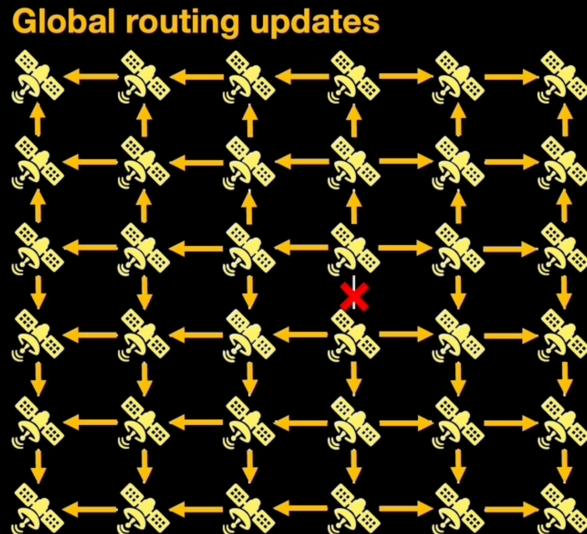
# Implications for Routing



# Flat routing?

## Proactive routing

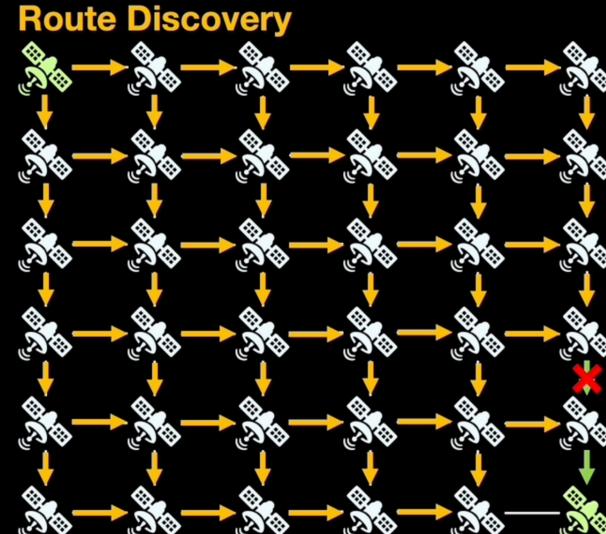
Link state/Distance vector, SDN



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**

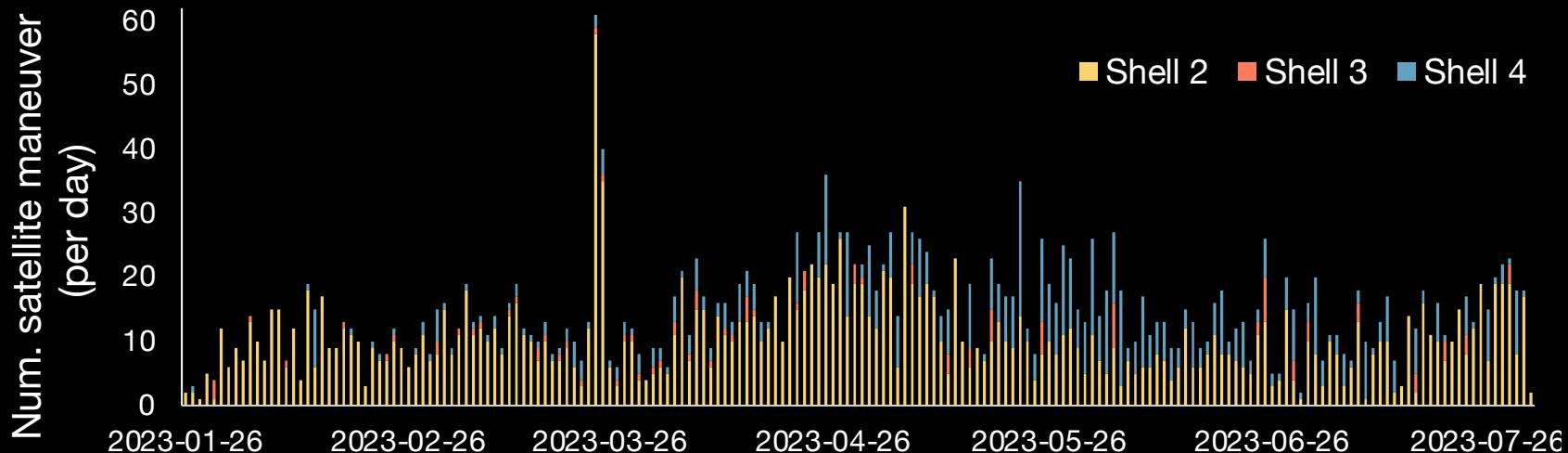


*Kepler's Law*

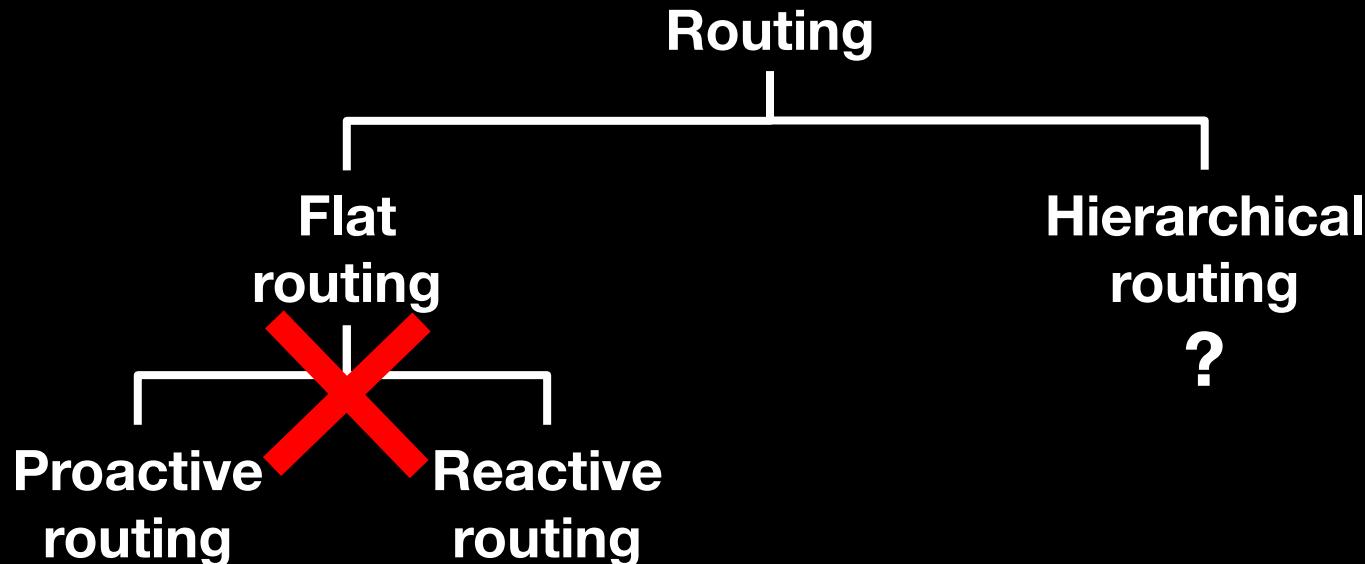
Is it enough for optional LEO networks?

# Flat predictive routing?

**Unpredictable and random orbital imperfections 😞**

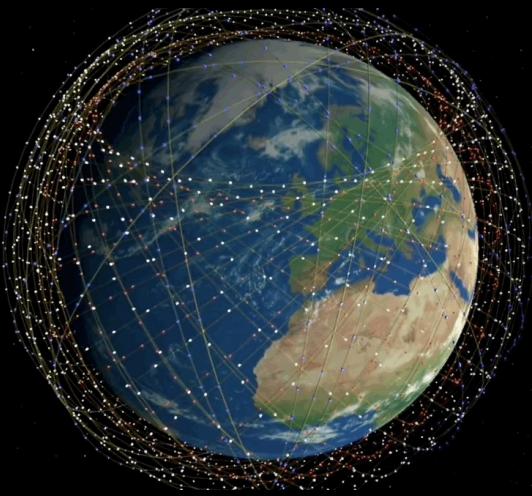
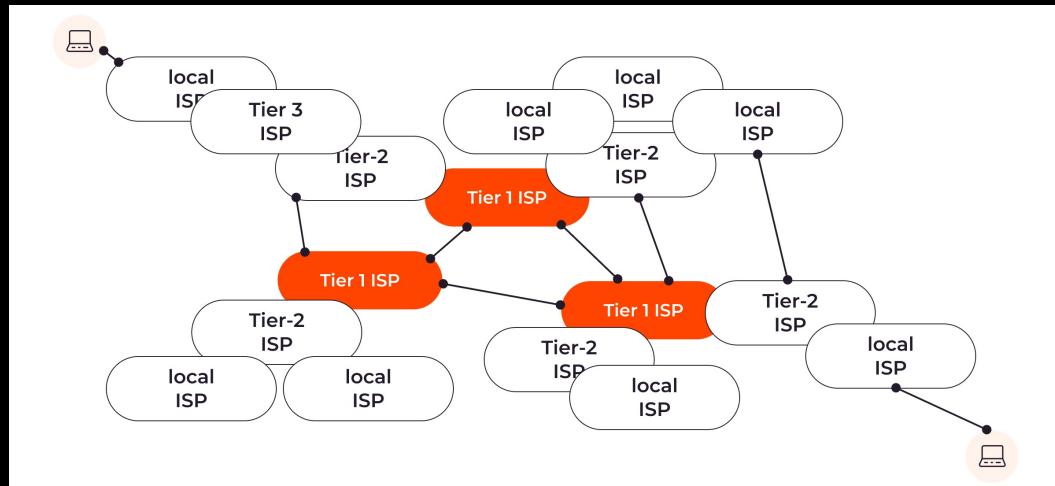


# Implications for Routing



# Hierarchical routing?

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

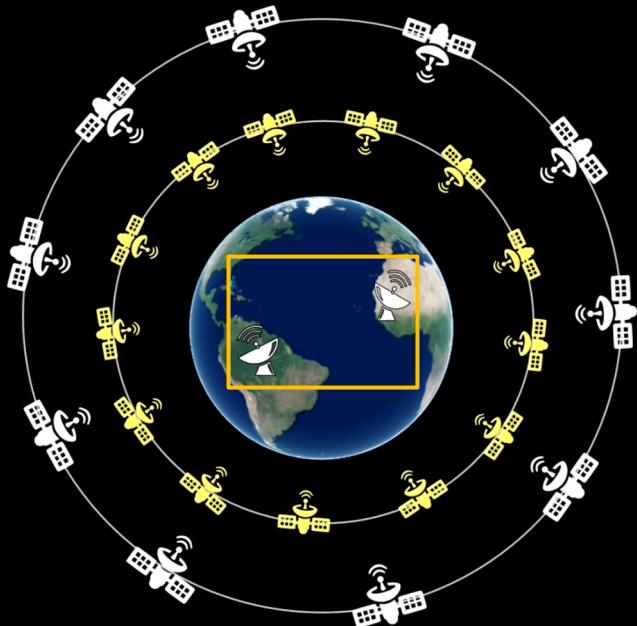


\*figure source: GCORE, Mark Handley

# How to **stabilize** hierarchical routing in **dynamic** LEO networks?

# Our work: Earth-centric geographic paradigm

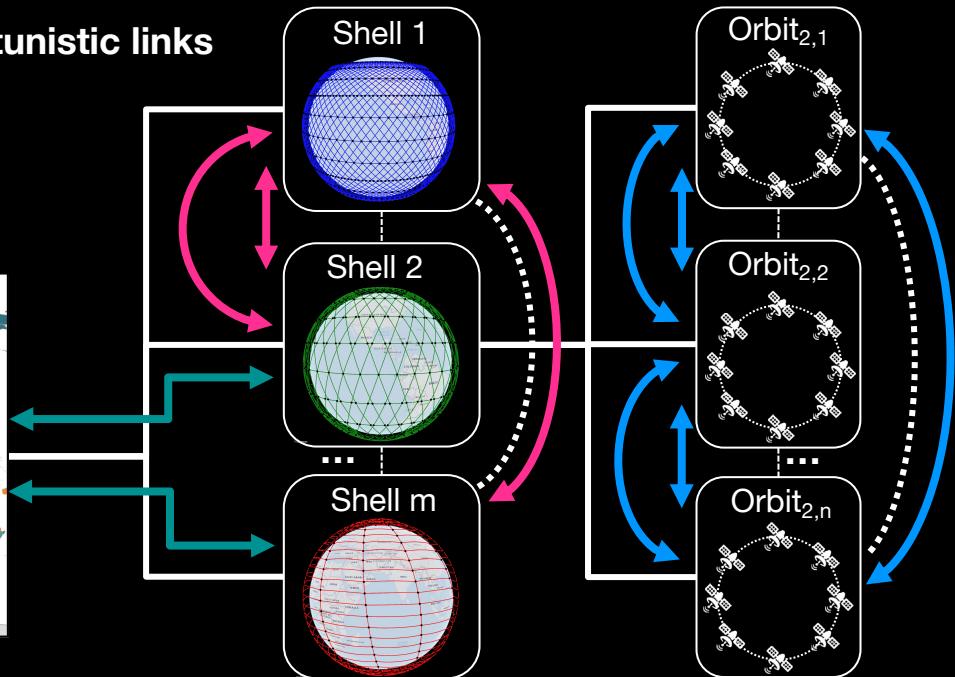
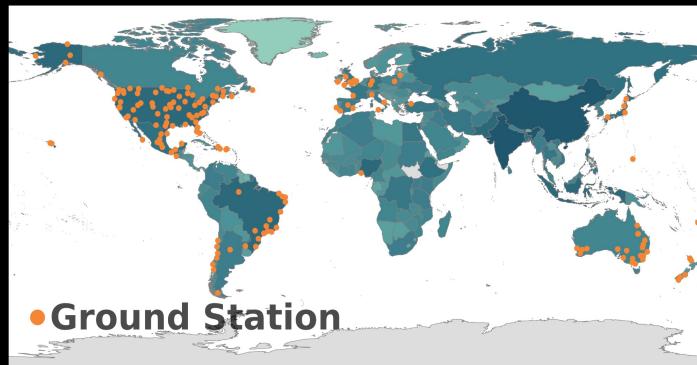
Earth's geographic locations are **invariant** of extreme satellite **mobility**



# An Earth-Centric Stable LEO Routing Hierarchy

**Decouple, localize, and mask LEO dynamics hierarchically**

- Backbone links    ..... Opportunistic links
- Space-terrestrial routing
- Intra-orbital-shell routing
- Inter-orbital-shell routing



Tier 1: terrestrial network

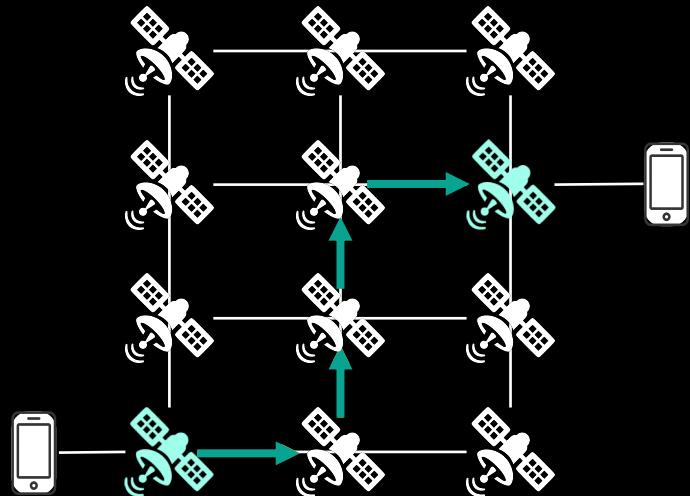
Tier 2: orbital shells

Tier 3: orbits

# Stabilizing Space-Terrestrial Routing

- Use **geographic routing** to **decouple** from fast-changing satellites

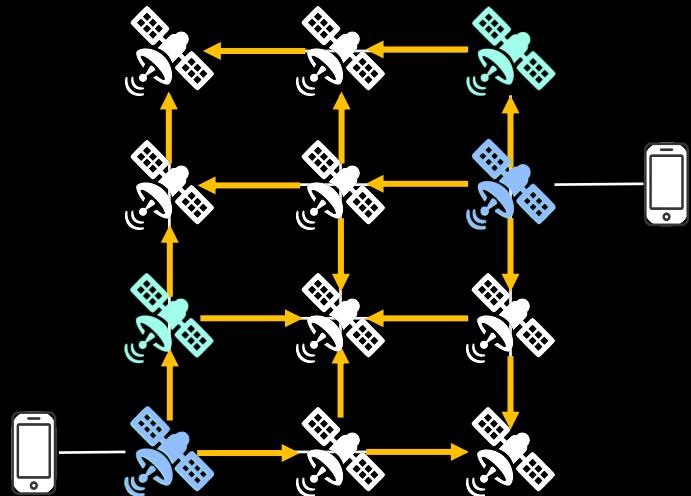
Logical routing



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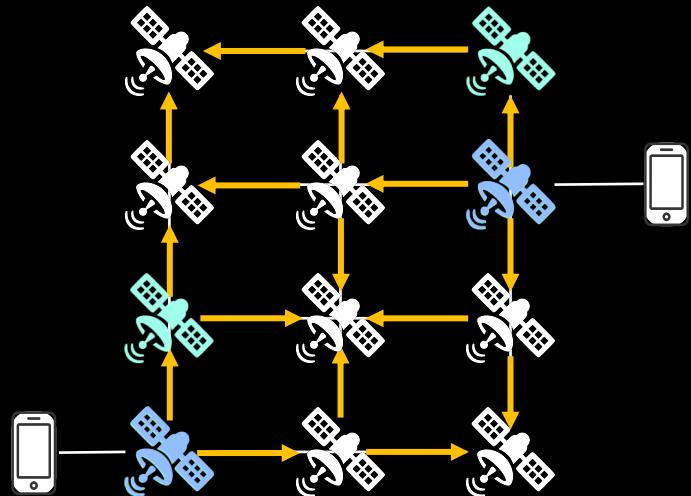
Logical routing



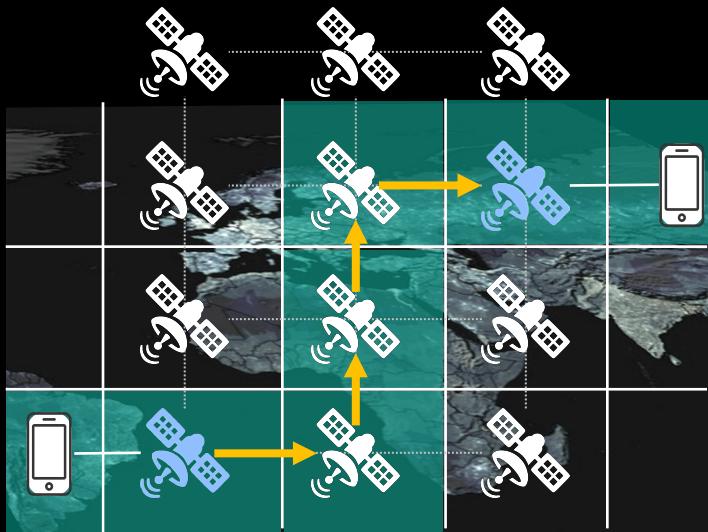
# Stabilizing Space-Terrestrial Routing

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Logical routing



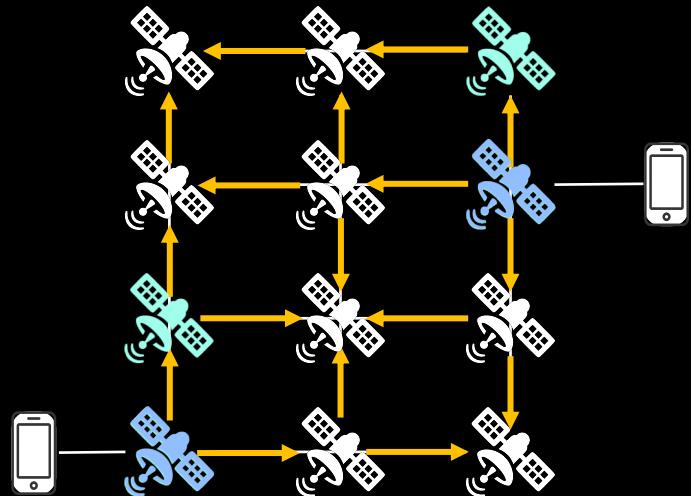
Geographic routing



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- Use **geographic routing** to **decouple** from fast-changing satellites

Logical routing



Geographic routing

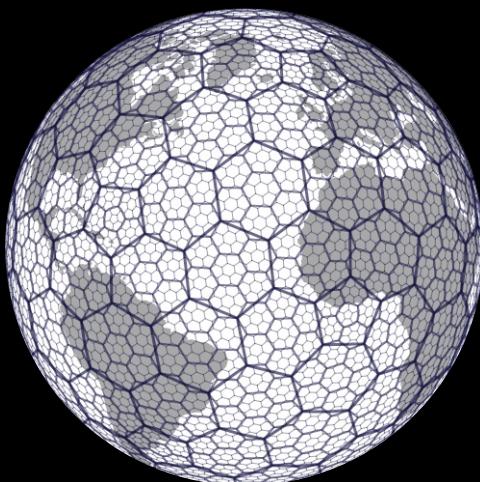


# Stabilizing Space-Terrestrial Routing

- How to lay out the geographic service areas?



Latitude-longitude  
cells



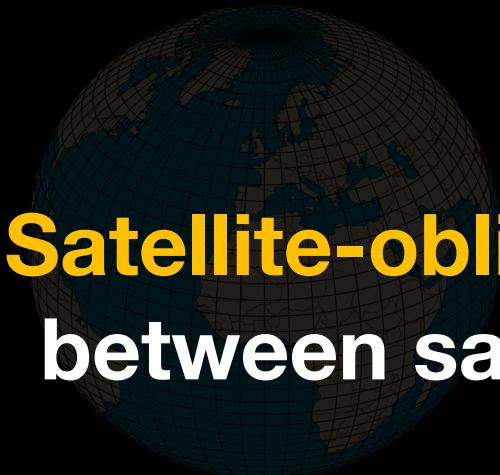
Hexagon cells  
(Uber H3)



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



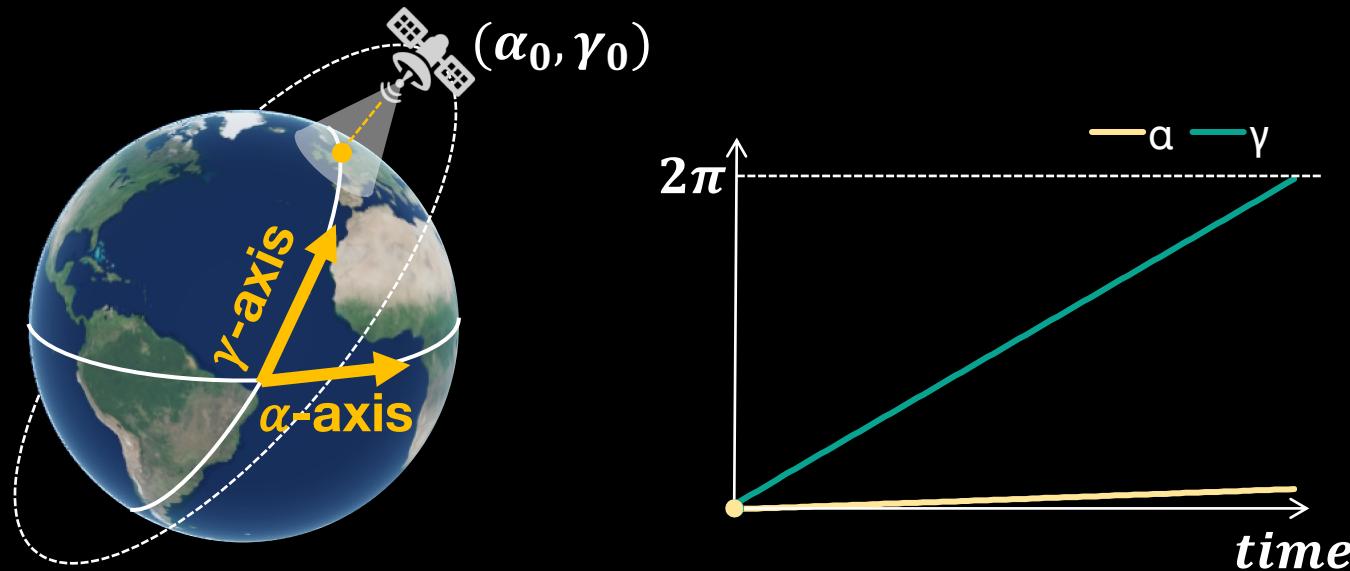
Hexagon cells  
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Space-filling curve  
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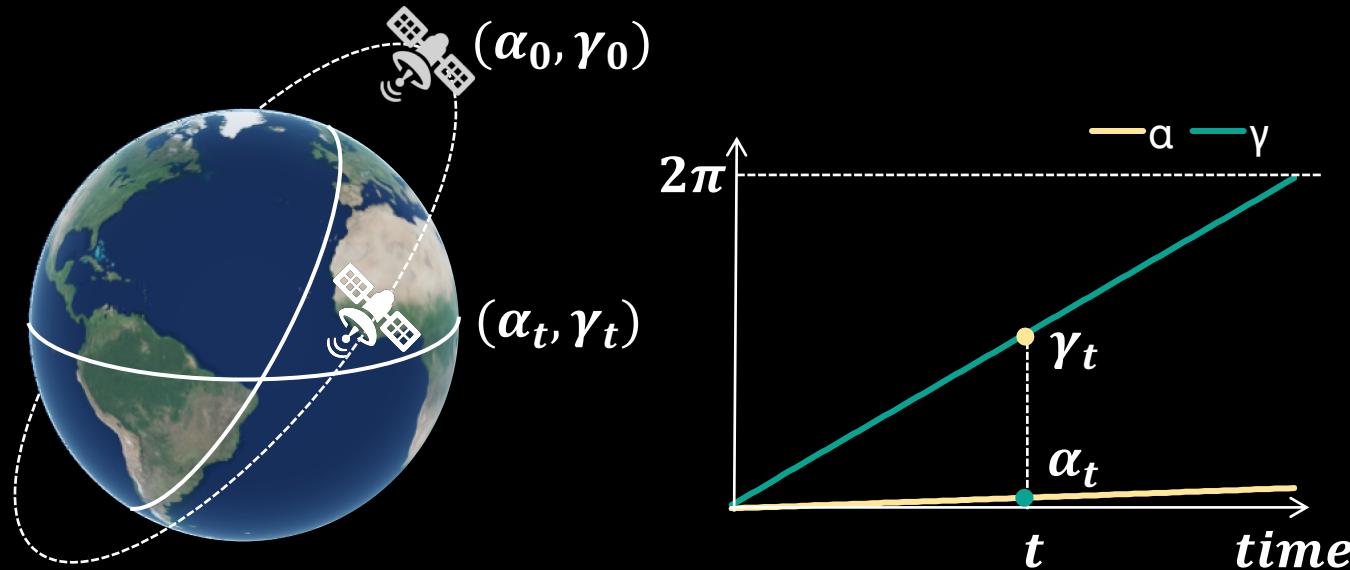
# Stabilizing Space-Terrestrial Routing

- Simplify satellite's runtime mapping



# Stabilizing Space-Terrestrial Routing

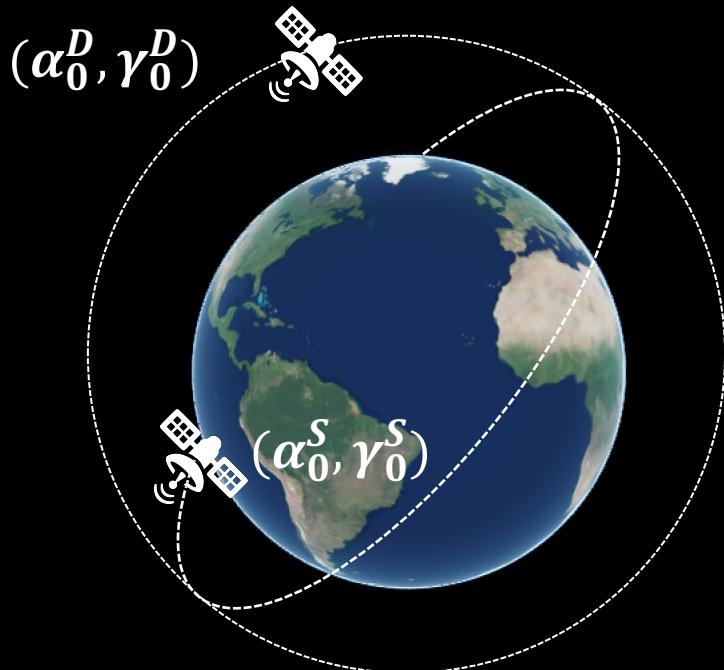
- Simplify satellite's runtime mapping



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

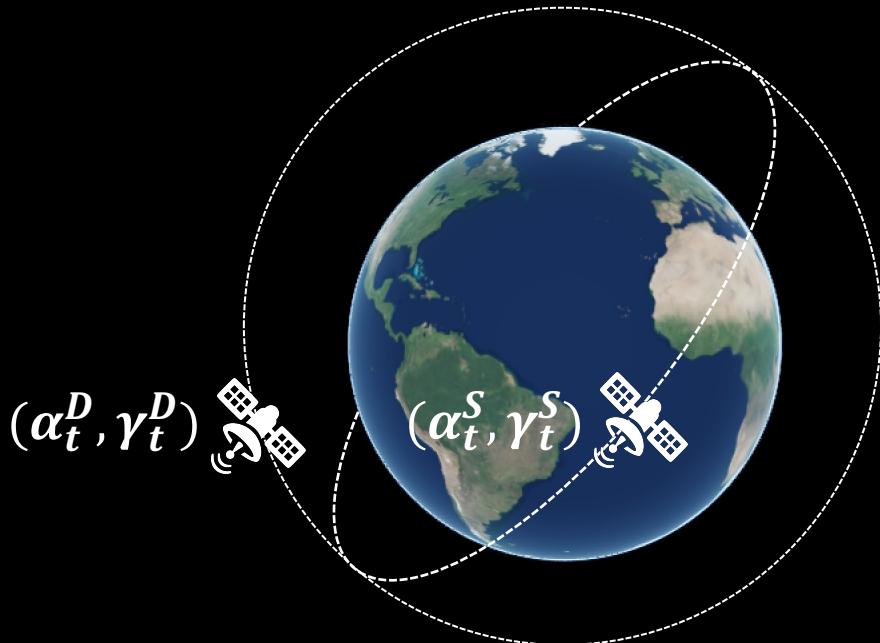
# Stabilizing Space-Terrestrial Routing

- Stabilize routing distance between satellites



# Stabilizing Space-Terrestrial Routing

- Stabilize routing distance between satellites

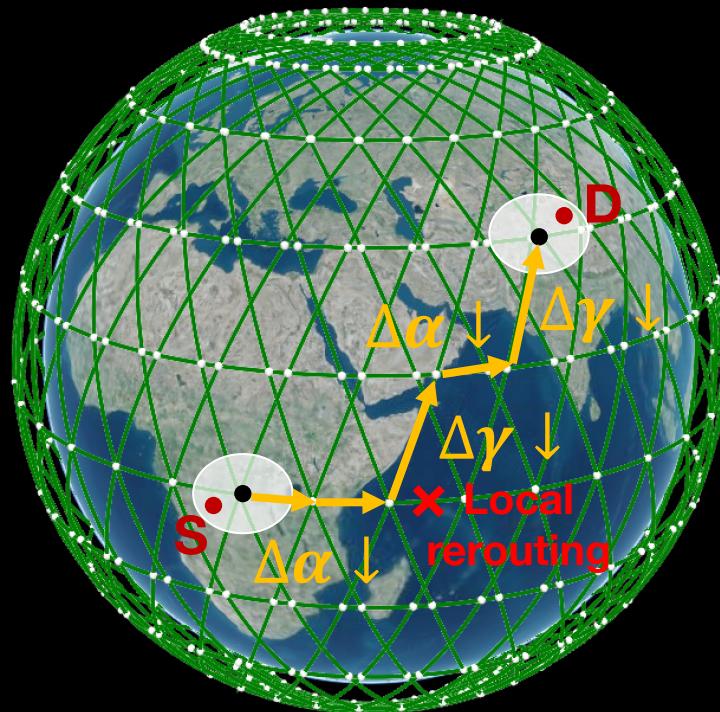
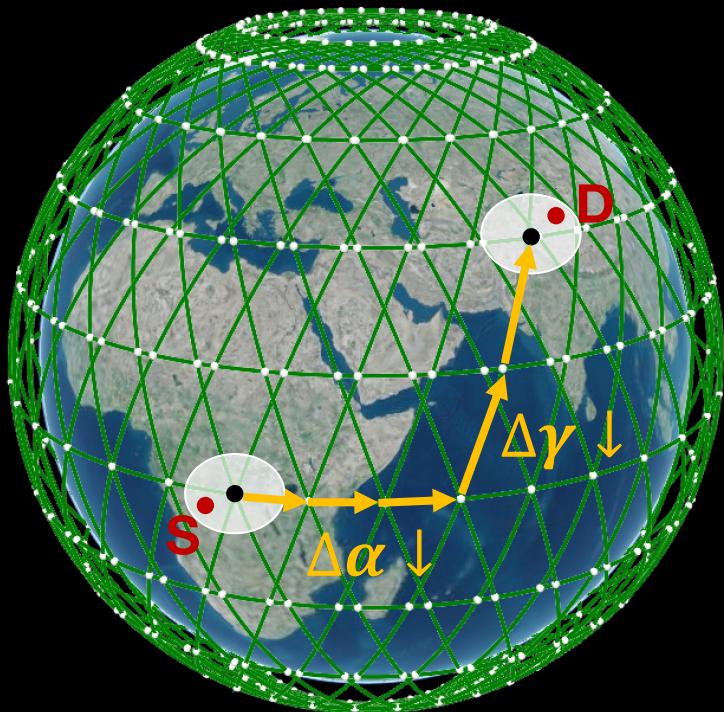


$$\boxed{\begin{aligned}\Delta\alpha_t^{S,D} &\equiv \Delta\alpha_0^{S,D} = \alpha_0^S - \alpha_0^D \\ \Delta\gamma_t^{S,D} &\equiv \Delta\gamma_0^{S,D} = \gamma_0^S - \gamma_0^D\end{aligned}}$$

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

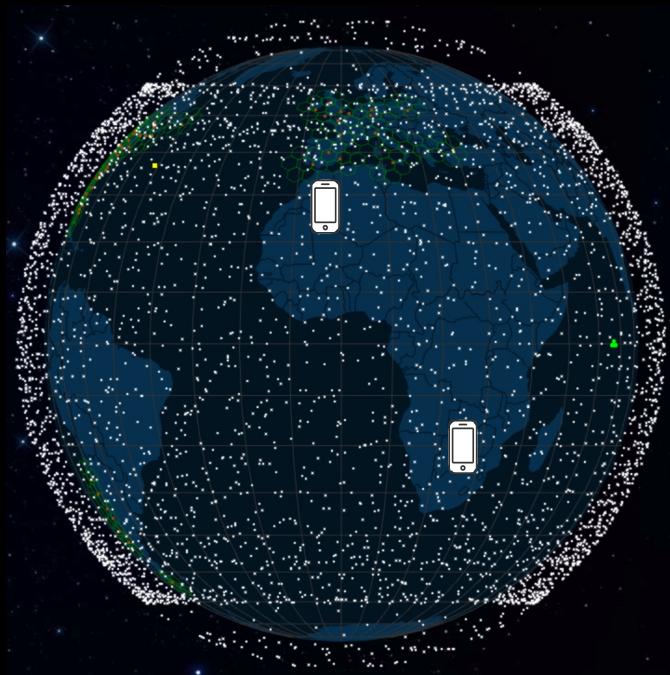
# Intra-Orbital-Shell Routing for Earth

- Stable and ISL churn resilient geographic routing



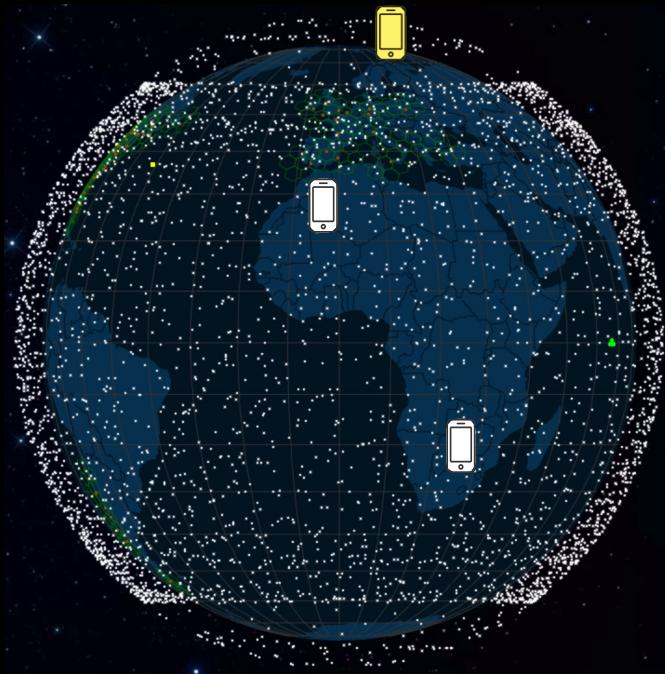
# Inter-Orbital-Shell Routing for Earth

## When will we need it?



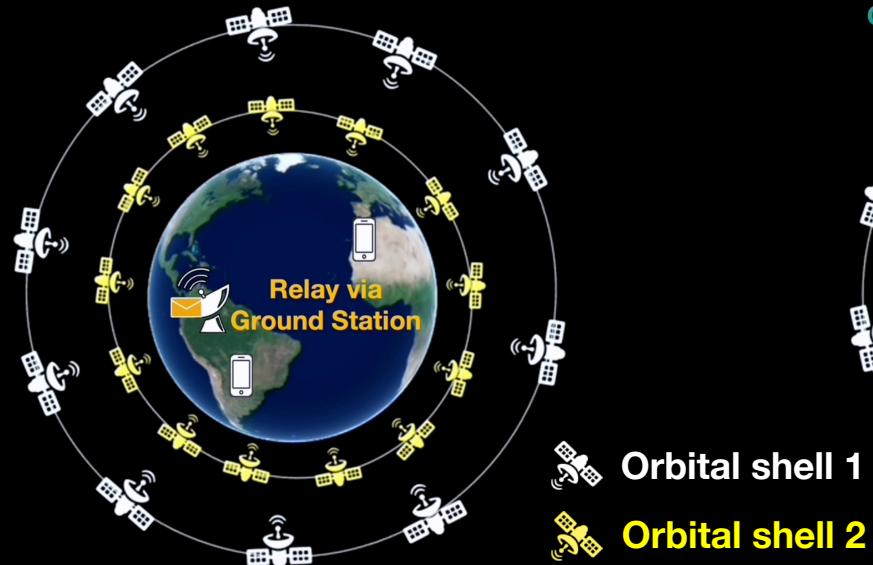
# Inter-Orbital-Shell Routing for Earth

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

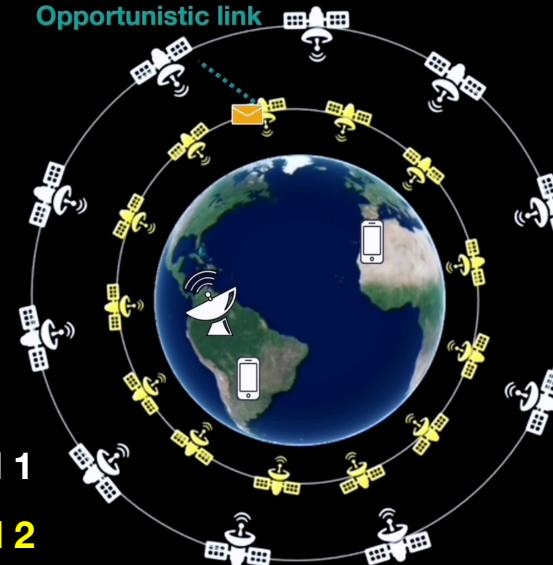


# Inter-Orbital-Shell Routing for Earth

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



Earth as the anchor



Opportunistic shortcuts

# Practical Deployment

- Take IPv6 as an example

## What IP address does Starlink provide?

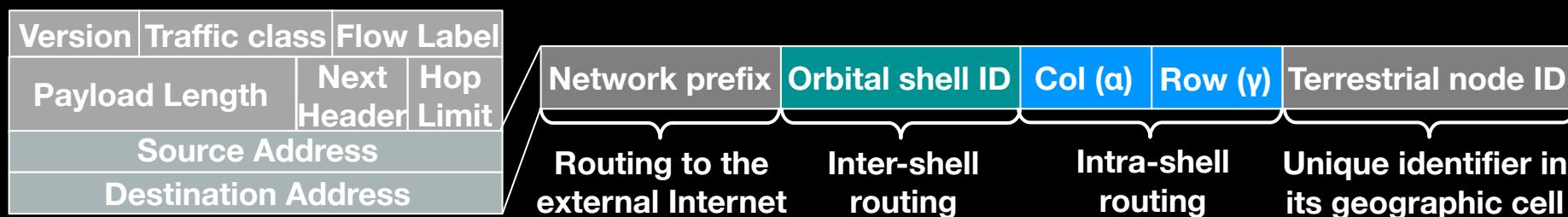
public IPv4 Addresses. Starlink supports native IPv6 across all Starlink routers, kit versions, and service plans. All IPv6 compatible Starlink router clients are assigned IPv6 addresses.

# Practical Deployment

- Take IPv6 as an example

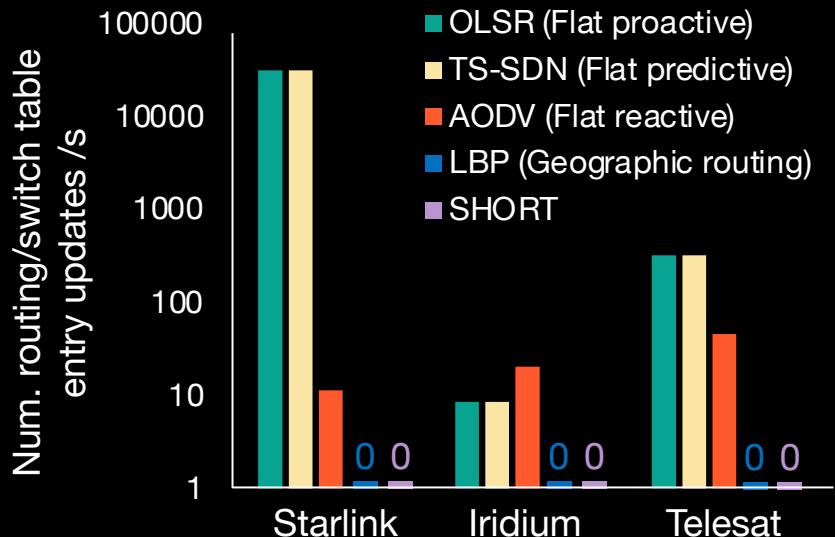


## IPv6 Header

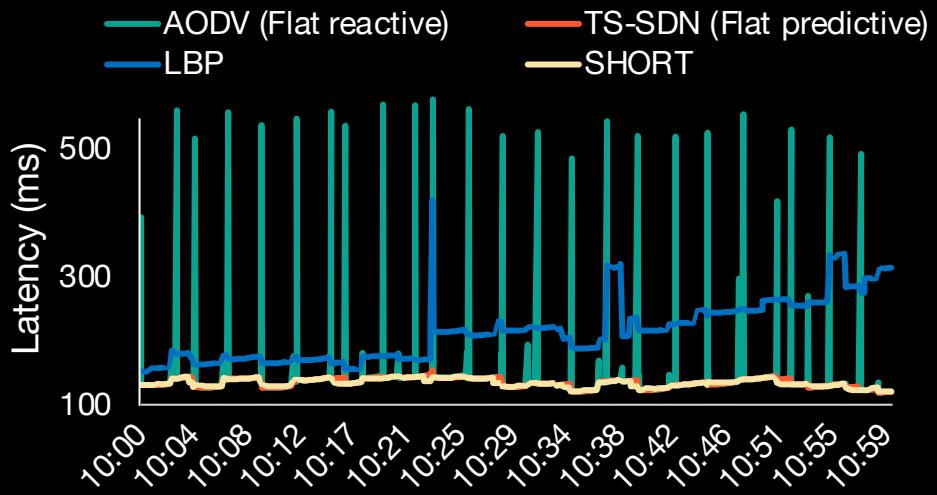


# Evaluation Highlights

**81-1489x routing updates ↓**

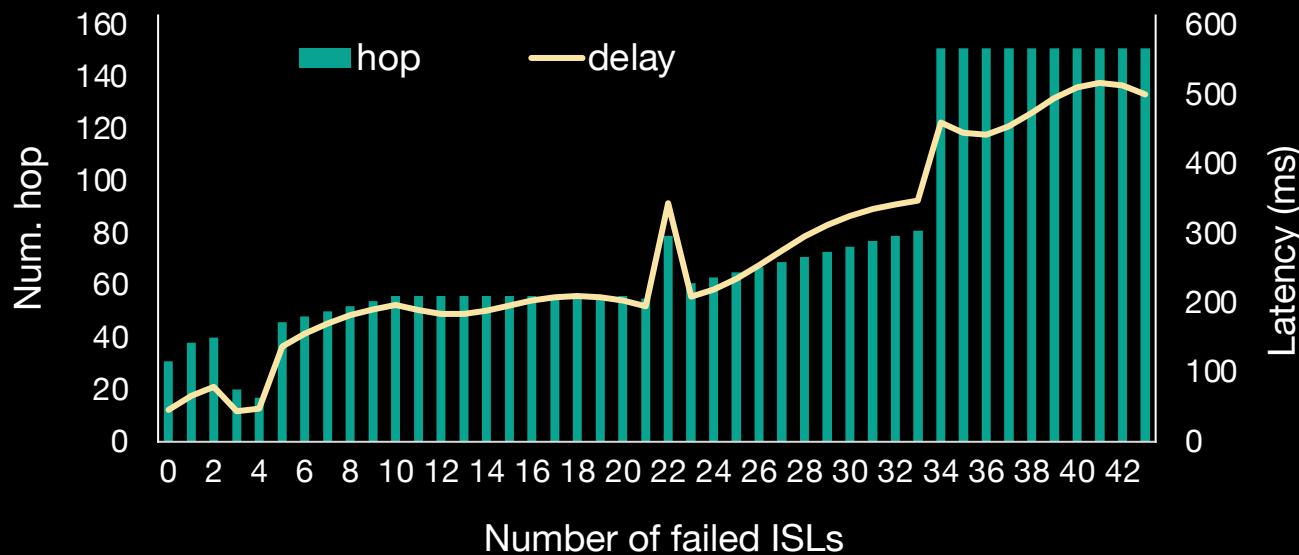


**Near optimal routing**



# 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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# Thank you!

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