Time-Dependent Network Topology Optimization for LEO Satellite Constellations

A dynamic programming approach to create the best topology over a time horizon

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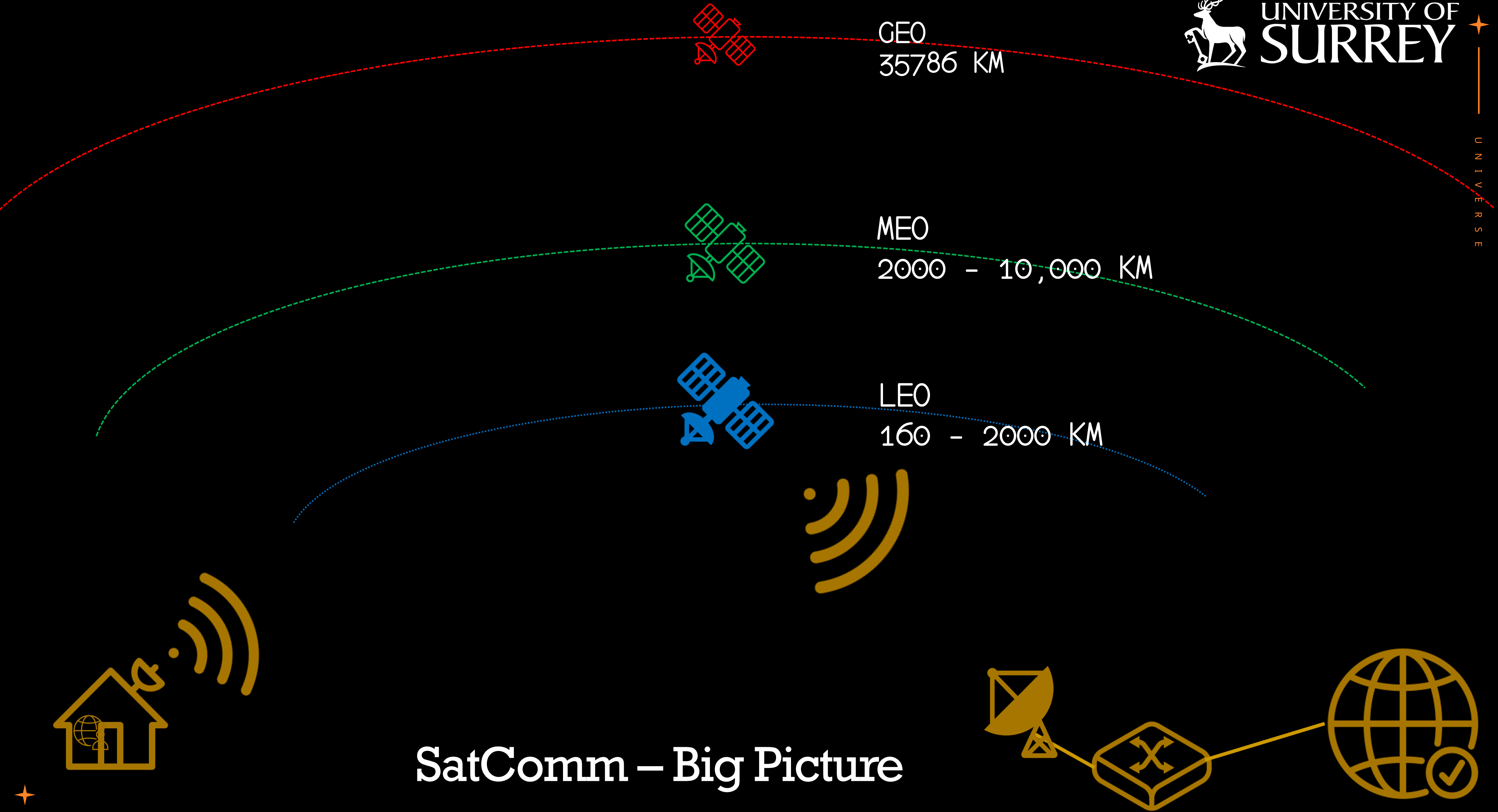

SatComm – Big Picture

The Meteoric Rise of Starlink

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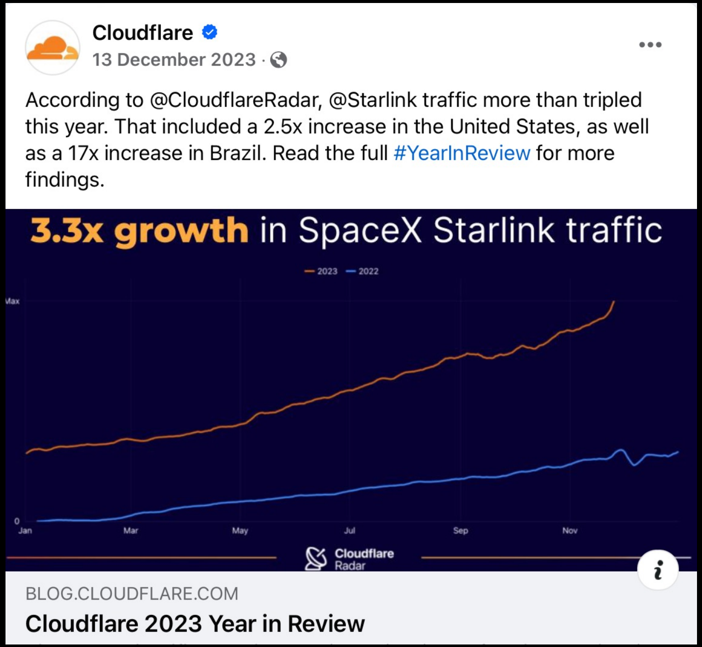
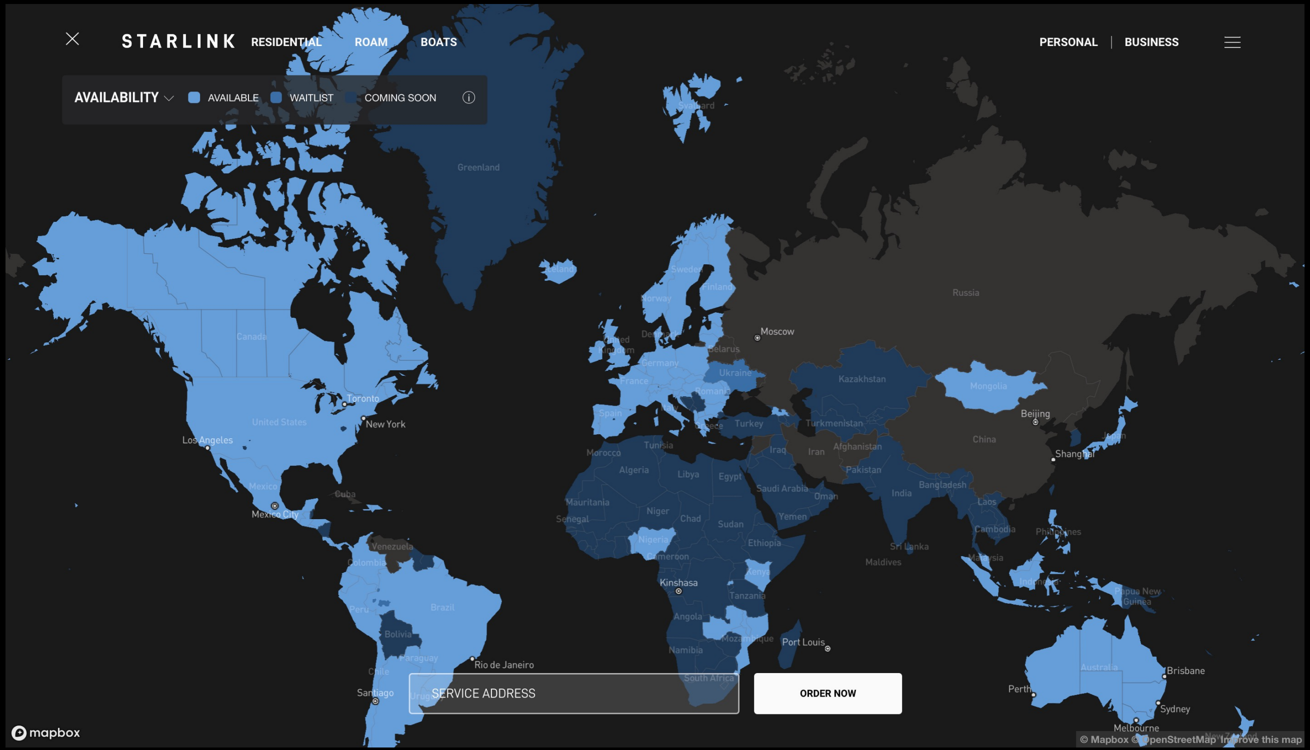


5 Million Subscribers



125 Countries – First truly global ISP

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{L,M,G}EO - What's the difference?

GEOSTATIONARY EARTH ORBIT (GEO)

Orbit: 35,786km
Earth Coverage: Very large (min. 3 satellites required)
Beam footprint size/km: 200-3500
Latency: High (~250 to 500ms)
 # Active: ~541
Usage:

- Mobile Backhaul
- Weather data & Broadcast TV
- HTS technology allow basic MBB

MEDIUM EARTH ORBIT (MEO)

Orbit: 2,000 to 34,000km
Earth Coverage: Large (min. 6 satellites required)
Beam footprint size/km: 100-1000
Latency: Medium (~180ms)
 # Active: ~159
Usage:

- PNT (GNSS, GPS)
- Higher throughput (HTS) Backhaul & data connectivity

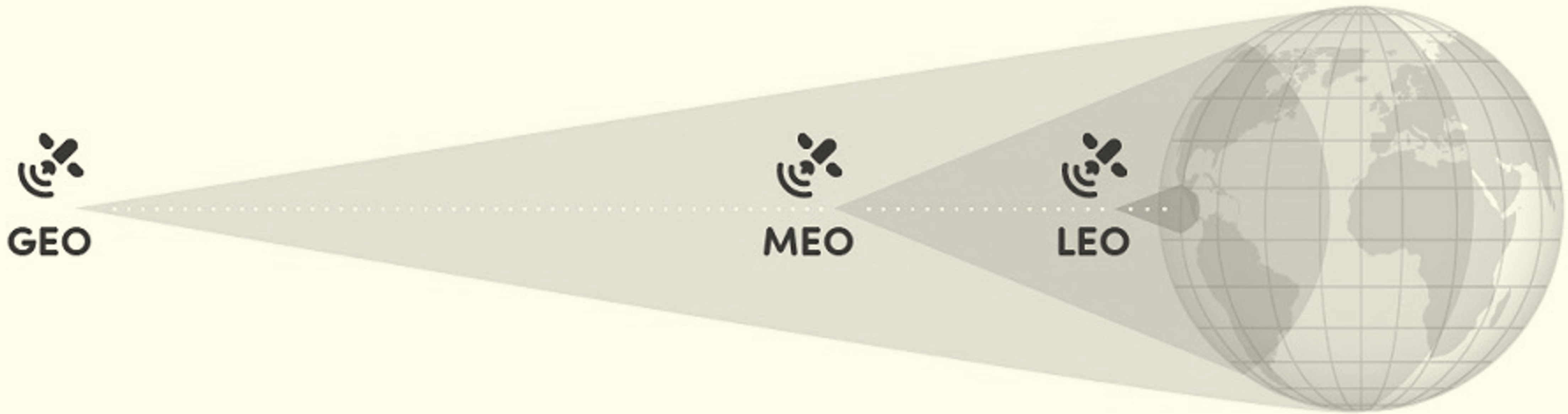
LOW EARTH ORBIT (LEO)

Orbit: 500 to 2000km
Earth Coverage: Small (100-1000 satellites required)
Beam footprint size/km: 100-1000
Latency: Low (~40ms)
 # Active: >3,700
Usage:

- Higher throughput & lower latency data services
- Direct to phone connectivity
- 3D Positioning

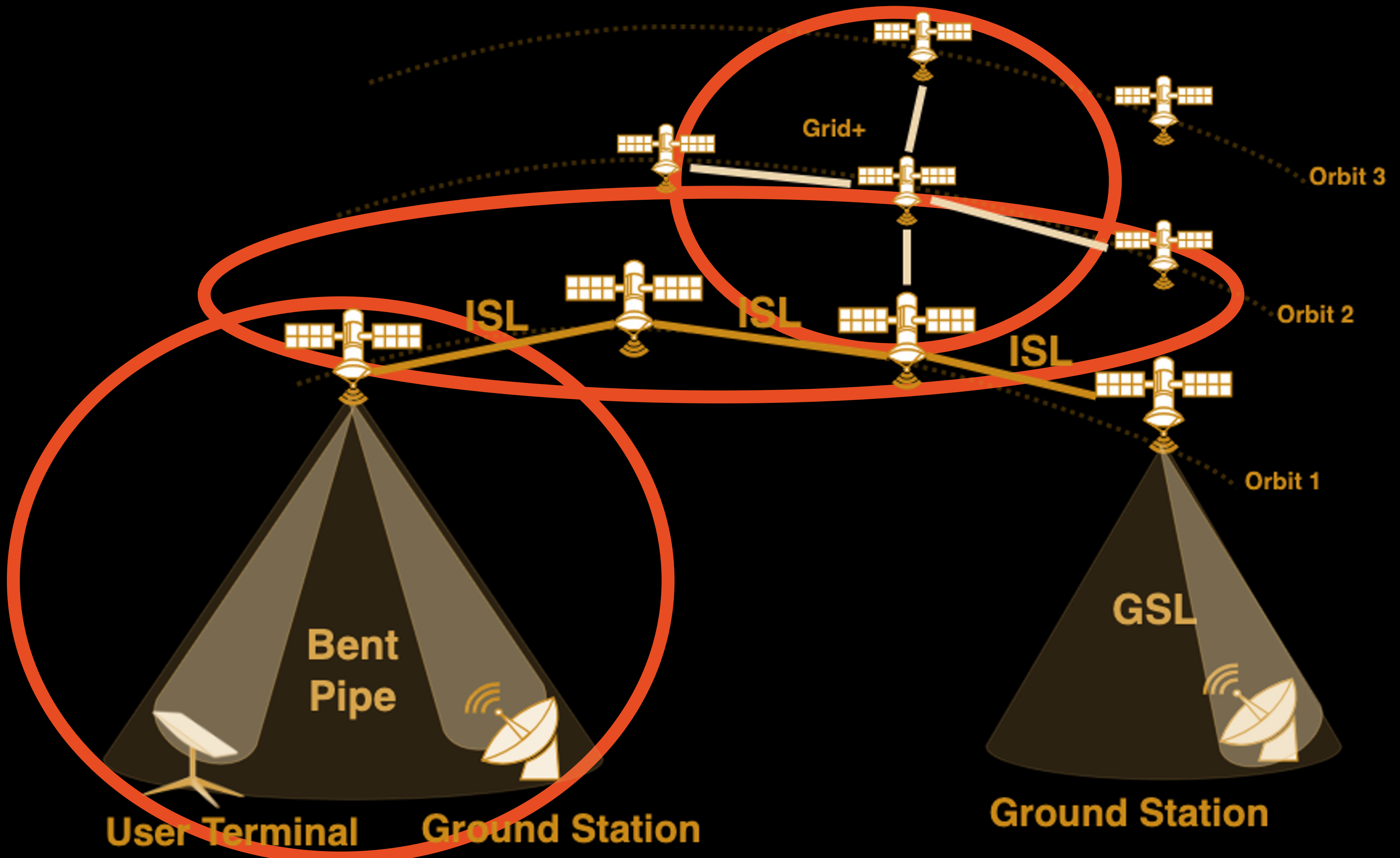
Potential:

- PNT (Relay or Satellite Time and Location [STL])



https://www.spirent.com/blogs/and-just-like-that-phone-to-satellite-connectivity-preps-for-the-masses

Architecture of Starlink & other LEO Mega constellations



+20,000 Satellites will be in Space by 2027

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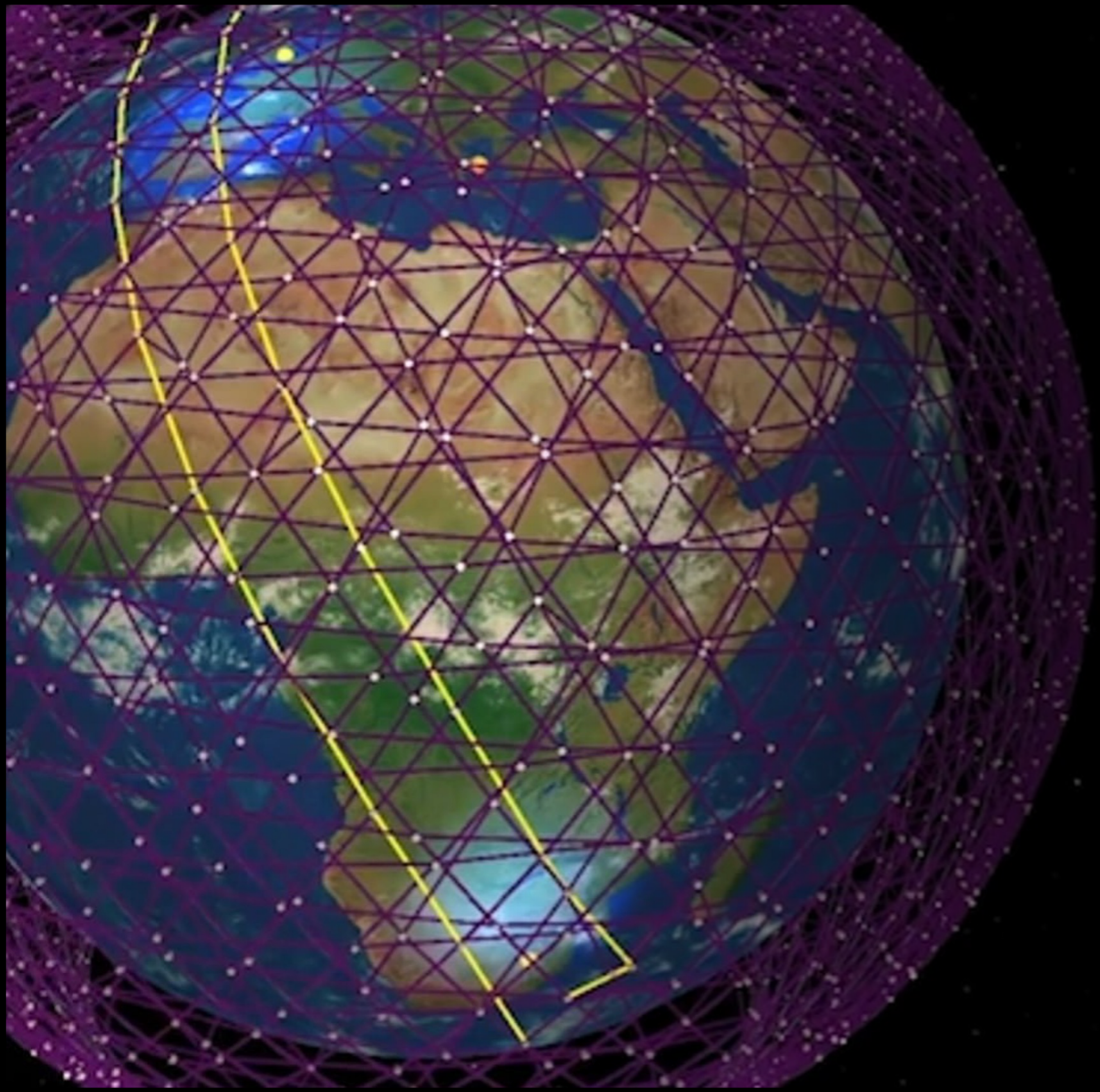


Fast-moving Routers

Traveling at 27,000 KM/h, making the connection with the ground segment ~3-6 mins

Large Scale, Dynamic Network

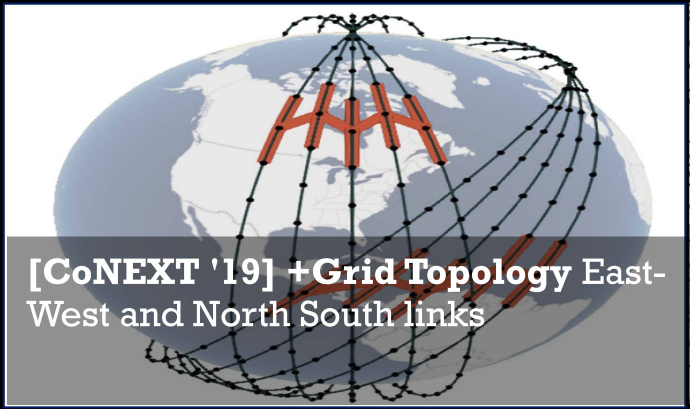
High dynamic network and rapid changes to the network topology

Network Protocols

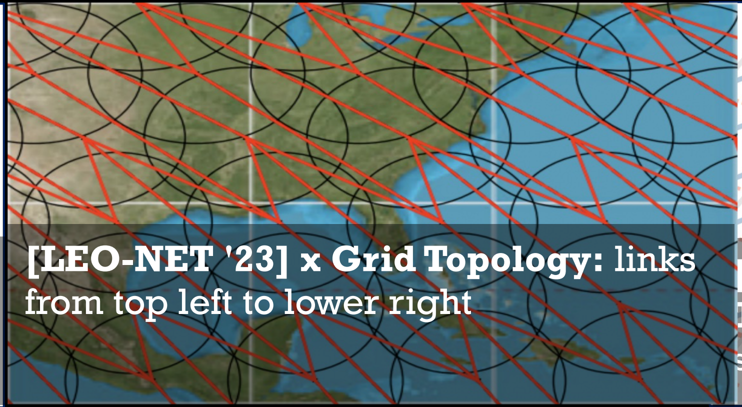
Challenge all our network management, transport and routing protocols

LEO → Unprecedented opportunities Despite challenges

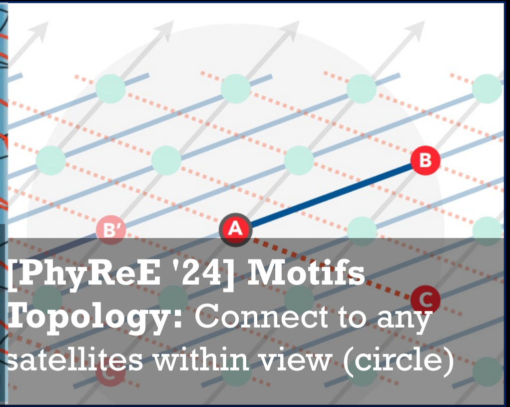
How to construct LEO Topologies?



[CoNEXT '19] +Grid Topology East-West and North South links



[LEO-NET '23] x Grid Topology: links from top left to lower right

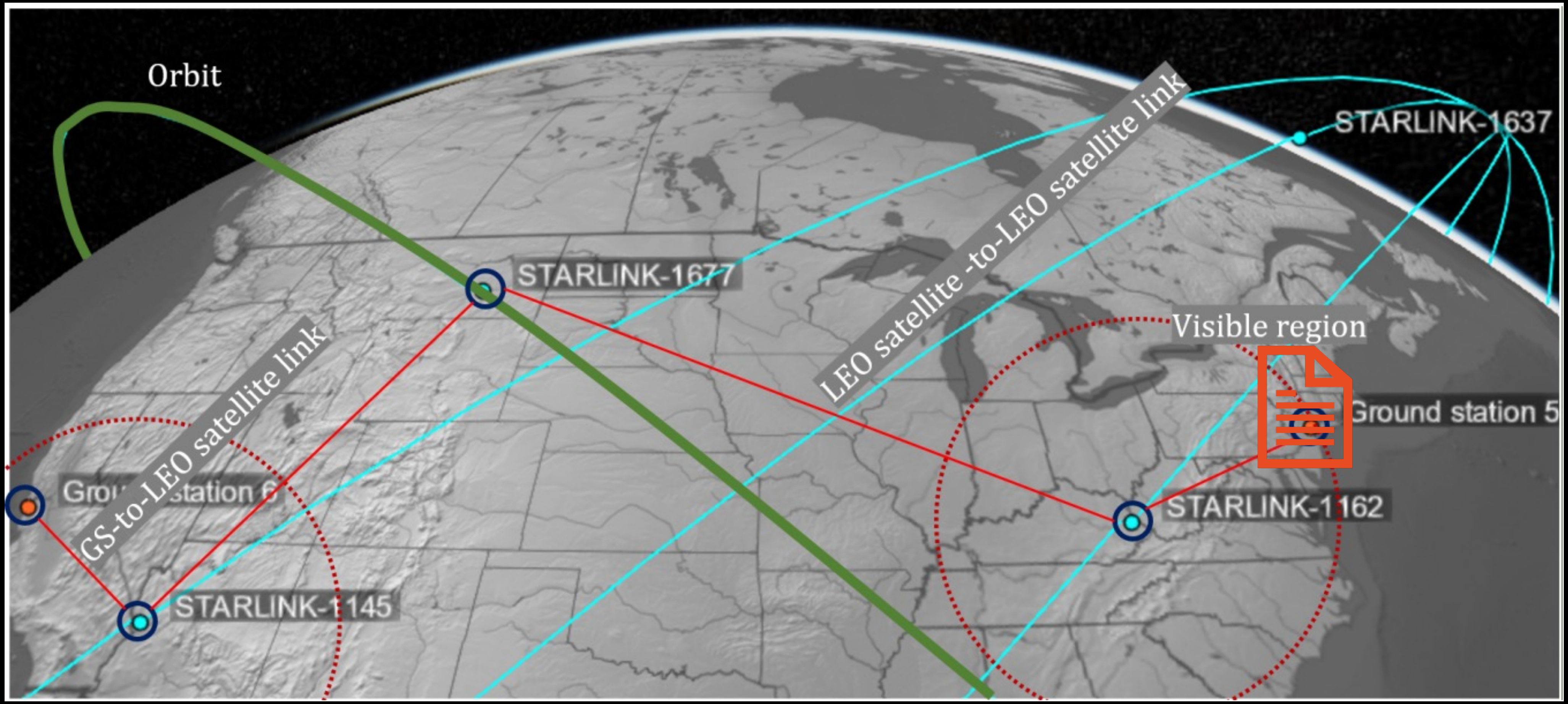


[PhyReE '24] Motifs Topology: Connect to any satellites within view (circle)

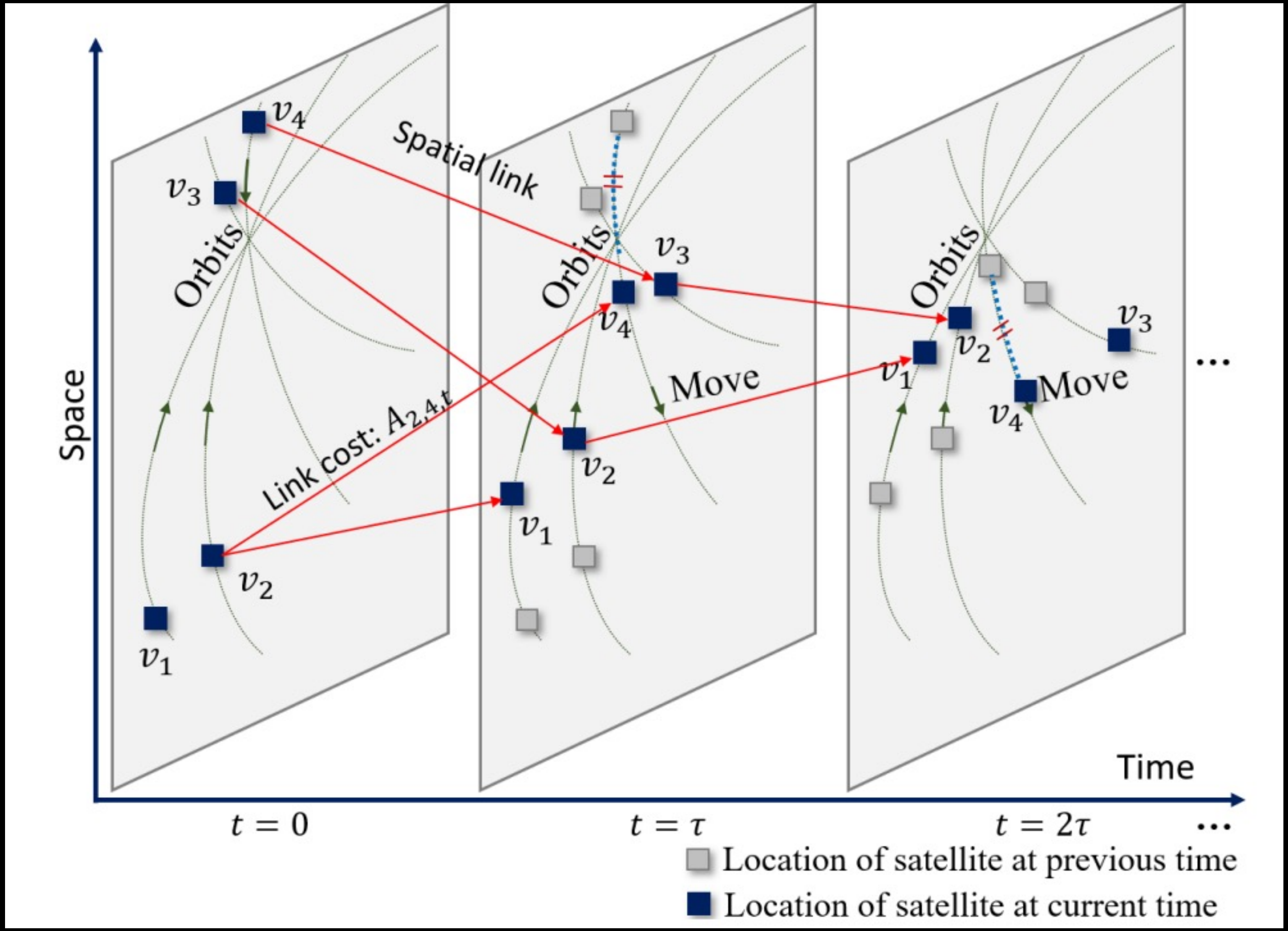
Challenges:

- **Stability requires nearby satellites**
- **Nearby satellites increase hop counts and latency**
- **Neither stability nor hop counts directly maximises capacity**

Challenge: Temporally varying links



Insight: Dynamic Time-Expanded Graphs



Connect satellite to itself (in the past & future) and *U* "**best**" neighbors at each time instant

DP: For "best" topology, choose best link *now* that will yield "best" results over entire time horizon

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Time-Space Optimization Problem: Objective function

$$\textbf{P1:} \max_{\Psi_t} \Big(\sum_{i=1}^{M} \sum_{j=1 \setminus \{i\}}^{M} \phi_{i,j,t} \big(S_{i,j,t} + \frac{1}{L_{i,j,t}} + \phi_{i,j,t-1} \big) \Big)$$

$$\text{s.t. C1: } \sum_{j=1}^{M} \phi_{i,j,t} \le U, \forall i \in \{1, \dots, M\}$$

$$\text{C2: } \phi_{i,j,t} = \phi_{j,i,t}, \forall i,j \in \{1, \dots, M\},$$

$$\text{C3: } \Gamma_{i,j,t} > \Gamma_{Atmosp}, \forall i,j \in \{1, \dots, M\},$$

$$\text{C4: } D_{i,j,t} < D_{Max}, \forall i,j \in \{1, \dots, M\},$$

Network capacity

Link churn

Latency

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Time-Space Optimization Problem: Constraints

$$\textbf{P1:} \max_{\Psi_t}\Big(\sum_{i=1}^{M}\sum^{M}\phi_{i,j,t}\big(S_{i,j,t}+\frac{1}{L}+\phi_{i,j,t-1}\big)\Big)$$

s.t. C1: $\sum_{j}$ …

C2: …

C3: …

$$\text{C4: } D_{i,j,t} < D_{Max}, \forall i,j \in \{1,\ldots,M\},$$

Select optimal subset U links that maximize the objective function and adhere to constraints to construct optimal topology

…ections for each

…U=4 links)

…lex

…ility

C4: Max communication range

Transforming the optimization problem - 1

Different objectives not directly comparable. Normalize capacity, latency, & link churn

$$\bar{S}_{i,j,t} = \frac{S_{i,j,t}}{S_{\text{Max},t}}; \bar{L}_{i,j,t} = \frac{L_{i,j,t}}{L_{\text{Max},t}}; \bar{\phi}_{i,j,t} = \frac{\phi_{i,j,t}}{U},$$

Scoring function to update the maximum capacity and latency achievable at each time step t:

$$g_{\text{Max},t} = \max\{g_{\text{Max},t-1}, \max_{i\in\mathcal{M},j\in\mathcal{M}}(\mathbf{1}_{\{\Gamma_{i,j,t}>\Gamma_{Atmosp}\}}\mathbf{1}_{\{D_{i,j,t}<D_{Max}\}}g_{i,j,t})\}, \quad (12)$$

$g_{\text{Max},t} \in \{S_{\text{Max},t}, L_{\text{Max},t}\}$, and $\mathcal{M}$ is the set of satellites.

Note that U is fixed so does not need updating

Lemma III.1. *The time-dependent maximum value $g_{Max,t}$ defined in Eq. 12 is the achievable maximum capacity, latency, and link churn, denoted by g, up to time t.*

Transforming the optimization problem - 2

Write down link cost which normalizes the objective function

$$A_{i,j,t} = w_1 \bar{S}_{i,j,t} + w_2(1 - \bar{L}_{i,j,t}) + (1 - w_1 - w_2)\bar{\phi}_{i,j,t-1}, \quad (13)$$

$w \in \{w_1, w_2, 1 - w_1 - w_2\}$ **are the weights**

Using this, write down a score update rule for each time step:

$$\Pi_{i,t} = \frac{1}{U} \sum_{j=1\backslash\{i\}}^{M} \phi^*_{i,j,t} \left(A_{i,j,t} + \Pi_{j,t-1}\right). \quad (16)$$

$$\phi^*_{i,j,t} = \underset{l \in \mathcal{M}}{\operatorname{argmin}}(\{\alpha_{i,l,t} | (\sum_{k=1}^{M} \phi^*_{i,k,t} < U \cap \sum_{k=1}^{M} \phi^*_{j,k,t} < U)\})$$

Lemma III.2. *The update rule of the score function in (Eq. 16) remains finite even as the observation time approaches infinity:* $\Pi_{i,t} < \infty, T \rightarrow \infty$.

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SpaceNet: Demo

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Experimental Results

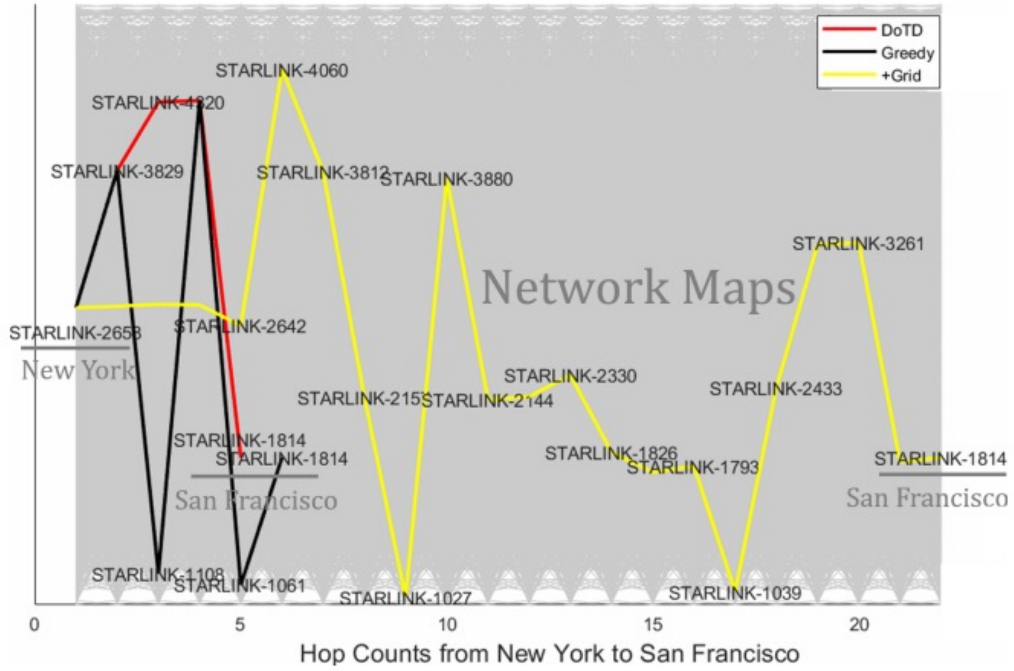


Fig. 4: Network maps created by DTEG, Greedy, and +Grid: Packets traveling from New York to San Francisco.

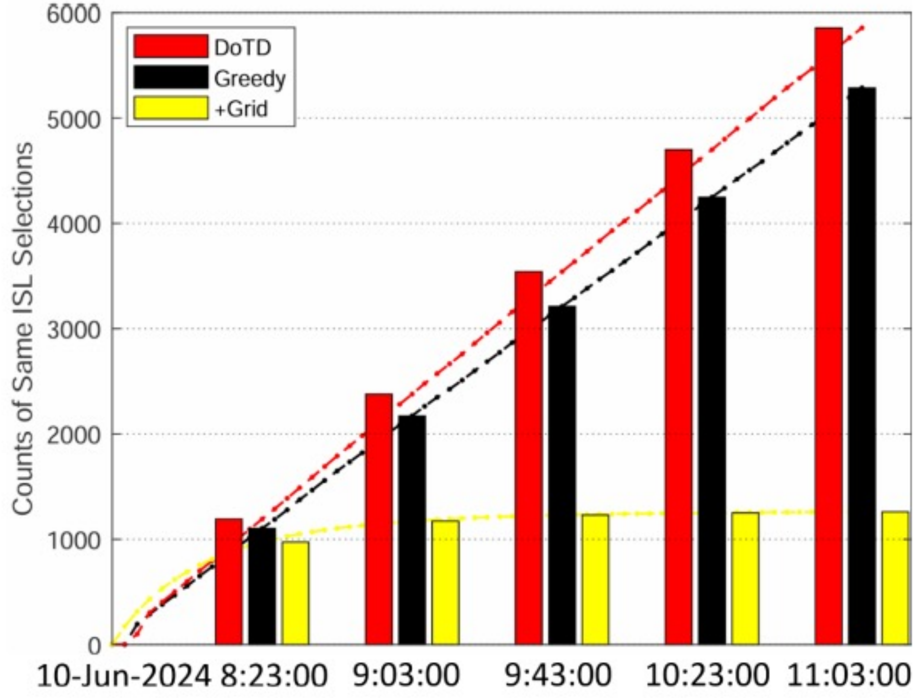


Fig. 6: Counts the number of ISL selections that are the same

Experimental Results

TABLE II: GS deployments on Earth using GCS

Scenarios	**Sources**	Latitudes	Longitudes	**Destinations**	Latitudes	Longitudes
S1	Sydney	−33.865143	151.209900	Darwin	−12.46	130.84
S2	Miami	25.761681	−80.191788	Calgary	51.049999	−114.066666
S3	New York	40.730610	−73.935242	Miami	25.761681	−80.191788
S4	New York	40.730610	−73.935242	San Francisco	37.773972	−122.431297
S5	Phnom Penh	11.562108	104.888535	Kathmandu	27.700769	85.300140

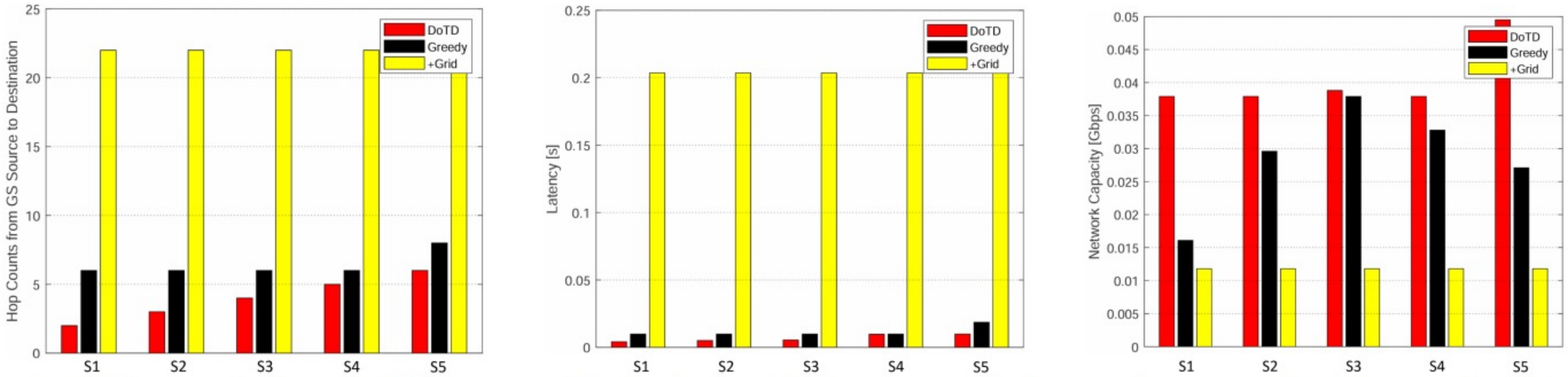
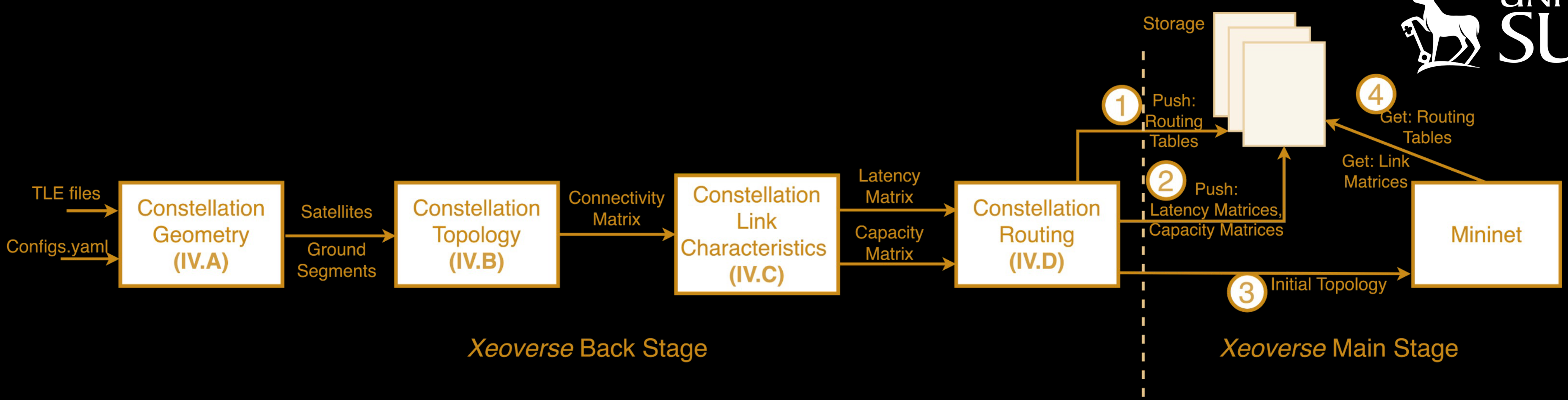


Fig. 5: (a) Hop counts from the GS source to the destination, (b) Latency evaluation, (c) Average achievable capacity of each link, under five different scenarios in TABLE II.



XEOVERSE "DIGITAL TWIN" (SIMULATOR)

Scalable,

Responsive,

High fidelity,

Low-footprint

Simulation of LEO/MEO/GEO (mega)constellations

IFIP Networking'24

University of Surrey

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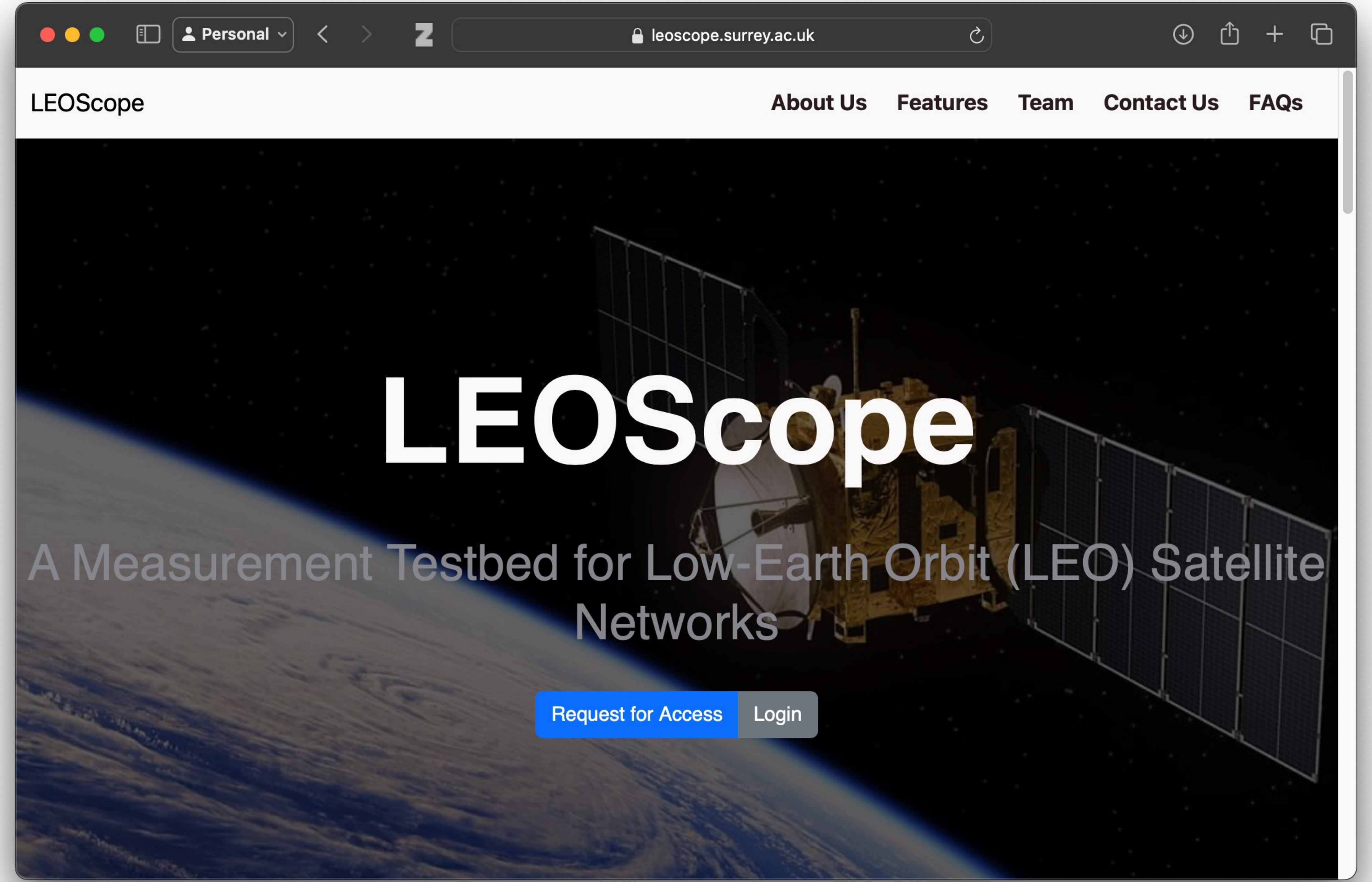
Leoscope: Measurement using Volunteer Nodes

AKA "Planetlab for Starlink"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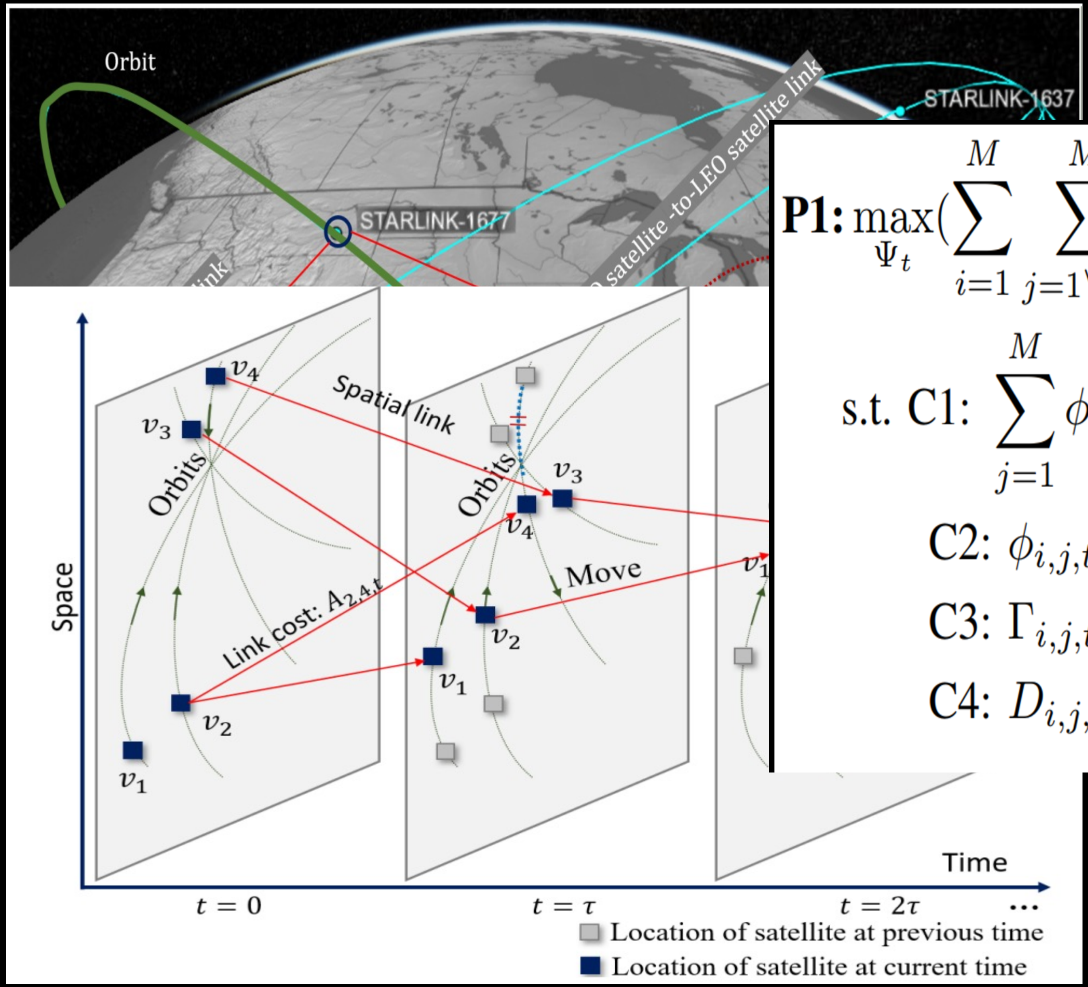
You can host a node too!
WiFi Router
(Optional)
Starlink Router
Power Supply
30 CM
ETH Bridge
Banana CM
RIPE

Summary



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Network capacity

Link churn

Latency

Thank you

☺

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