QoS-Aware Resource Placement for LEO Satellite Edge Computing

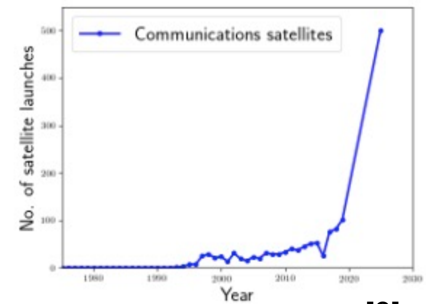
Tobias Pfandzelter, David Bermbach | Mobile Cloud Computing | ICFEC '22

LEO Satellites

NASA awards millions to SpaceX and Amazon's Project Kuiper for satellite communications

BY ALAN BOYLE on April 20, 2022 at 3:24 pm

https://www.geekwire.com/2022/nasa-awards-millions-to-spacex-and-amazons-project-kuiper-for-satellite-communications/



[8]

Arianespace Soyuz rocket launches 34 OneWeb internet satellites into space

By Mike Wall published August 22, 2021

Arianespace has now lofted a total of 288 OneWeb satellites.

https://www.space.com/arianespace-sozyuz-launches-oneweb-9-internet-satellite-mission

INVESTING IN SPACE

About 150,000 people in Ukraine are using SpaceX's Starlink internet service daily, government official says

PUBLISHED MON, MAY 2 2022·12:03 PM EDT | UPDATED MON, MAY 2 2022·1:25 PM EDT

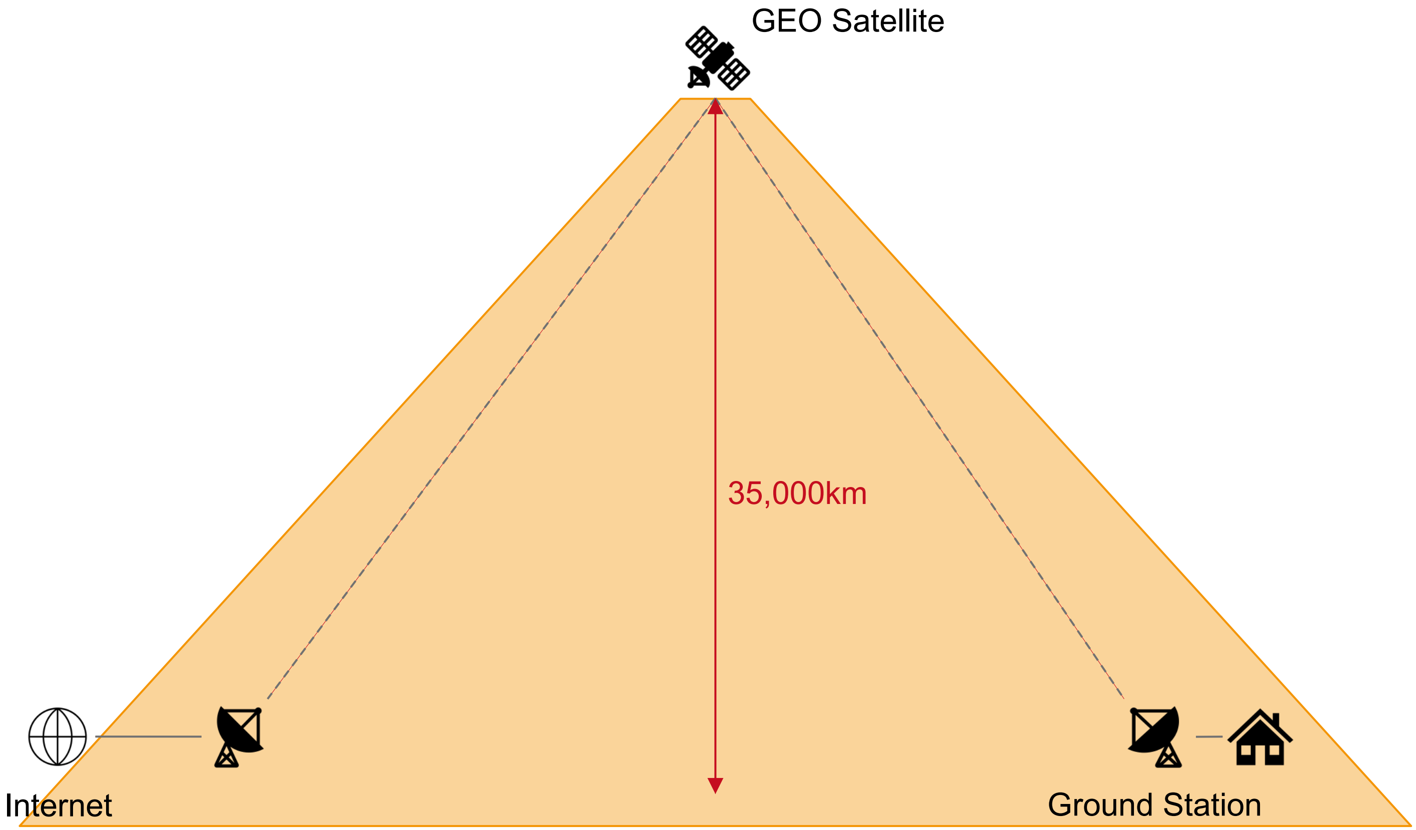
https://www.cnbc.com/2022/05/02/ukraine-official-150000-using-spacexs-starlink-daily.html

SpaceX deploys more Starlink satellites, aims for higher launch cadence

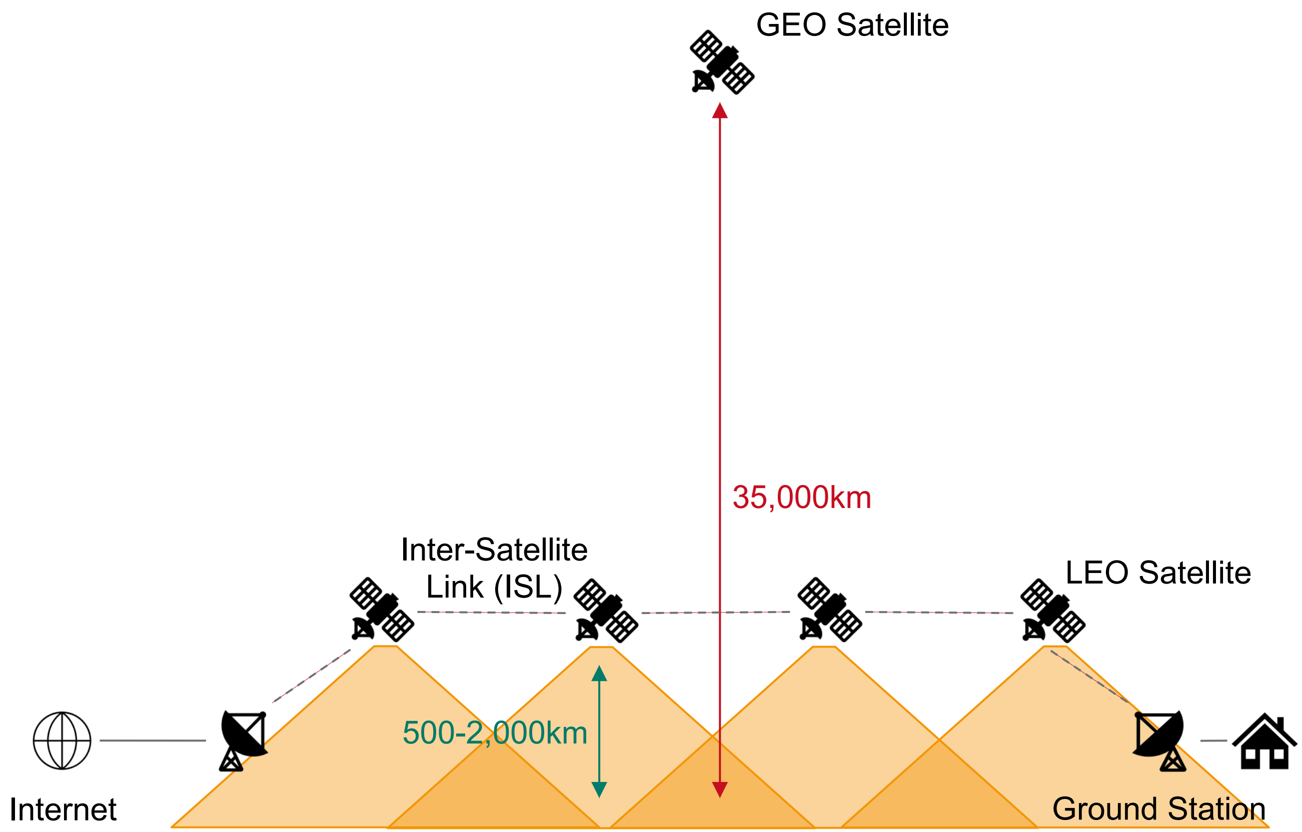
April 21, 2022 Stephen Clark

https://spaceflightnow.com/2022/04/21/spacex-deploys-more-starlink-satellites-aims-for-higher-launch-cadence/

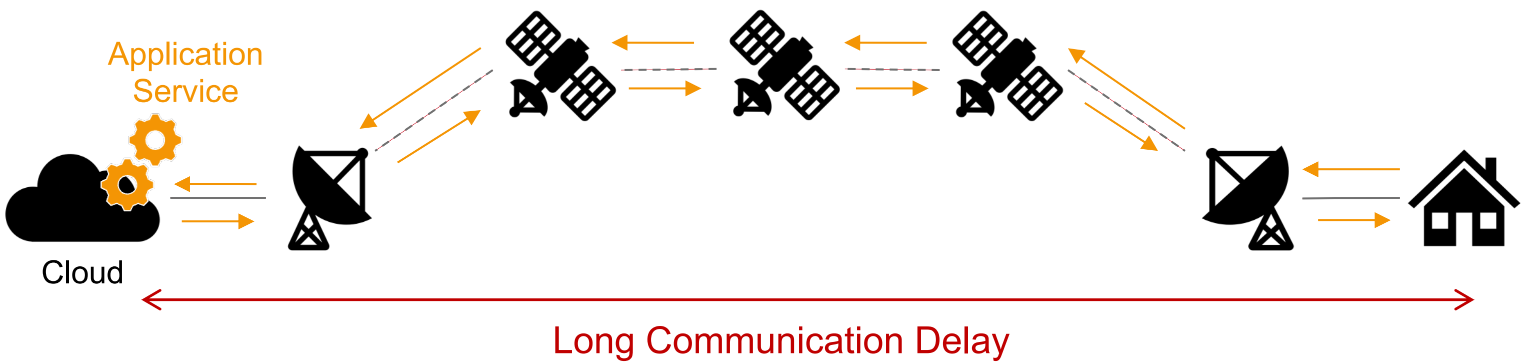
LEO Satellites



LEO Satellites



LEO Satellite Edge Computing



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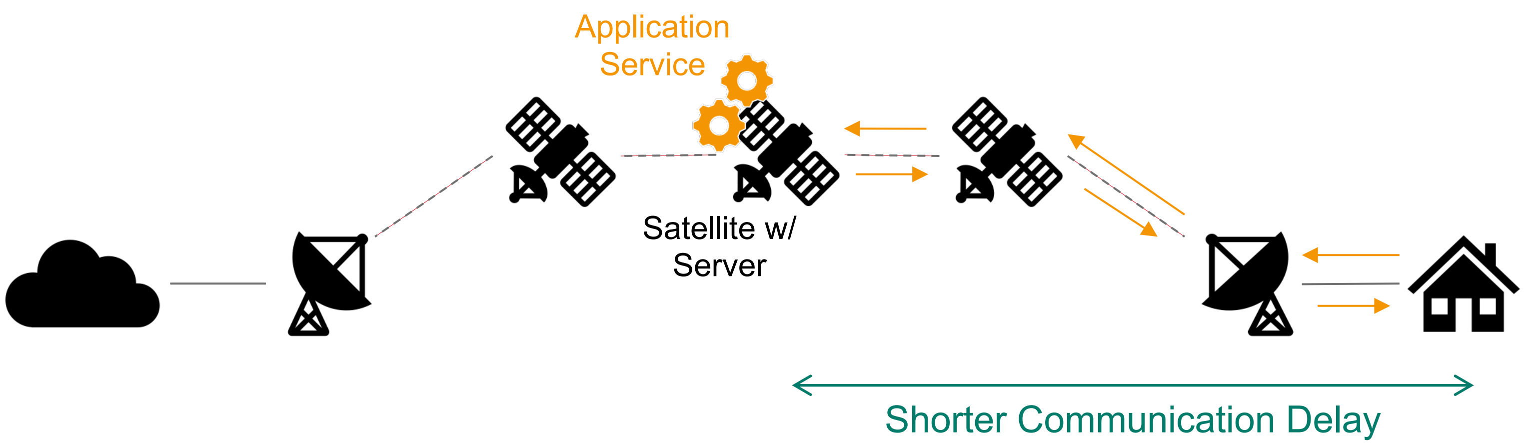
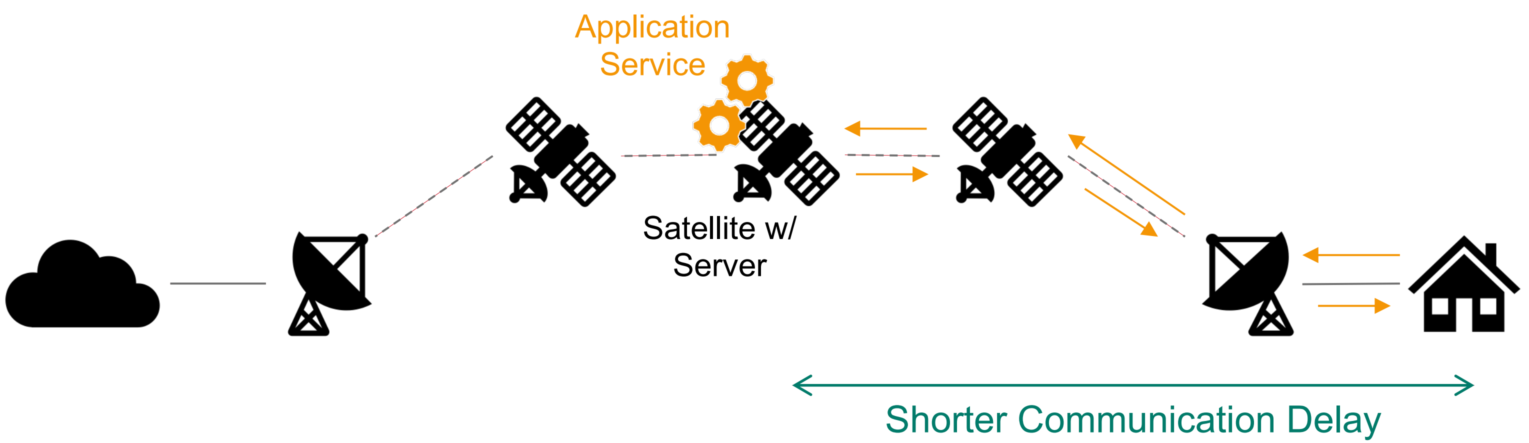


[7] D. Bhattacherjee, S. Kassing, M. Licciardello, and A. Singla, "In-orbit computing: An outlandish thought experiment?" in *Proceedings of the 19th ACM Workshop on Hot Topics in Networks (HotNets 2019)*, Nov. 2020, pp. 197–204.

LEO Satellite Edge Computing



Where do we allocate servers?

Opportunities for Resource Placement

- Server Allocation
- Data Replica Allocation
- Cache Node Placement
- Application Service Replication
- …

LEO Satellite Edge Computing

Where do we allocate servers?

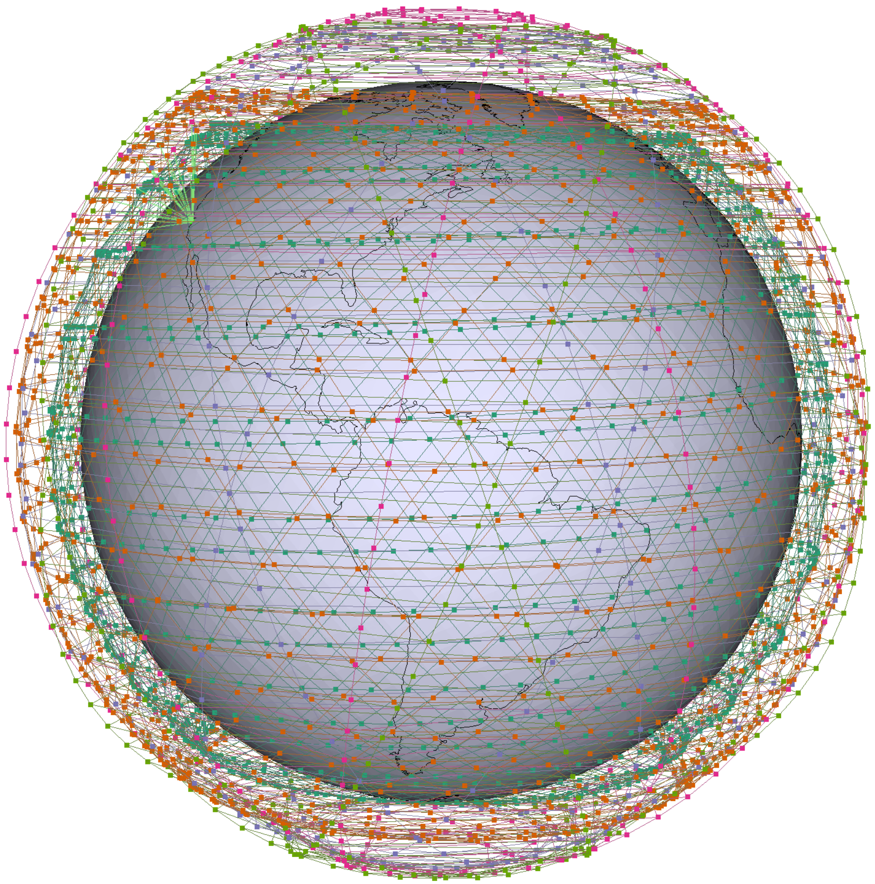
At every satellite?

Starlink Phase I Constellation

- 4,409 satellites in five “shells”
- Walker Delta constellation
- Each shell is independent
- 4,409 satellite servers is a large upfront investment

Altitude in km	Planes	Nodes per Plane	Orbital Inclination	Color
550	72	22	53°	turquoise
1,110	32	50	53.8°	orange
1,130	8	50	74°	purple
1,275	5	75	81°	pink
1,325	6	75	70°	green

[12]



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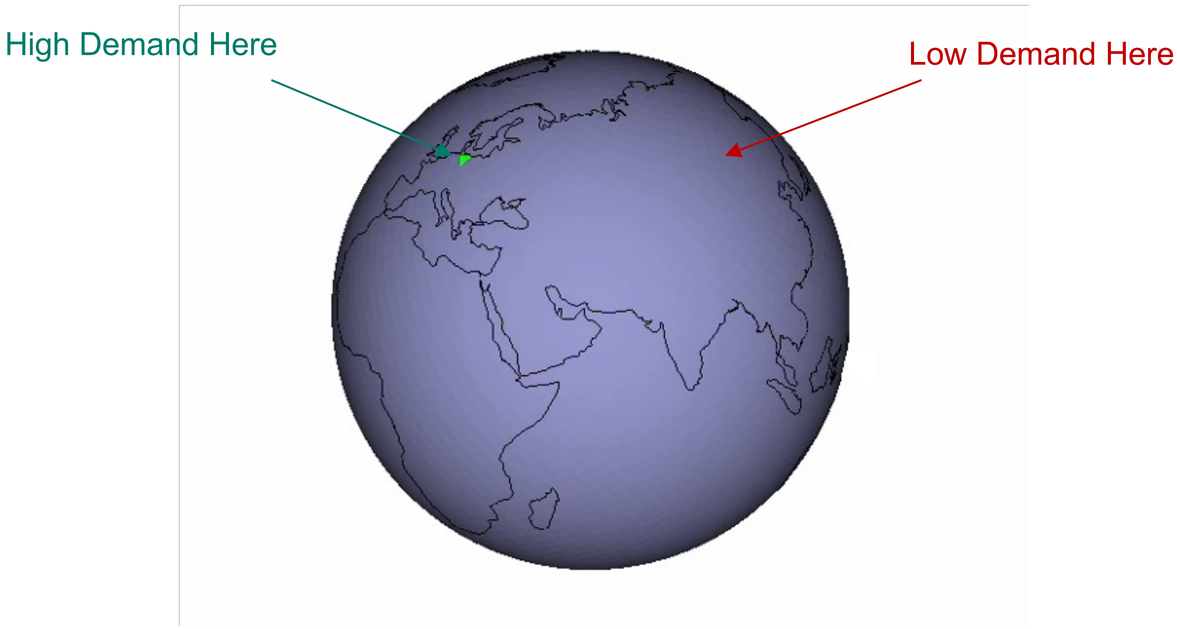
LEO Satellite Edge Computing

Where do we allocate servers?

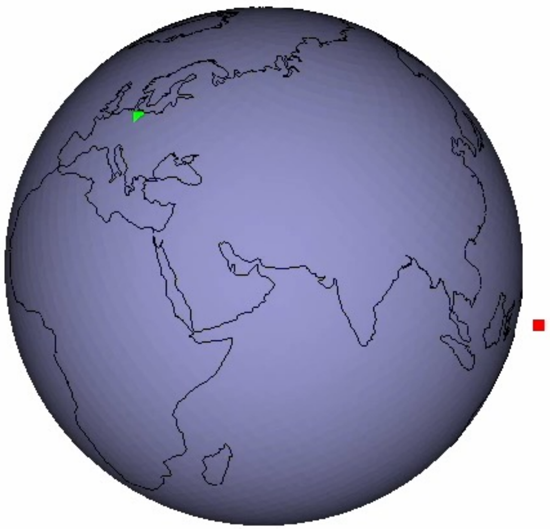
~~At every satellite?~~

Where demand is?

LEO Satellite Mobility

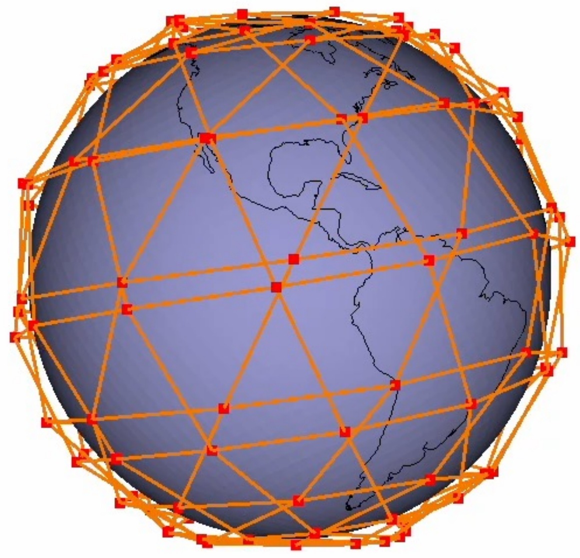


LEO Satellite Mobility



550km Orbit → 95 minute orbital period

LEO Satellite Mobility



LEO Satellite Edge Computing

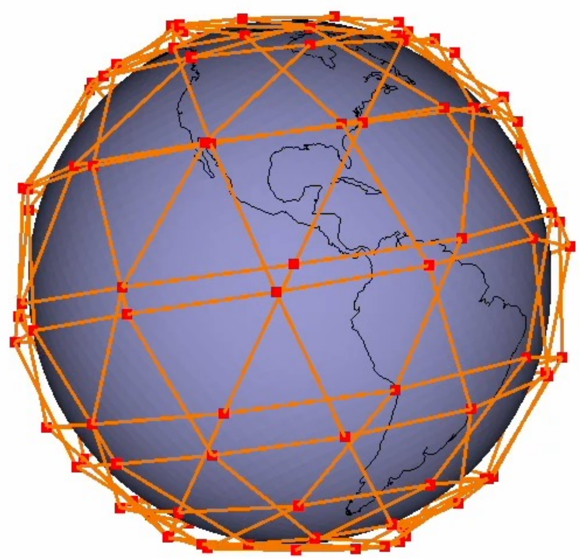
Where do we allocate servers?

~~At every satellite?~~

~~Where demand is?~~

Evenly across the constellation

LEO Satellite Network Topology



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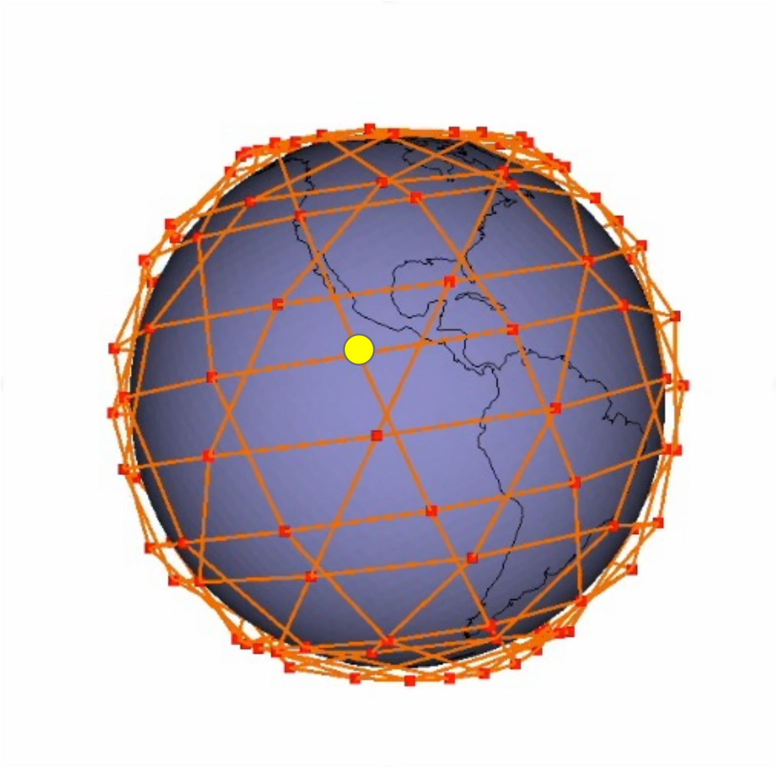

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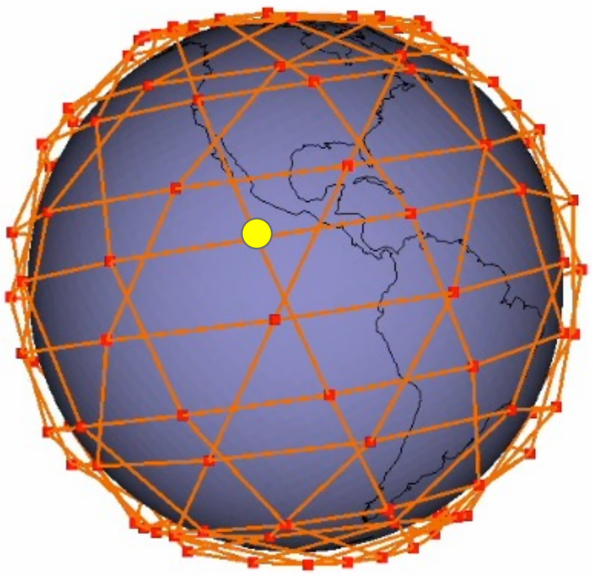

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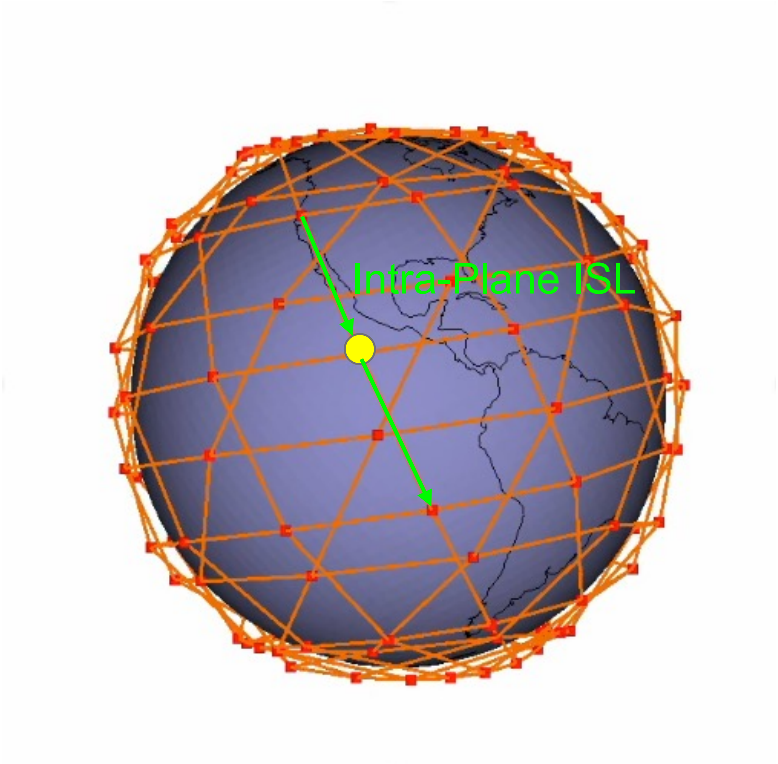

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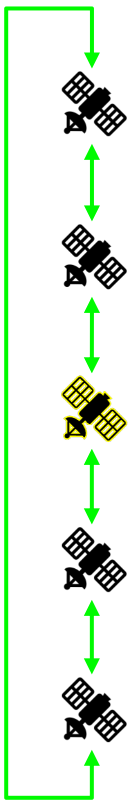

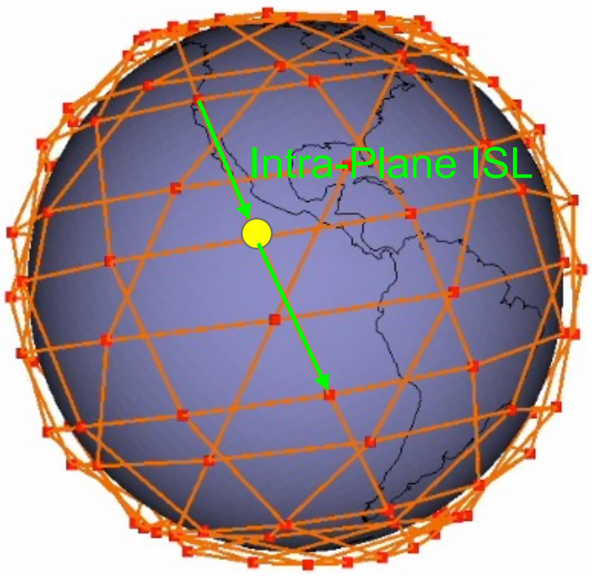

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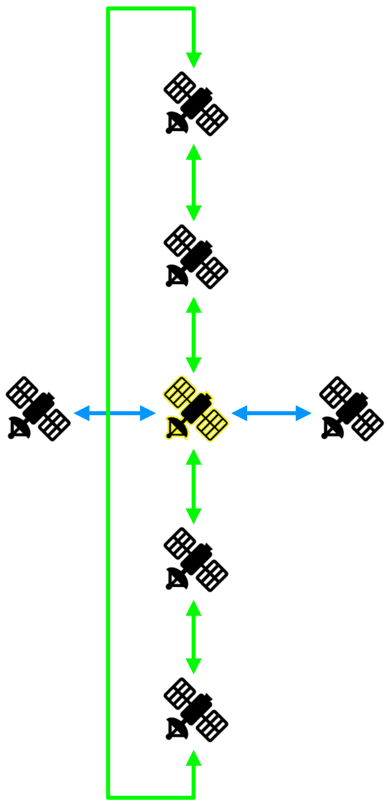

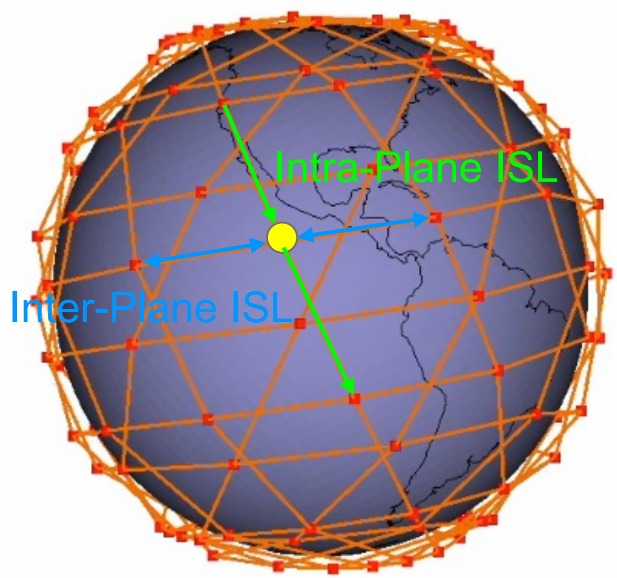

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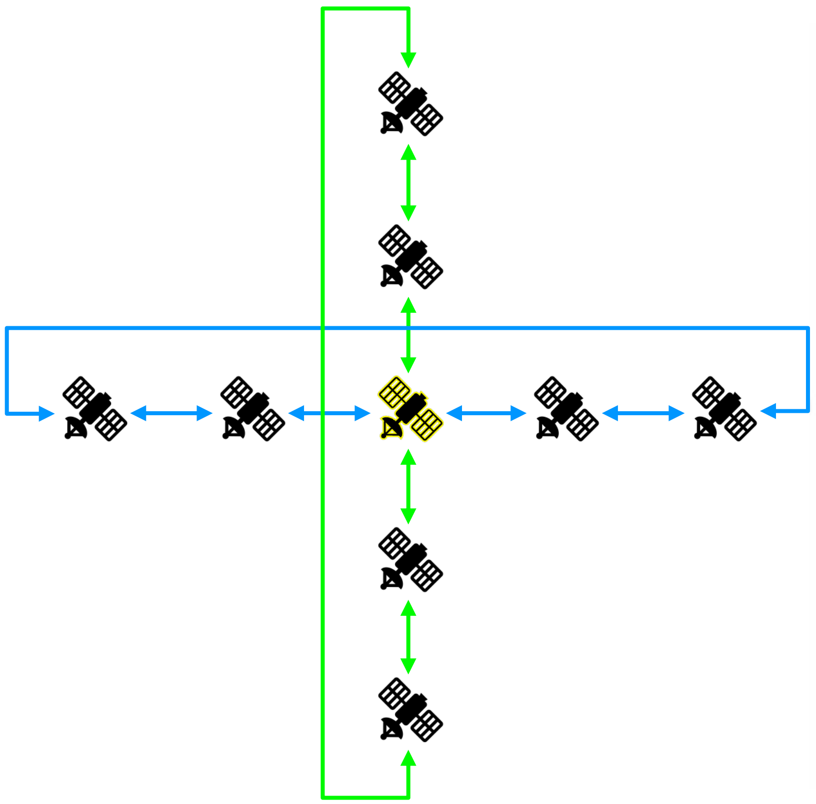

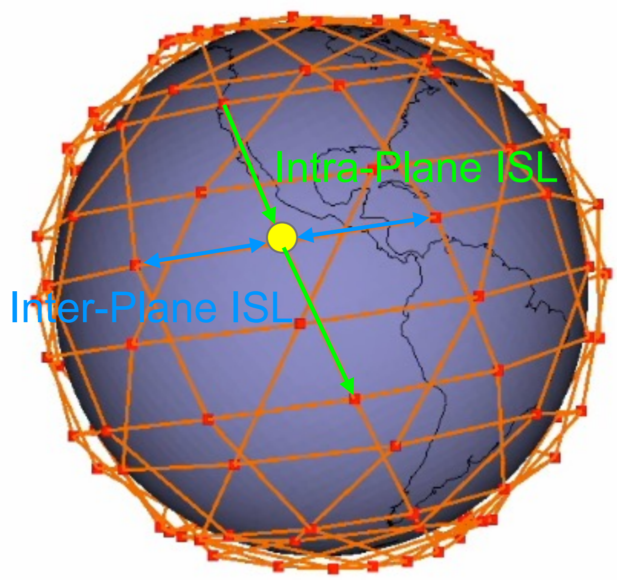

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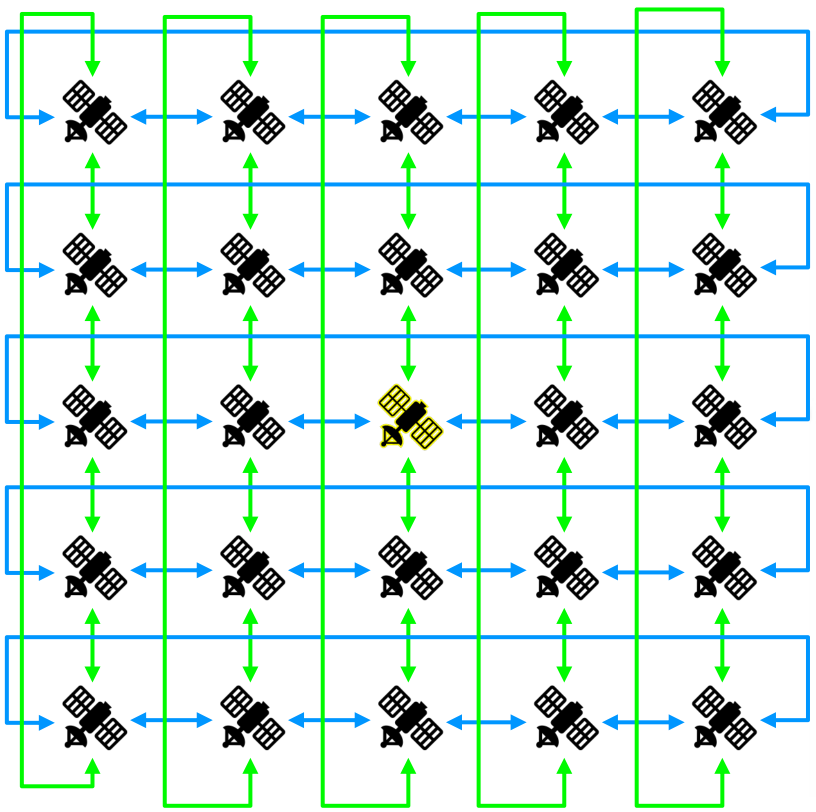

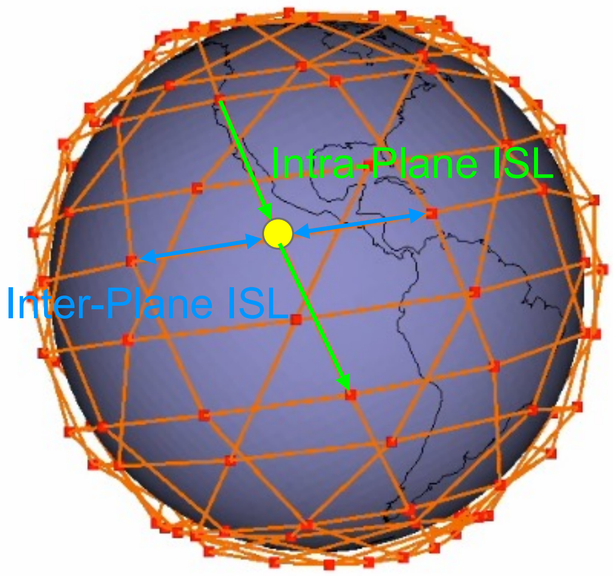

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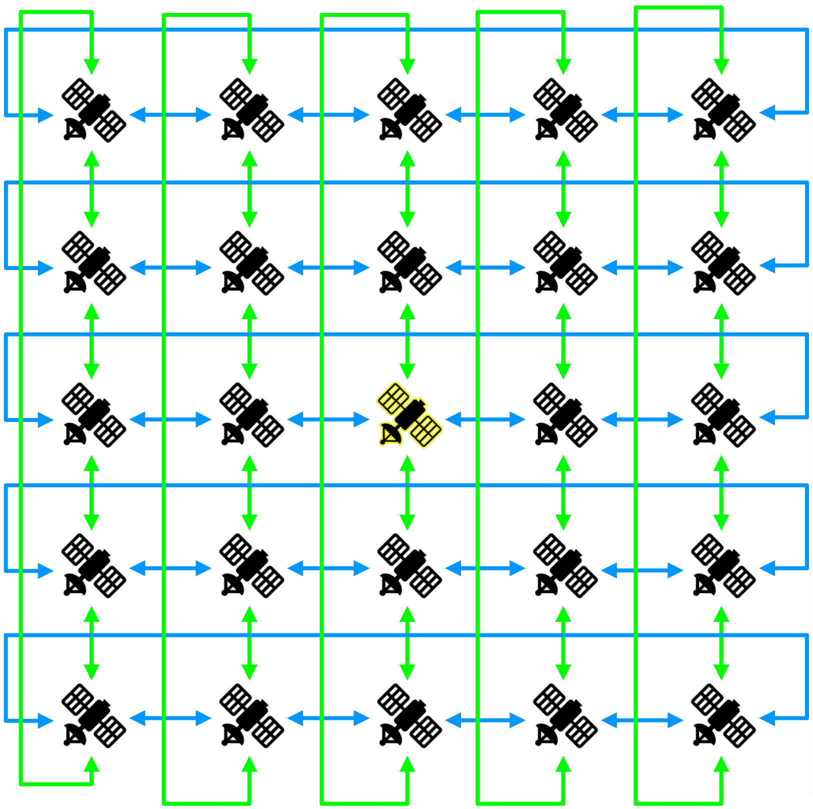

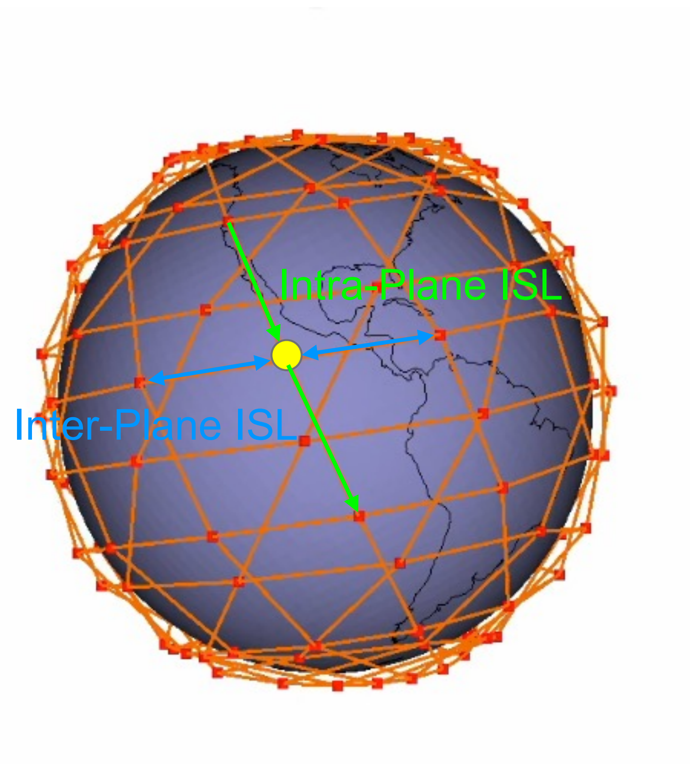

= 2D Torus

Resource Placement on 2D Tori

- Well-studied problem
- Had some grid/cluster computing applications in the 1990s
- Considers the discrete „hop“ distance metric
- Bae [27], Albdaiwi and Livingston [28], Bae and Bose [29] propose solutions based on Lee error correcting codes
- „Perfect“ solutions exist under some constraints
- Non-perfect solutions exist for all tori

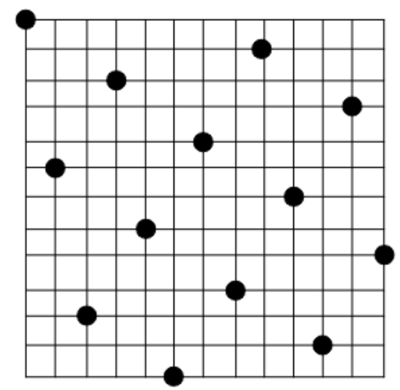

Figure 1. A perfect distance-2 placement in a 13×13 torus (wraparound edges not shown).

[27]

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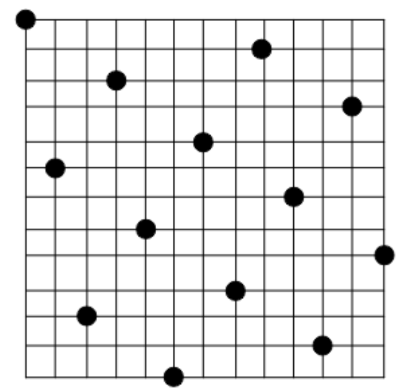

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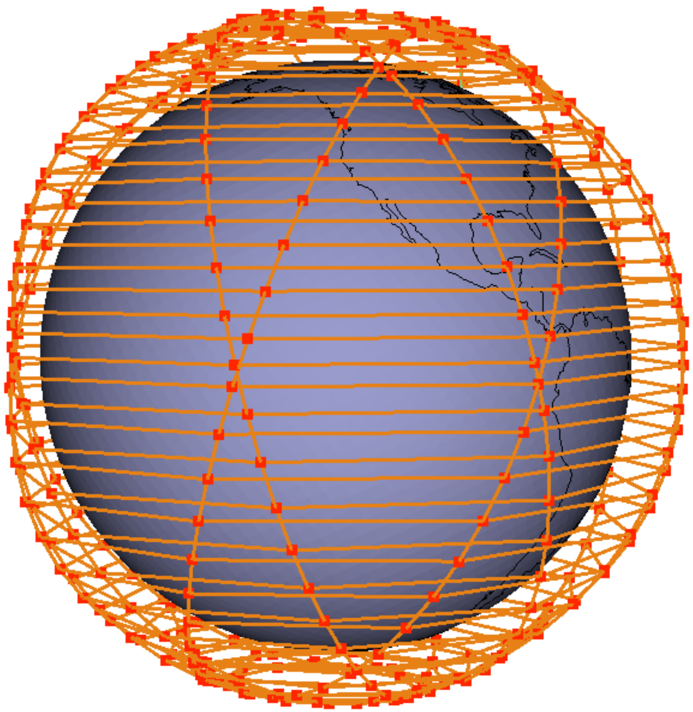
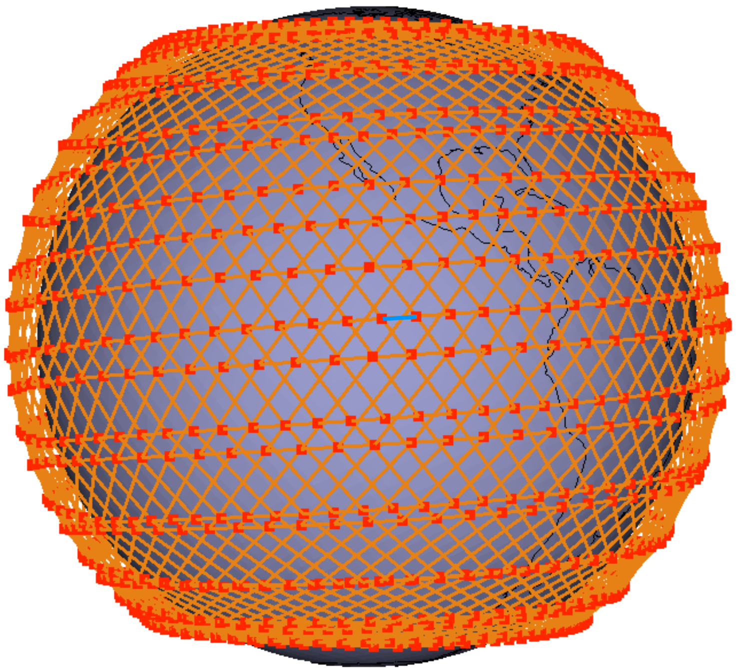
The Issue with Discrete Distances: Two Starlink Shells



Planes (N): **8**
Nodes/Plane (M): **50**
Altitude: **1,130km**
Inclination: **74°**



Planes (M): **72**
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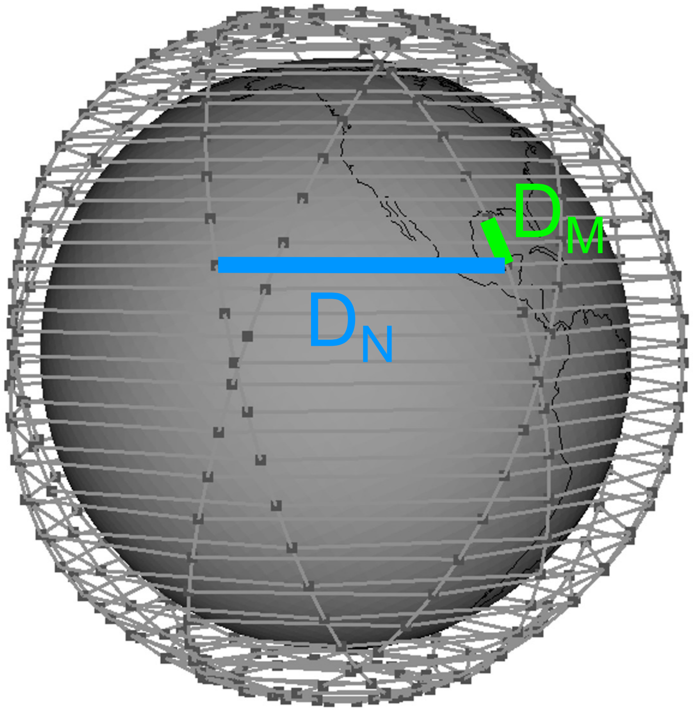

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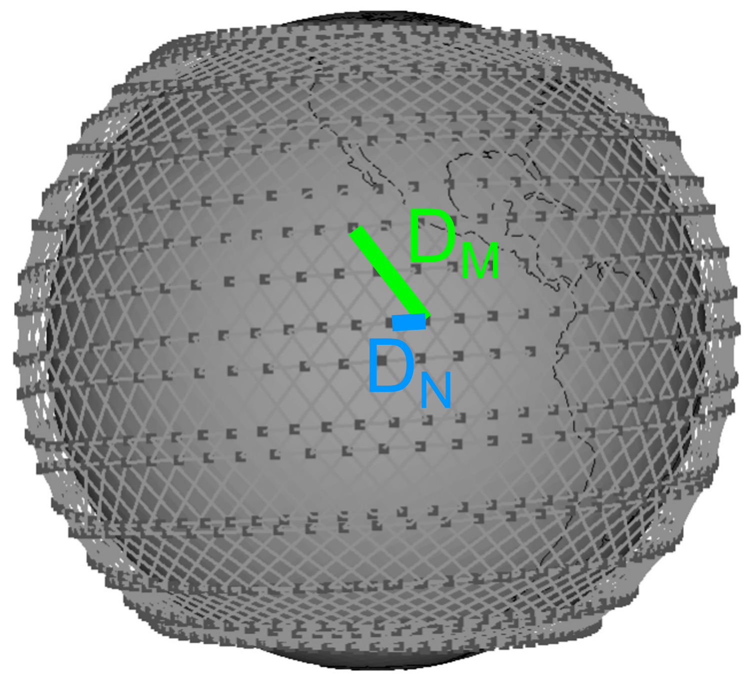

Planes (M): **72**
Nodes/Plane (M): **22**
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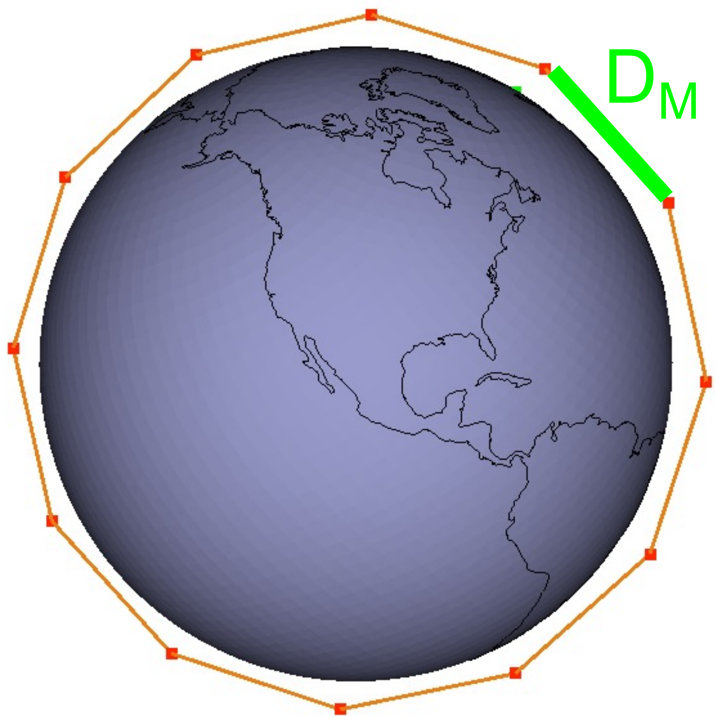
Calculating the Distances

- D_M is easy as satellites are evenly spaced along their orbit

$$D_M = (\underbrace{r_E}_{\text{Earth Radius}} + \overbrace{h}^{\text{Altitude}})\sqrt{2(1-\cos(\frac{2\pi}{M}))}$$

* assuming the Earth is a sphere



Calculating the Distances

- D_N changes over time
- Can only use aggregate distances
- *Maximum* distance gives upper limit

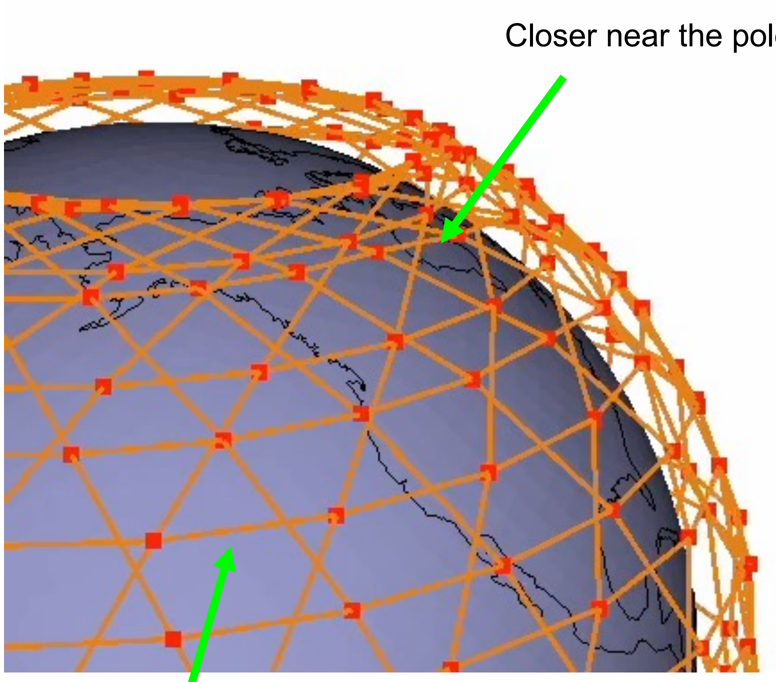
$$D_N^{\max} = \max_{t \in [0,T]} D_N = (r_E + h)\sqrt{2(1 - \cos(\frac{2\pi}{N}))}$$

- *Mean* distance gives a closer approximation of effects observed over time

$$\bar{D}_N = \frac{1}{T}\int_0^T D_N(t)dx$$
$$= \frac{2}{\pi}(r_E + h)\sqrt{2(1 - \cos(\frac{2\pi}{N}))}E(1 - \cos^2(i))$$

* assuming the Earth is a sphere

Closer near the poles

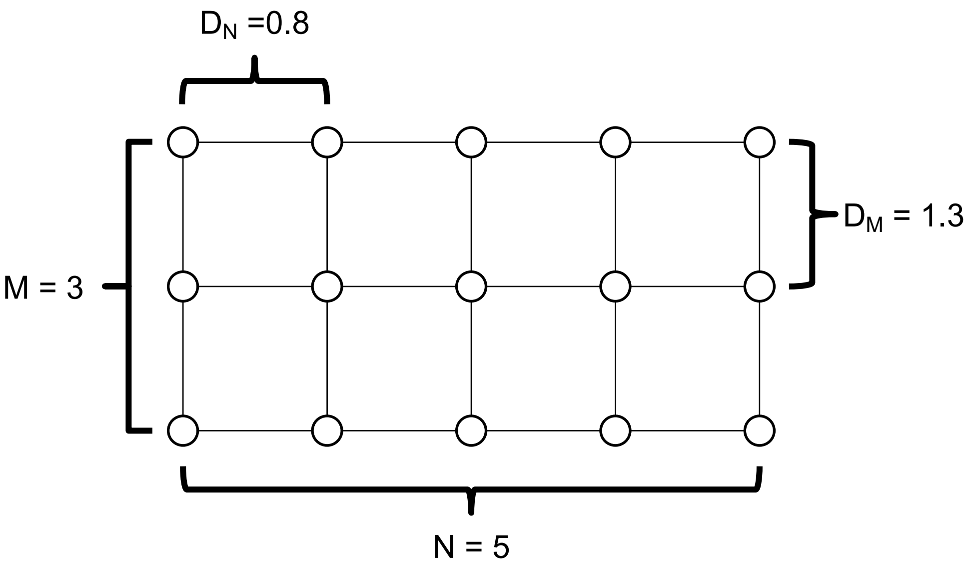


Further apart here

Integrating Real Distances

Example: 5x3 torus

- $N = 5$
- $M = 3$
- $D_N = 0.8$
- $D_M = 1.3$
- Target distance $d = 1.4$



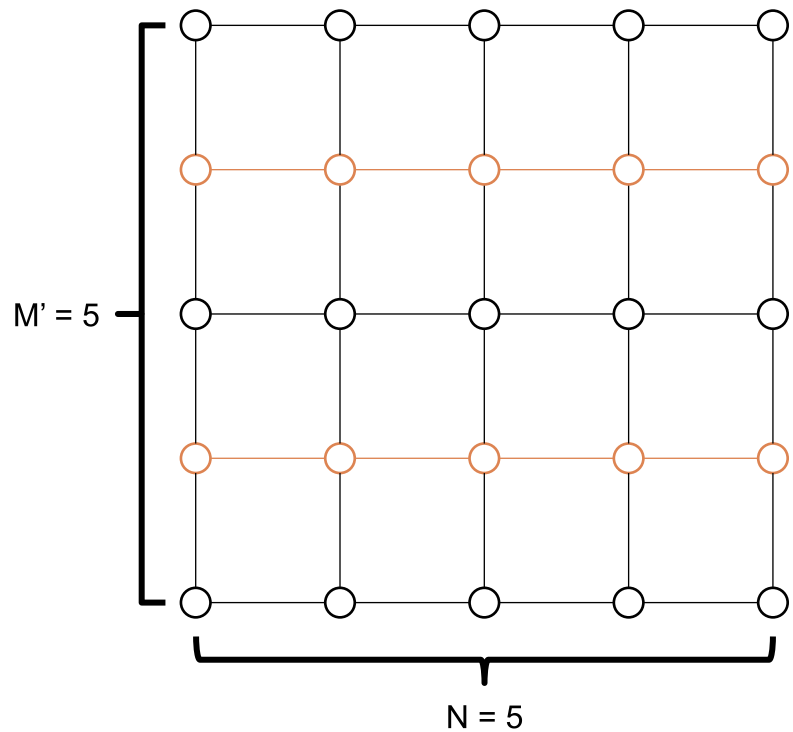
Integrating Real Distances

- Introduce virtual nodes so that:

$$M' = \left\lceil M \frac{D_M}{D_N} \right\rceil$$

- Here:

$$M' = \left\lceil 3 \frac{1.3}{0.8} \right\rceil = 5$$



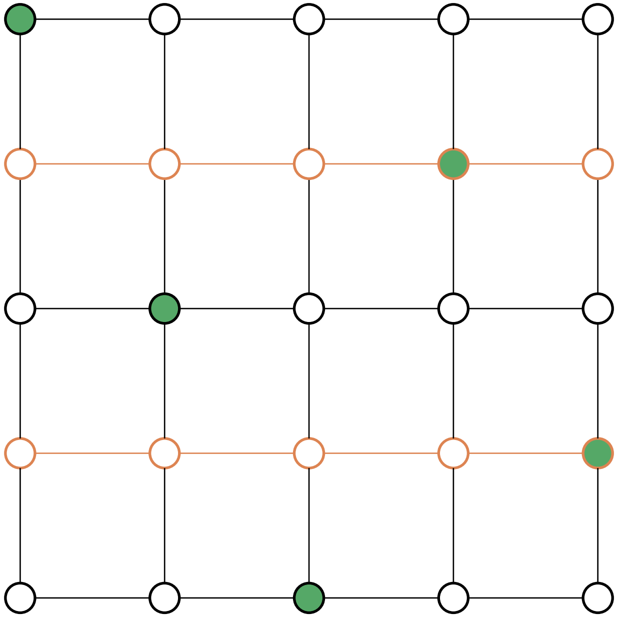
Integrating Real Distances

- Perform a $\left\lfloor \frac{d}{D_M} \right\rfloor$-hops placement using the known algorithms

- Here:

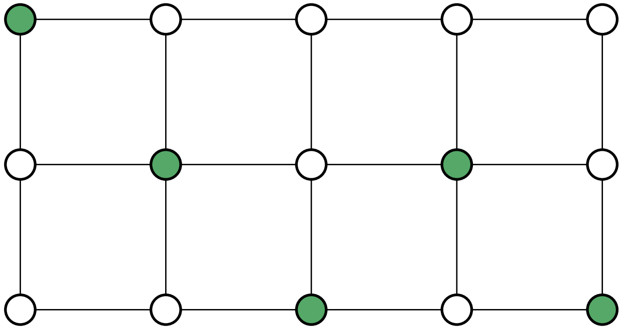
$$\left\lfloor \frac{d}{D_M} \right\rfloor = \left\lfloor \frac{1.4}{1.3} \right\rfloor = 1$$

, so we do a 1-hop placement



Integrating Real Distances

- Multiply y-coordinates of resource nodes with $\frac{M}{M'}$ to have the placement on the original torus



Evaluation: Simulation

- Create resource placements for different satellite networks
- Simulate network behavior with realistic parameters
- Measure observed network distances
- See if observed network distances conform to the limits we set

Evaluation: Simulation Framework

- Based on *SILLEO-SCNS* [30]
- Extended with support for *SGP4* perturbations models and *WGS84* world geodetic system
- **Open-Source! →**

https://github.com/pfandzelter/optimal-leo-placement

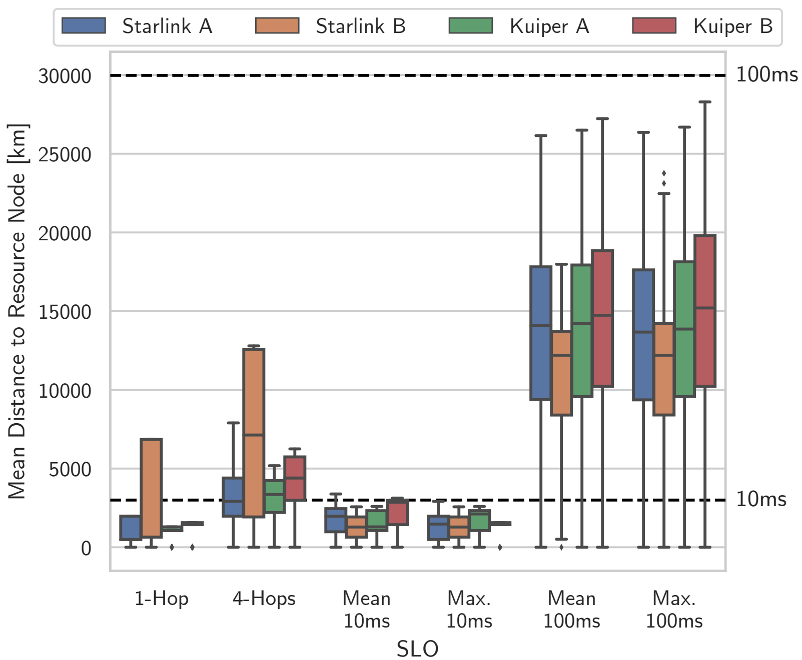
Evaluation: Parameters

Constellation	Shell	Planes (N)	Satellites/ Plane (M)	Altitude in km	Inclination
SpaceX Starlink	A	72	22	550	53.0°
	B	5	75	1,275	81.0°
Amazon Kuiper	A	34	34	630	51.9°
	B	28	28	590	33.0°

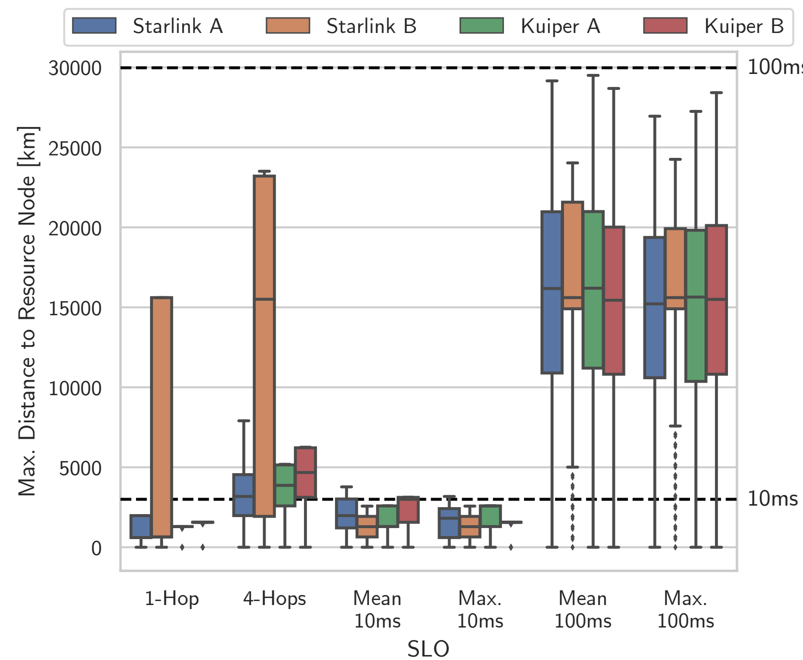
Evaluation: Required Resource Nodes

Shell	# Nodes	# Resource Nodes					
		1-Hop	4-Hops	Mean 10ms	Max. 10ms	Mean 100ms	Max. 100ms
Starlink A	1,584	354	55	94	135	2	2
Starlink B	375	75	17	45	45	2	2
Kuiper A	1,156	245	41	128	106	2	2
Kuiper B	784	178	25	80	178	2	2

Evaluation: Results



Mean Resource Distance in km



Maximum Resource Distance in km

Limitations & Future Work

- **Service placement**: if service migration (and, by extension, *virtual stationarity*) are an option, our static placement algorithm is not needed
- **Fault tolerance/availability**: for efficiency, algorithm places only one resource node within d-distance of every other node – if resource node fails, there is no backup
- **Routing & link congestion**: placement ignores routing, links to resource nodes will have higher load
- **Other QoS dimensions/factors**: placement only takes physical distance (= network distance) into account

Conclusion

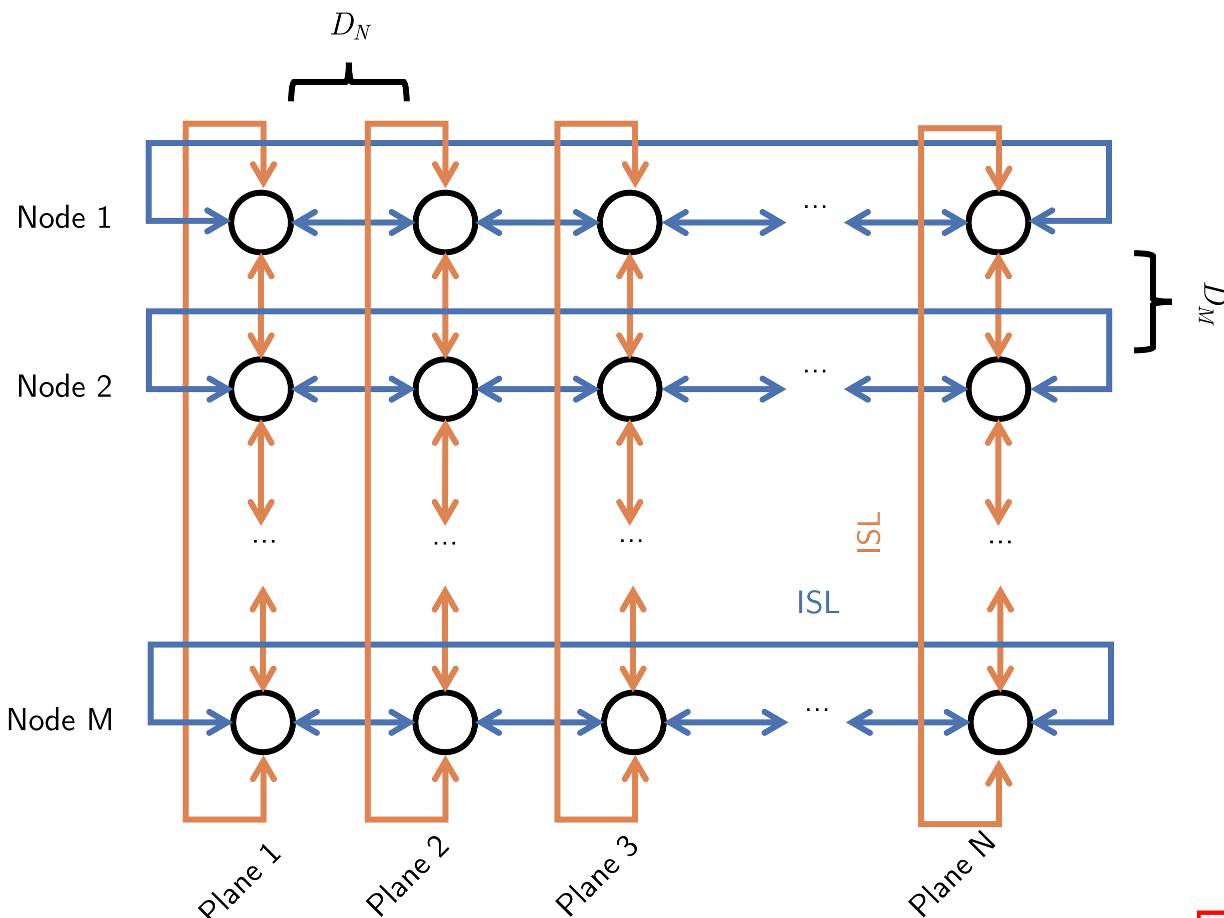
- LEO satellite edge computing is becoming more relevant to bring compute closer to the edge of the network for a global userbase
- Efficient placement of resources (servers, services, data replicas…) is non-trivial
- Satellite constellations can be modeled as 2D tori
- Existing resource placement techniques for 2D tori cannot be applied directly as they only support discrete distances (i.e., *hops*)
- Extended technique to support real distances
- Evaluated algorithm using realistic network simulations

Questions?

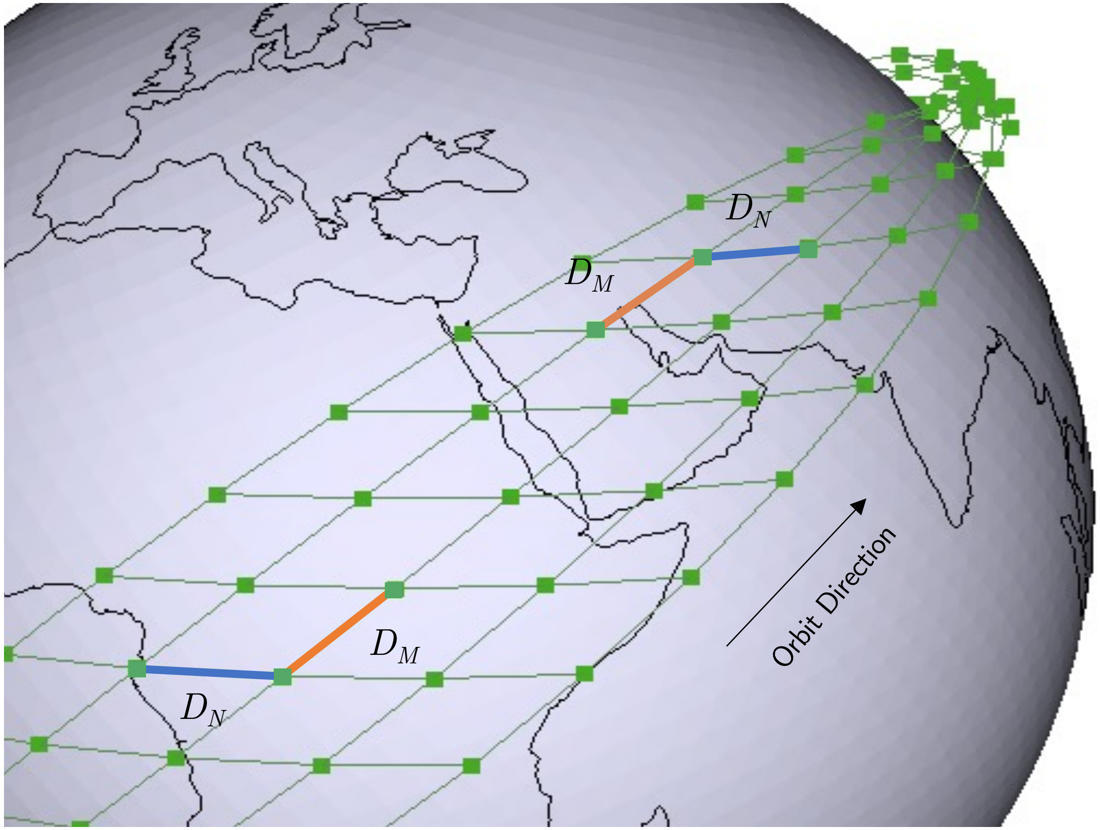
tp@mcc.tu-berlin.de

https://www.tu.berlin/en/mcc/

Satellite Torus



Satellite Torus



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