LEOCraft: Towards Designing Performant LEO Networks

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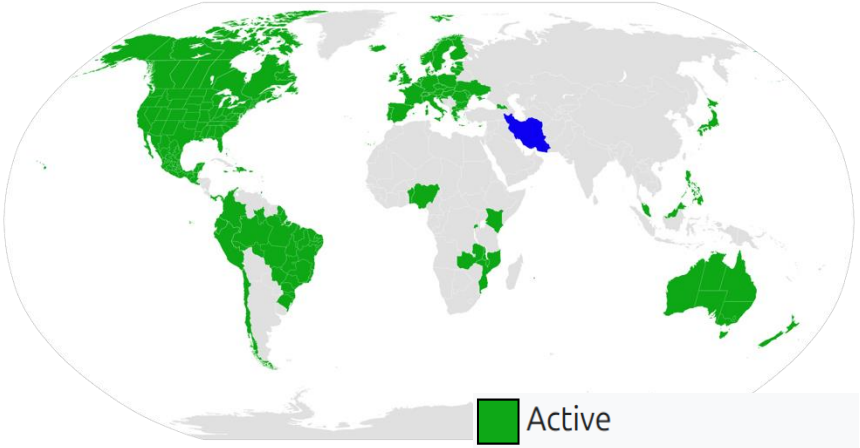
2025 USENIX Annual Technical Conference

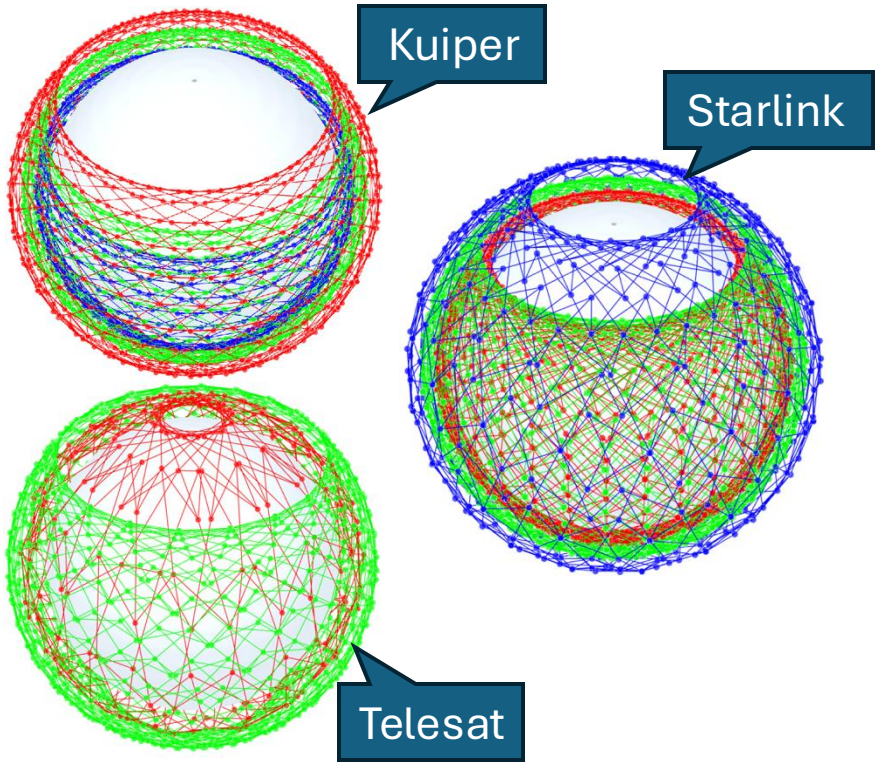
A new networking landscape

Beaming Internet from space

- **Starlink**
  1. Already 7000+ satellites
  2. Available across 100+ countries
  3. Aiming to deploy at least 30,000+ satellites
- **OneWeb**
  1. OneWeb already operating 600+ satellites
- **Amazon Project Kuiper**
  1. Aims for 3000+ satellites
- **Telesat**
  1. Aims for 512 satellites



Starlink's Availability [*]



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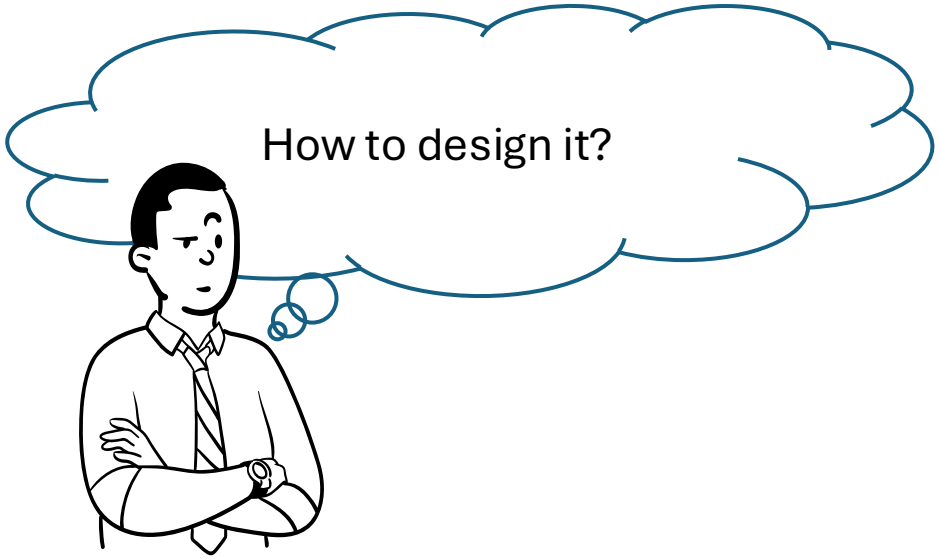

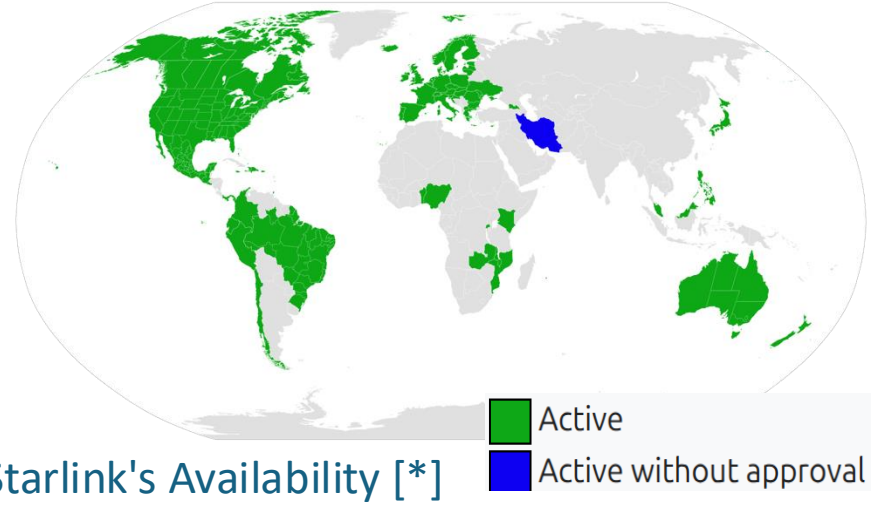

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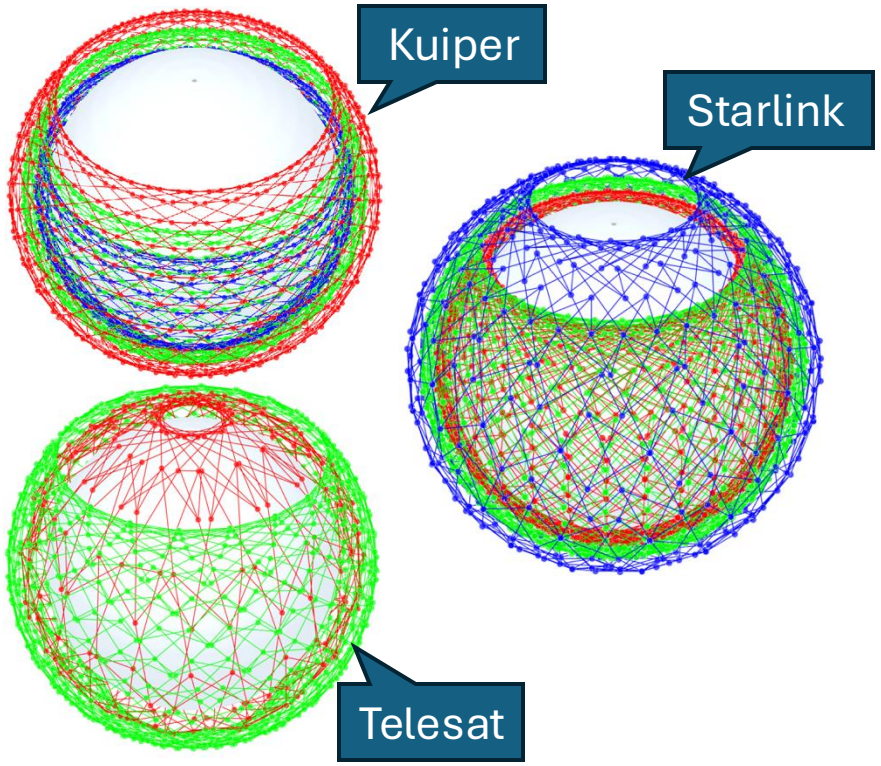

Two major challenges!

[*] https://en.wikipedia.org/wiki/Starlink

Challenges

#1: Missing the right tools

xeoverse, IFIP/IEEE Networking'24

Not public

StarryNet, USENIX NSDI'23

- Partially available
- Uses Docker containers
- Scalability is limited

Hypatia, ACM IMC'20

- Publicly available
- Uses ns-3 platform
- No atmospheric loss

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Do not measure constellation wide performance metrics!

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Do not measure constellation wide performance metrics!

Requirements

1. Rapid evaluation
2. Scale seamlessly
3. Quick implementation
4. Plug and play
5. Interactive views

LEOCraft

An LEO satellite constellation design evaluation, optimization, and visualization framework

Could measure
1. **Throughput**
2. **Coverage**
3. Latency
4. Hop counts
5. Traffic accommodation
6. # End to end selected routes
7. Link utilization
8. …

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Simulate using LEOCraft's APIs

```
leo_con = LEOConstellation('Starlink')
leo_con.add_ground_stations(GroundStation(
  GroundStationAtCities.TOP_100
))
leo_con.add_shells(PlusGridShell(
  id=0, orbits=72,
  sat_per_orbit=22,
  altitude_m=550000.0,
  inclination_degree=53.0,
  angle_of_elevation_degree=25.0,
  phase_offset=50.0,
))
leo_con.set_time(second=3)
leo_con.set_loss_model(loss_model)
leo_con.build()
leo_con.create_network_graph()
leo_con.generate_routes(k=20)
th = Throughput(
  leo_con,
  InternetTrafficAcrossCities.ONLY_POP_100
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th.build()
th.compute()
```

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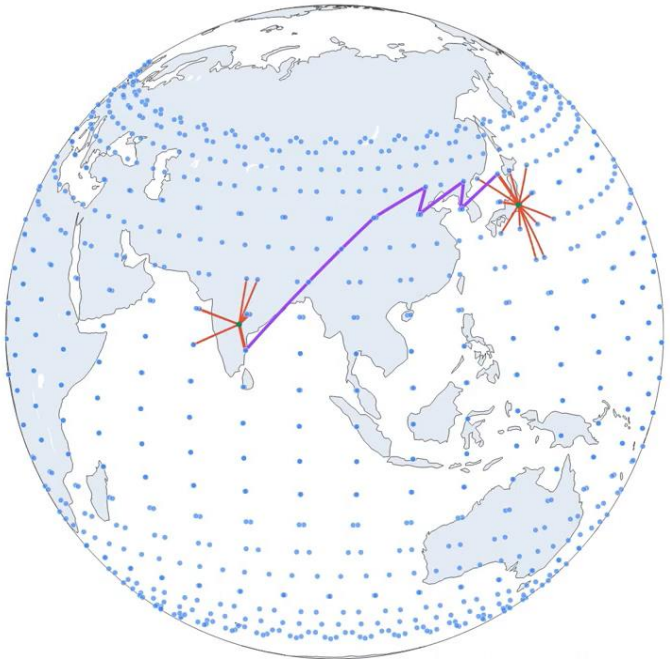
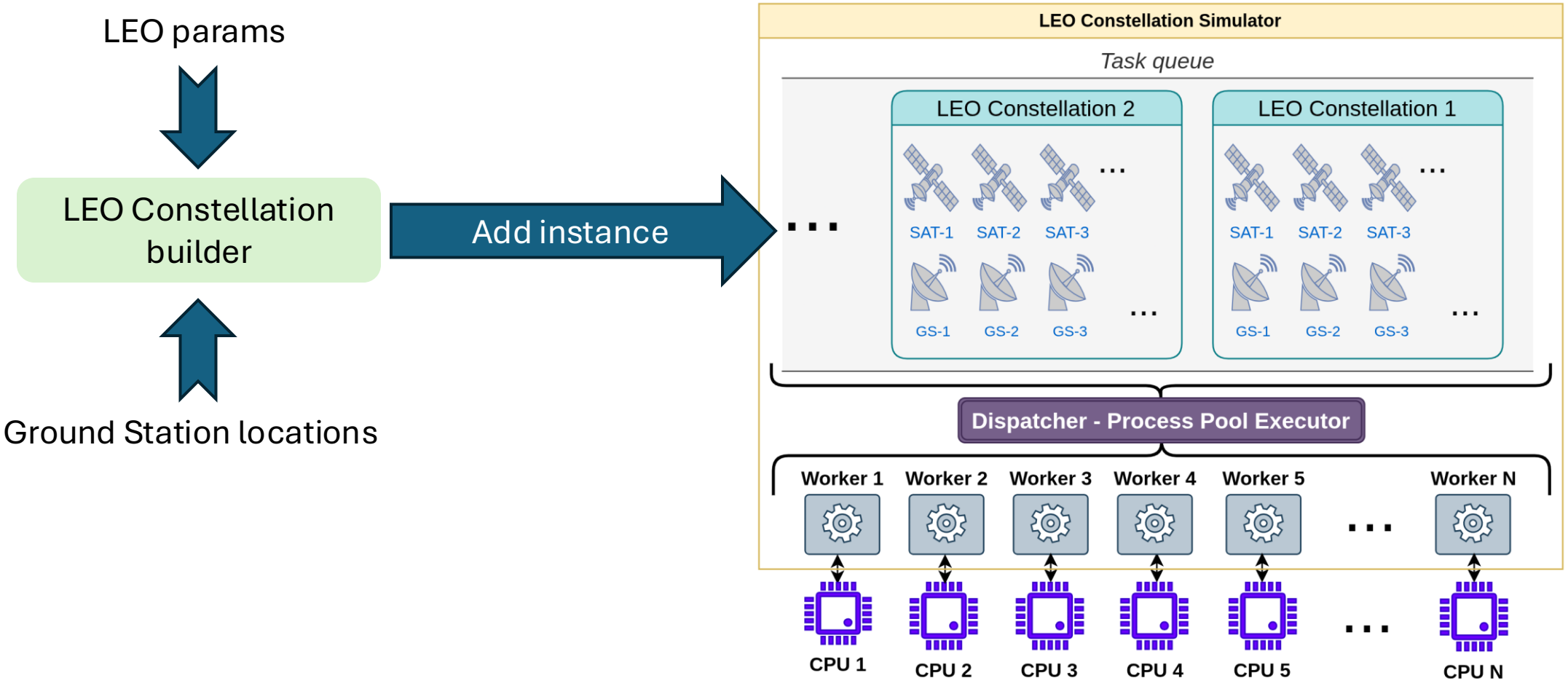
Visualize route changes



LEOCraft - deep drive

Workflow of LEOCraft's simulation framework



Challenges

#2: The curse of dimensionality

Ground stations

Traffic Matrix

From \ To	A	B	C	D
A	0	20	30	10
B	50	0	40	60
C	30	0	0	20
D	10	60	20	0

Find

1. Design parameters
2. ISL topology

Maximize network performance

Challenges

#2: The curse of dimensionality

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Find

1. Design parameters
2. ISL topology

|h| x |e| x |i| x |o| x |n| x |p| x |s|

Maximize network performance

Challenges

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Find

1. Design parameters
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Maximize network performance

|h| x |e| x |i| x |o| x |n| x |p| x |s|

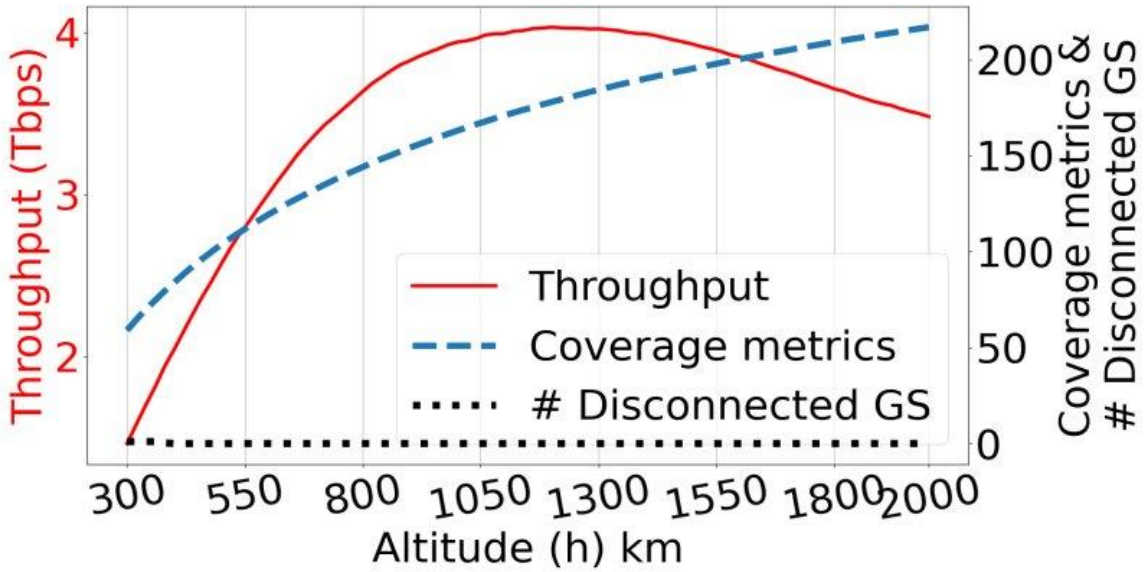
Could take many **years** even on a many core machine!

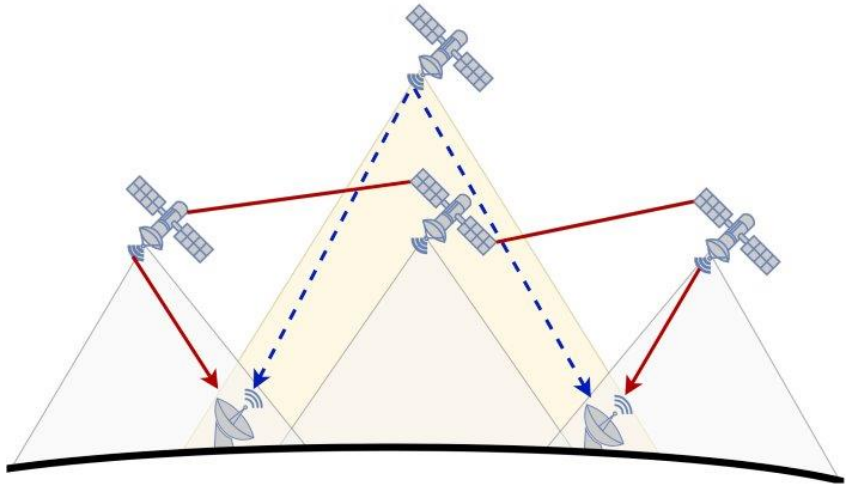
Exploring the search space

Performance impact of altitude (h)

Starlink (1584 sats)

Number of orbit:	*72*
Satellites/Orbit:	*22*
Inclination:	*53°*
Altitude:	*550 km*
Angle of elevation:	*25°*
Phase offset:	50%





Takeaways

1. Should be decided upon communication capabilities
2. Change in 5-10s km is insignificant

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Inclination:	*53°*
Altitude:	*550 km*
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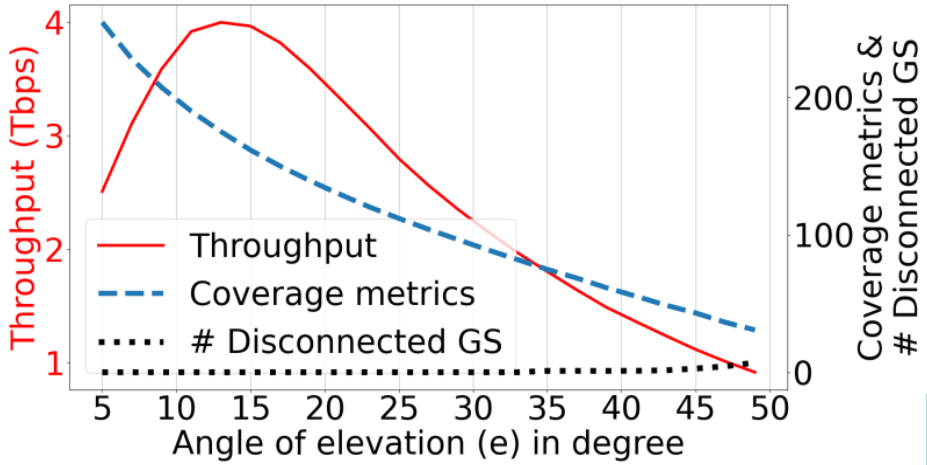
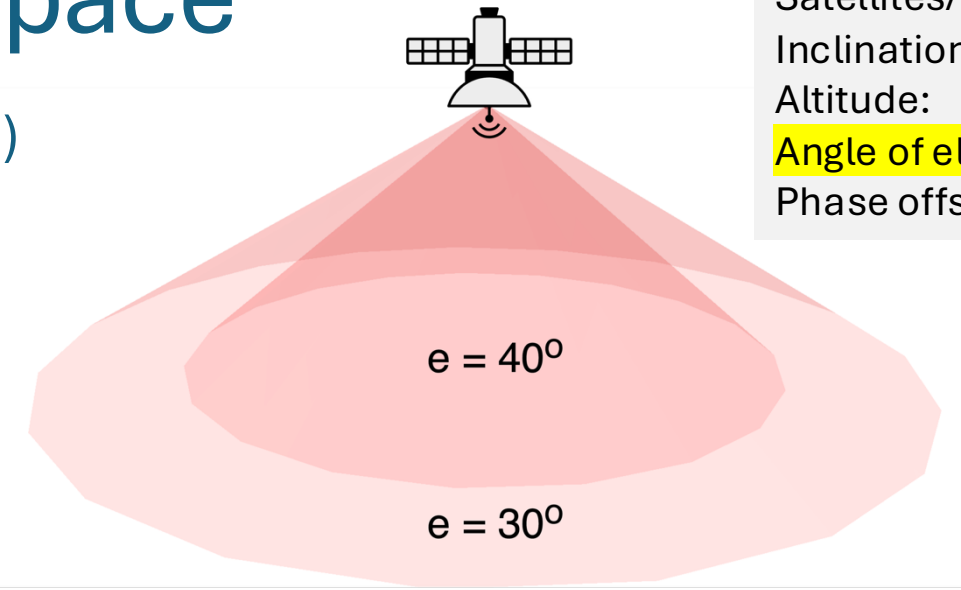
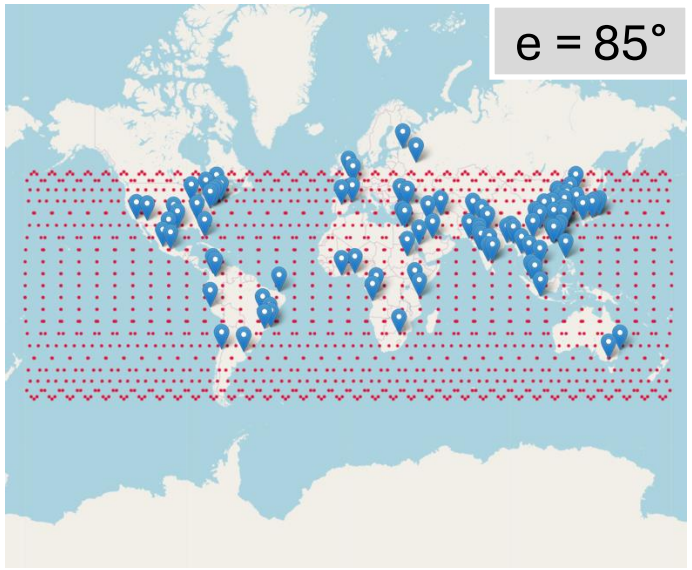
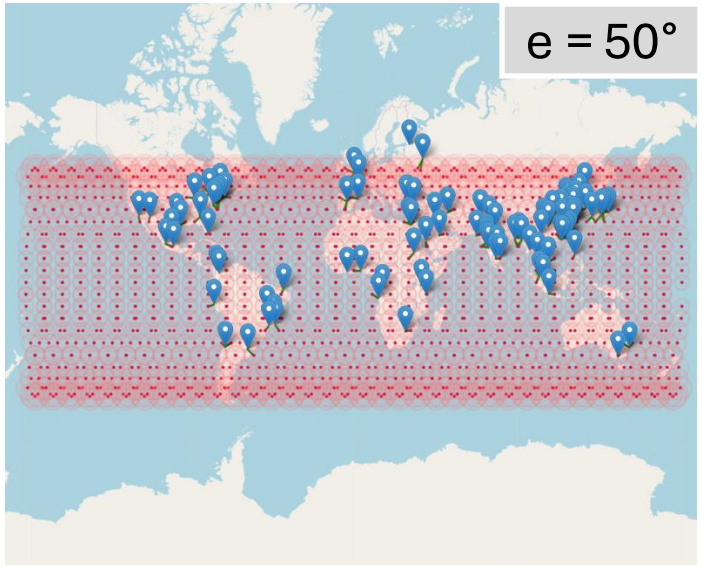
Phase offset:	50%

Performance impact of elevation angle (e)









Takeaways

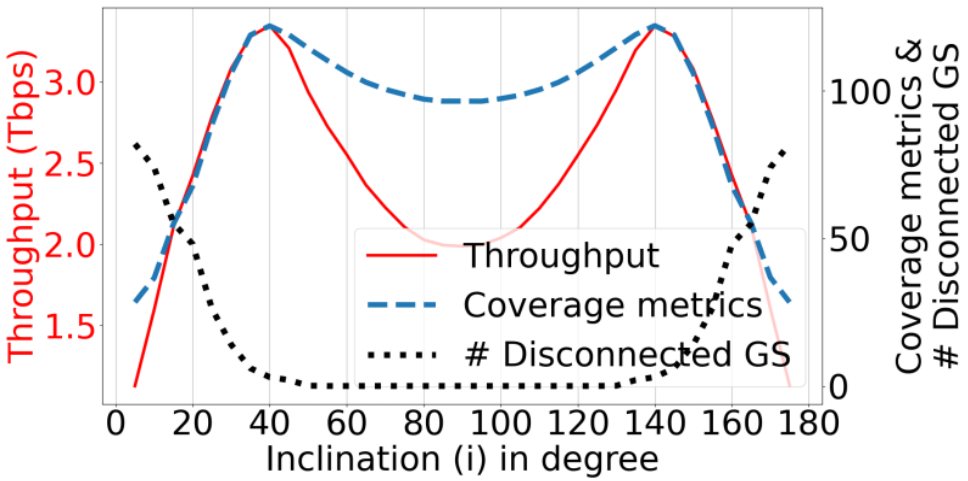
Altitude (h) and elevation angle (e) needs to be balanced for the desired performance

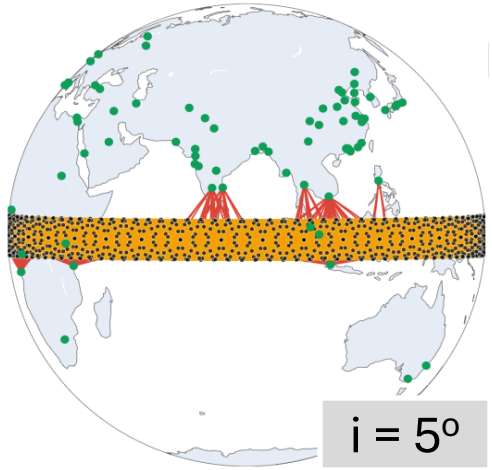
Exploring the search space

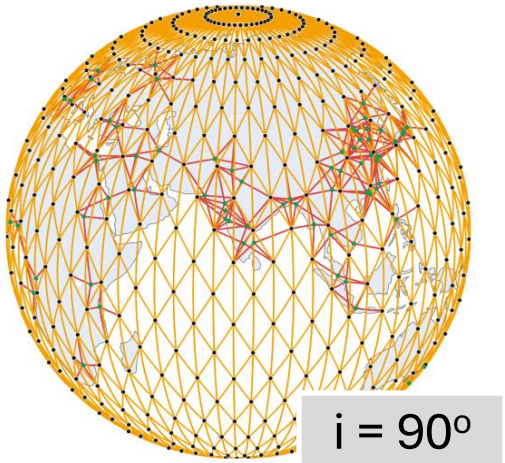
Starlink (1584 sats)

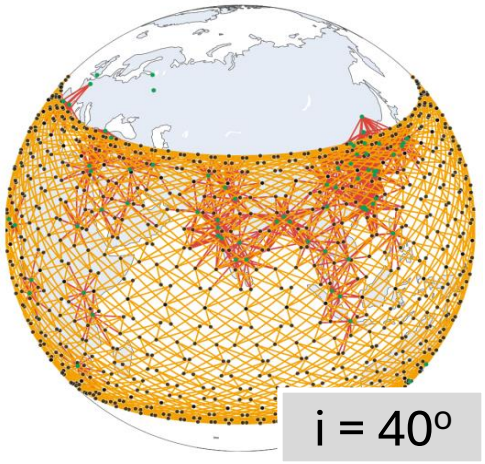
Number of orbit:	*72*
Satellites/Orbit:	*22*
Inclination:	*53°*
Altitude:	*550 km*
Angle of elevation:	*25°*
Phase offset:	50%

Performance impact of inclination angle (i)









Takeaways

Restrict the presence of satellites above population centers

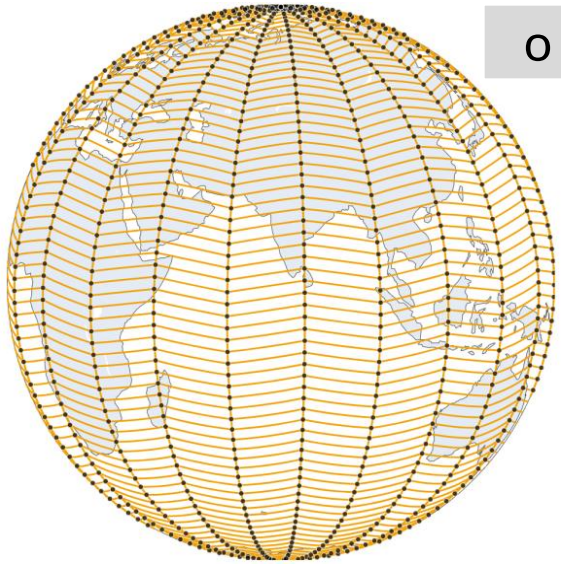
Exploring the search space

Performance impact of the number of orbits (o) and satellites/orbit (n)

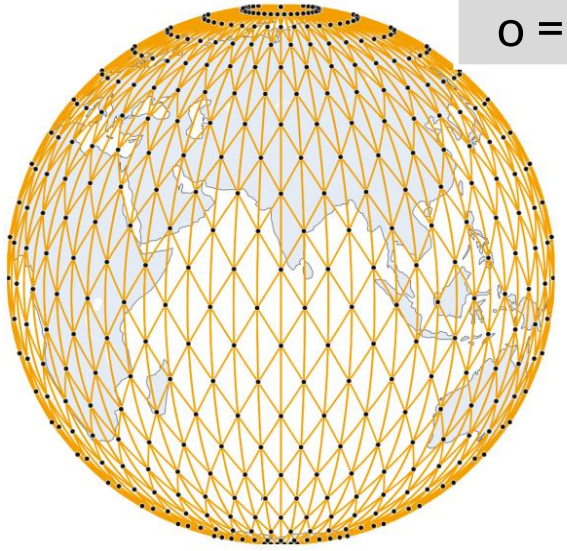
Starlink (1584 sats)	
Number of orbit:	*72*
Satellites/Orbit:	*22*
Inclination:	*53°*
Altitude:	*550 km*
Angle of elevation:	*25°*
Phase offset:	50%

Total number of satellites: **1584**

o = 22, n = 72



o = 72, n = 22

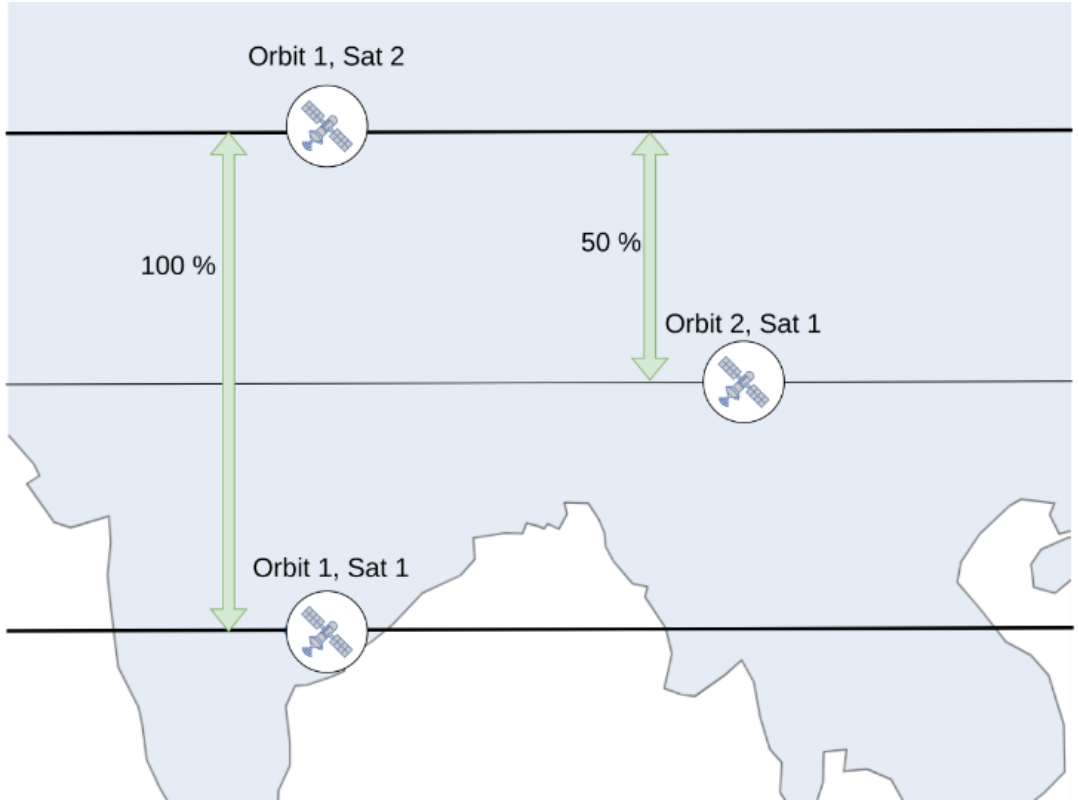


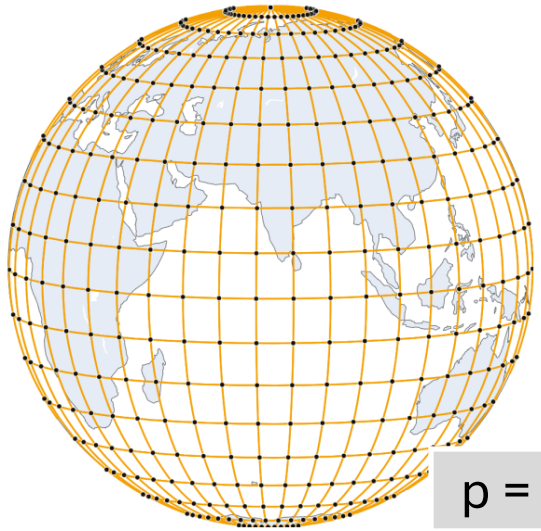
Exploring the search space

Performance impact of phase offset (p)

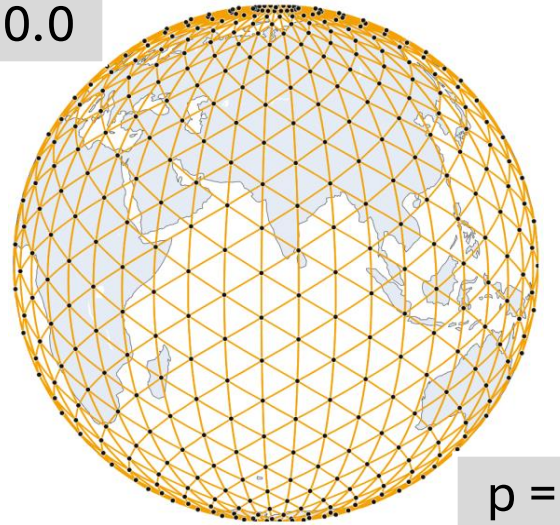
Starlink (1584 sats)

Number of orbit:	*72*
Satellites/Orbit:	*22*
Inclination:	*53°*
Altitude:	*550 km*
Angle of elevation:	*25°*
Phase offset:	50%





p = 0.0



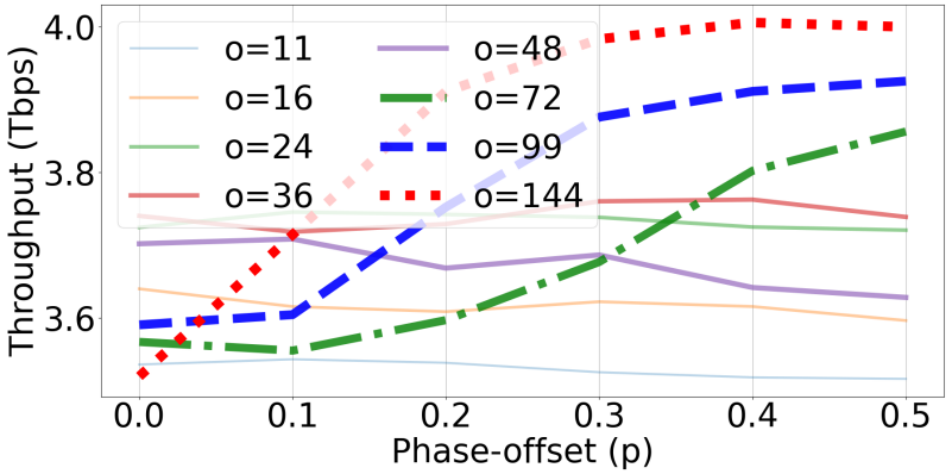
p = 0.5

Takeaways

o, n, and p tweaks the ISL topological structures

Exploring the search space

Performance impact of the number of orbits (o) and phase offset (p)



Starlink (1584 sats)

Number of orbit:	*72*
Satellites/Orbit:	*22*
Inclination:	*38.6°*
Altitude:	*550 km*
Angle of elevation:	*12.1°*
Phase offset:	50%

Takeaways

Any ***o*** such that ***o*** **>>** ***n*** at **p = 0.5** will produce higher throughput

Exploring the search space

Performance impact of the number of orbits (o) and phase offset (p)

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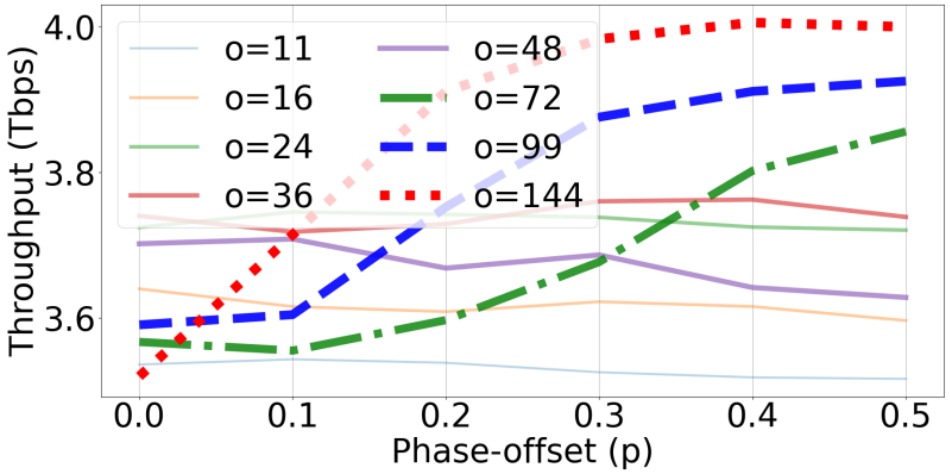
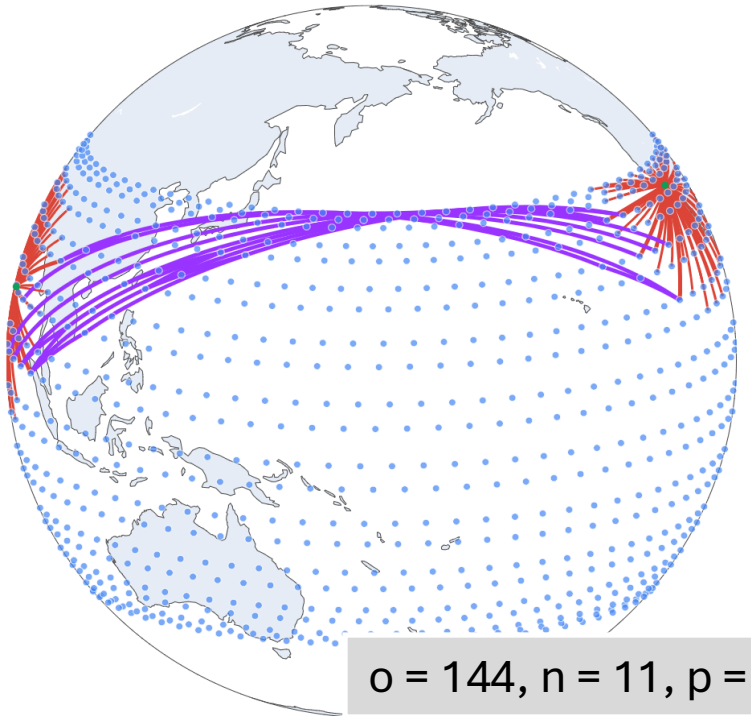


Takeaways

Any ***o*** such that ***o*** **>>** ***n*** at **p = 0.5** will produce higher throughput

20 shortest routes from **Bangalore, India** to **Los Angeles, US**



o = 144, n = 11, p = 50%

Shaping an optimization strategy

Reducing the search space

Design params

1. Altitude (h)
2. Elevation (e)
3. Inclination (i)
4. Orbits (o)
5. Satellites/orbit (n)
6. Phase offset (p)

Impacts the coverage

Group-I

1. Altitude (h)
2. Elevation (e)
3. Inclination (i)

Group-II

1. Orbits (o)
2. Satellites/orbit (n)
3. Phase offset (p)

Tweaks the ISL topological structures

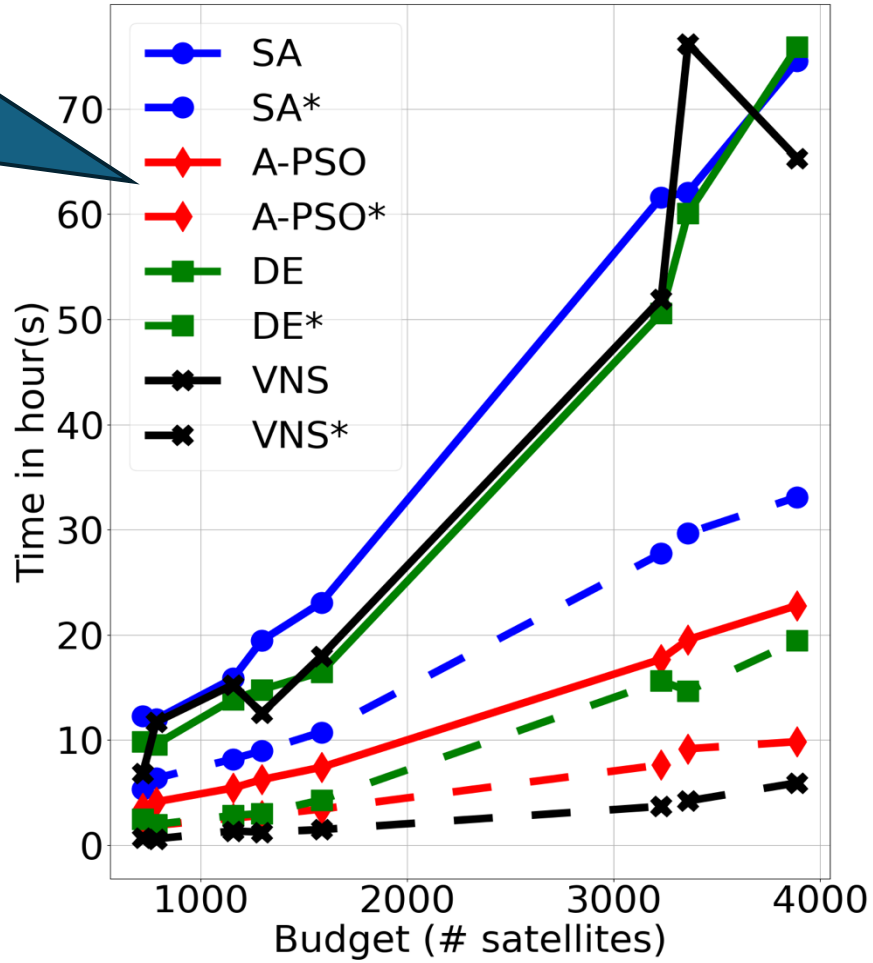
Additional domain knowledge

1. *Altitude (h)*: FCC, ITU regulation
2. *Inclination (i)*: bound (30, 90) and start at 29.6
3. *Elevation (e)*: Communication H/W limitation and bound (10, 60)

Shaping an optimization strategy

Running time of optimization techniques without and with domain knowledge (*)

- Simulated Annealing (SA)
- Adaptive Particle Swarm Optimization (A-PSO)
- Differential evolution (DE)
- Variable Neighborhood Search (VNS)



Hyperparameters

- **A-PSO**
  - *# iterations: 25*
  - *# particles: 20*
- **A-PSO***
  - *# iterations: 25*
  - *# particles: 10*
- **SA**
  - *# iterations: 100*
- **SA***
  - *# iterations: 60*

Exploring the search space

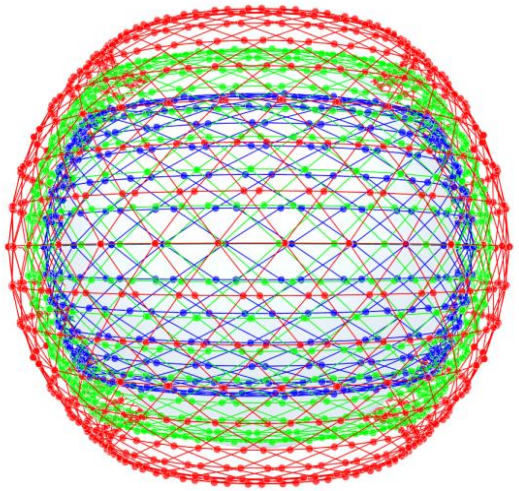
Performance impact of multiple shells (s)

Amazon Project Kuiper **3,236** satellites across **3** shells [*]

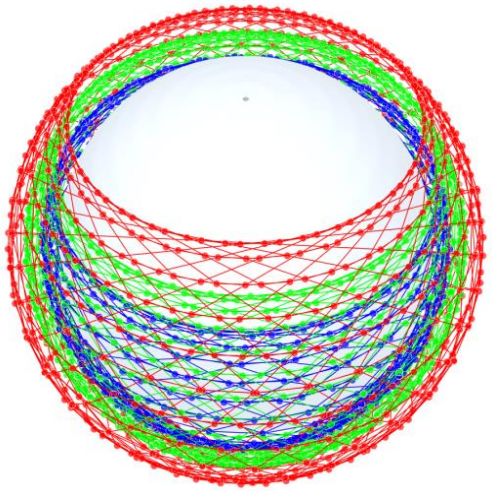
o	n	i	e	h
34	34	51.9°	35°	630 km
36	36	42°	35°	610 km
28	28	33°	35°	590 km

LEOCraft can evaluate multi-shell design too!

Impact of inter-shell ISLs?



View from equator



View from pole

[*] https://fcc.report/IBFS/SAT-LOA-20190704-00057/1773885

Conclusion & future work

Source code is available at - https://github.com/suvambasak/LEOCraft.git

Conclusion

- Designing a LEO constellation is utterly complex task
- We build `LEOCraft` – modular framework

Future work

- Topology & trajectory joint optimization
- Multi objective like - throughput, coverage, latency

Thank you!