On improving low-Earth orbit satellite network performance

Debopam Bhattacherjee, ETH Zürich

Agenda

- What is the hype about?
- Basics of LEO networking
- LEO topology design
  - Utility of inter-satellite lasers or ISLs
  - Topology design with repetitive patterns
- Enabling broader research

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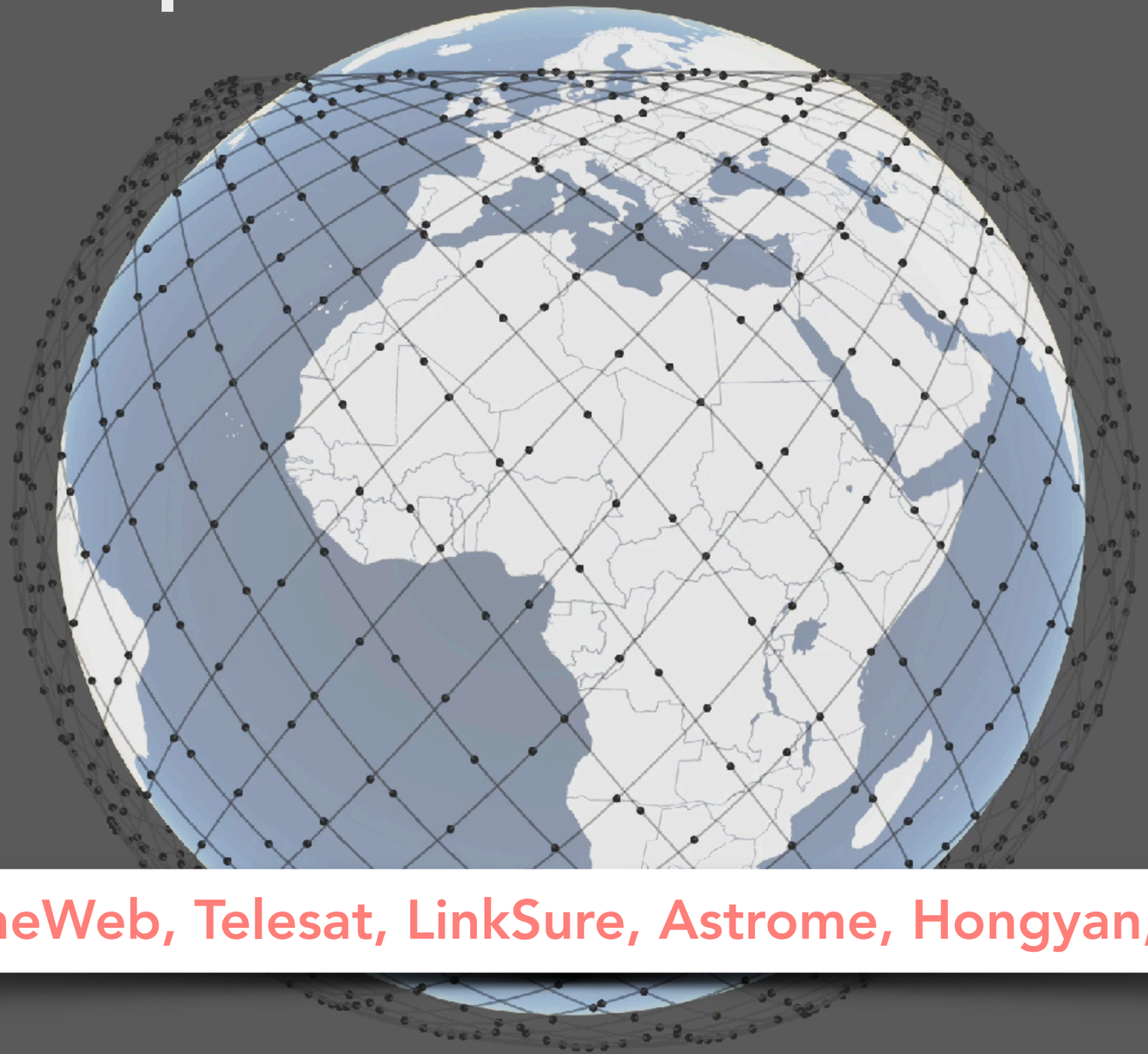
SpaceX Starlink

1,600 satellites initially

42,000 planned

Amazon Kuiper

3,200 planned
in 3 phases

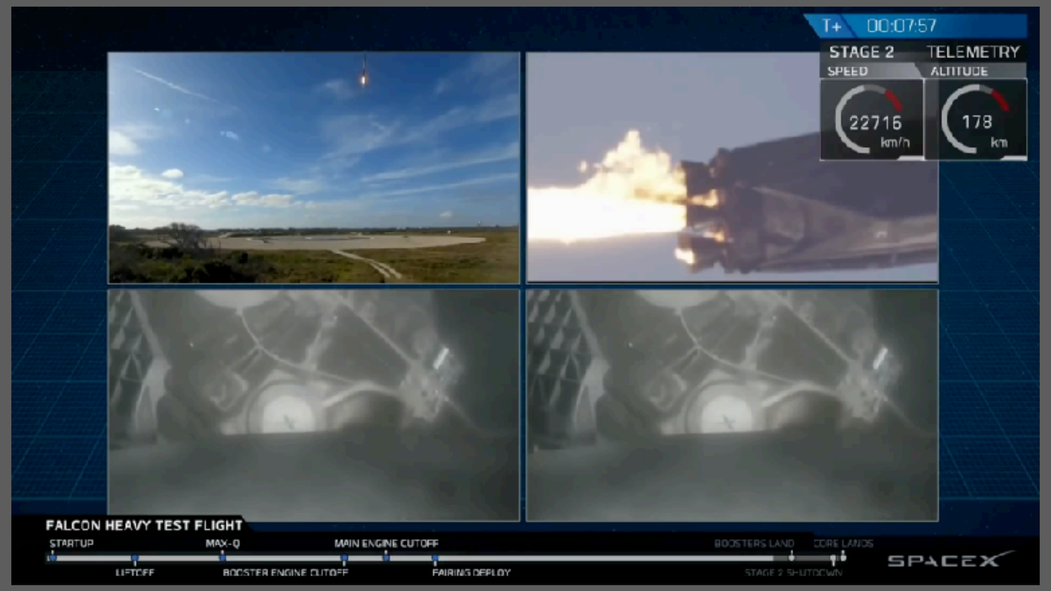


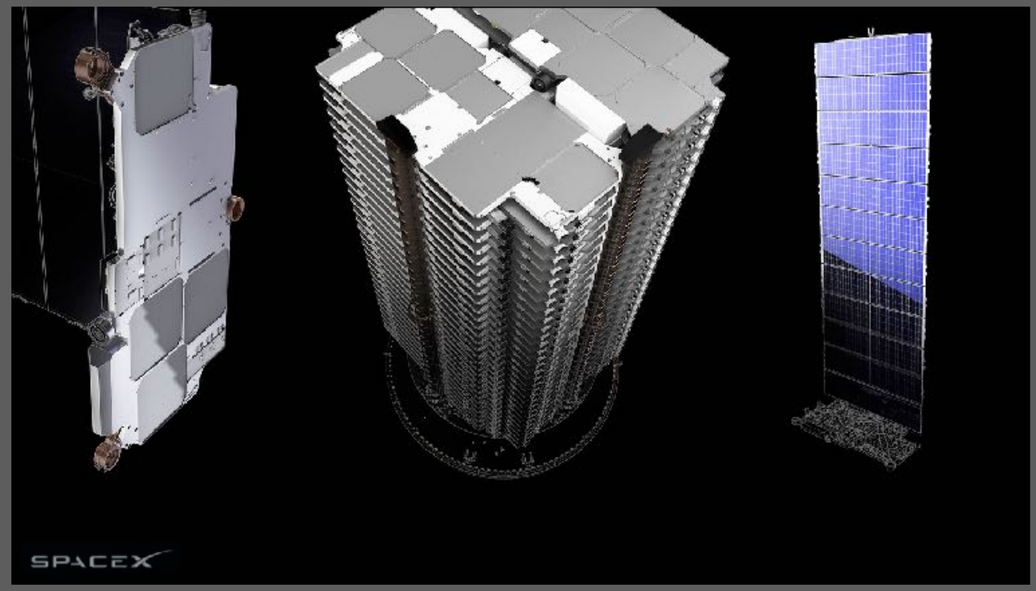
OneWeb, Telesat, LinkSure, Astrome, Hongyan, …

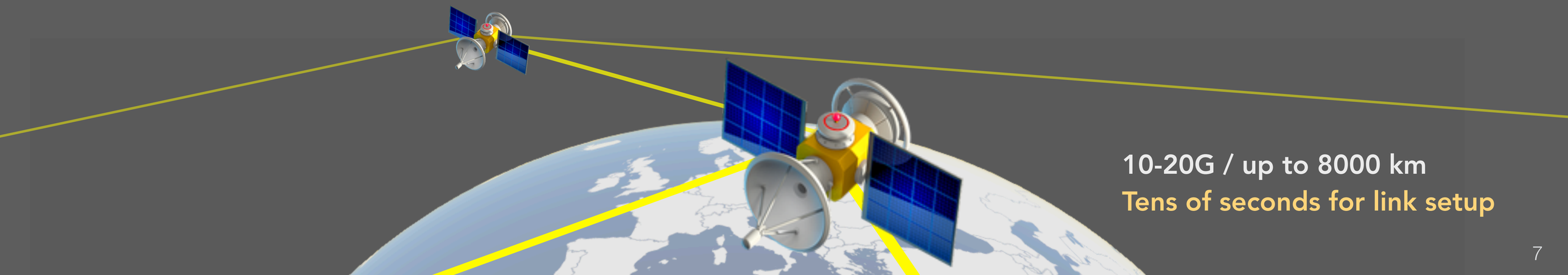
Isn’t satellite networking old?

- Scale: 10s → 10,000s
- Goals: niches → global broadband
- Dynamics: GEO → LEO

Recent advances







10-20G / up to 8000 km

Tens of seconds for link setup

Global low-latency Internet coverage

How do we …

… pick satellite trajectories to serve target areas?

… interconnect satellites?

Topology

… route efficiently within a constellation?

… integrate such networks into Internet routing?

Routing

… do efficient congestion control on such networks?

Transport

… design applications that run on top?

Apps

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… do ef

… desig

Transport

Apps

Gearing up for the 21st century space race

Debopam Bhattacherjee[1], Waqar Aqeel[2], Ilker Nadi Bozkurt[2], Anthony Aguirre[3], Balakrishnan Chandrasekaran[4], P. Brighten Godfrey[5], Gregory Laughlin[6], Bruce Maggs[2,7], Ankit Singla[1]
[1]ETH Zürich, [2]Duke, [3]UCSC, [4]MPI-INF, [5]UIUC, [6]Yale, [7]Akamai Technologies

HotNets 2018

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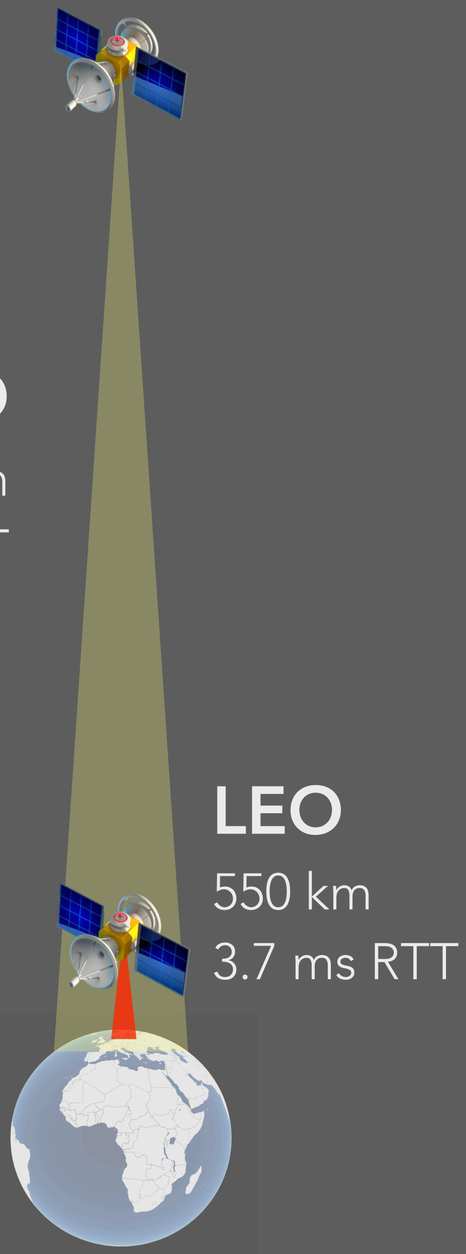
1. Altitude



GEO

35,768 km

~238.4 ms RTT

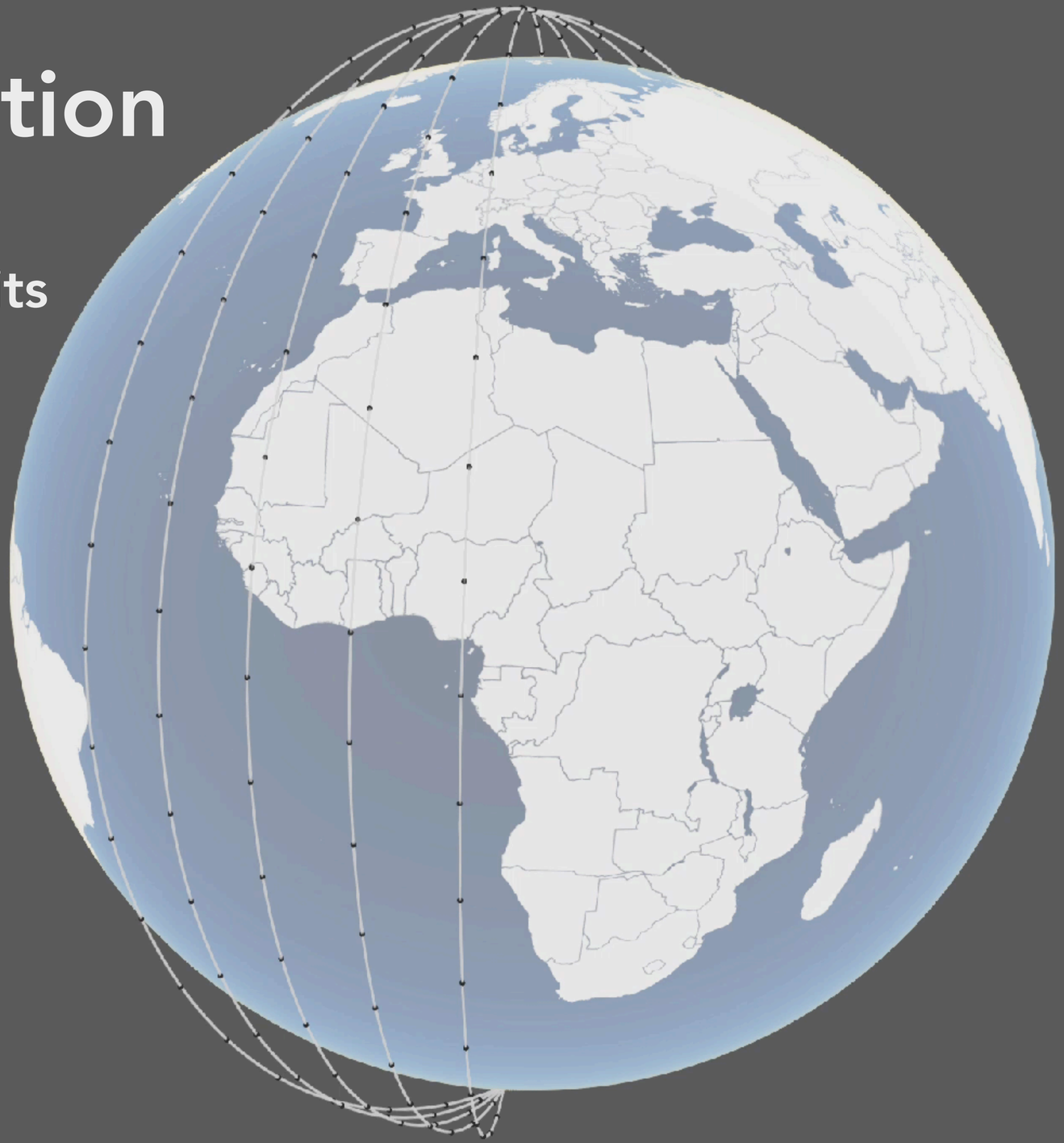
LEO

550 km

3.7 ms RTT

2. Inclination

Polar orbits



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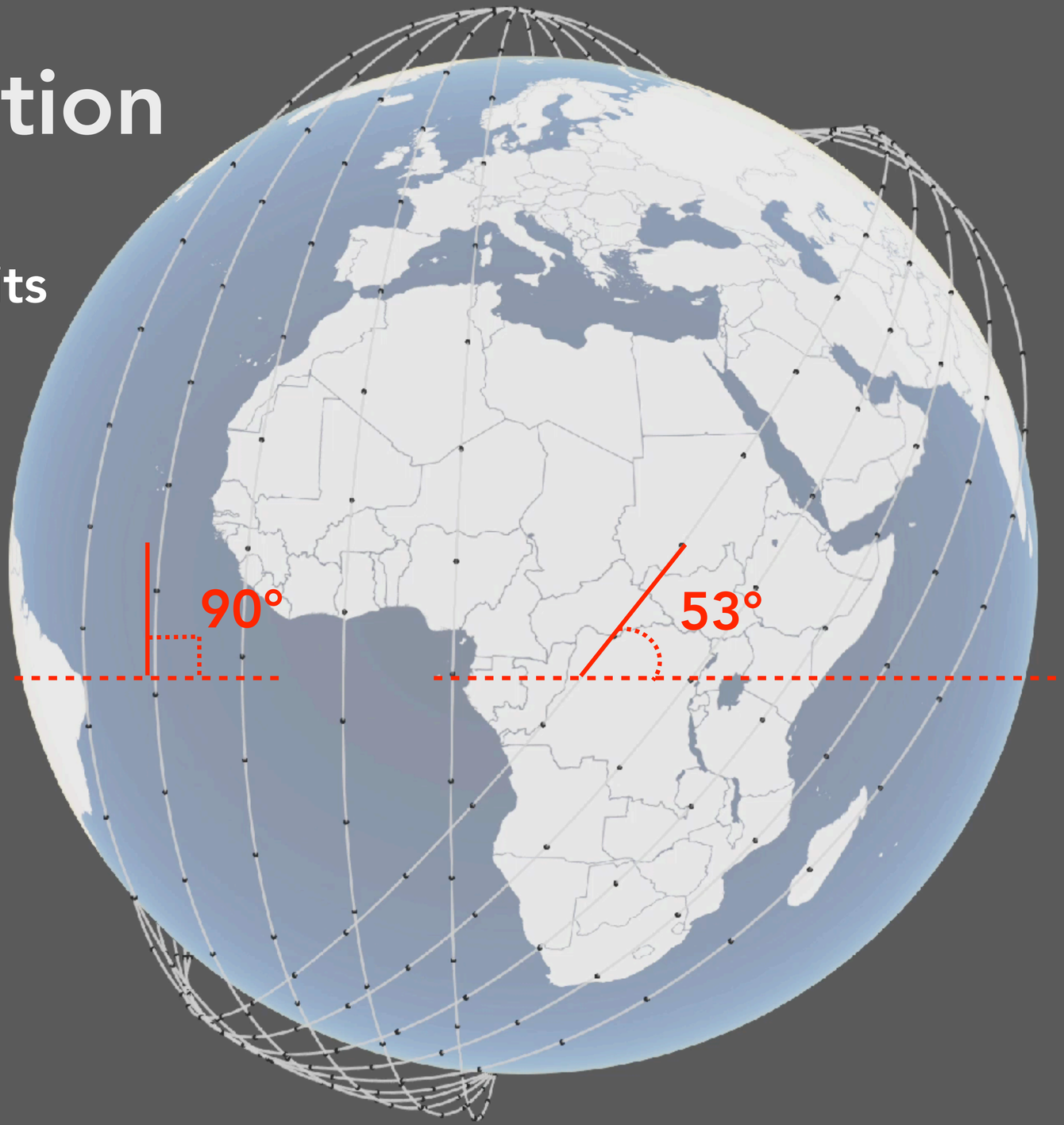


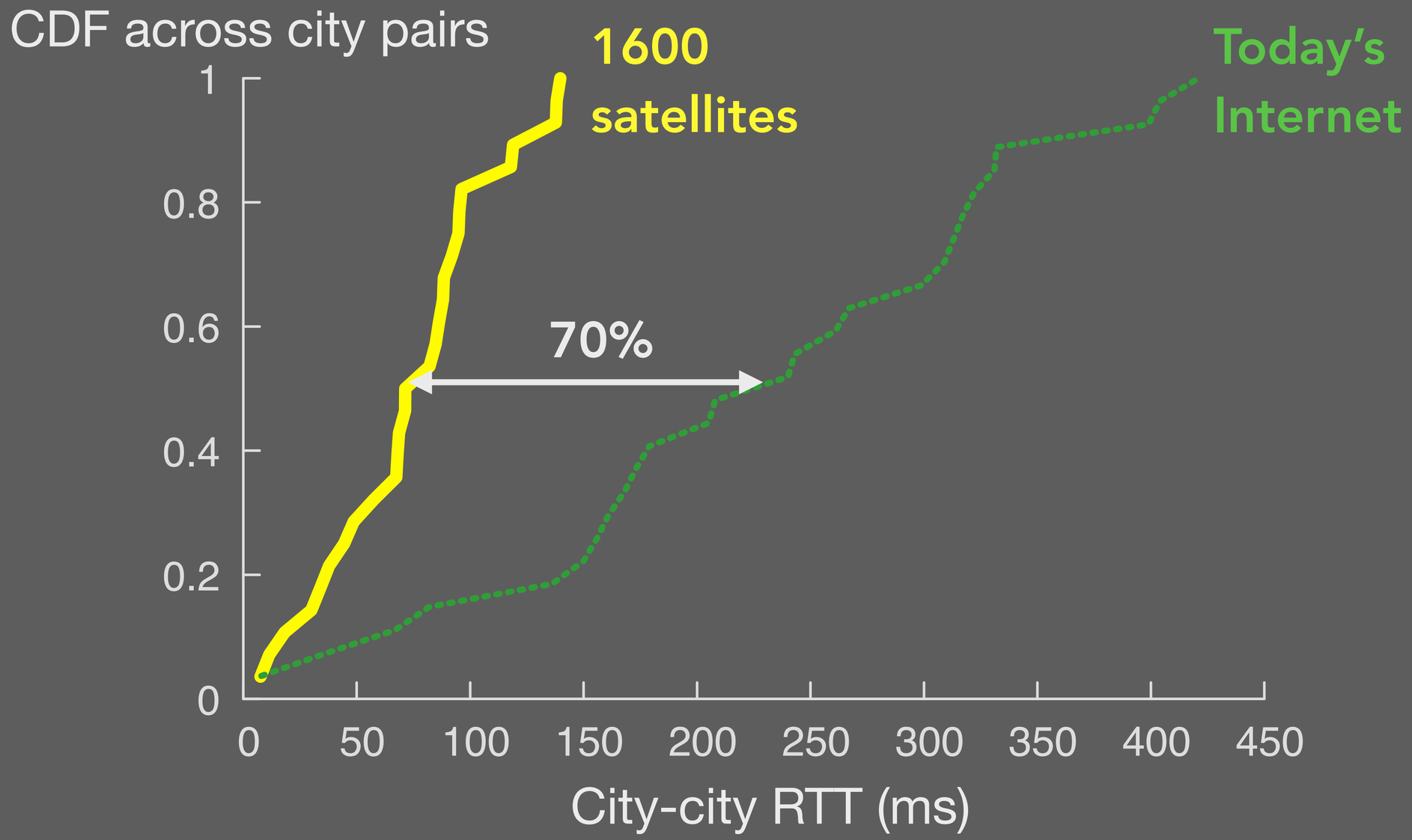
Inclined orbits

3. Connectivity

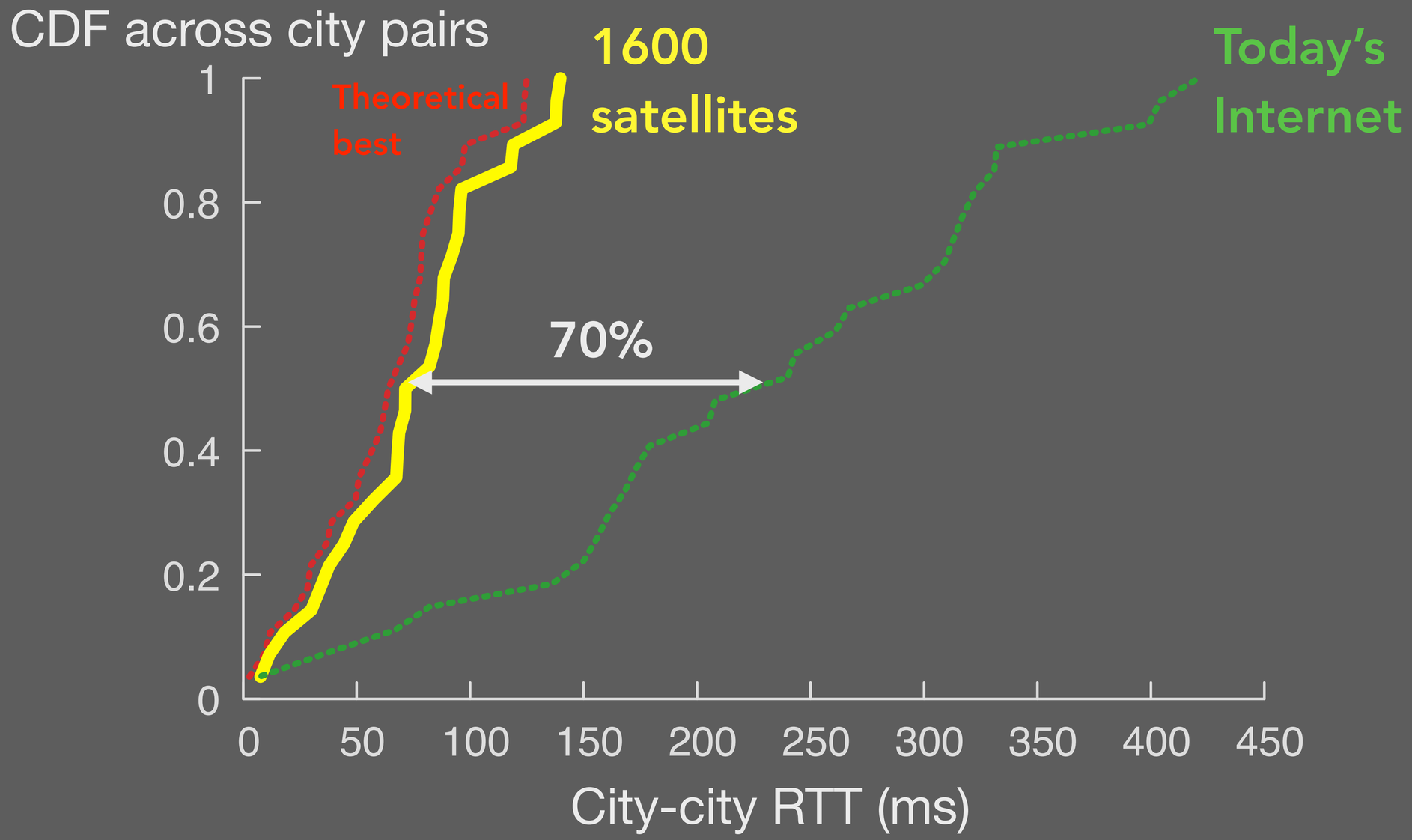
+Grid

4. Latency

4. Latency


CDF across city pairs
1600
satellites
Today's
Internet
70%
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
450
City-city RTT (ms)

4. Latency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5. System dynamics

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Utility of Inter-satellite laser

“Internet from Space” without Inter-satellite Links?

Yannick Hauri, Debopam Bhattacherjee, Manuel Grossmann, Ankit Singla
ETH Zürich

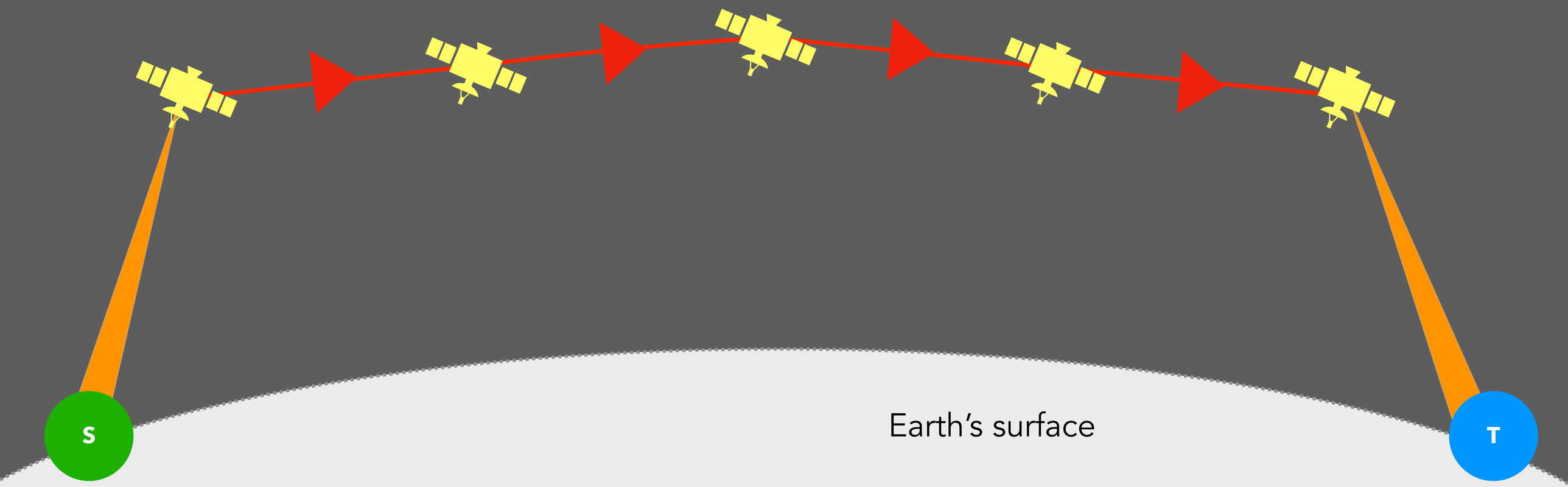
HotNets 2020

FCC specification

presumptively acceptable risk and encourage "design for demise," i.e. designing spacecraft so that they burn up completely upon re-entry into the Earth's atmosphere,[450] but maintain the possibility for approval

- No mention of silicon carbide component

Bent-pipe connectivity (BP)



Bent-pipe connectivity (BP)

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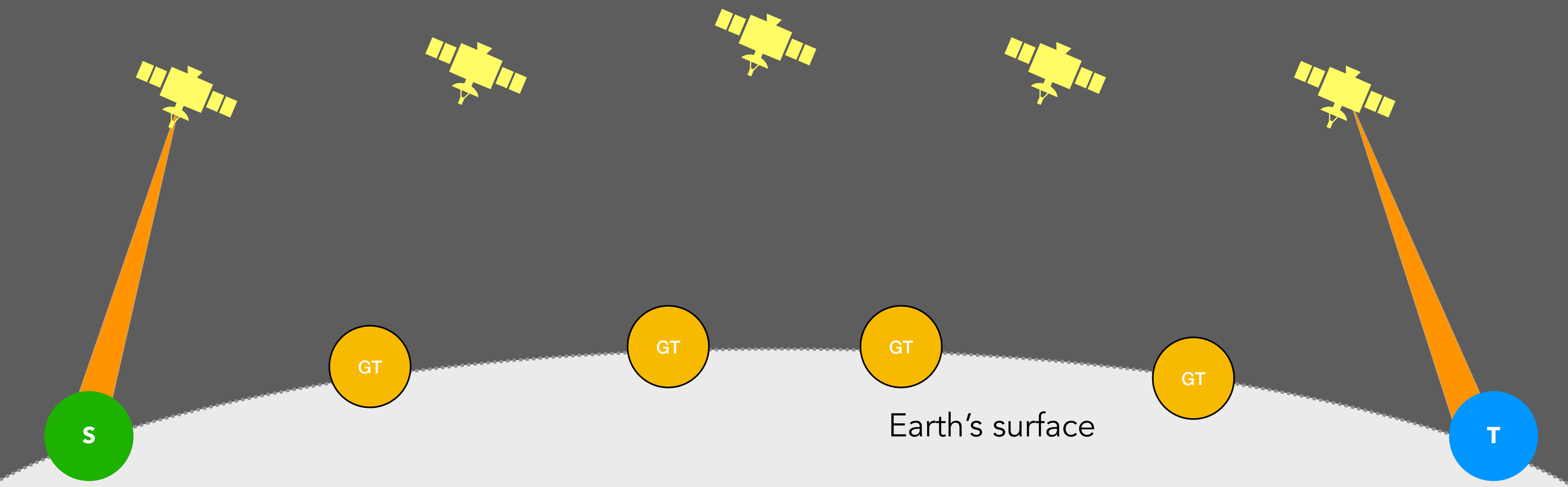

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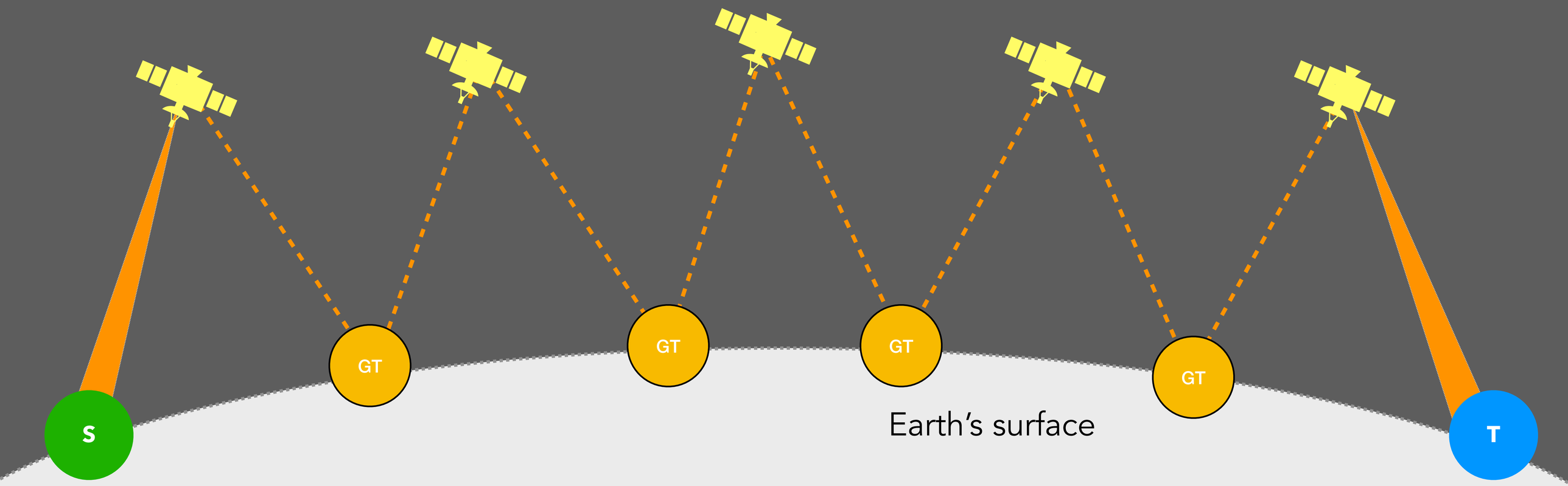

ISL versus BP

- Latencies and **variations** thereof
- Impact on network-wide **throughput**
- Resilience to **weather**

“Internet from Space” without Inter-satellite Links?

Yannick Hauri, Debopam Bhattacherjee, Manuel Grossmann, Ankit Singla
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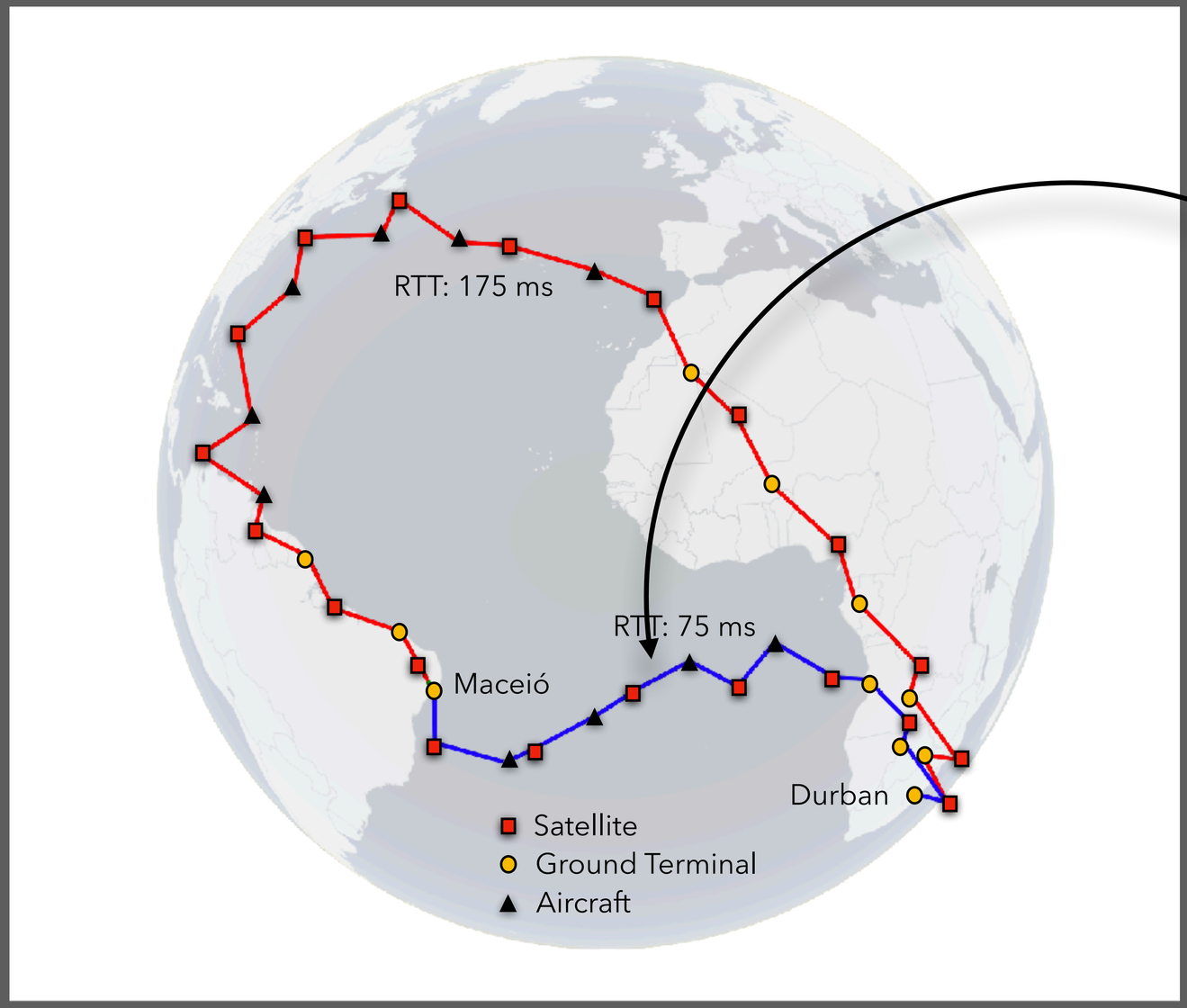
HotNets 2020

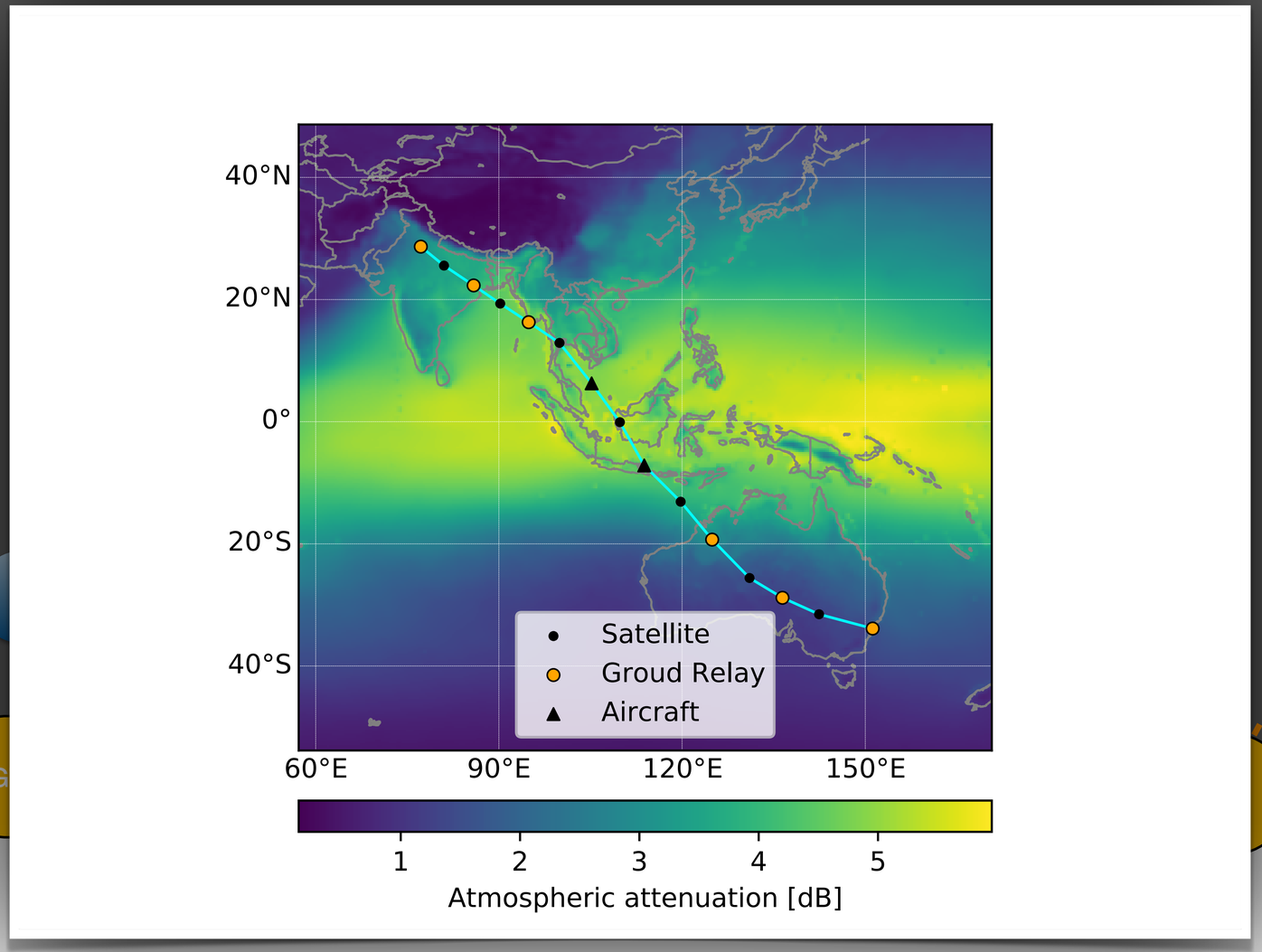
High latency variations in BP



Sparser air traffic over South Atlantic

- Inflation of ~100 ms
- North Atlantic paths get congested

Impact of weather

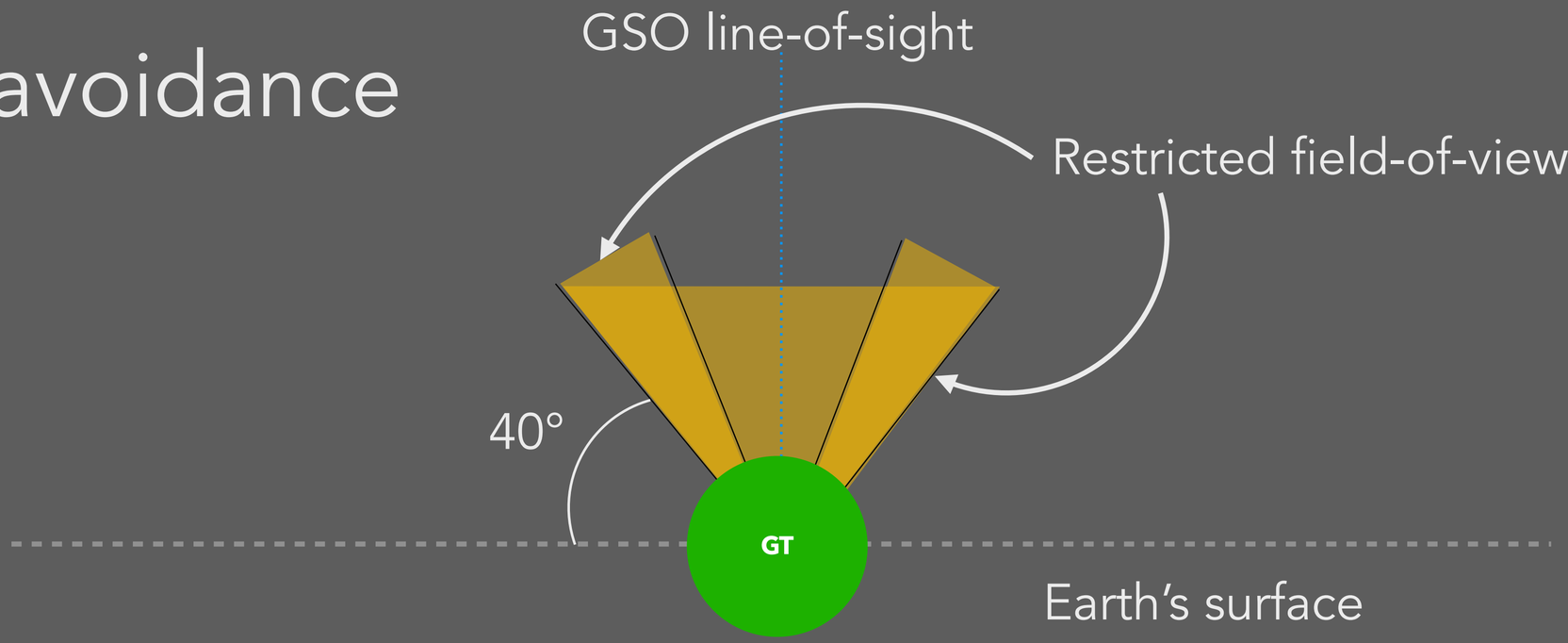


Other benefits of ISLs

- Crossing challenging territory
- Spectrum efficiency

Other benefits of ISLs

- Crossing unfriendly territory
- Spectrum efficiency
- GSO arc avoidance



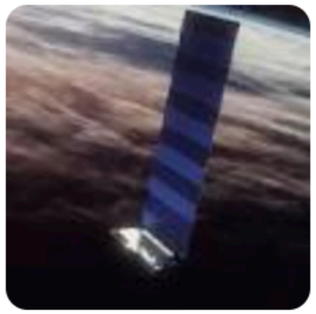
Recent news on ISLs

SN SpaceNews

SpaceX adds laser crosslinks to polar Starlink satellites

SpaceX adds laser crosslinks to polar Starlink satellites. by Jeff Foust — January 26, 2021. The 10 Starlink satellites launched to polar orbit Jan. 24 feature ...

3 weeks ago



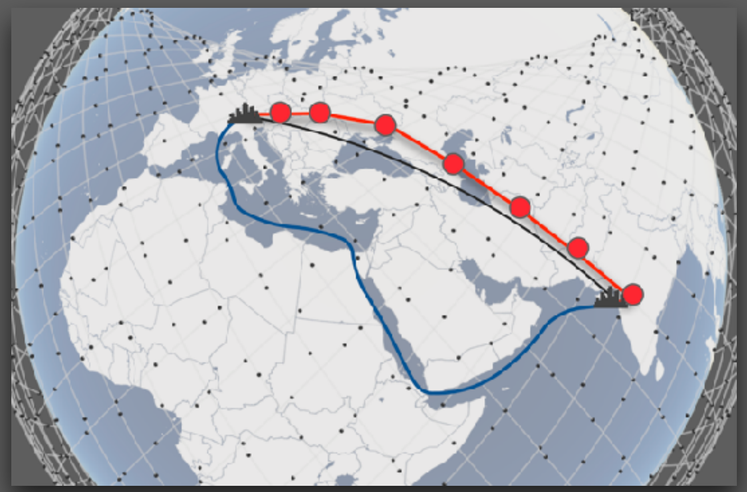
Uncertainties

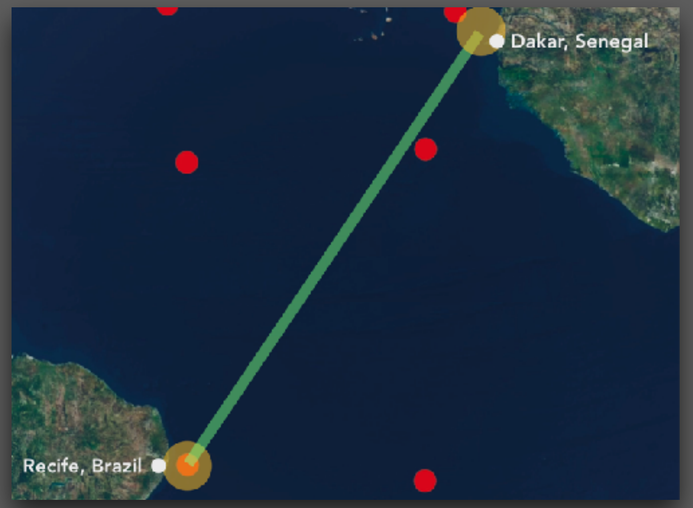
- ISL capacities?
- Pointing, acquisition, and tracking
- Topology
- OneWeb's no-ISL design

Network topology design at 27,000 km/hour

Debopam Bhattacherjee, Ankit Singla
Department of Computer Science, ETH Zürich

How do we interconnect satellites?





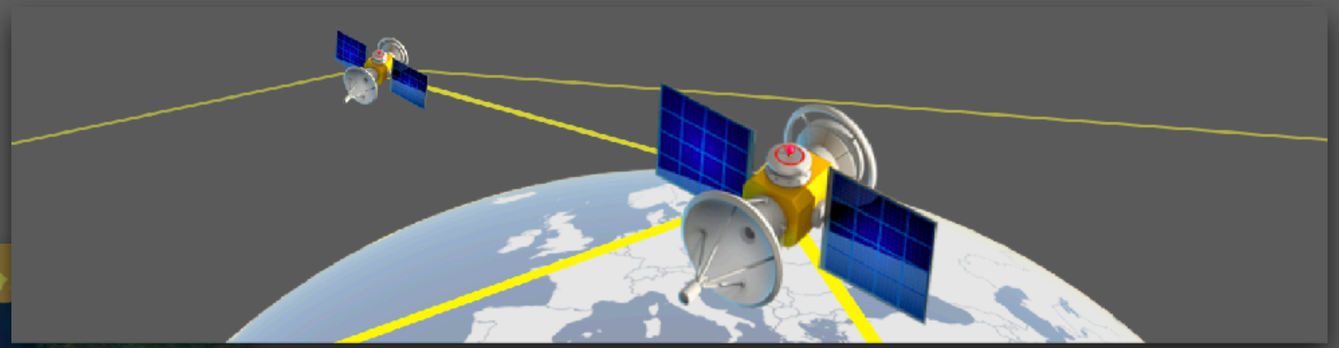
Network topology design at 27,000 km/hour

Debopam Bhattacherjee, Ankit Singla
Department of Computer Science, ETH Zürich

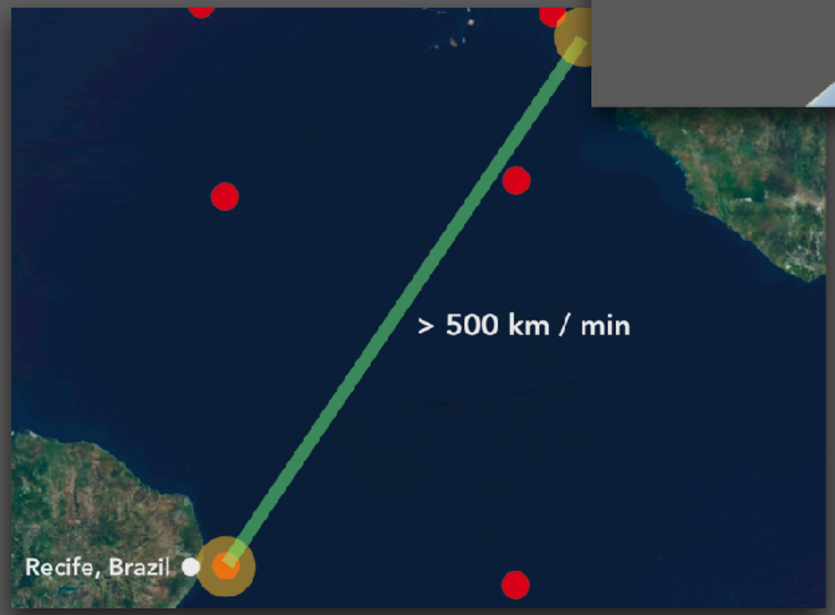
CoNEXT 2019, IRTF Applied Networking Research Prize 2020

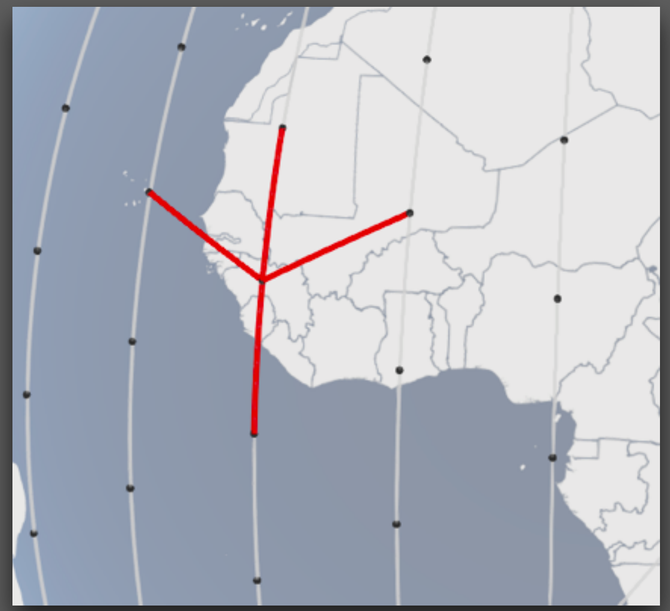
Key constraints

Link setup times



System dynamics





Max. no of links per satellite

Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition
- Ground-satellite connectivity is range-bounded
- +Grid is the baseline

Work on trajectory design is under review; available on request.

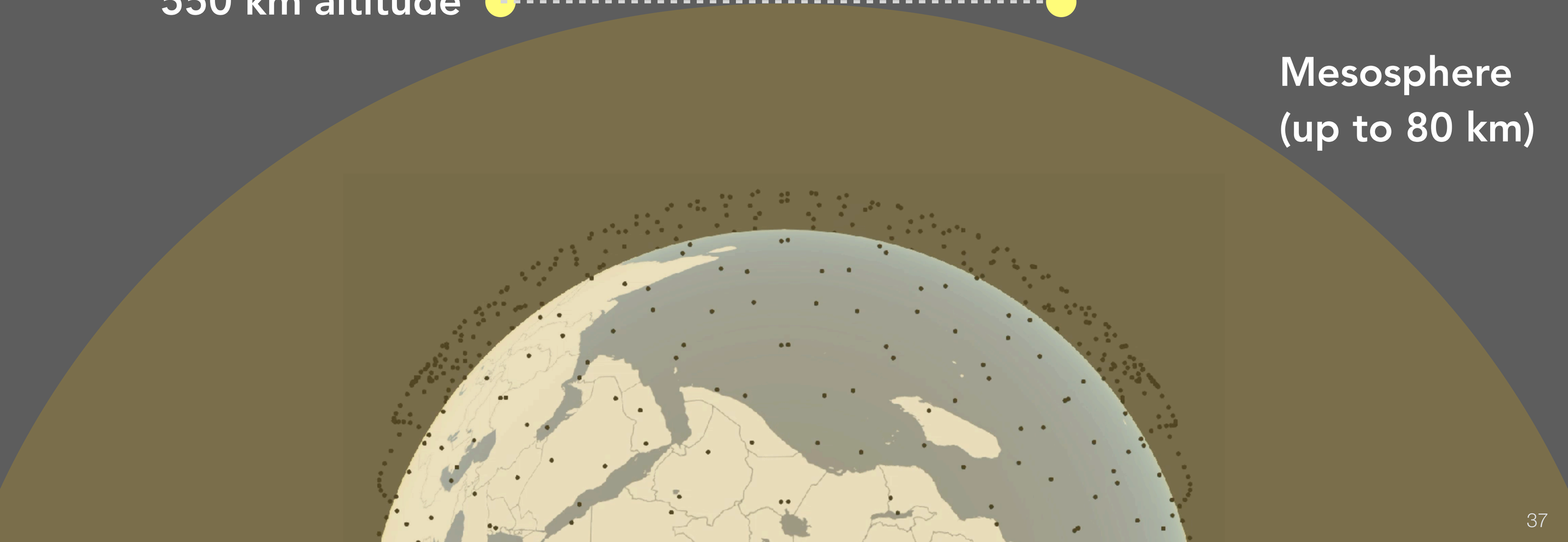
+Grid

Can use much longer links

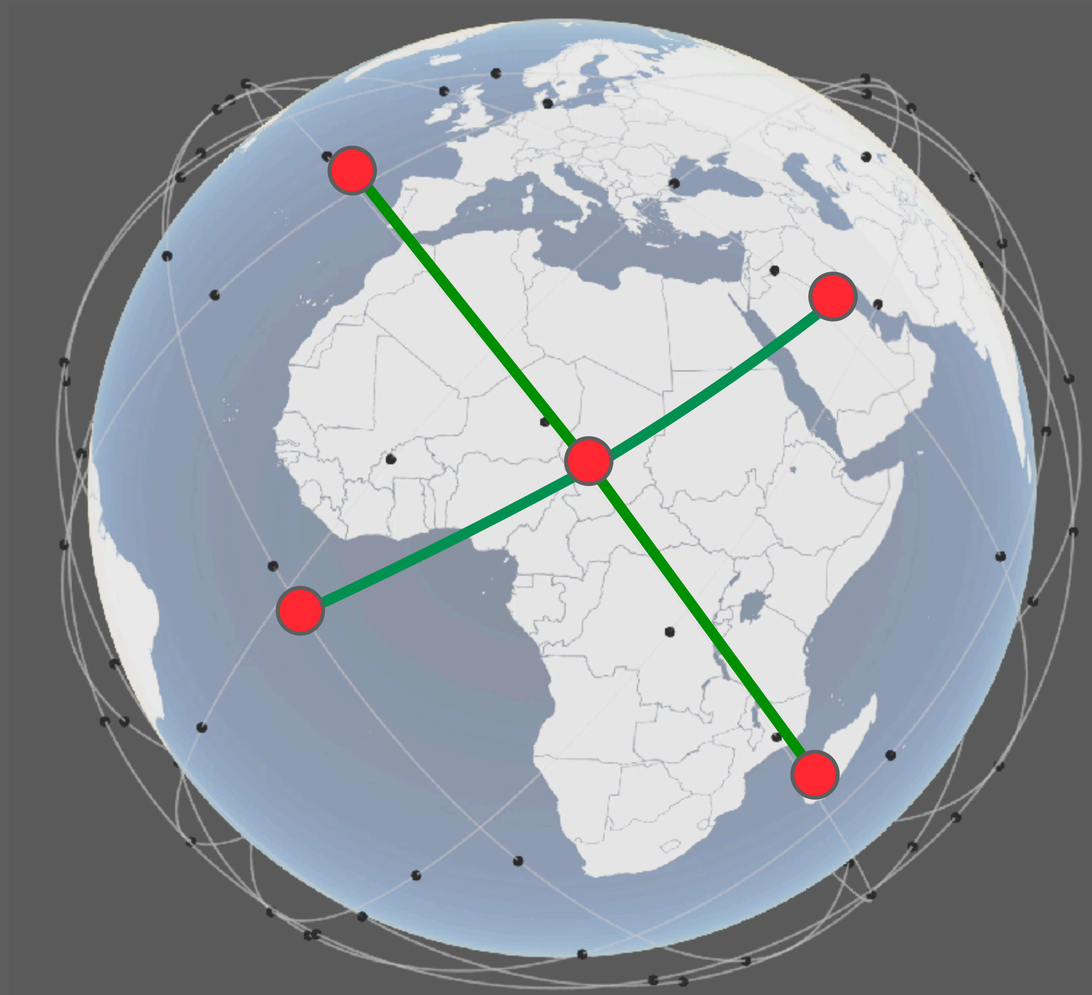
5014 km inter-satellite link

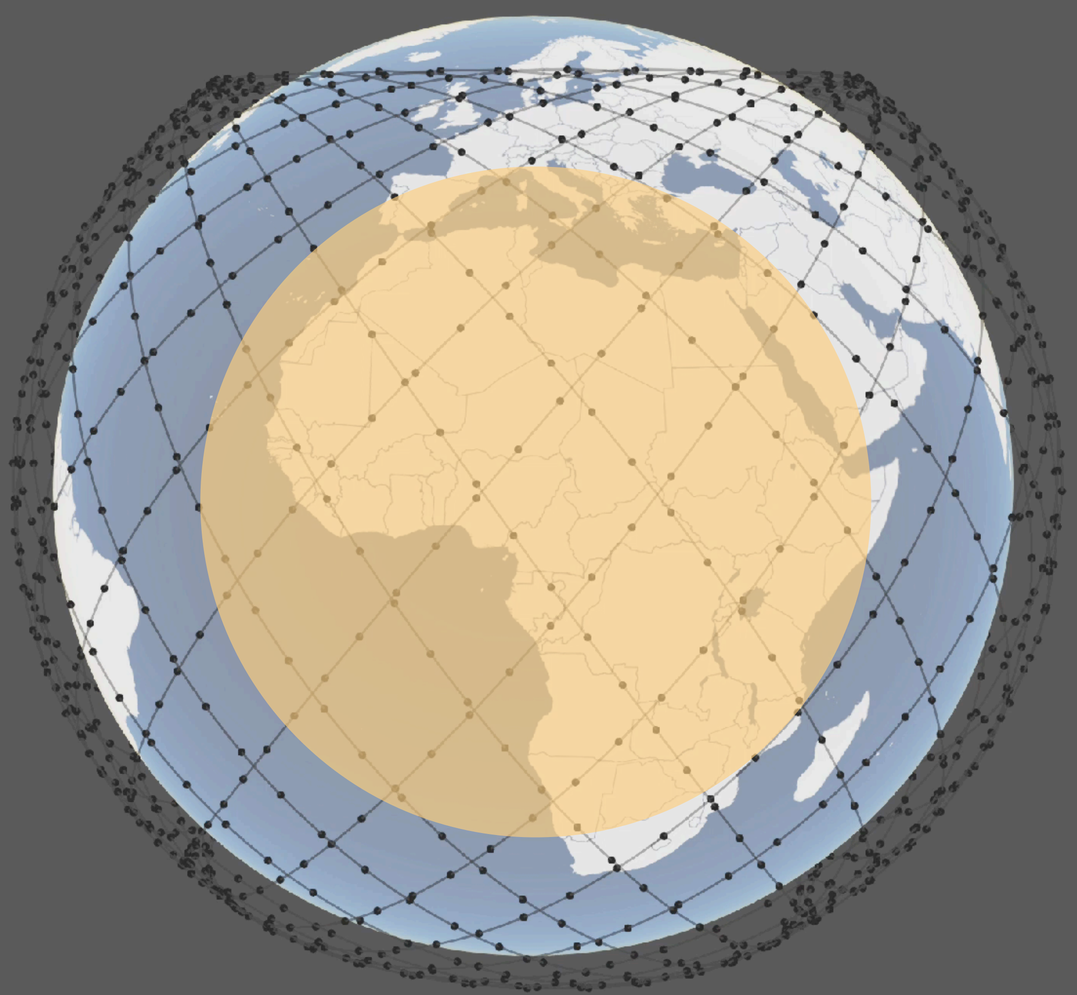
550 km altitude

Mesosphere
(up to 80 km)



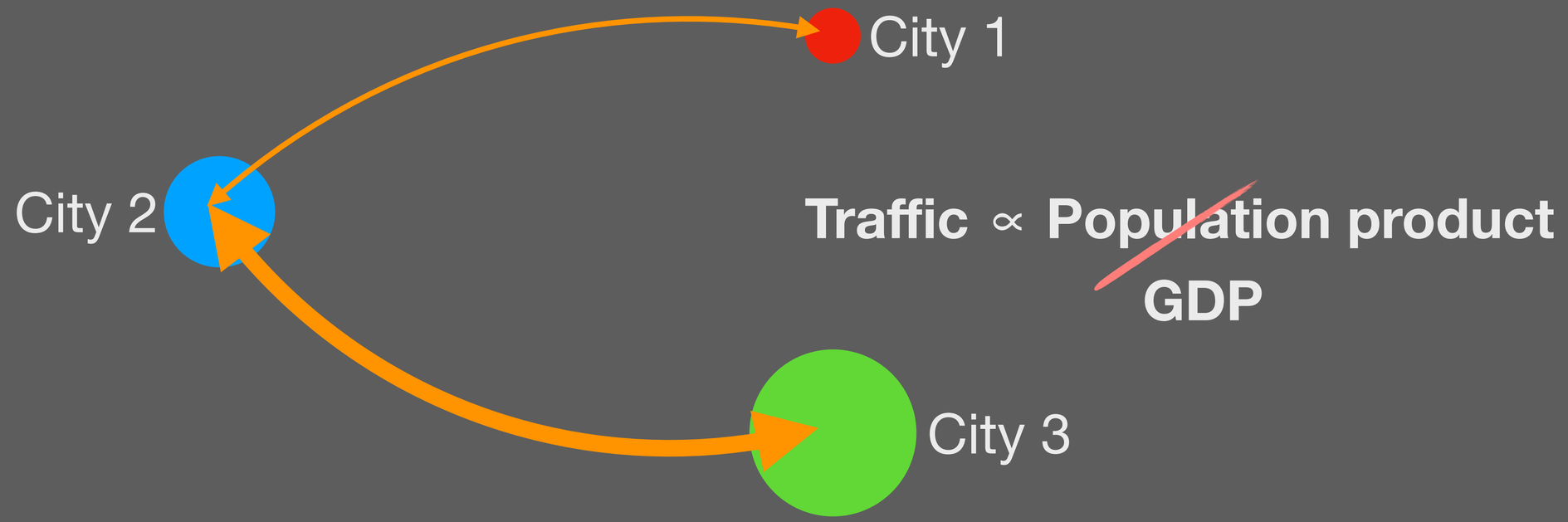
Much larger design space



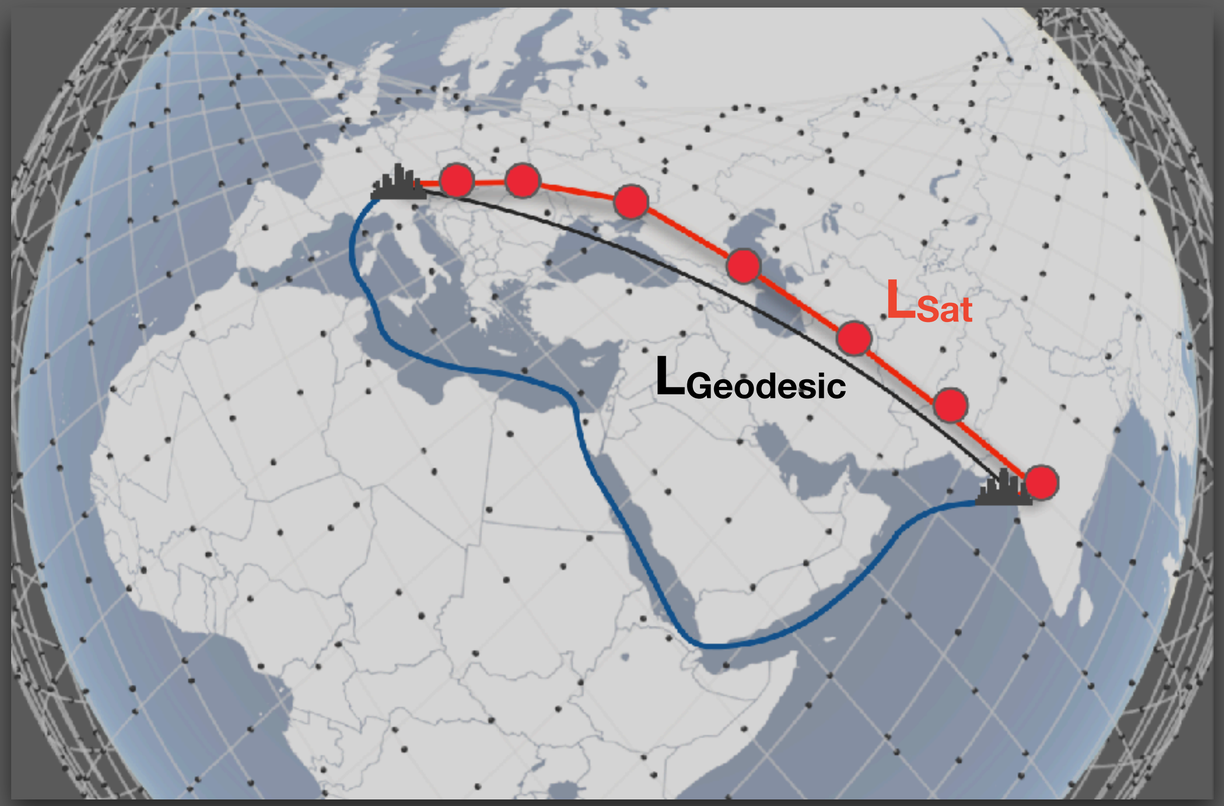


What do we optimize for?

Traffic matrix



Metrics



$$\text{Stretch} = \frac{L_{Sat}}{L_{Geodesic}}$$

Hop count

M = α Stretch + Hop count

Why aren’t obvious / traditional methods enough?

Why not use Integer programming?

For 1000 cities, would take ~10^{29} days

One minute apart ~91% links are different

ISL setup times: few seconds to 10s of seconds

Why not use random graphs?

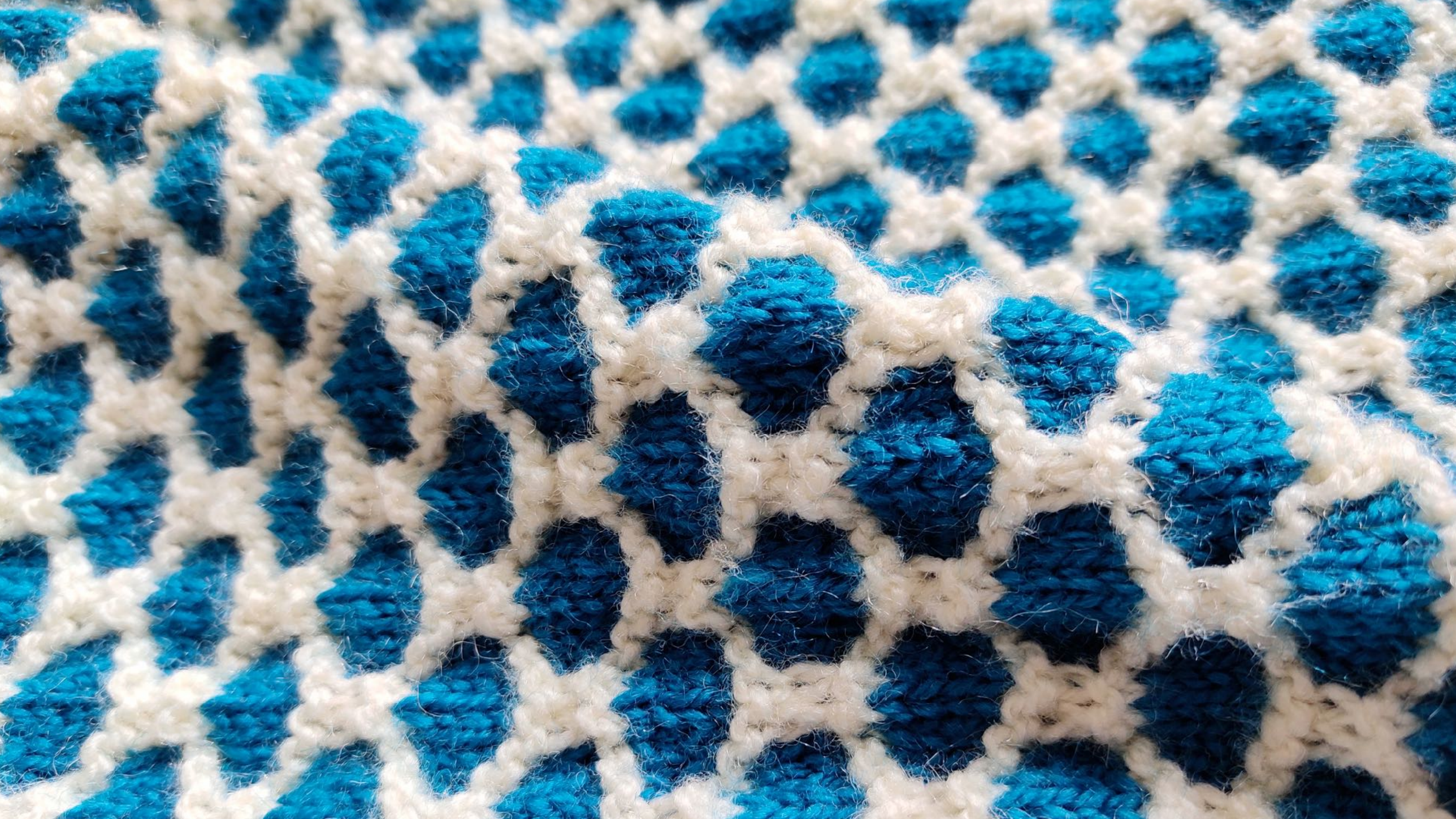
In 5 mins, 19% of links become infeasible

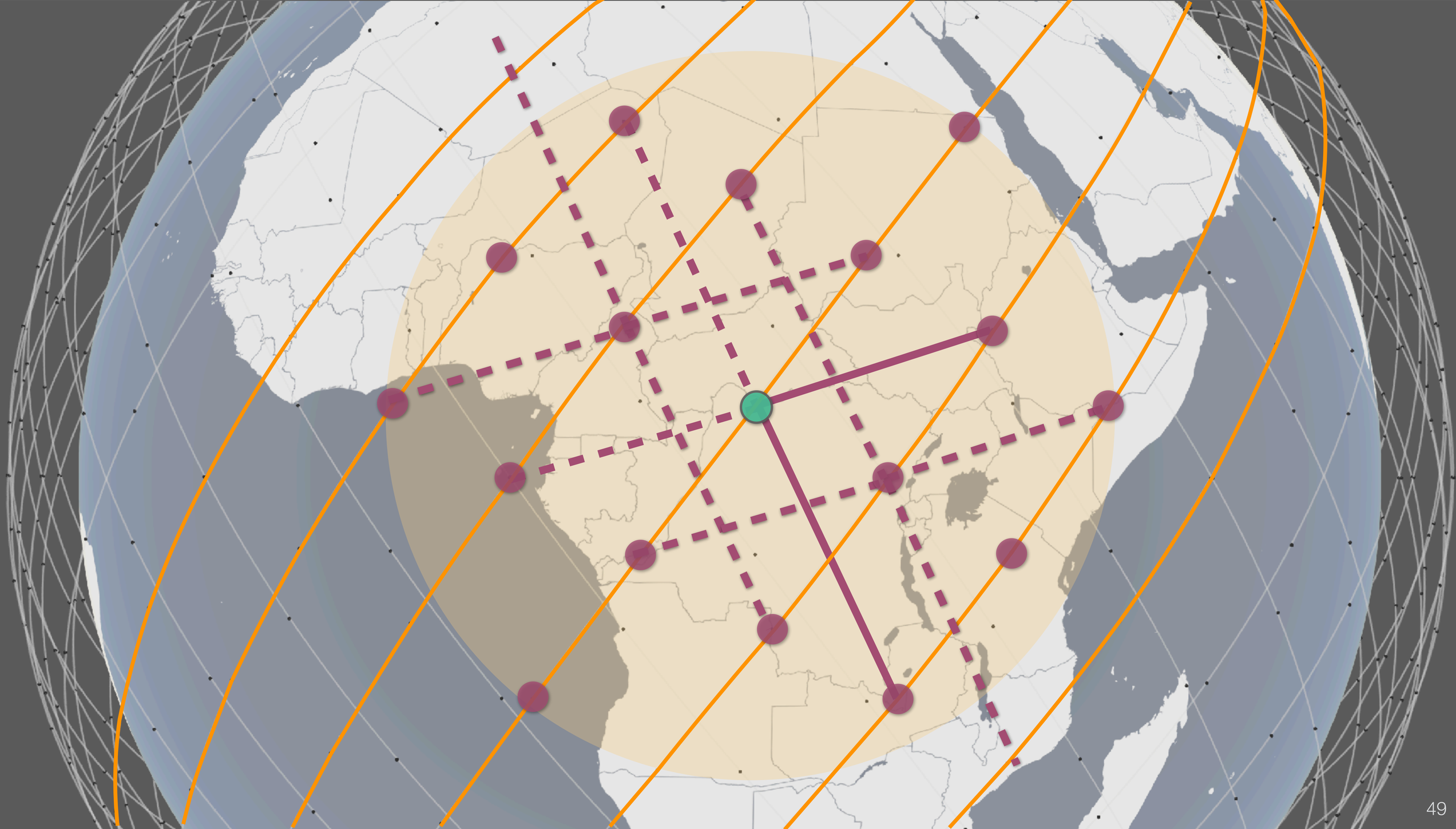
Cannot optimize for arbitrary objectives

Our approach


pexels.com


pexels.com

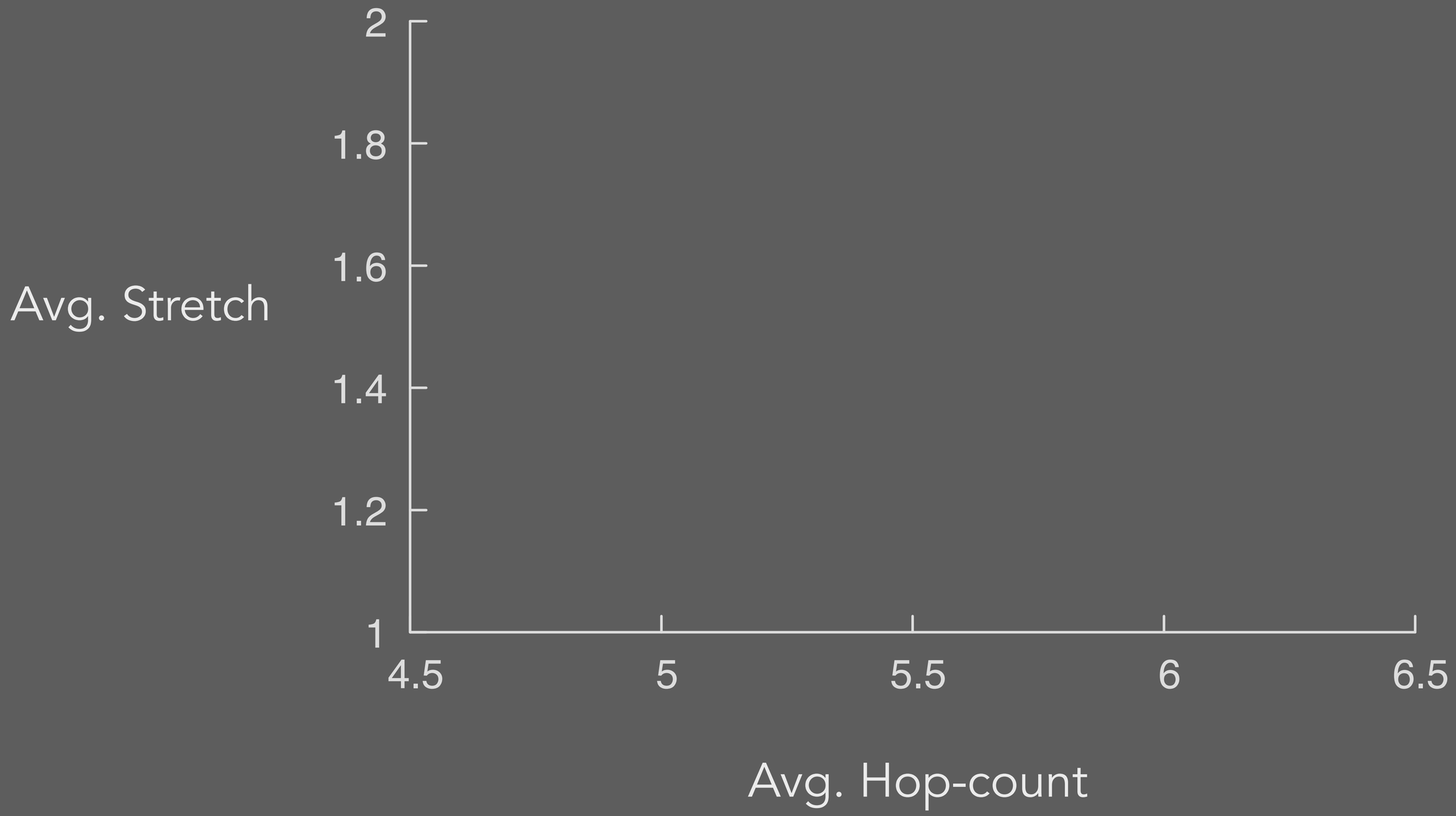




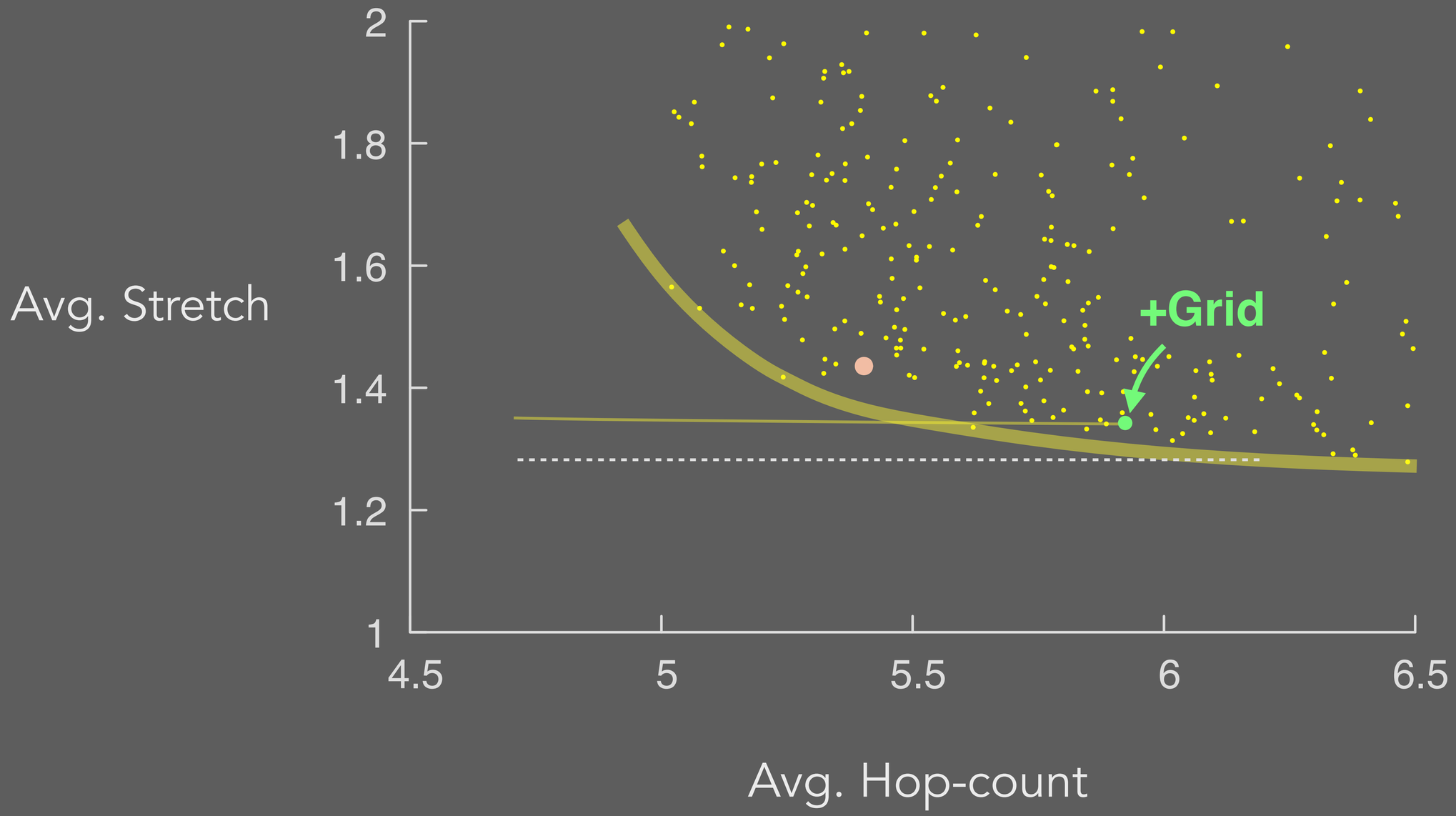
Constellations explored

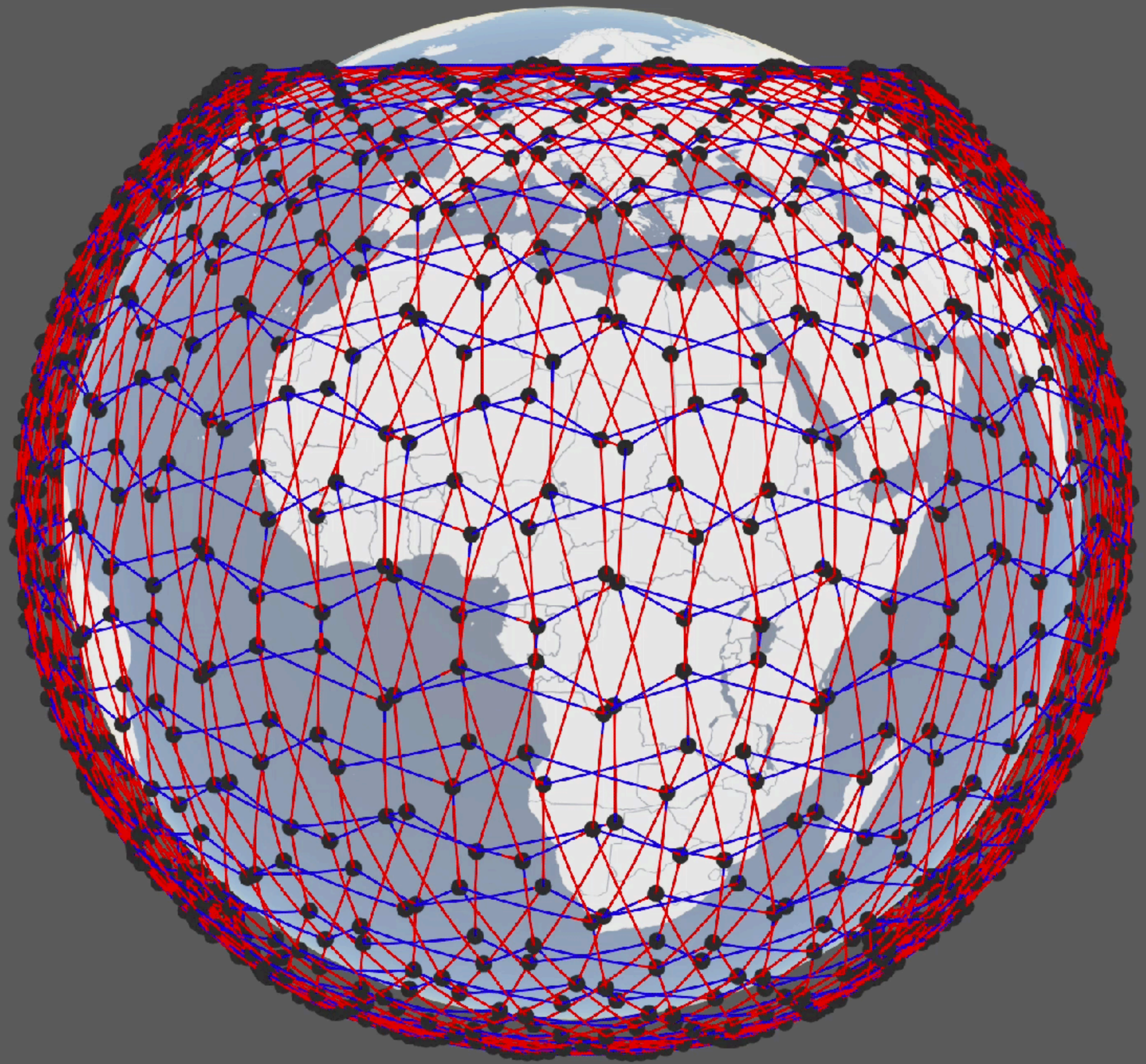
- Uniform 40x40 (40^2) 53° inclination, 550 km altitude
- SpaceX **Starlink** Phase 1 (24x66, 53°, 550 km) [Configuration changed recently]
- Amazon **Kuiper** Phase 1 (34^2, 51.9°, 630 km)

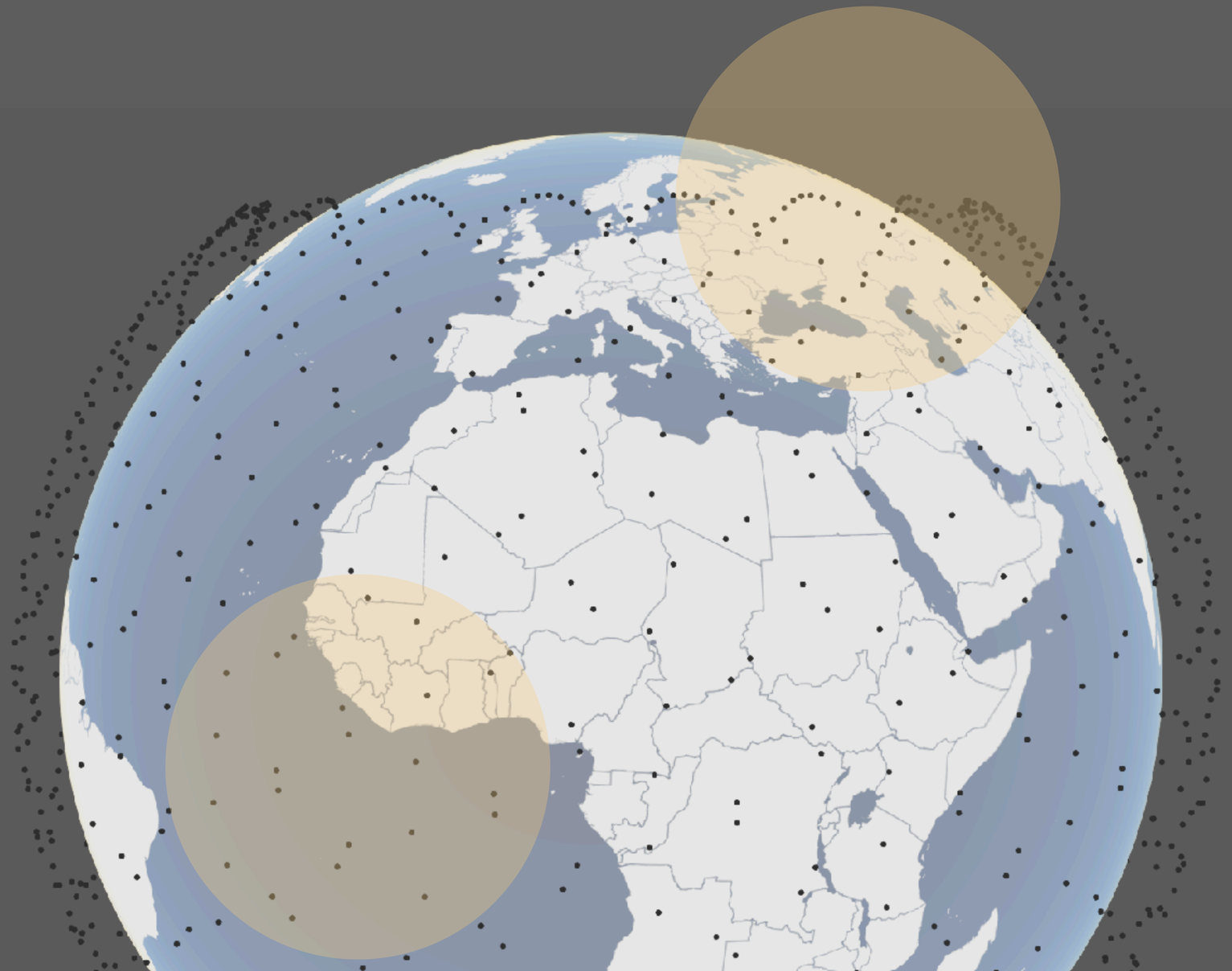
A large number of design points



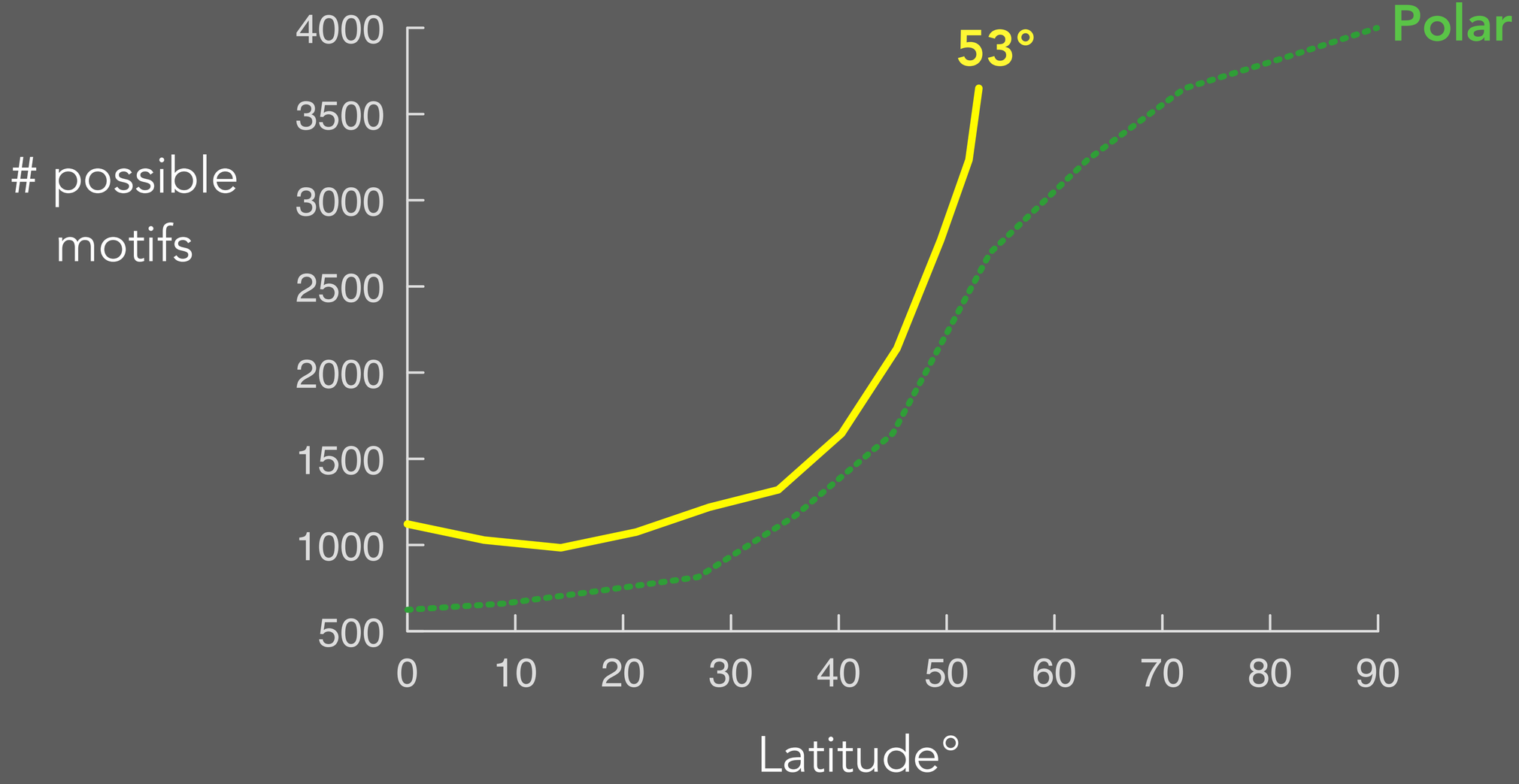
+Grid is a low-efficiency motif

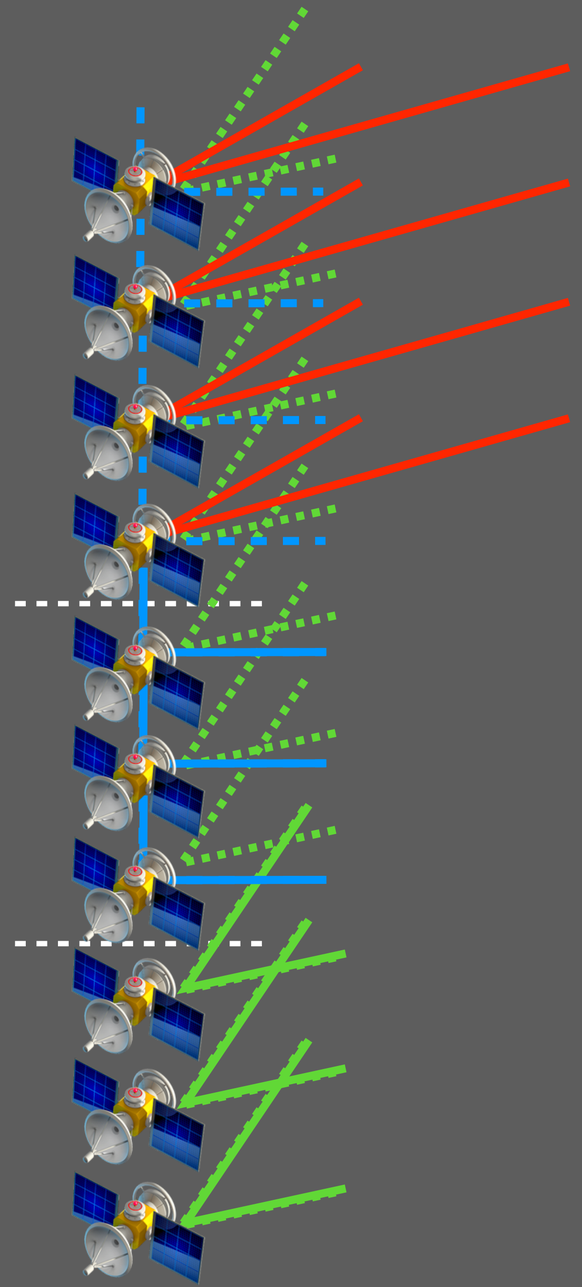


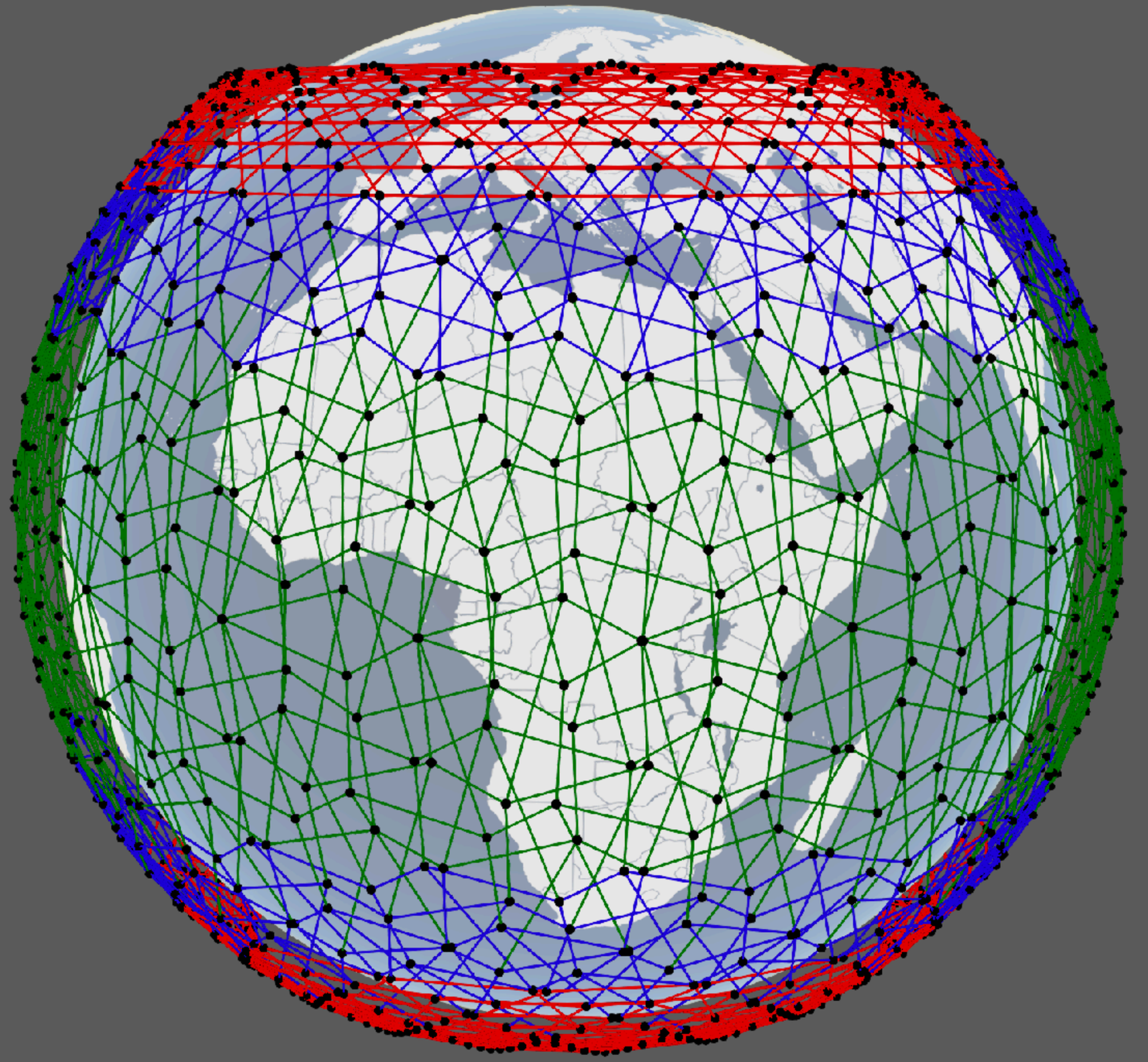




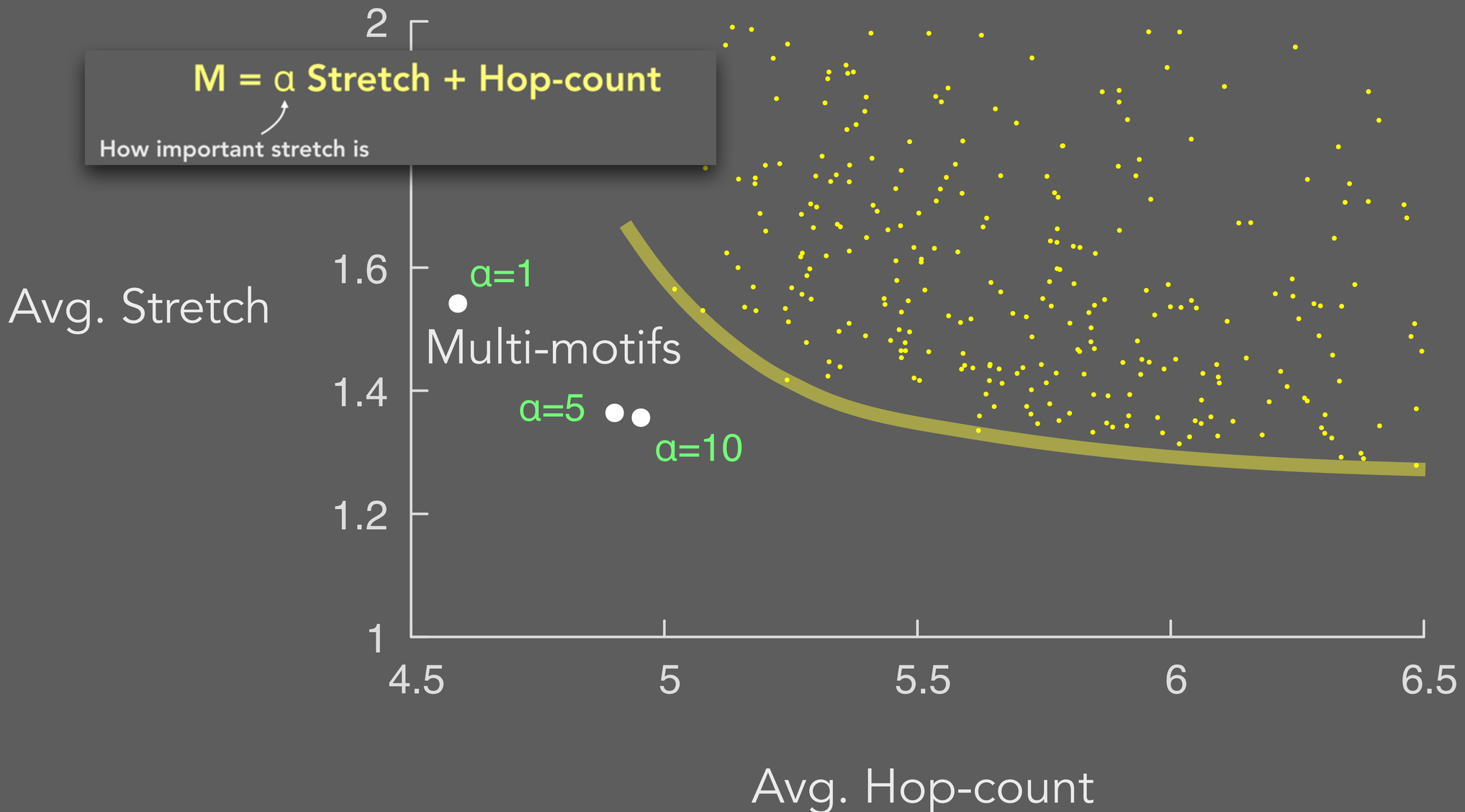
More options at higher latitudes







Beyond single motif frontier



Performance improvements

		Severely power-limited links
Starlink	54%	40%
Kuiper	45%	4%
40^2	48%	7%

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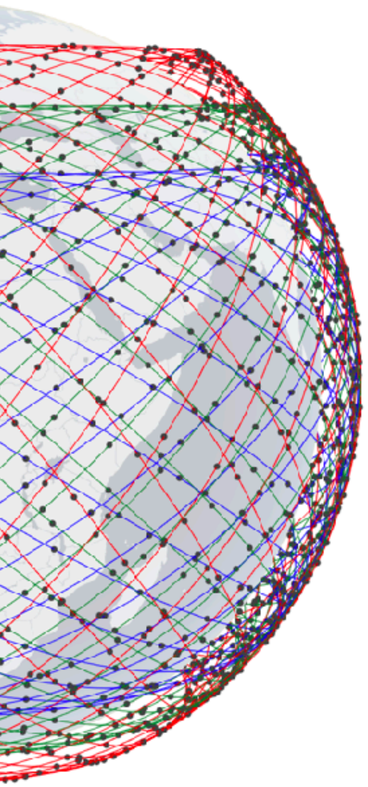
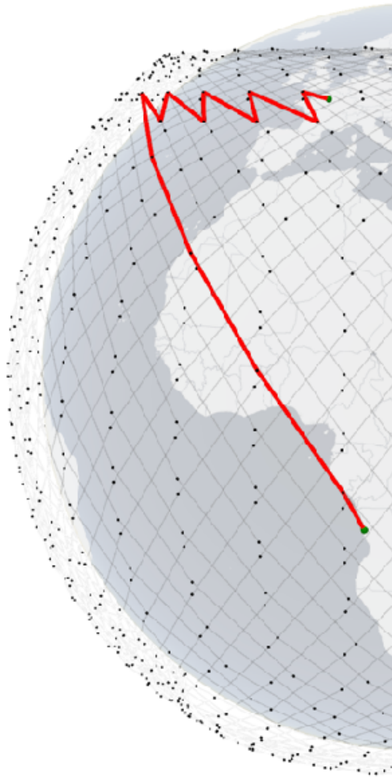


Hypatia

A simulation and visualization tool for satellite networks



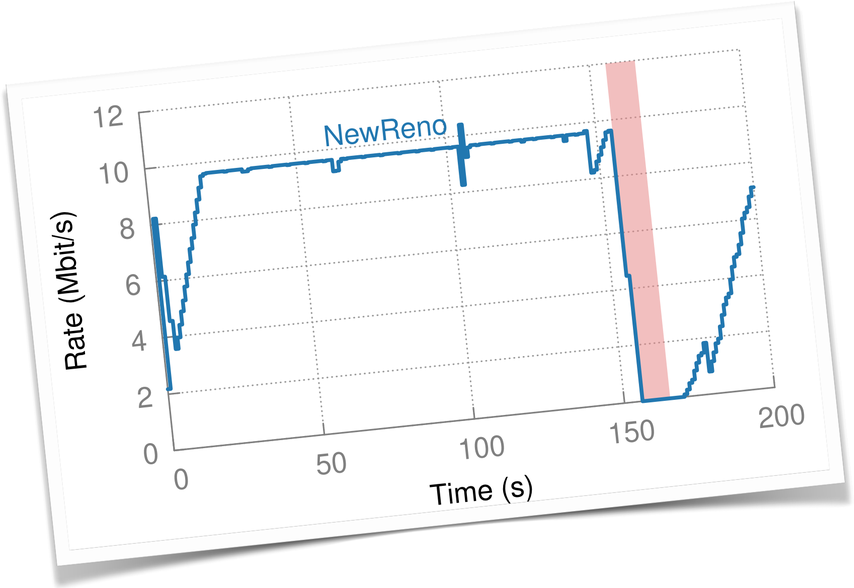
Exploring the "Internet from space" with HYPATIA

Simon Kassing*, Debopam Bhattacherjee*, André Baptista Águas, Jens Eirik Saethre, Ankit Singla
ETH Zürich

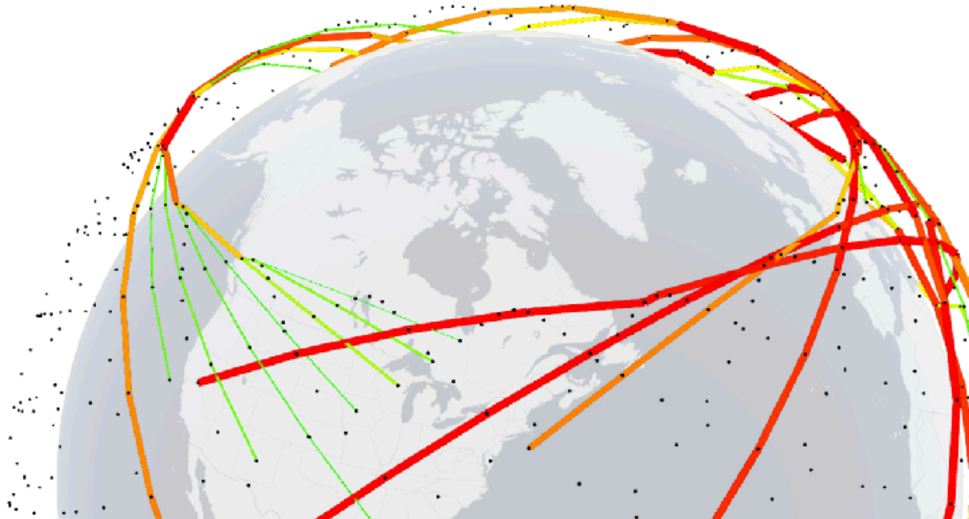
IMC 2020, Best Paper Award

*equal contribution

Satellite trajectories
Network topology
Ground stations
Traffic flows



Extends ns-3
LEO dynamics
Precomputed states
Cesium 3D library



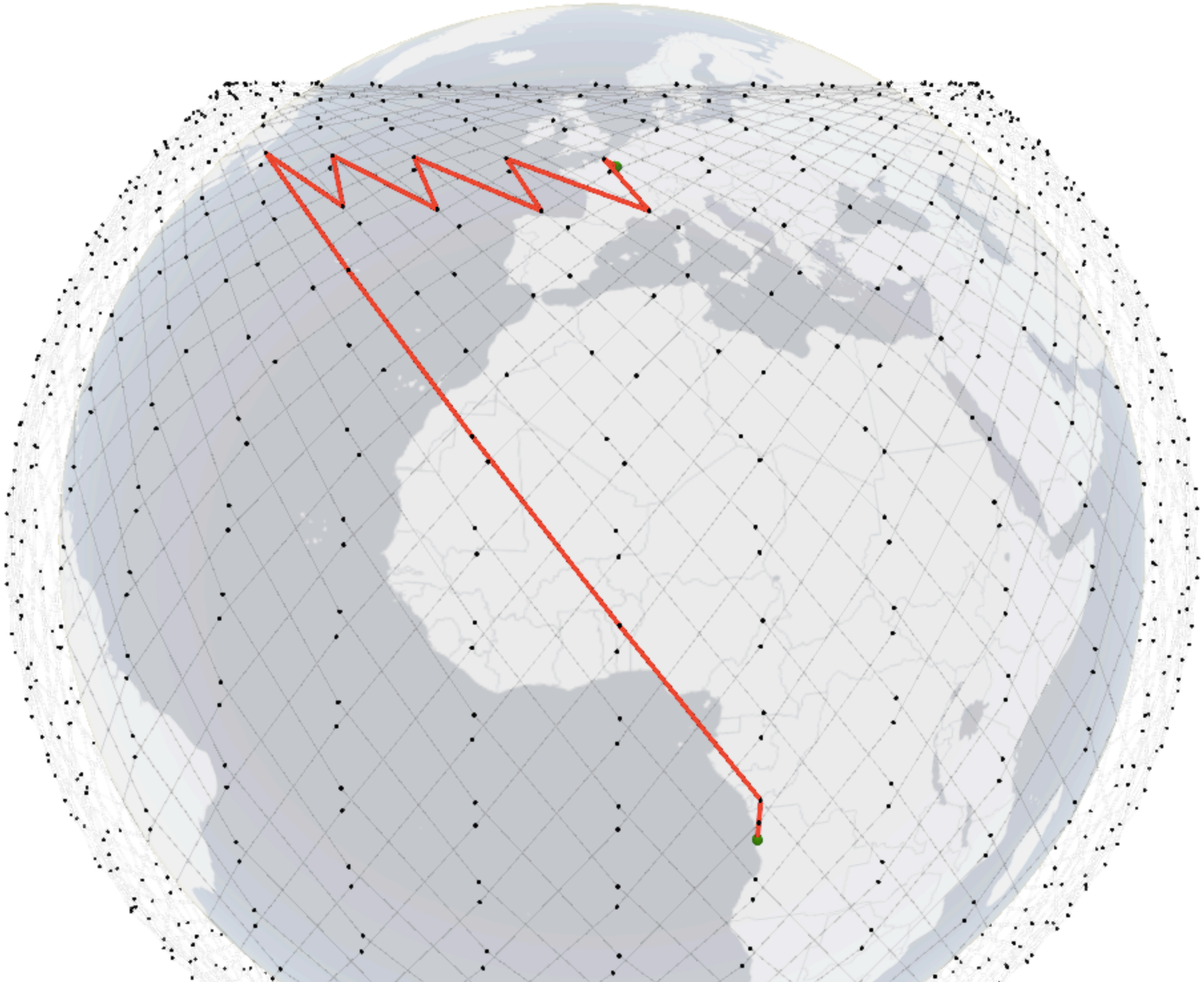
Experiment setup

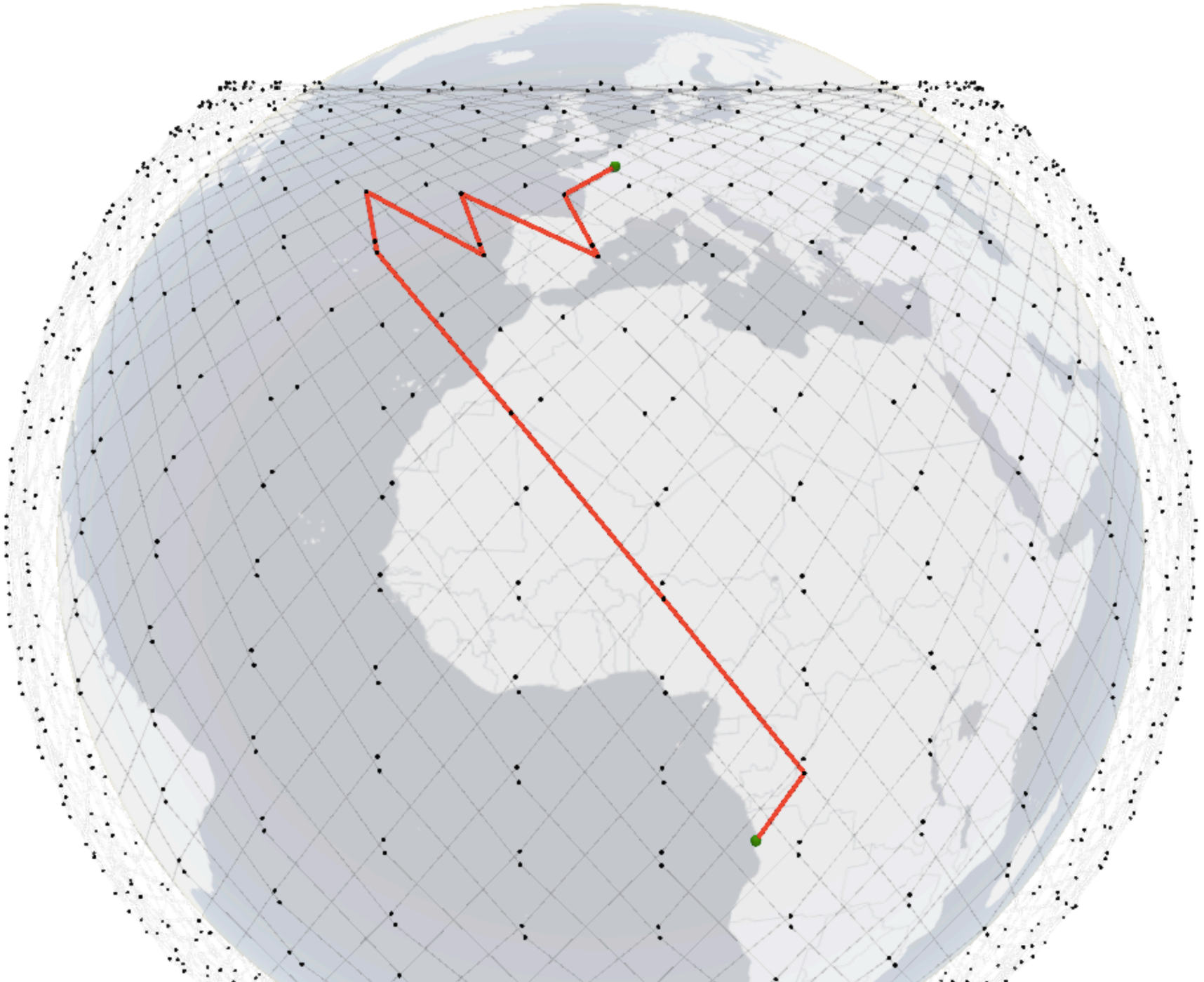
First shell of Kuiper

- 630 km height
- 34 orbits, each with 34 satellites
- 51.9° inclination

Connectivity is +Grid, routing is shortest path

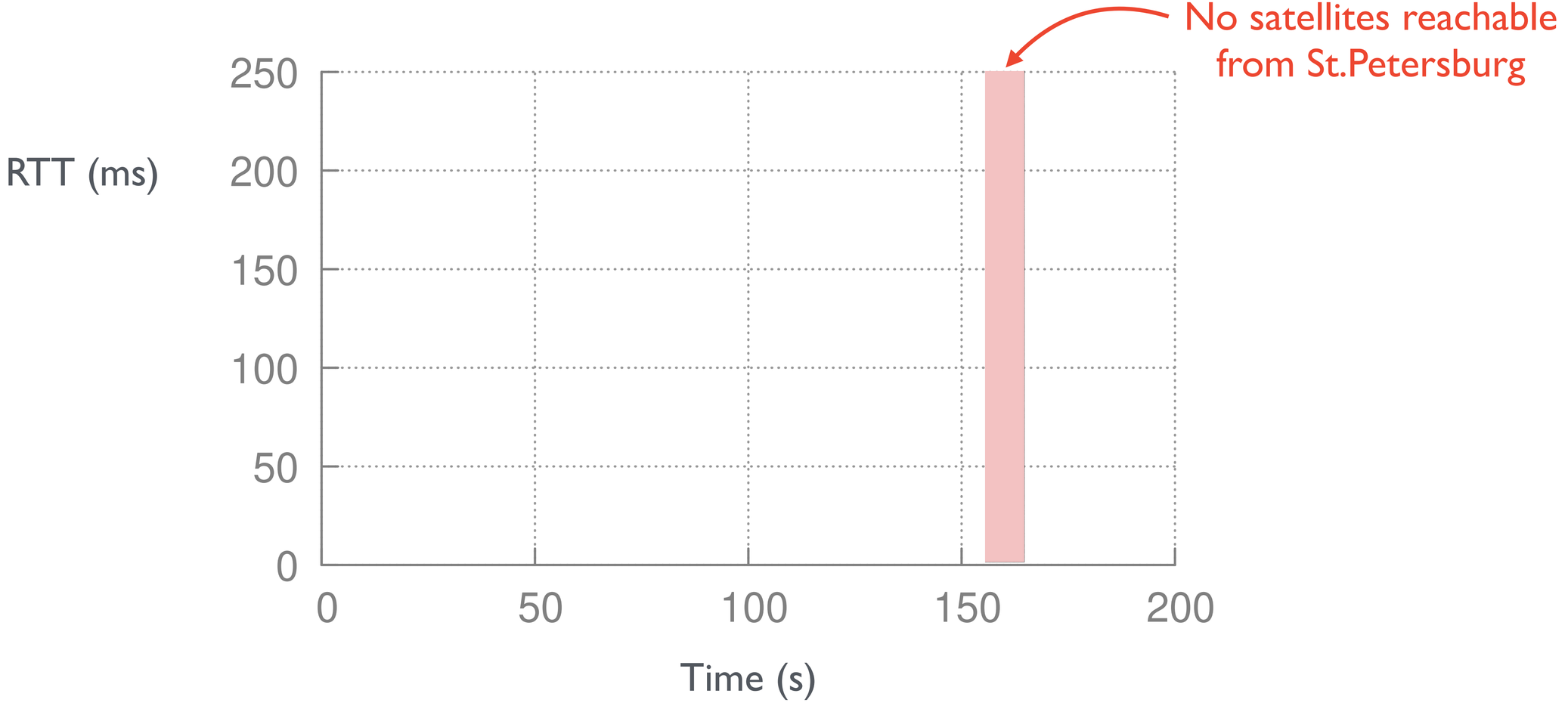
Ground stations in top-100 most populous cities





RTT fluctuation: Rio de Janeiro to St. Petersburg

This is without any other traffic in the network



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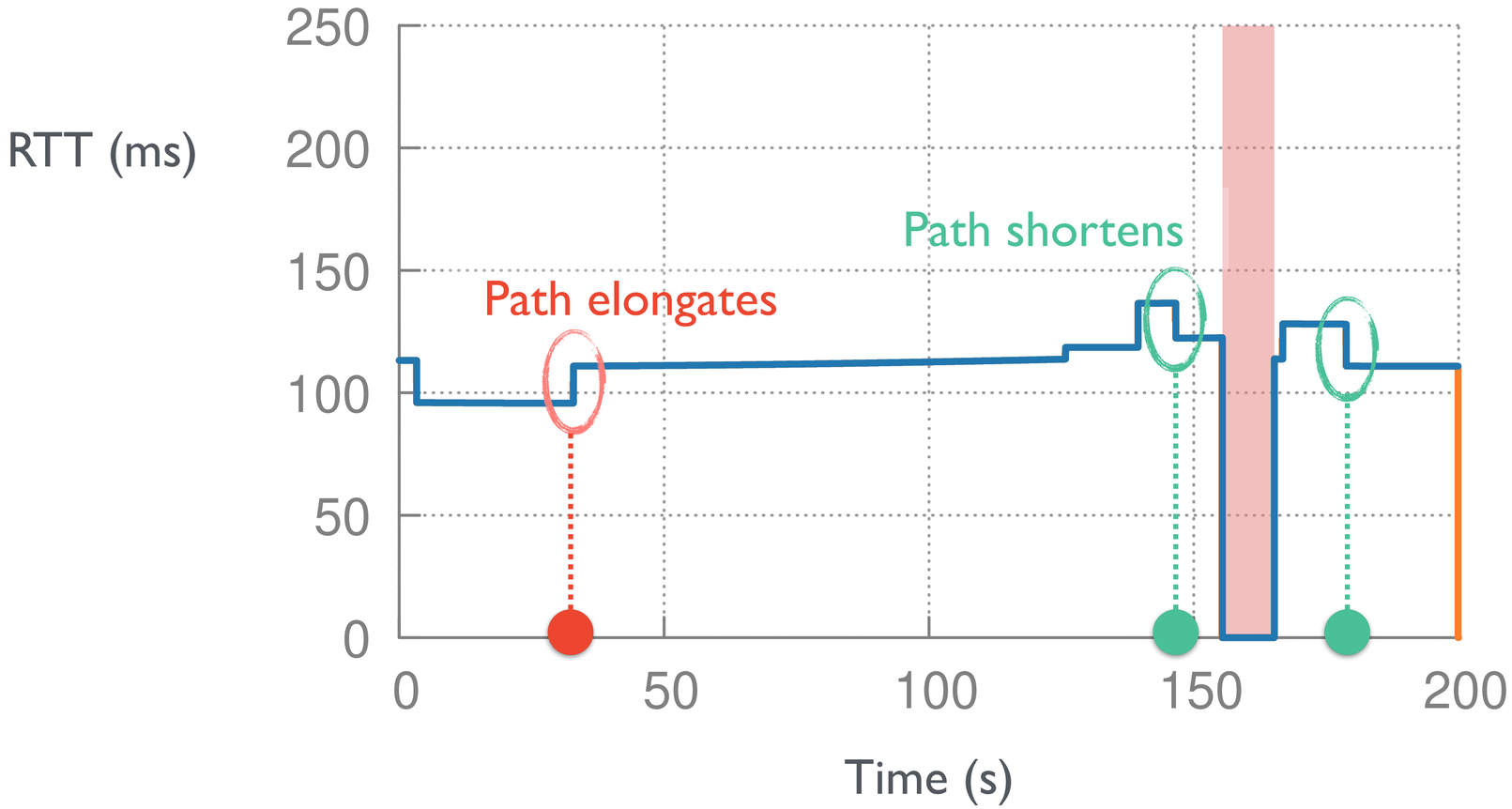
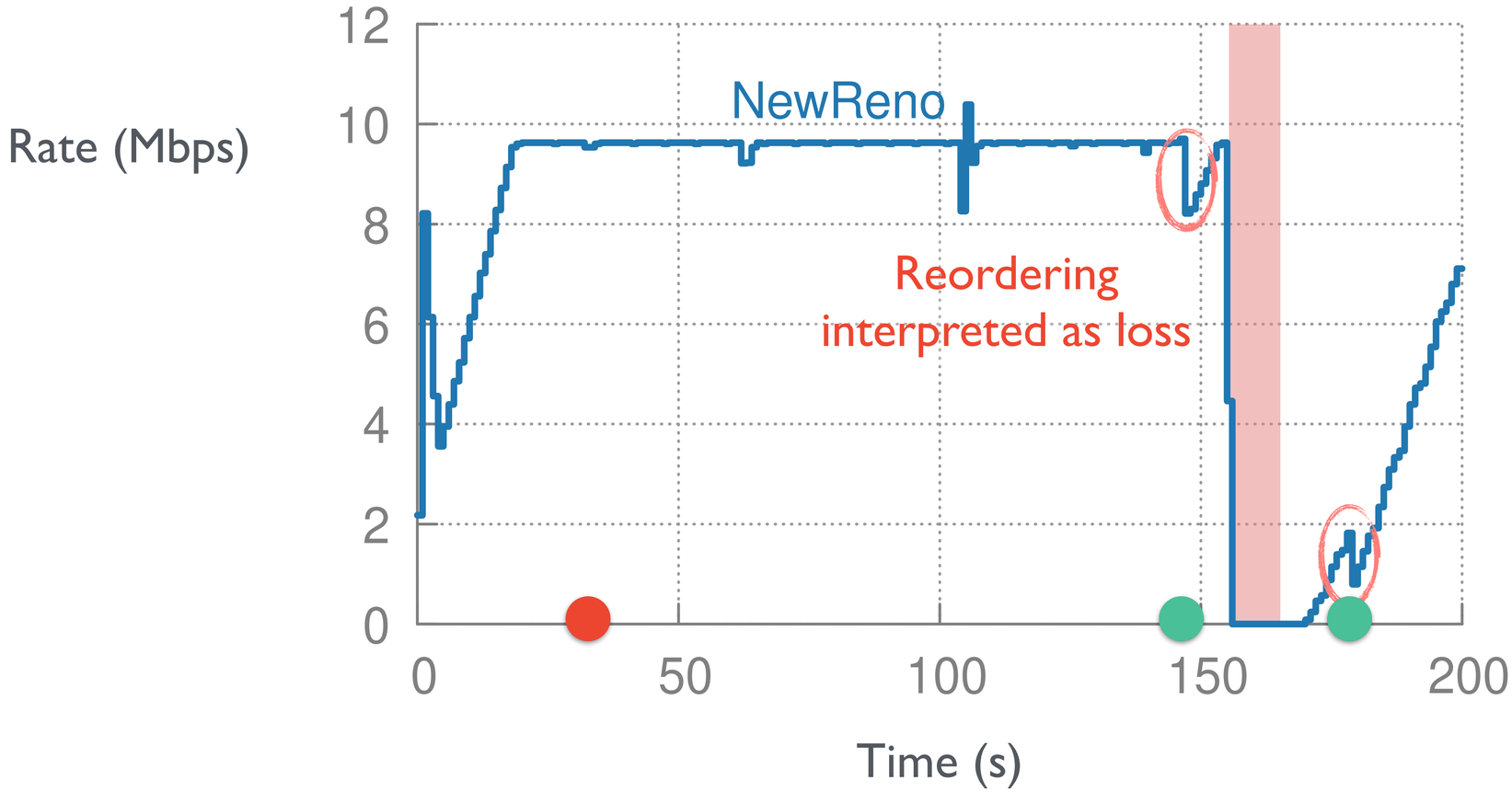


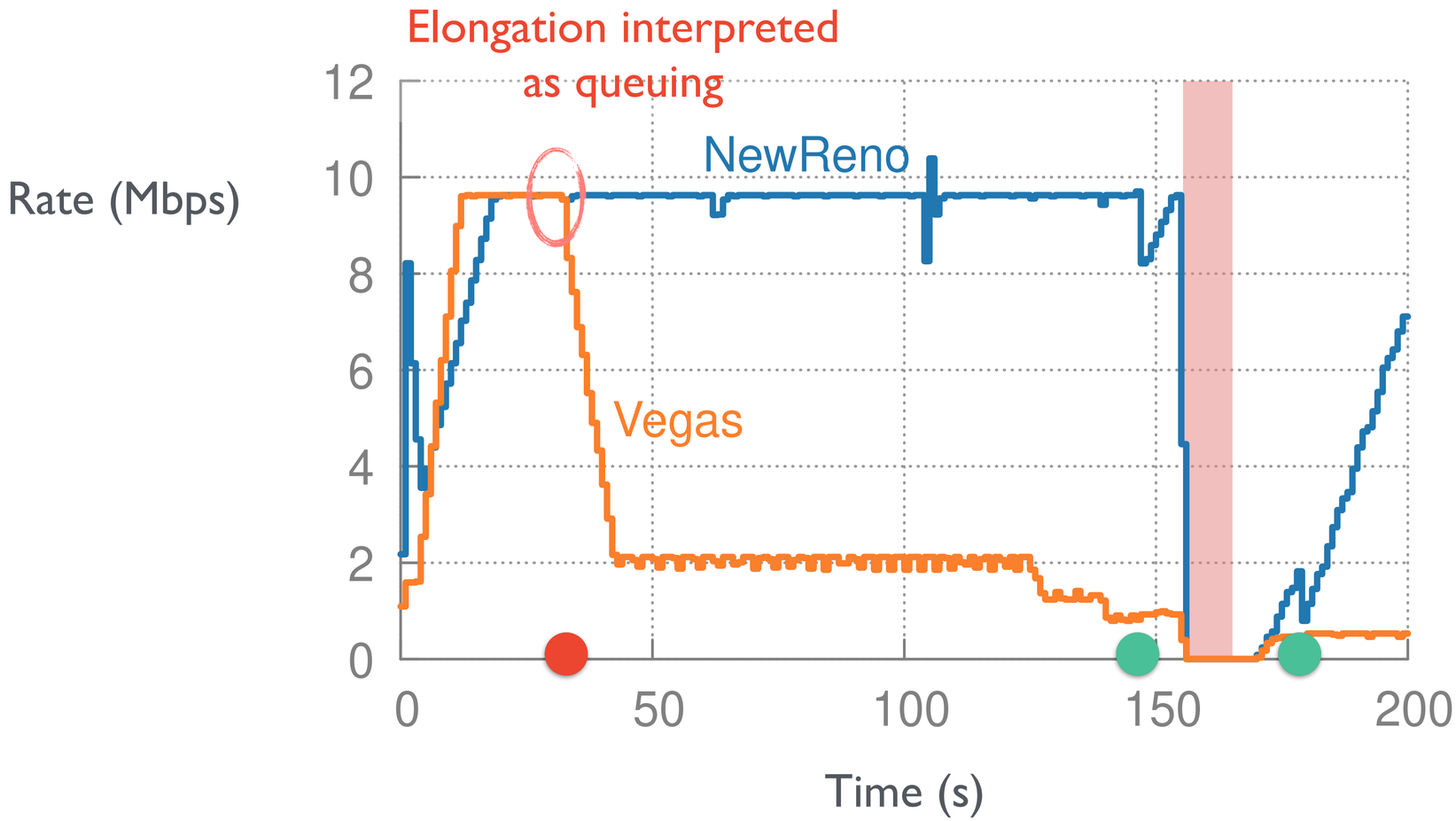
Impact on loss-based CC is small

This is without any other traffic in the network



Delay-based CC suffers

This is without any other traffic in the network



RTT variation and congestion control

RTT changes can hamper delay-based CC

Loss-based CC is also problematic

- Typically, able to maintain high rate
- But unlucky flows can suffer

Further work needed on CC,
especially, analysis of more recent delay-based protocols

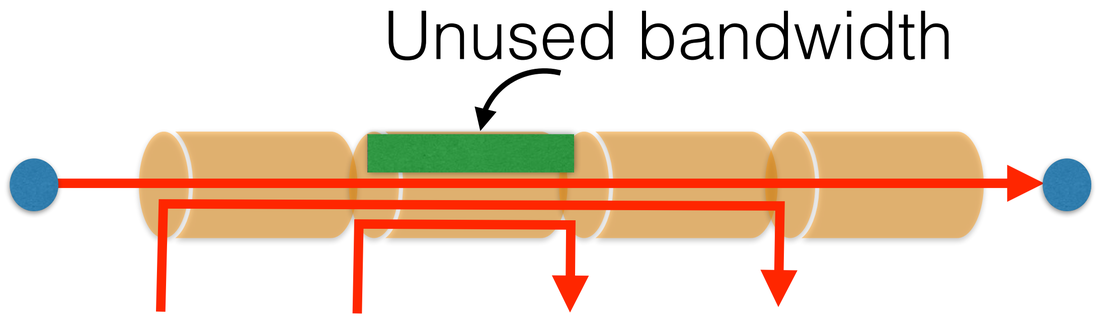
Path structure change has network-wide impact

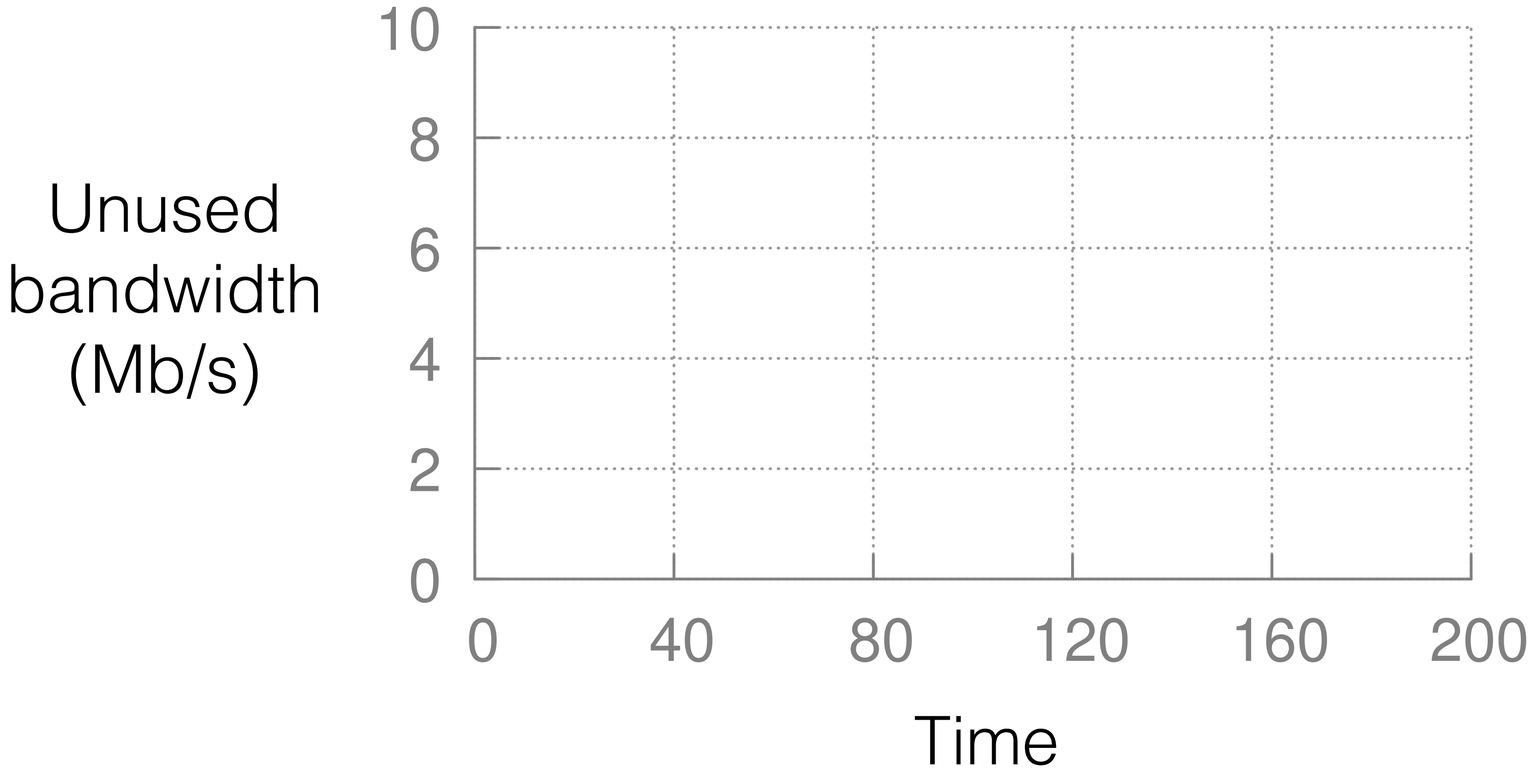
Few link changes per city-pair per minute

But large number of changes network-wide

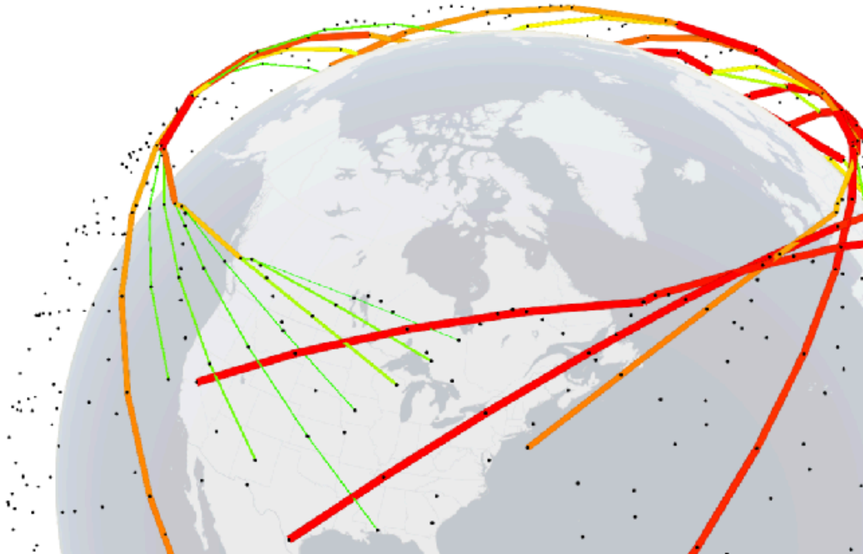
An uncongested link can suddenly see added traffic

Cross-traffic

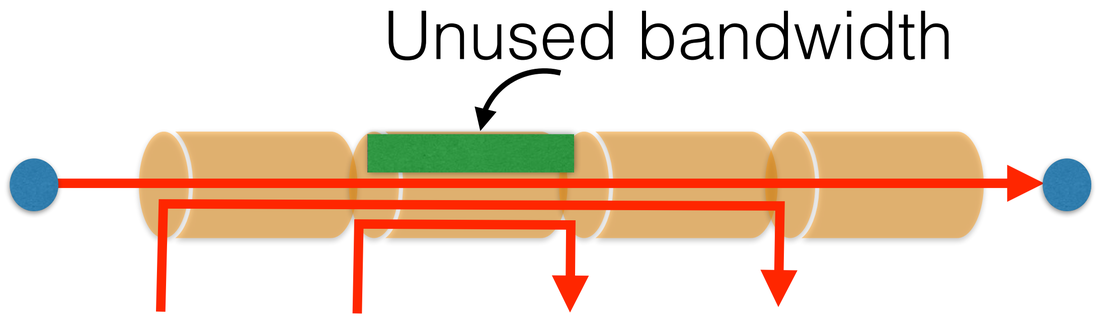


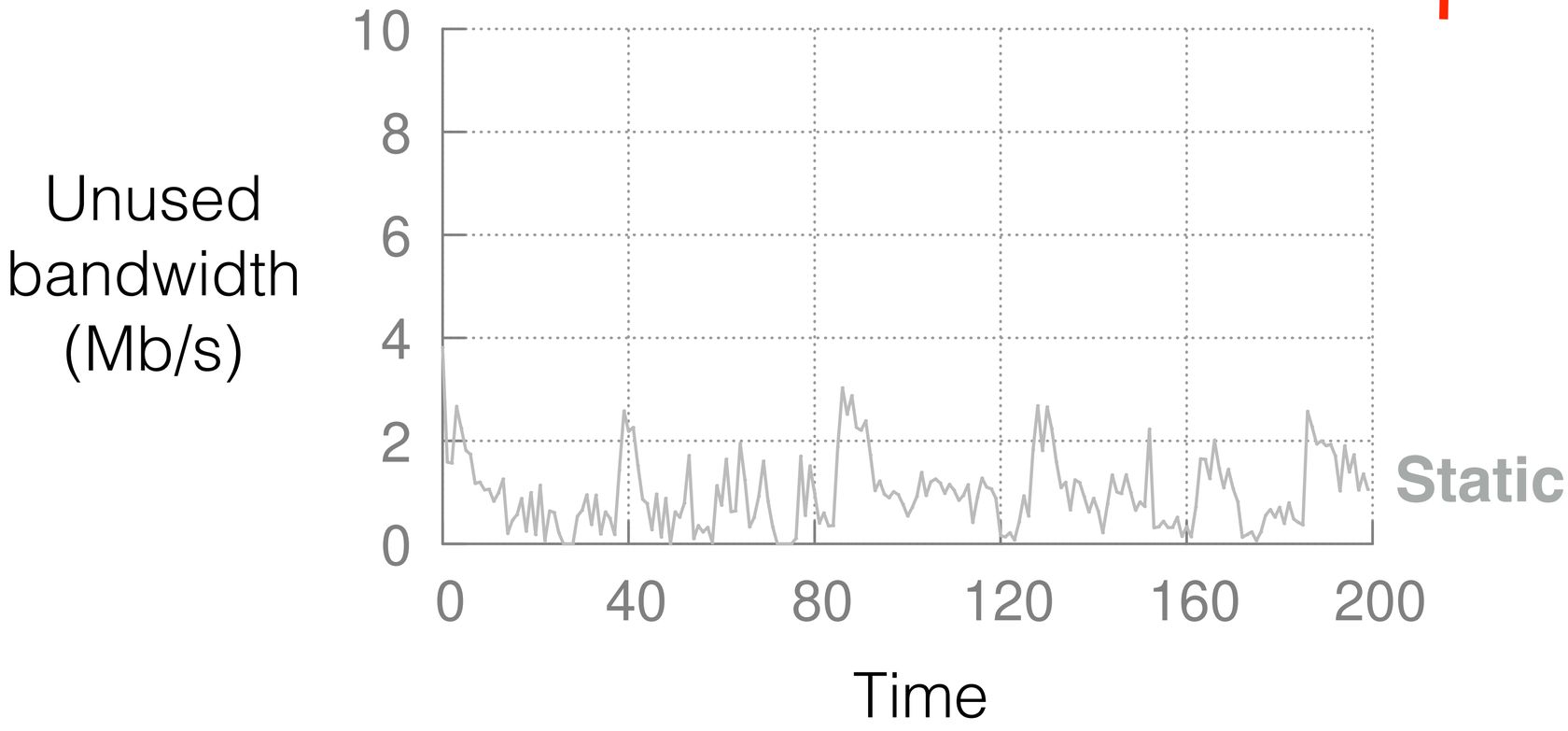


Kuiper K1



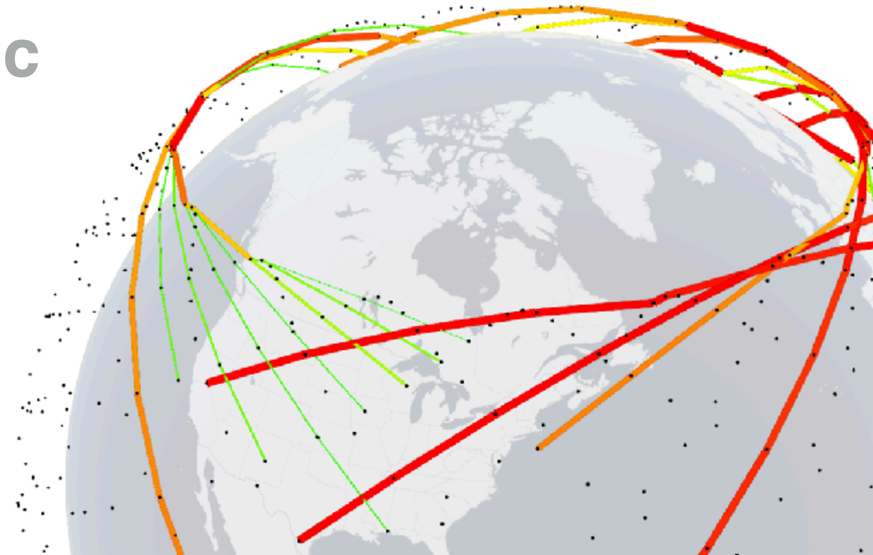
Cross-traffic



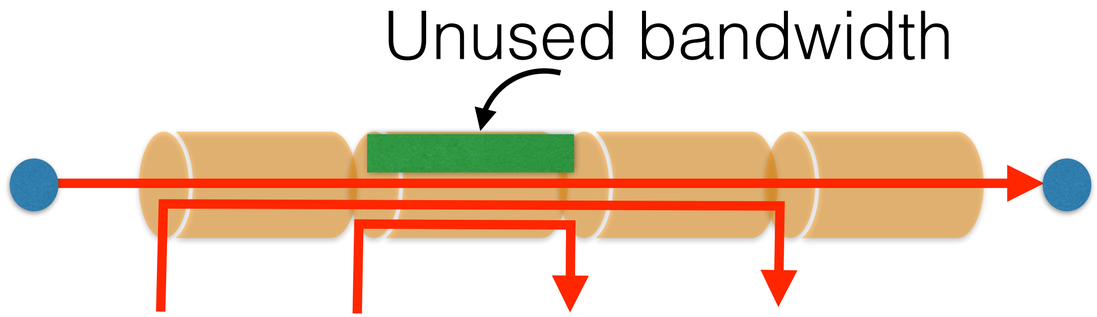


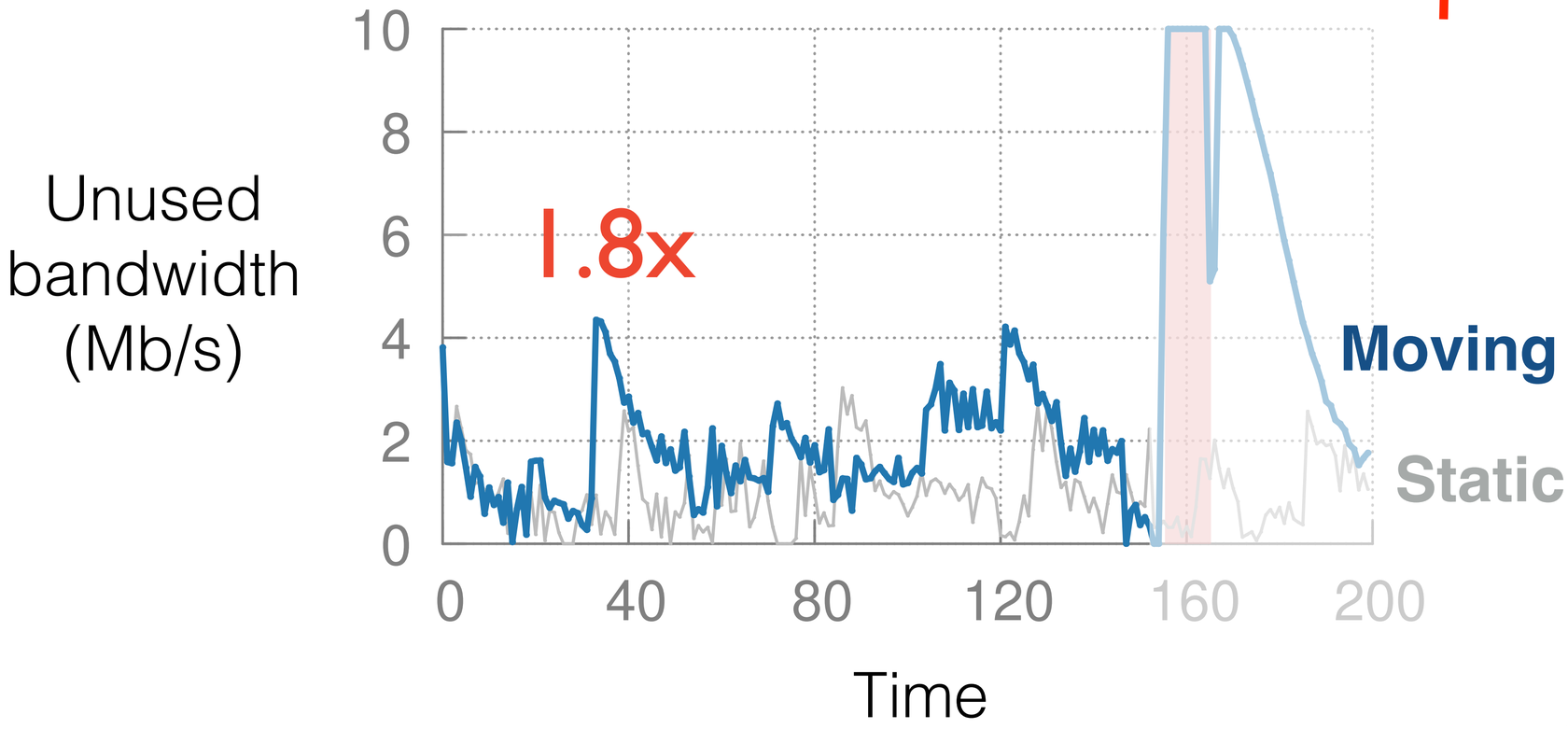
Static

Kuiper K1

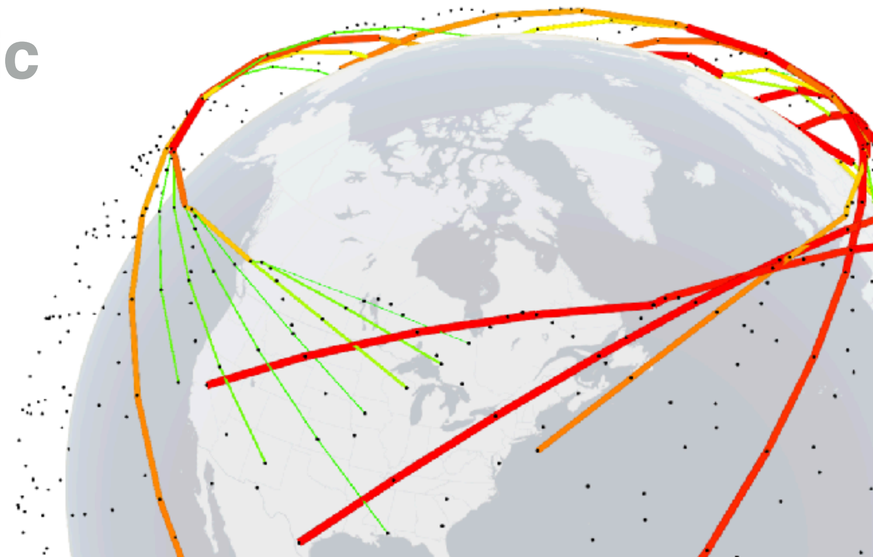


Cross-traffic

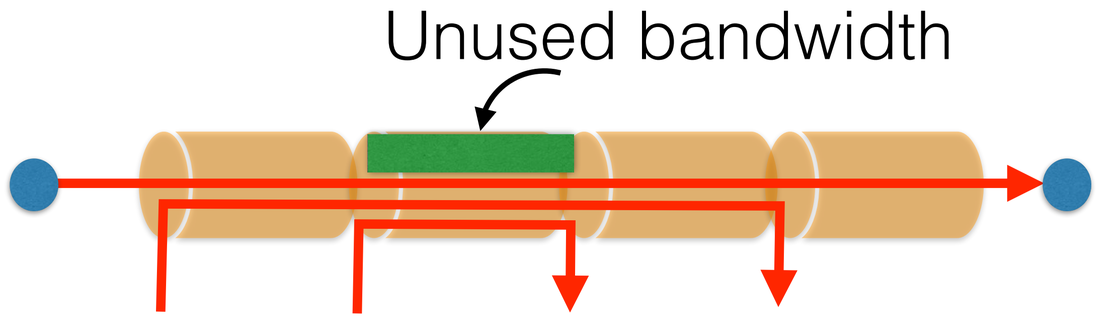


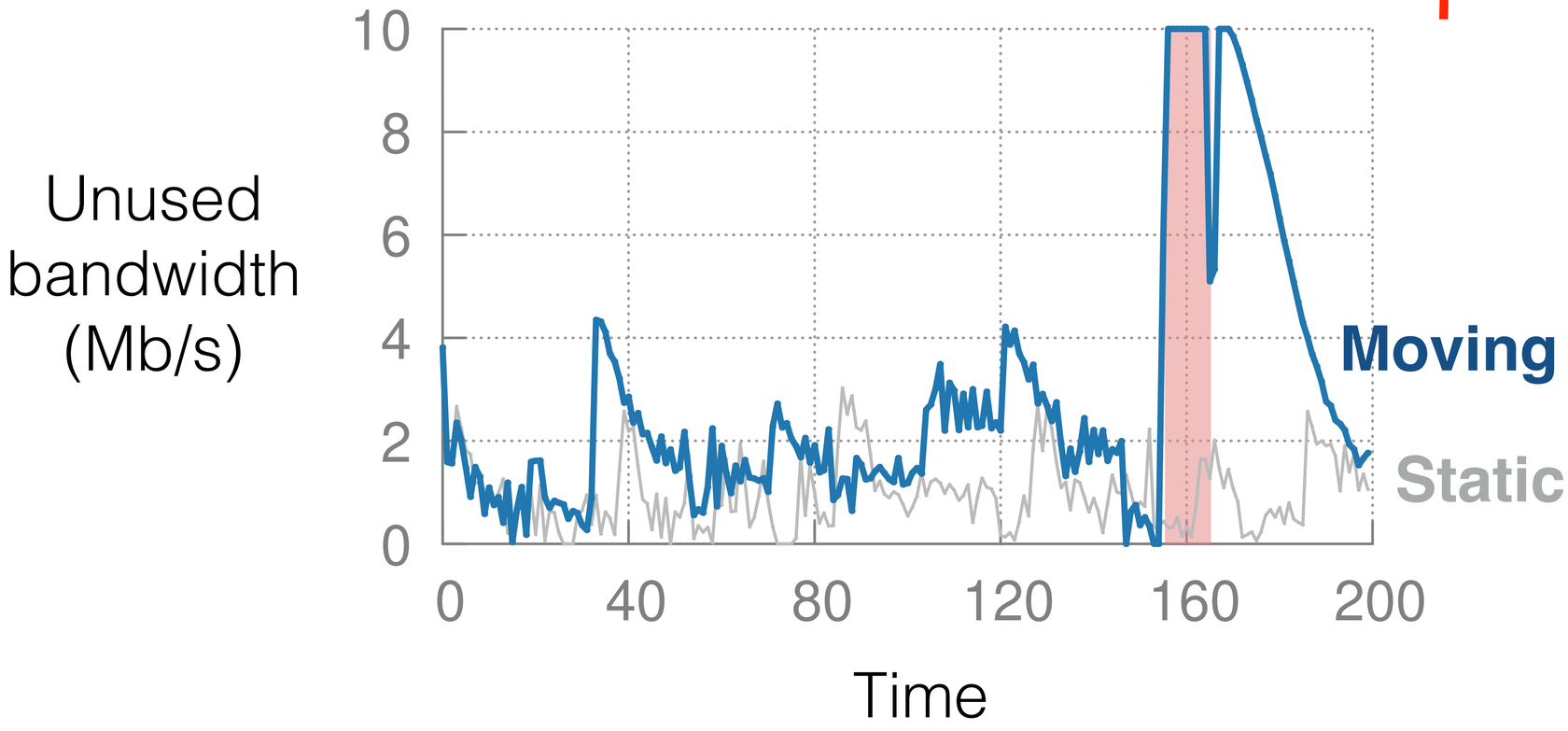


Kuiper K1

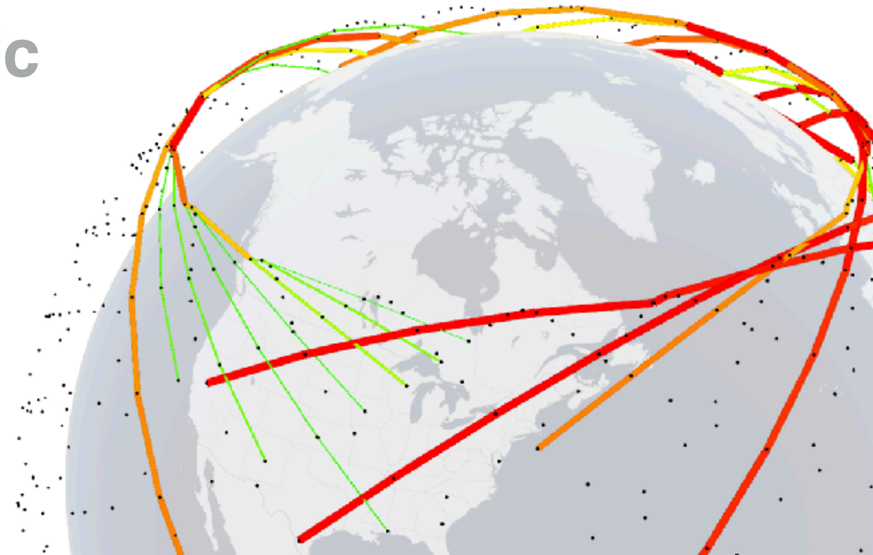


Cross-traffic





Kuiper K1



Challenge for transport: fast convergence

Challenge for TE: planning across time

Hypatia wish-list

Incorporate various interference avoidance strategies

Expand set of example ground stations and constellations

Implement additional routing approaches

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Agenda

- What is the hype about? 
- Basics of LEO networking 
- LEO topology design 
  - Utility of inter-satellite lasers or ISLs
  - Topology design with repetitive patterns
- Enabling broader research