Network topology design at 27,000 km/hr

Debopam Bhattacharjee, ETH Zürich

IETF -109
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IETF -109
Recent advances
Recent advances
Recent advances
Recent advances
Recent advances

10-20G / up to 8000 km
Tens of seconds for link setup
Global low-latency Internet coverage
SpaceX Starlink
1,600 satellites initially
42,000 planned
SpaceX Starlink
1,600 satellites initially
42,000 planned
Amazon Kuiper

3,200 planned
in 3 phases
Amazon Kuiper

3,200 planned
in 3 phases
Amazon Kuiper
3,200 planned
in 3 phases

OneWeb, Telesat, LinkSure, Astrome, Hongyan, …
How do we connect satellites?
Primer on constellations
1. Altitude

GEO
35,768 km
~238.4 ms RTT
1. Altitude

GEO
35,768 km
~238.4 ms RTT
1. Altitude

**GEO**
- 35,768 km
- ~238.4 ms RTT

**LEO**
- 550 km
- 3.7 ms RTT
2. Inclination

Polar orbits
2. Inclination

Polar orbits
2. Inclination

Polar orbits

Inclined orbits
2. Inclination

Polar orbits

Inclined orbits
2. Inclination

Polar orbits

Inclined orbits
2. Inclination
2. Inclination

Polar orbits

Inclined orbits

90°

53°
3. Connectivity
+Grid
4. Latency
4. Latency
4. Latency
4. Latency
4. Latency

CDF across city pairs

City-city RTT (ms)

1600 satellites

Today’s Internet

Today’s Internet

1600 satellites
4. Latency

CDF across city pairs

1600 satellites

70%

Today’s Internet
4. Latency

CDF across city pairs

Theoretical best

1600 satellites

70%

City-city RTT (ms)

Today’s Internet
5. System dynamics
5. System dynamics

Recife, Brazil  Dakar, Senegal

> 500 km / min
Challenges
Challenges

Gearing up for the 21st century space race

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\textsuperscript{1}ETH Zürich, \textsuperscript{2}Duke, \textsuperscript{3}UCSC, \textsuperscript{4}MPI-INF, \textsuperscript{5}UIUC, \textsuperscript{6}Yale, \textsuperscript{7}Akamai Technologies
Topology design problem
Topology design problem
Topology design problem
A high dimensional optimization problem

Topography design problem

Longitude of ascending node
Argument of periapsis
True anomaly
Inclination
Ascending node
Inclination
Celestial body
Plane of reference
Orbit
Ω
ω
ν
i
♉
Challenge for BGP?

AS_{Sat}

AS_1

AS_2

AS_3

AS_4
Challenge for BGP?

\( \text{AS}_{\text{Sat}} \)
Satellite networks are here

Challenge for BGP?

$\text{AS}_{\text{Sat}}$
Challenge for BGP?

Satellite networks are here

AS\textsubscript{Sat}
Challenge for BGP?
AsSat

AS path lengths are poor proxies for performance

Challenge for BGP?
Weather awareness
Weather awareness
Weather awareness
Weather awareness

Higher loss rates
Weather awareness

Higher loss rates
Weather awareness

Higher loss rates

Lower loss rates but higher latency
Challenges for congestion control
Challenges for congestion control

Delay-based congestion control schemes do not fare well
Utility of ISLs

“Internet from Space” without Inter-satellite Links?

Yannick Hauri, Debopam Bhattacharjee, Manuel Grossmann, Ankit Singla
ETH Zürich
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, but maintain the possibility for approval
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, but maintain the possibility for approval
FCC specification

- No mention of silicon carbide components
FCC specification

- No mention of silicon carbide components
- Constellation under deployment does not have ISLs
Bent-pipe connectivity (BP)
Bent-pipe connectivity (BP)
Bent-pipe connectivity (BP)
Bent-pipe connectivity (BP)
Using ground relays for low-latency wide-area routing in megaconstellations

Mark Handley, University College London
ISL versus BP
ISL versus BP

• Latencies and variations thereof
ISL versus BP

• Latencies and *variations* thereof
• Impact on network-wide *throughput*
ISL versus BP

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

ETH Zürich

HotNets 2020
High latency variations in BP

RTT: 175 ms
RTT: 75 ms

Maceió
Durban

Satellite
Ground Terminal
Aircraft
High latency variations in BP

Sparser air traffic over South Atlantic
High latency variations in BP

- Sparser air traffic over South Atlantic
- Inflation of ~100 ms
High latency variations in BP

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

Sparsier air traffic over South Atlantic
Impact of weather
Impact of weather
Impact of weather
Impact of weather
Other benefits of ISLs
Other benefits of ISLs

- Crossing unfriendly territory
Other benefits of ISLs

• Crossing unfriendly territory
• Spectrum efficiency
Other benefits of ISLs

• Crossing unfriendly territory
• Spectrum efficiency
• GSO arc avoidance
Other benefits of ISLs

- Crossing unfriendly territory
- Spectrum efficiency
- GSO arc avoidance

Earth’s surface
Other benefits of ISLs

- Crossing unfriendly territory
- Spectrum efficiency
- GSO arc avoidance
Other benefits of ISLs

- Crossing unfriendly territory
- Spectrum efficiency
- GSO arc avoidance
"Recently as the Starlink team completed a test of two satellites in orbit that are equipped with our inter-satellite links which we call space lasers. With these space lasers, the Starlink satellites were able to transfer hundreds of gigabytes of data."
Recent news

• SpaceX September 3 launch video

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• ISL capacities?
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• ISL capacities?
• Pointing
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• ISL capacities?
• Pointing
• Topology

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• ISL capacities?
• Pointing
• Topology
• OneWeb’s no-ISL design

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How do we connect satellites?
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CoNEXT 2019
Key constraints
Key constraints

System dynamics

> 500 km / min
Key constraints

System dynamics

Link setup times

> 500 km / min
Key constraints

System dynamics

Link setup times

Max. no of links per satellite
Assumptions
Assumptions

• Given satellite trajectories
Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition
Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition
- Ground-satellite connectivity is range-bounded
Assumptions

- Given satellite trajectories
- Traffic matrices drawn from intuition
- Ground-satellite connectivity is range-bounded
- +Grid is the baseline
Can use much longer links
Can use much longer links
Can use much longer links
Can use much longer links

550 km altitude

Mesosphere (up to 80 km)
Mesosphere (up to 80 km)

Can use much longer links

550 km altitude
Can use much longer links

550 km altitude

Mesosphere (up to 80 km)
Can use much longer links

- 550 km altitude
- 5014 km inter-satellite link
- Mesosphere (up to 80 km)
Much larger design space
Much larger design space
Much larger design space
Much larger design space
What do we optimize for?
Traffic matrix
Traffic matrix
Traffic matrix

Traffic \propto \text{Population product}
Traffic matrix

Traffic $\propto$ Population product

GDP
Metrics

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

Hop count
Metrics

\[ M = \alpha \text{ Stretch} + \text{Hop count} \]

\[ \text{Stretch} = \frac{L_{\text{Sat}}}{L_{\text{Geodesic}}} \]
Why aren’t obvious / traditional methods enough?
Why not use Integer programming?
Why not use Integer programming?

For 1000 cities, would take $\sim 10^{29}$ days
Why not use Integer programming?

For 1000 cities, would take $\sim 10^{29}$ days

One minute apart $\sim 91\%$ links are different
Why not use random graphs?
Why not use random graphs?

In 5 mins, 19% of links become infeasible
Why not use random graphs?

In 5 mins, 19% of links become infeasible

Cannot optimize for arbitrary objectives
Our approach
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
A large number of design points
A large number of design points

Avg. Stretch vs. Avg. Hop-count

Motifs

Pareto frontier
A large number of design points

Avg. Stretch vs Avg. Hop-count

Motifs

Random

Pareto frontier
+Grid is a low-efficiency motif

![Graph showing the relationship between Avg. Stretch and Avg. Hop-count with a trend line and data points indicating low efficiency.](image-url)
+Grid is a low-efficiency motif
More options at higher latitudes

# possible motifs

Latitude°

# possible motifs

Latitude°
Beyond single motif frontier

Avg. Stretch

Multi-motifs

Avg. Hop-count
Beyond single motif frontier

$M = \alpha \text{Stretch} + \text{Hop-count}$

How important stretch is

Avg. Stretch

Avg. Hop-count

Multi-motifs

$\alpha = 1$

$\alpha = 5$

$\alpha = 10$
Performance improvements

Starlink  54%
Kuiper    45%
$40^2$    48%
Performance improvements

Severely power-limited links

Starlink 54% 40%
Kuiper 45% 4%
40² 48% 7%
Baking in our lab
Baking in our lab

- Trajectory Design
Baking in our lab

• Trajectory Design
• Multi-dimensional
Baking in our lab

- Trajectory Design
- Multi-dimensional
- Routing & Congestion Control
Baking in our lab

- Trajectory Design
  - Multi-dimensional
- Routing & Congestion Control
- Simulators
Baking in our lab

- Trajectory Design
  - Multi-dimensional
- Routing & Congestion Control
- Simulators
  - Packet-level
Baking in our lab

- Trajectory Design
  - Multi-dimensional
- Routing & Congestion Control
- Simulators
  - Packet-level
  - Flow-level