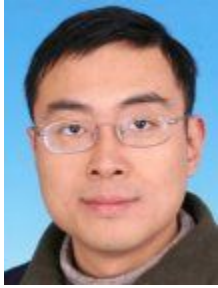

Routing in LEO Sat Nets

— A case study on Starlink and OneWeb

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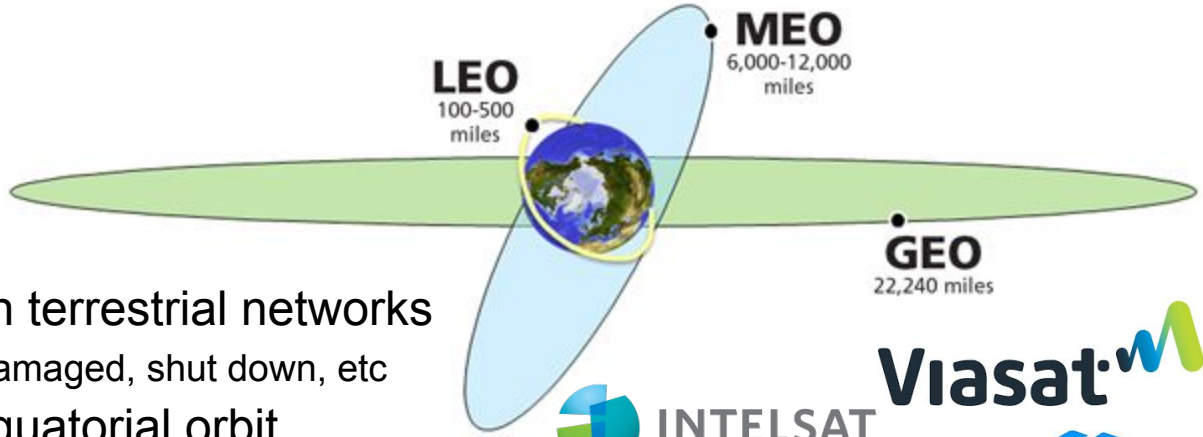
Parallel, Networking and Distributed Applications Laboratory

University of Victoria

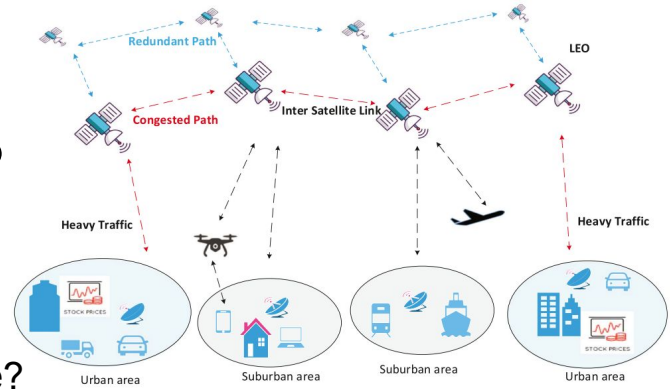
Why **satellites**?



- For global coverage when terrestrial networks
  - Not available, too costly, damaged, shut down, etc
- GEO: geosynchronous equatorial orbit
  - ~36 kkm above the earth, limited capacity, very high latency
  - HughesNet, Intelsat, ViaSat, etc: round-trip time (RTT) 600+ ms
- MEO: medium-earth orbit (between LEO and GEO)
  - SES O3b mPOWER: 6 satellites now, 8 kkm, 200+ ms RTT
- *2nd*-gen **LEO**: low-earth orbit (below 2 kkm), < 100ms RTT
  - SpaceX's **Starlink**: 6k+ satellites, mostly 550 km in 53° inclination
    - 4+ million users in 100+ countries/regions by Sep 2024
  - Eutelsat **OneWeb**: 6h+ satellites, 1.2 kkm altitude in polar orbits
    - mostly targeting enterprise and government customers
  - Amazon Kuiper: two prototype satellites recently tested in space
  - Telesat Lightspeed: series test satellites for space demonstration

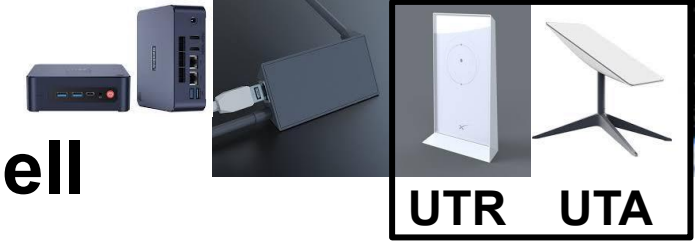
Viasat
INTELSAT
hughesnet
O3b Networks
STARLINK
OneWeb
amazon | project kuiper
TELESAT LIGHTSPEED™
Telesdesic
Globalstar
iridium

What *shall* the satellite **routing** be?



- In an ideal LEO satellite network (LSN)?
  - Between two user terminals (UTs): 10% of traffic by volume?
    - **Shortest** path routing: latency, distance, cost, etc
    - UT - **Sat** - UT (“bent pipe”)
    - UT - Sat***** - UT (with inter-satellite links, ISL)
    - UT - Sat* - **GS** - Sat* - UT (through a ground station)
    - UT - Sat* - GS - **PoP** - GS - Sat* - UT (through different ground stations)
    - UT - Sat* - GS - PoP - **Internet** - PoP - GS - Sat* - UT (through the Internet)
  - Between a UT and a (content distribution network, CDN, or cloud) **server**: 90% now?
    - Server possibly at the Sat, GS or PoP, or on the Internet
    - **Widest** path routing: throughput, downlink (from the Internet to user), uplink (from user)
    - Extras: broadcast, multicast, anycast, incast, etc
- Multiple LSNs?
  - Intra vs inter-domain routing: where are the transit/peering points? in space or on ground?

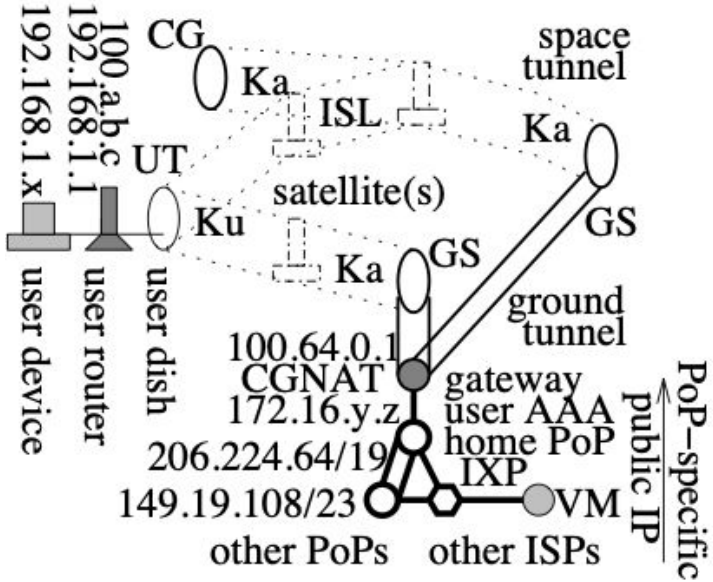
X. Deng, L. Chang, S. Zeng, L. Cai and J. Pan, "Distance-Based Back-Pressure Routing for Load-Balancing LEO Satellite Networks," in *IEEE Transactions on Vehicular Technology*, vol. 72, no. 1, pp. 1240-1253, Jan. 2023, doi: 10.1109/TVT.2022.3206616.



Starlink in a **nutshell**

- An ***outgoing*** packet's journey to the Internet (reverse for the incoming one)
  - User devices (i.e., measurement devices)
    - 192.168.1.*x* if the default gateway at 192.168.1.1/24
  - **User <u>router</u>** (User Terminal Router, **UTR**, provided by Starlink, can be *replaced* or *bypassed*)
    - LAN: 192.168.1.1 (by *default*)
    - WAN: **100.64/10** (*unique* per user dish)
  - **User dish** (Antenna, **UTA**, provided by Starlink)
    - 192.168.**100**.1 (*fixed* address as modem)
  - ***Satellite**** (inter-satellite links, **ISL**s, possible)
  - Landing ground station (**GS**, transparent to IP)
  - **<u>CGNAT</u>** (Carrier-Grade NAT) gateway (GW)
    - **100.64.0.1** (or public IP user's gateway)
  - Home **PoP** (Point-of-Presence) entry
    - 172.16/12
  - PoP, other PoPs/ISPs, ICPs, etc: the **Internet**

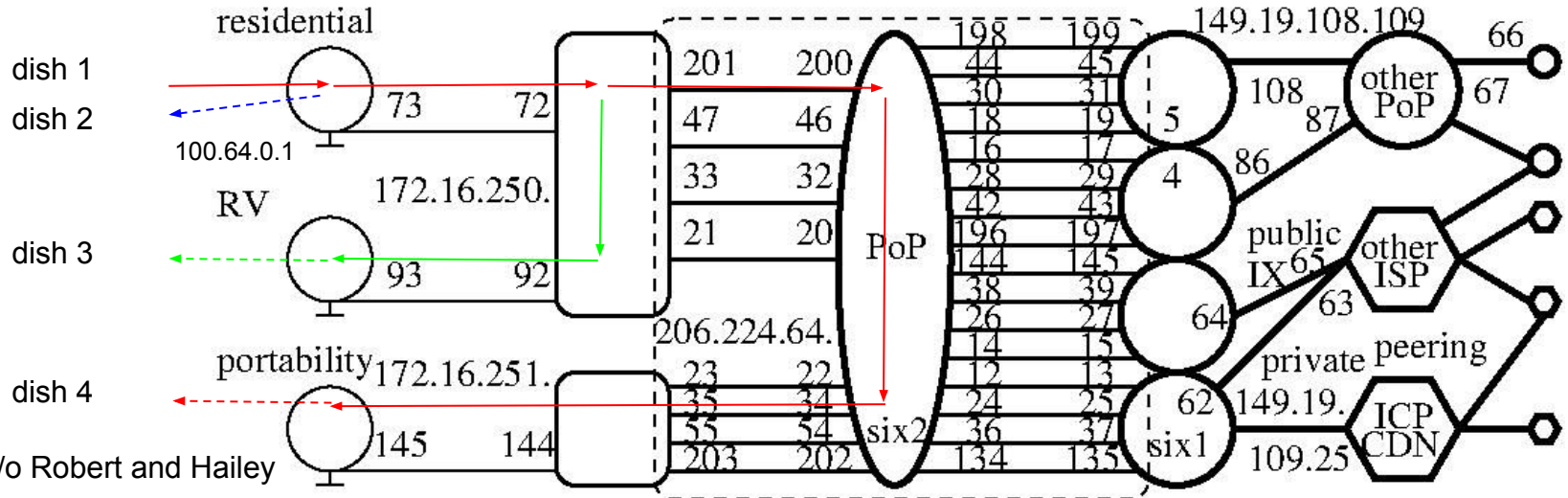
1 IP hop



* UT-(space/ground tunnel)-GW-PoP-backbone

Ground station and infrastructure

- Inside a point-of-presence (PoP, e.g., Seattle)
  - Gateway: 172.16.250/23 expanded to 172.16.252/24 (also 172.16.248/23 in other PoPs)
    - Odd ending digit: toward CGNAT
    - Even ending digit: toward the PoP
  - **Parallel** links within the PoP: 206.224.64/23 expanded to 206.224.66/24 (some inter-PoP too)
    - UDP over ECMP; ICMP unique path; TCP unique path per flow
  - Interconnection to other PoPs (mostly 149.19.108/24), ISPs and ICP/CDNs (149.19.109/24)



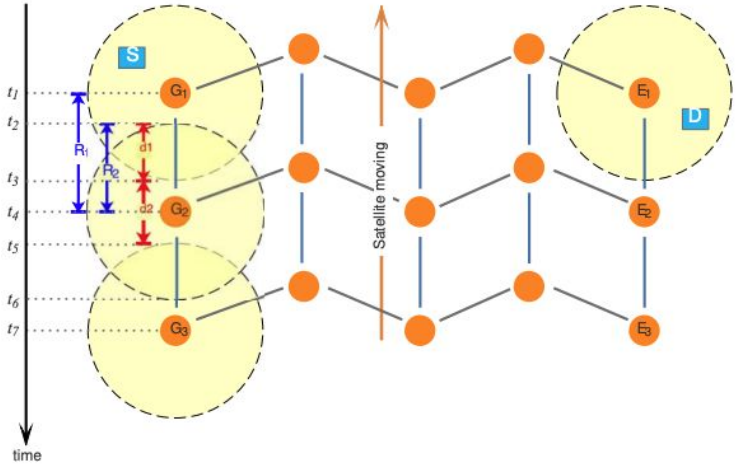
c/o Robert and Hailey

How is the routing in LSN *access network* **now**?

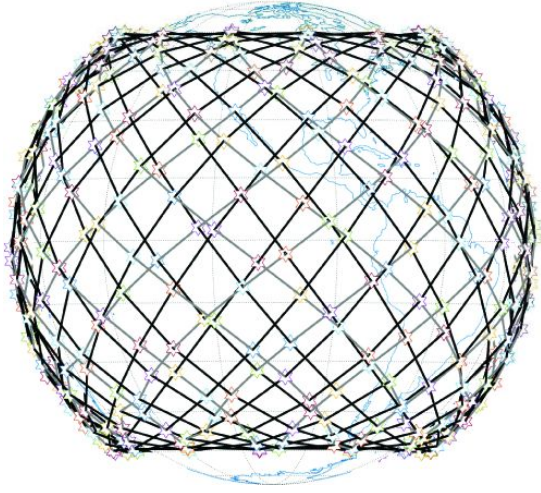
- In Starlink
  - UT - **[(space tunnel) - landing GS - (group tunnel)]** - PoP - the Internet
    - UT router (UTR): 192.168.1.1 by default or user's own router; **100.64/10** on WAN side
    - UT antenna (UTA): **192.168.100.1** fixed as the modem reachable from the LAN side
  - **One (long) IP hop** between UTR and PoP
    - Default (private) IP users: 100.64.0.1 (carrier-grade network address translator, CGNAT)
    - Public IP users: e.g., 188.92.254.1 for 188.92.254.0/24 (**GeoIP**: RO, RO-B, Bucharest)
    - PoP revealed in DNS PTR, e.g., customer.**sfiabgr1**.pop.starlinkisp.net in Sofia, Bulgaria
  - No direct user traffic exchange
    - UT - Sat* - UT, or UT - Sat* - GS - Sat* - UT
  - **All through UT's PoP**
    - UT - Sat* - GS - PoP - GS - Sat* - UT, or UT - Sat* - GS - PoP -...- PoP - GS - Sat* - UT
    - Imagine two Alaska Starlink users exchanging packets in Seattle: unnecessary latency!
- Similarly in OneWeb often used as a mid-mile connectivity now

J. Pan, J. Zhao and L. Cai, "Measuring a Low-Earth-Orbit Satellite Network," *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Toronto, ON, Canada, 2023, pp. 1-6, doi: 10.1109/PIMRC56721.2023.10294034.

Inter-satellite routing?

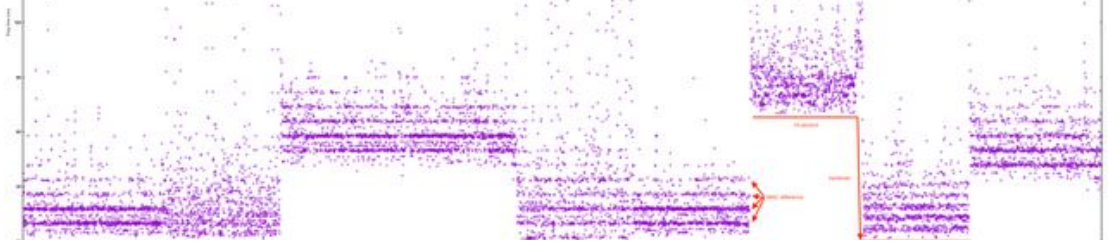


- In Starlink
  - Currently a black box
    - UT - (space tunnel) - landing GS
  - Bent-pipe vs ISL through distance/atency inference
    - If UT - nearest GS > 2000 km, have to use ISL
    - If UT - PoP minimum RTT nowadays > 100ms, likely ISL
  - Space tunnel?
    - ISL to reach a faraway satellite to land user traffic
  - Ground tunnel?
    - A faraway satellite lands traffic at a faraway GS
    - Then has to be tunneled back to the home PoP
- In OneWeb
  - No ISL for now
  - Promised in Gen2 (not launched yet)

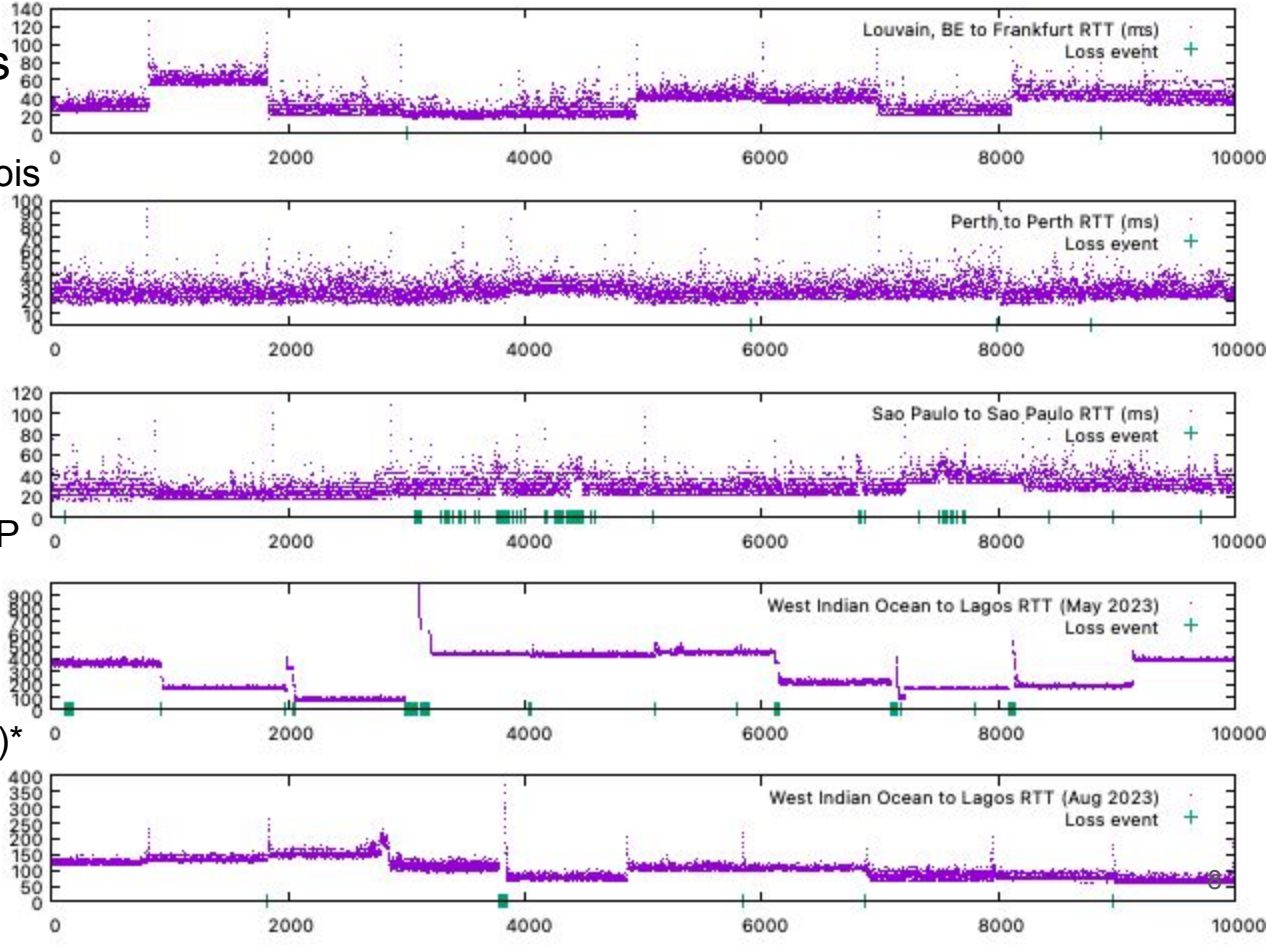


J. Pan, J. Zhao and L. Cai, "Measuring the Satellite Links of a LEO Network," *ICC 2024 - IEEE International Conference on Communications*, Denver, CO, USA, 2024, pp. 4439-4444, doi: 10.1109/ICC51166.2024.10623111.

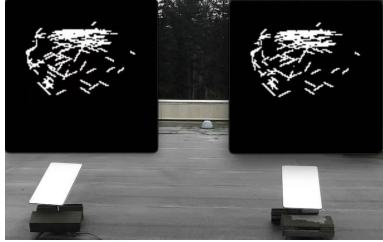
Access performance



- Ping in 15-ms intervals
  - Louvain, BE
    - Shared by Francois
    - To Frankfurt PoP
  - Perth, AU^
    - By a Redditor
    - To Perth PoP
  - São Paulo, BR
    - By a Redditor
    - To São Paulo PoP
  - Seychelles (May 2023)
    - By Dominique
    - To Lagos PoP
  - **Seychelles** (Aug 2023)*
    - **ISL improved**

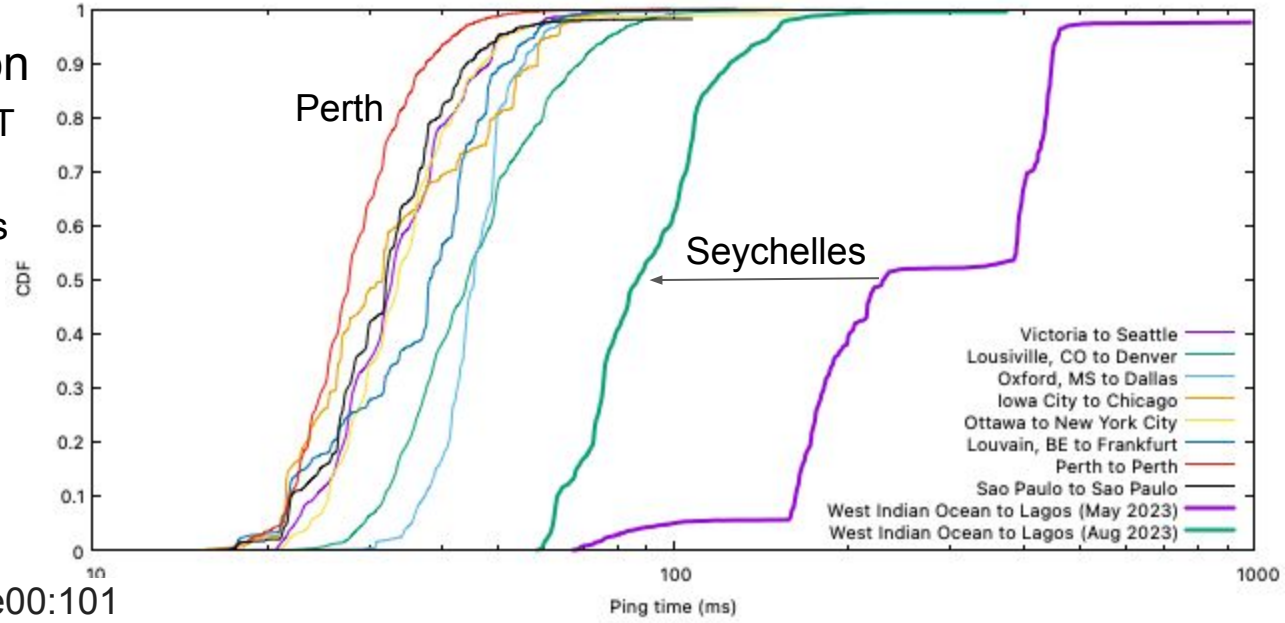


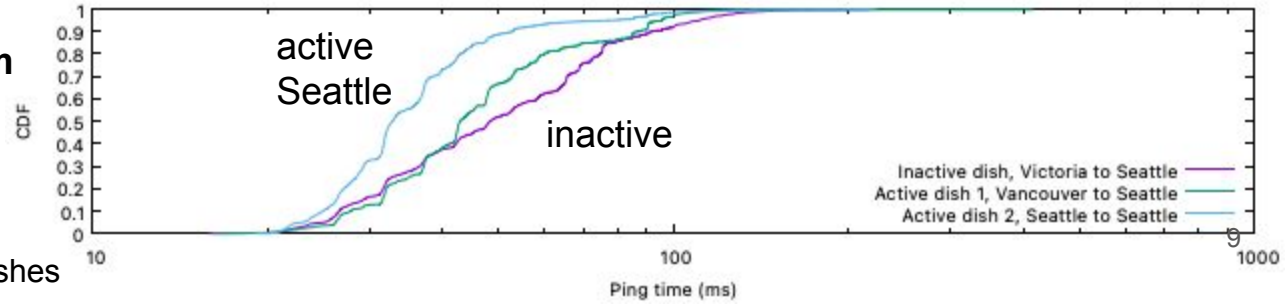
* GEO protection; ^ user population; **MAC**



From sequence to **frequency**

- *Cumulative* distribution
  - ISL, much **higher** RTT
  - Non-ISL
    - min RTT: ~20ms
    - Still high **jitter**
- ***Inactive*** dishes
  - IPv4 gateway
    - 100.64.0.1
    - By ARPing
  - IPv6 gateway
    - fe80::200:5eff:fe00:101
    - By Ping
  - **connect.starlink.com**
    - 34.107.166.226
    - By (HTT)Ping





* **active** measurement on many ***inactive*** dishes

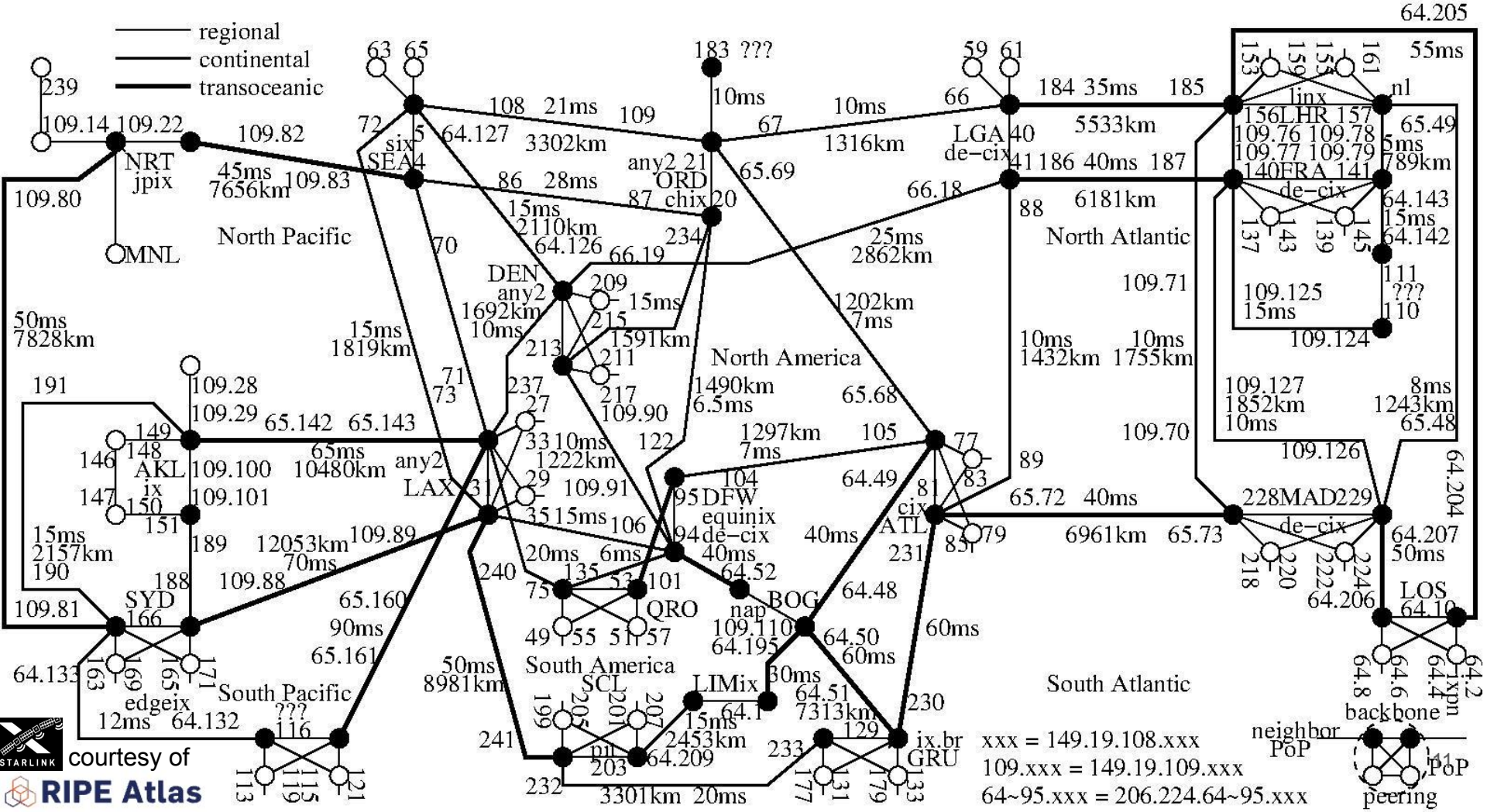
How is the routing in LSN *backbone network* **now**?

- In Starlink
  - Route toward the home PoP first, regardless of the landing GS and destination
    - CGNAT needed at the home PoP for private IPv4 users
    - Even so for public IPv4 due to possible source filtering
    - Even so for public IPv6
    - CDN, “stateful anycast”, etc
  - External traffic: exit the home PoP ASAP
    - “Hot potato” routing
  - Incoming traffic: mostly enter at the home PoP only
    - Why and why not?
  - Internal traffic: through the Starlink global backbone
    - Mostly ground/undersea fiber network
    - Possible to use ISL for backbone?
- OneWeb: mostly a mid-mile pipe now and no its own backbone yet?

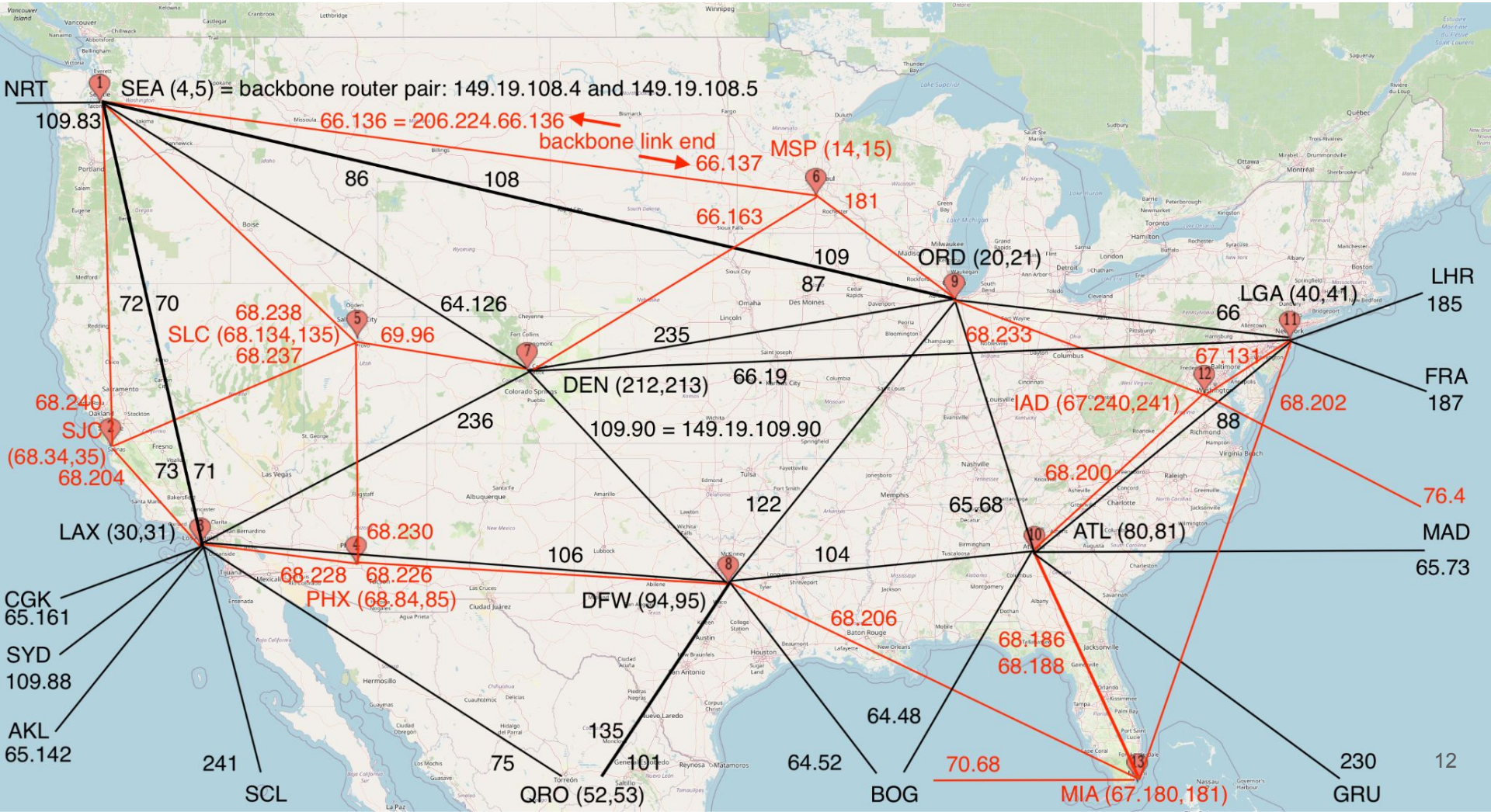
J. Pan, J. Zhao and L. Cai, "Measuring a Low-Earth-Orbit Satellite Network," *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Toronto, ON, Canada, 2023, pp. 1-6, doi: 10.1109/PIMRC56721.2023.10294034.

data used by http://tinyurl.com/starlinkmap

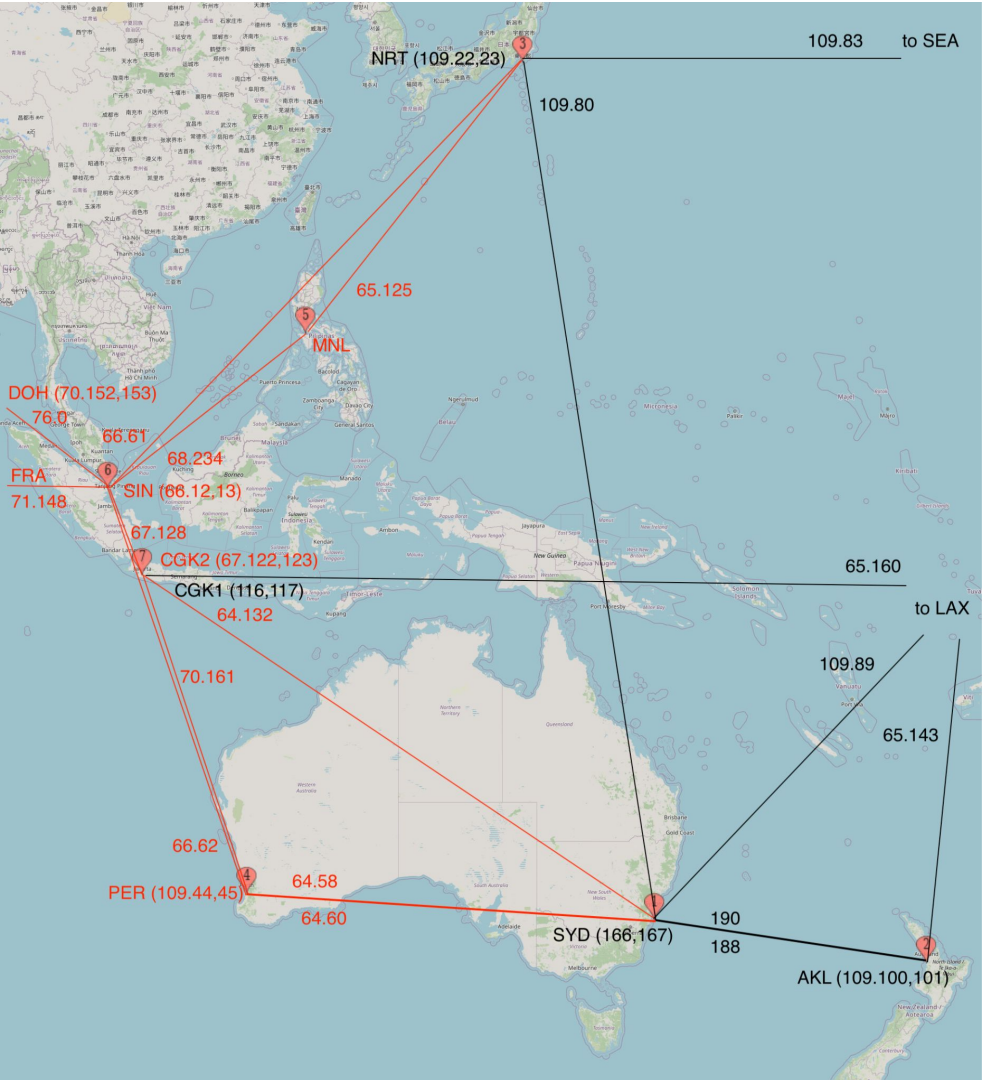
Starlink *Global* **backbone network** in *2023*

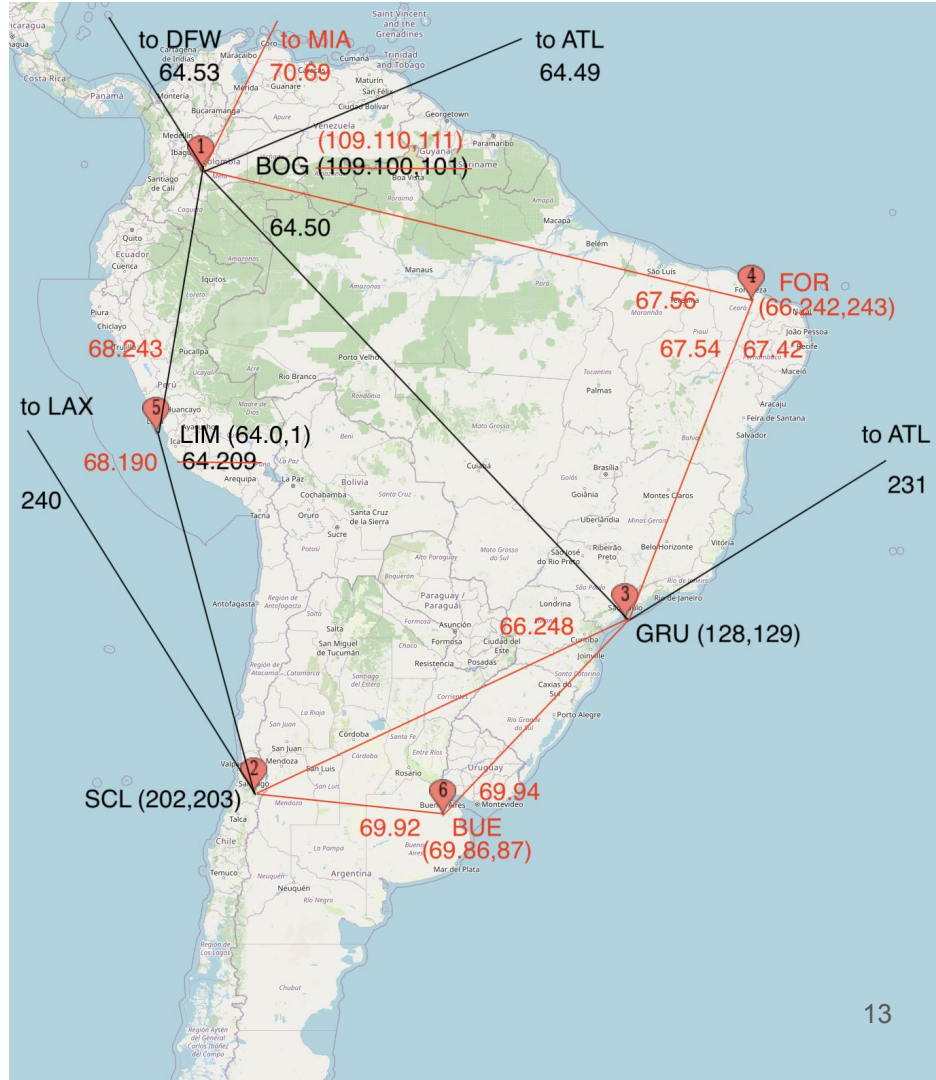


Starlink added 6 new PoPs in the US in **2024**



Asia-Pacific and South America see great growth too





Europe and Africa to ASEAN

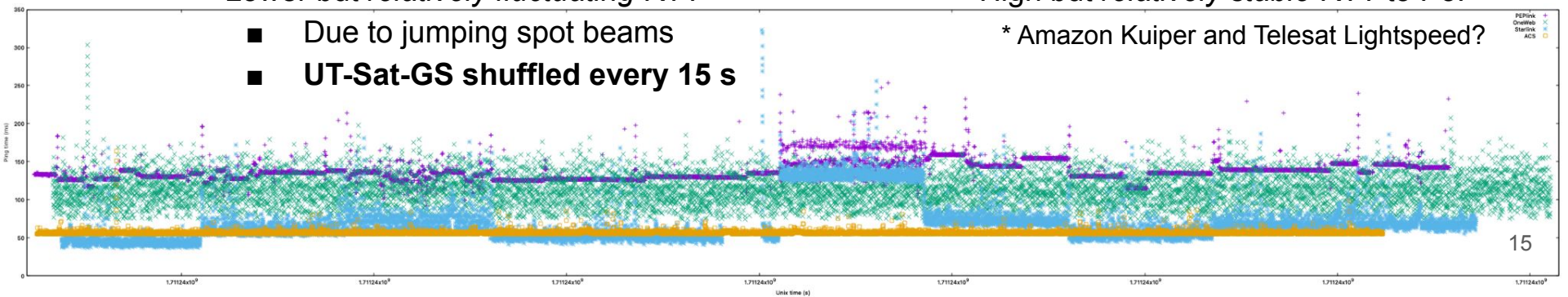
- Used to be from West to East Indian Ocean
  - Lagos, London, NYC, Denver, LAX, Sydney, Perth
  - Instead of inter-satellite links across Indian Ocean
  - RTT above 500ms
- Now going through Middle East
  - Lagos, London, Frankfurt, Doha, Singapore, Perth
  - Starlink now has a **global** network, on ground too
  - RTT about 300ms
- Hopefully near *future*?
  - Direct inter-satellite links across the Ocean
  - Route toward destination instead of home PoP
  - Likely around 100ms
- Routing in dynamic but regular topology
  - Extended from routing in data center networks

Comparing two LEO satellite networks

- **Starlink**
  - Initially target *consumer* users
  - Mostly 53° inclination
  - Mostly 550km above the Earth
  - **Spotting** beams for individual dishes
    - Ku for UT and Ka for GS
  - Currently >6000 active satellites
    - All launched by SpaceX
  - Currently >200x ground stations
  - Many PoPs around the world
  - Lower but *relatively fluctuating* RTT
    - Due to jumping spot beams
    - **UT-Sat-GS shuffled every 15 s**

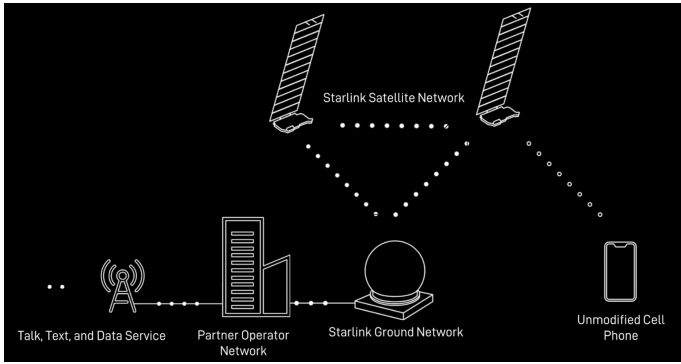
- **OneWeb**
  - Currently target *enterprise* users
  - Polar orbits
  - Around 1200km in altitude
  - **Sweeping** beams for community dishes
    - Similarly Ku and Ka
  - Currently ~600 active satellites
    - Limited 3rd-party launch capacity
  - Currently ~20x ground stations
  - Very few customer PoPs now
  - High but *relatively stable* RTT to PoP

* Amazon Kuiper and Telesat Lightspeed?



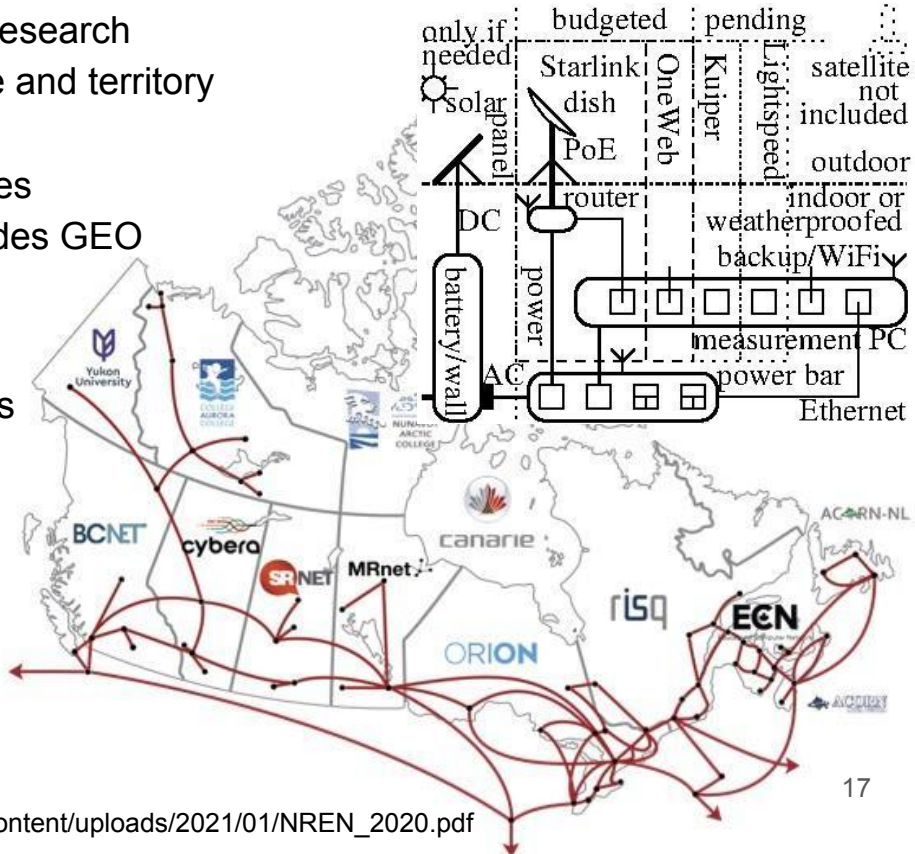
Space networking in a big picture: different routing?

- Broadband Internet: 100/20 mbps and higher
  - SpaceX's Starlink
  - Eutelsat's OneWeb
  - Amazon's Project Kuiper
  - Telesat's Lightspeed
  - EU's IRIS^2 and China's Thousand Sails ("Qian-Fan")
- Direct-to-cell (phone): 1~10mbps?
  - Unmodified phones: Starlink (with T-Mobile, etc), AST SpaceMobile (with AT&T, etc), etc
    - 3GPP "Base station" in space
  - Enhanced phones: iPhone 14 Pro+ (GlobalStar), Huawei Mate 60 Pro+ (Tiantong), etc
    - SMS, highly compressed voice, etc
- Internet of things (IoT): (way) below 1mbps?
  - SWARM (acquired by Starlink)
    - Asset tracking, agriculture, forestry, environment, etc



Why a cross-country/continent satellite **testbed**?

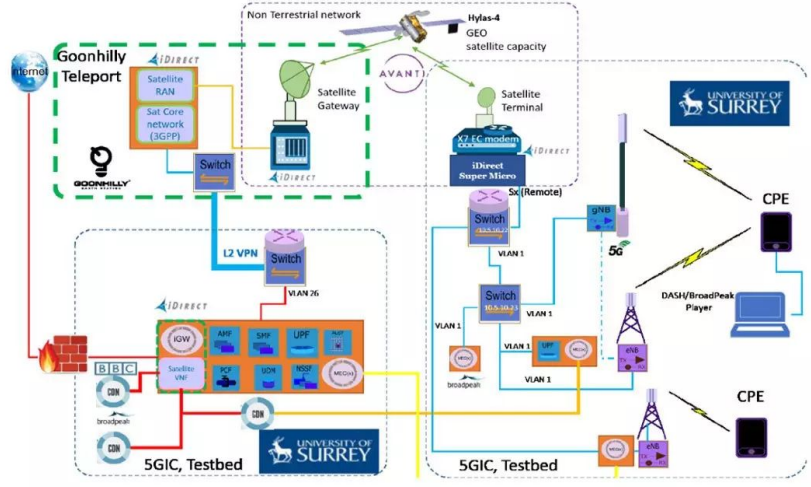
- For network researchers, leveraging CANARIE/Internet2 but on LEO satellites
  - **Geo-diversity** needed for satellite network research
    - At least one site in each province/state and territory
  - Much more capable than RIPE Atlas
    - Container-based measurement modules
  - Possibly different satellite technologies besides GEO
    - Starlink, OneWeb, Kuiper, Telesat, etc
- For community users
  - In remote areas and indigenous communities
    - Improved Internet access capacity
  - No security and privacy affected
    - End-to-end encryption of user traffic
  - A level playground for a fair comparison
    - For vendors, operators and regulators

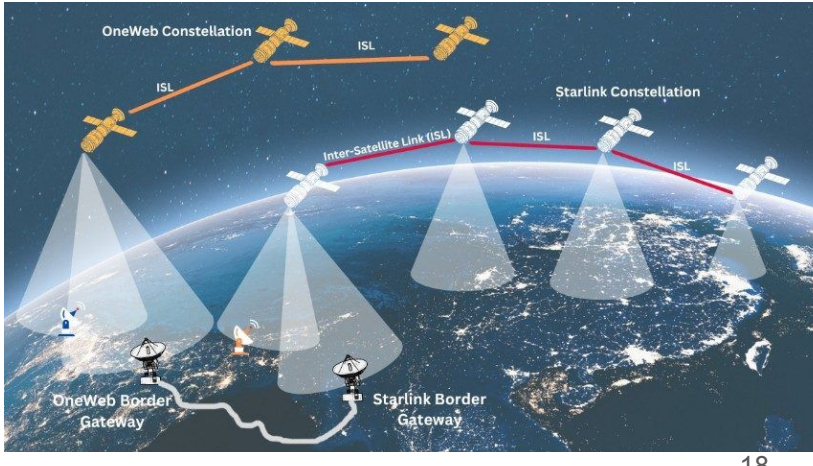


https://www.canarie.ca/wp-content/uploads/2021/01/NREN_2020.pdf

Other efforts around the **world**

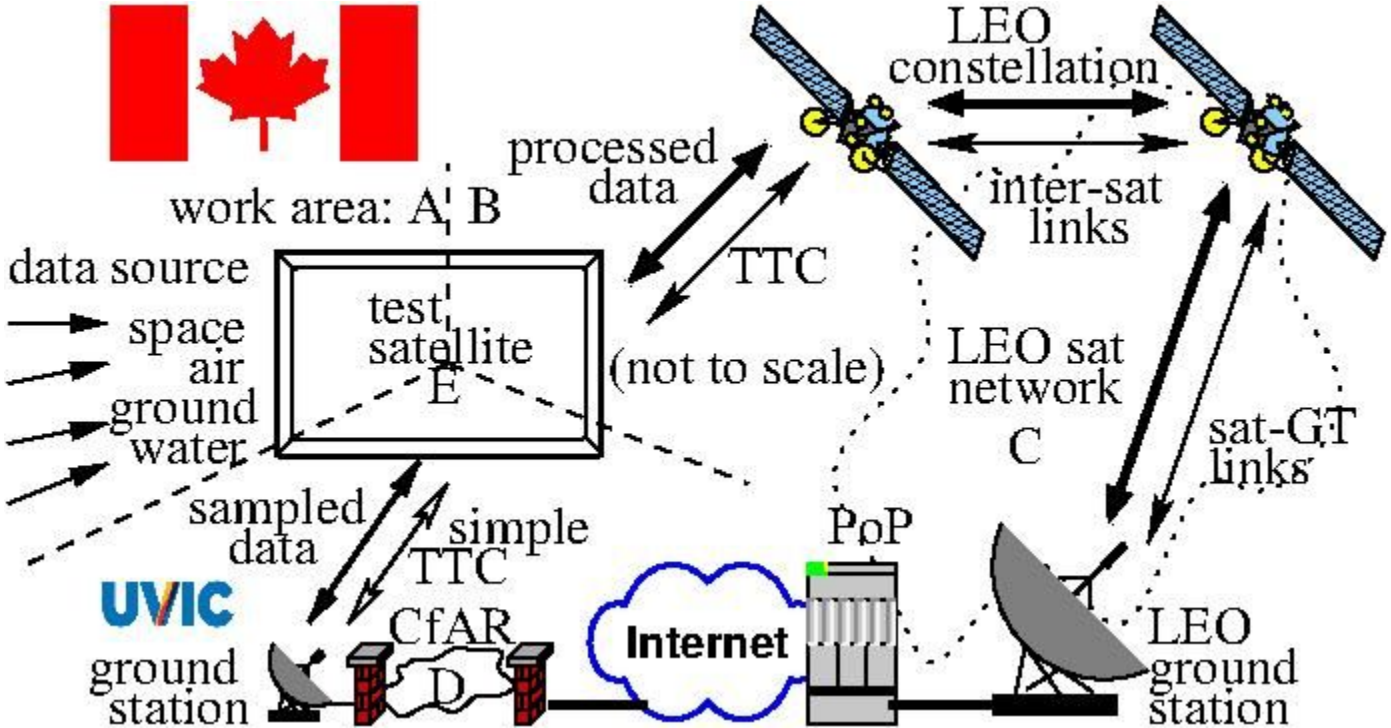
- With a focus on (LEO) satellites
  - University of Surrey, UK
    - Hylas-4 GEO with 5/6G integration
    - **LEOScope**: an emerging global testbed
  - Virginia Tech and George Mason University, USA
    - NeTSat: NSF project recently approved
    - Starlink and OneWeb mentioned
  - Carleton University, Canada
    - UAV-HAP-LEO integration with 6G O-RAN
    - Collaboration with NRC, MDA, DRDC, etc
- Unique features of us as part of LEOScope
  - Geo-distributed: coast-to-coast-to-coast
  - LEO-focused: consumers and enterprises
  - User-oriented testbed: by and for researchers





We are *no longer* just doing the **groundwork** …

- **PolarLink**: An Integrated, High Bandwidth, Low Latency, Vendor Neutral Space Based Communication Backbone for Canada, sponsored by DRDC



Thanks!

- Questions?
  - Email: pan@uvic.ca
  - Web: http://web.uvic.ca/~pan
  - Lab: http://pan.uvic.ca
- Join us!
  - **http://oac.uvic.ca/starlink**
    - See our work, papers, datasets and code
  - **LENS: low earth network of satellites**
    - Host a virtual machine behind your dish, and/or
    - Enjoy the dataset for trace-driven evaluation
  - *LOTS: low-earth orbit testbed of satellites*
    - Currently pending NSERC funding
    - Host a testbed node with dish provided
  - *CFI NTN* (*pending*), DRDC **PolarLink** (**selected**), etc

https://pan.uvic.ca/~clarkzjw/starlink/ http://tinyurl.com/starlinkmap