Routing in space-air-ground-integrated networks

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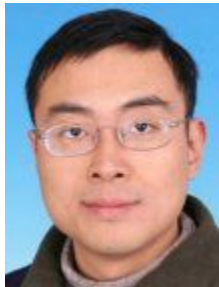
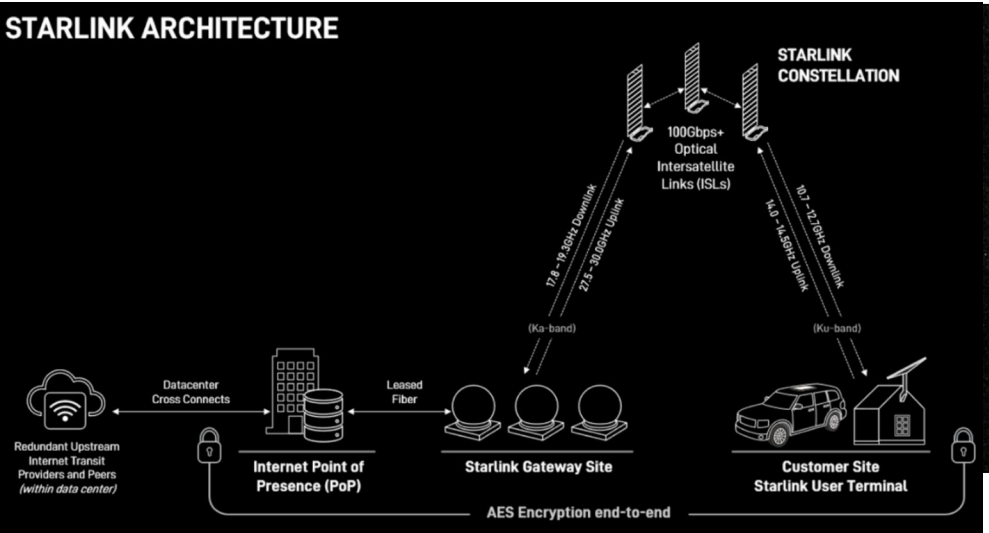
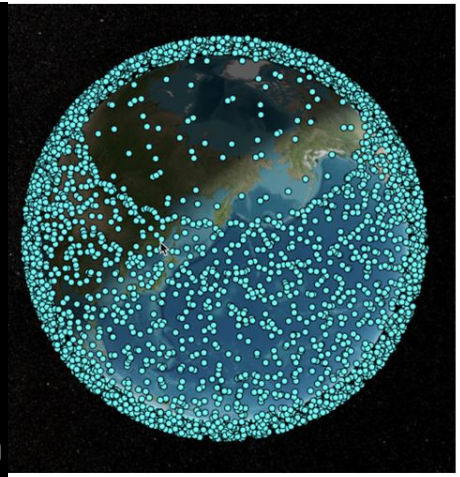


PANDALAB
Parallel, Networking and Distributed Applications Laboratory

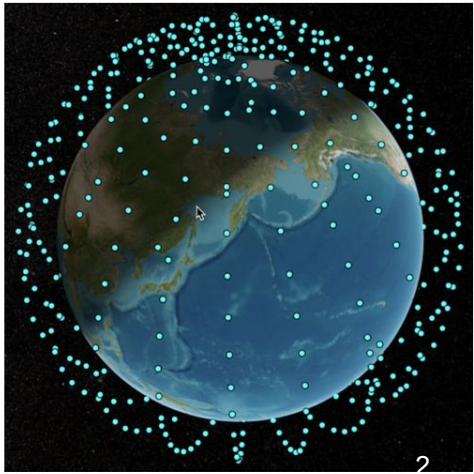
Network architecture: Addressing, naming & routing

- Low-earth-orbit (LEO) satellite networks (LSNs)
  - Hundreds to thousands of satellites in LEO for global coverage and capacity
  - Different inclinations and altitudes: Multiple orbits and shells per constellation
  - SpaceX's Starlink, Eutelsat's OneWeb, Amazon's Project Kuiper, Telesat's Lightspeed, etc
  - Non-terrestrial Network (NTN) architectures similar to terrestrial LTE but with new challenges
    - User terminal (UT), satellite (SAT), ground station (SAG), point of presence (PoP), etc
  - In addition to Space Broadband Internet, also Direct-to-Cell and Space Internet of Things (IoT)



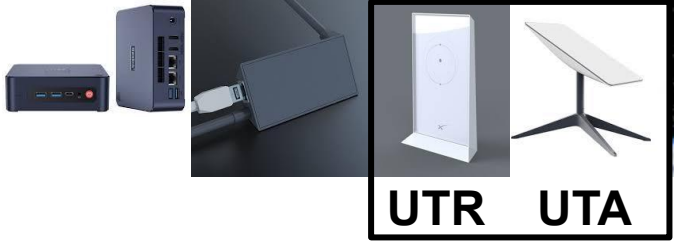


(a) Starlink



(b) OneWeb

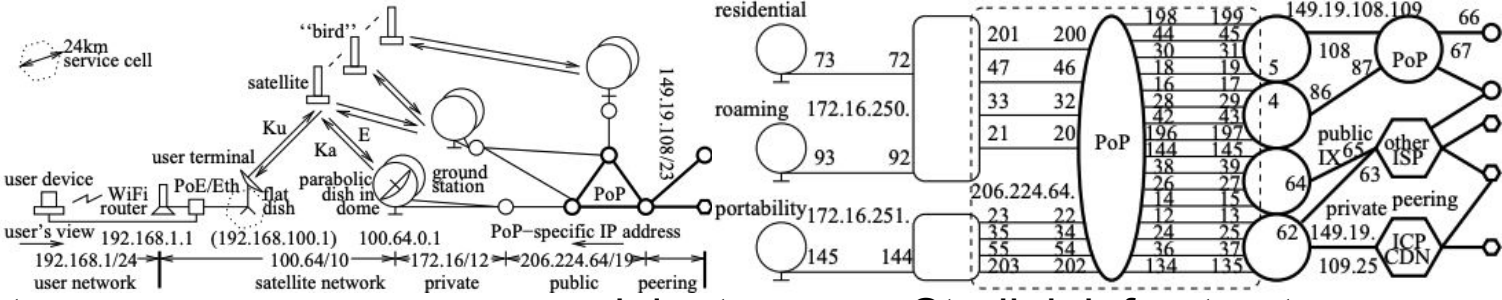
Addressing



- Starlink**ISP**.net, 5+ million **customers** now
  - ASN: 14593 globally and 45700 in Indonesia only
    - Also customer ASNs with community gateway
  - Customer IP addresses with Geofeed published
    - http://geoip.starlinkisp.net: Country, region, “city”
    - Both IPv4 (often in /24 blocks) and IPv6 (/40)
  - E.g., a stationary dish in Victoria, BC, Canada
    - UT Router LAN: 192.168.1.1/24 by default
    - UT Router WAN: 100.76.147.112/10 by hash
    - CGNAT gateway: 100.64.0.1 fixed
    - CGNAT external: 170.203.205.12 dynamic
    - GeoIP: 170.203.205.0/24,CA,CA-BC,Vancouver,
- OneWeb: ASN 800
  - Customers (enterprise, etc) bring their own addresses
- Starlink infrastructure
  - Backbone network
    - 149.19.108/23
    - 206.224.64/19
    - Within/btw PoPs
  - Satellite access network
    - 172.16/12 reused
- Starlink.com corporate
  - Website, etc
  - Hosted by Fastly.com
- SpaceX.com corporate
  - ASN: 27277
  - Employees, etc
  - On Microsoft Azure

Starlink allows priority/business/enterprise users to opt in public IPv4 addresses
For IPv6: UTR WAN: /64 by SLAAC; UTR LAN: /56 by DHCPv6-PD; all public addresses

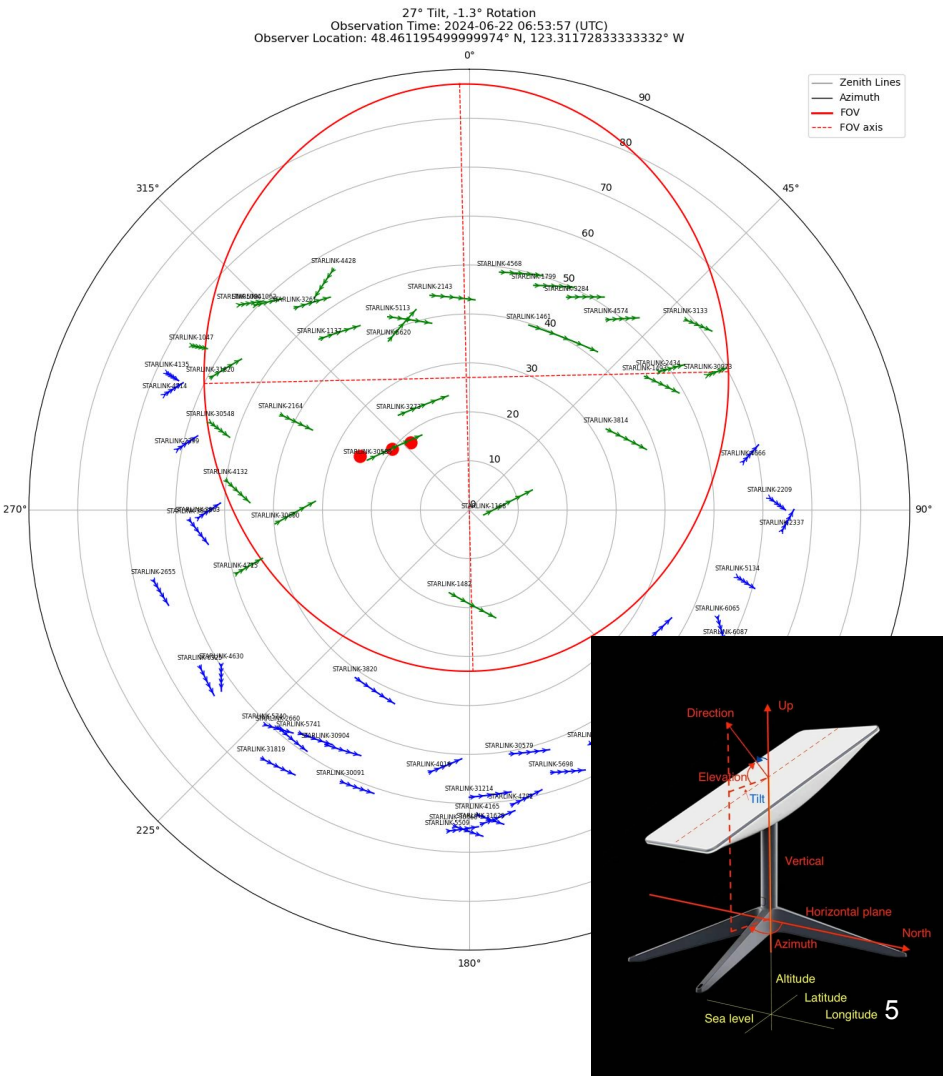
Naming



- Starlink customers: consumer, commercial, etc
  - Again, the same dish in Victoria, BC, Canada
    - Dish: dishy.starlink.com (192.168.100.1)
    - Dynamic CGNAT public IP: 170.203.205.12
    - DNS PTR: customer.sttlwax1.**pop**.starlinkisp.net.
    - Extended CLLI: “sttlwax1” is Seattle, WA, USA
  - At the Starlink point-of-presence (PoP) granularity
    - Also (mis)used by some content providers
    - Geofeed has a finer granularity but no TTL
  - Hosted by cloudns.net
    - Only PTR, no A record for pop.starlinkisp.net.
    - PTR resource record TTL: 300 seconds
- OneWeb
  - Customers DNS provisioning
- Starlink infrastructure
  - Public 149.19.108/23
    - No PTR record
  - Public 206.224.64/19
    - undefined.hostname.localhost.
  - Private 172.16/12
    - No PTR record
  - IPv6 addresses (public)
    - host.starlinkisp.net
- Starlink.com corporate
  - DNS hosted by Azure
- SpaceX.com corporate
  - DNS hosted by Google

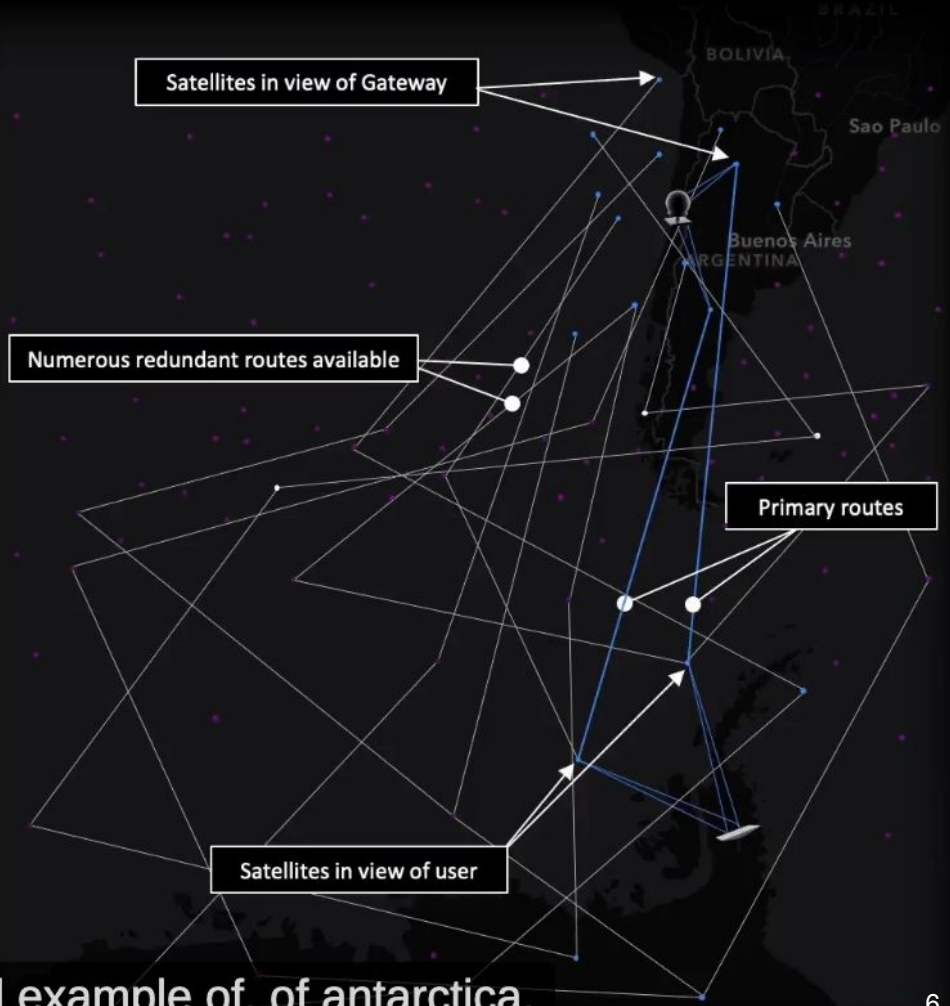
Routing in space

- Starlink **satellite** access networks
  - UT-SAT
    - Starlink dictates satellite selection
    - Preferably higher elevation (closer)
    - Depending on the UT location
    - One primary beam, one secondary
    - Fast switch if obstructed
  - SAT-SAT
    - Intra and inter-plane routing
  - SAT-SAG
    - Until a landing ground station
  - SAG-PoP
    - Tunneled back to “home” PoP
    - AAA and CGNAT functions there



According to Travis from SpaceX …

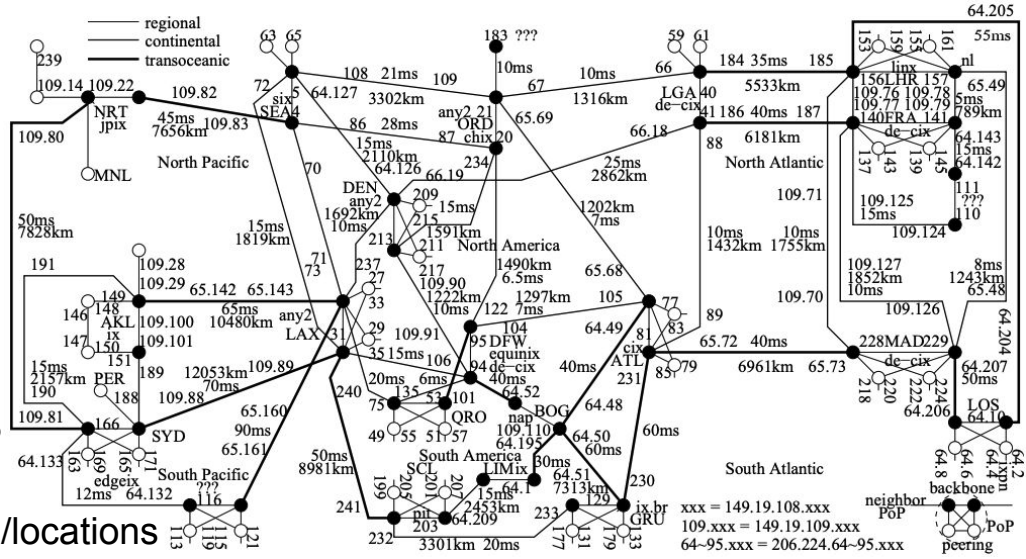
Routing in the mesh



and this is a really good example of, of antarctica.

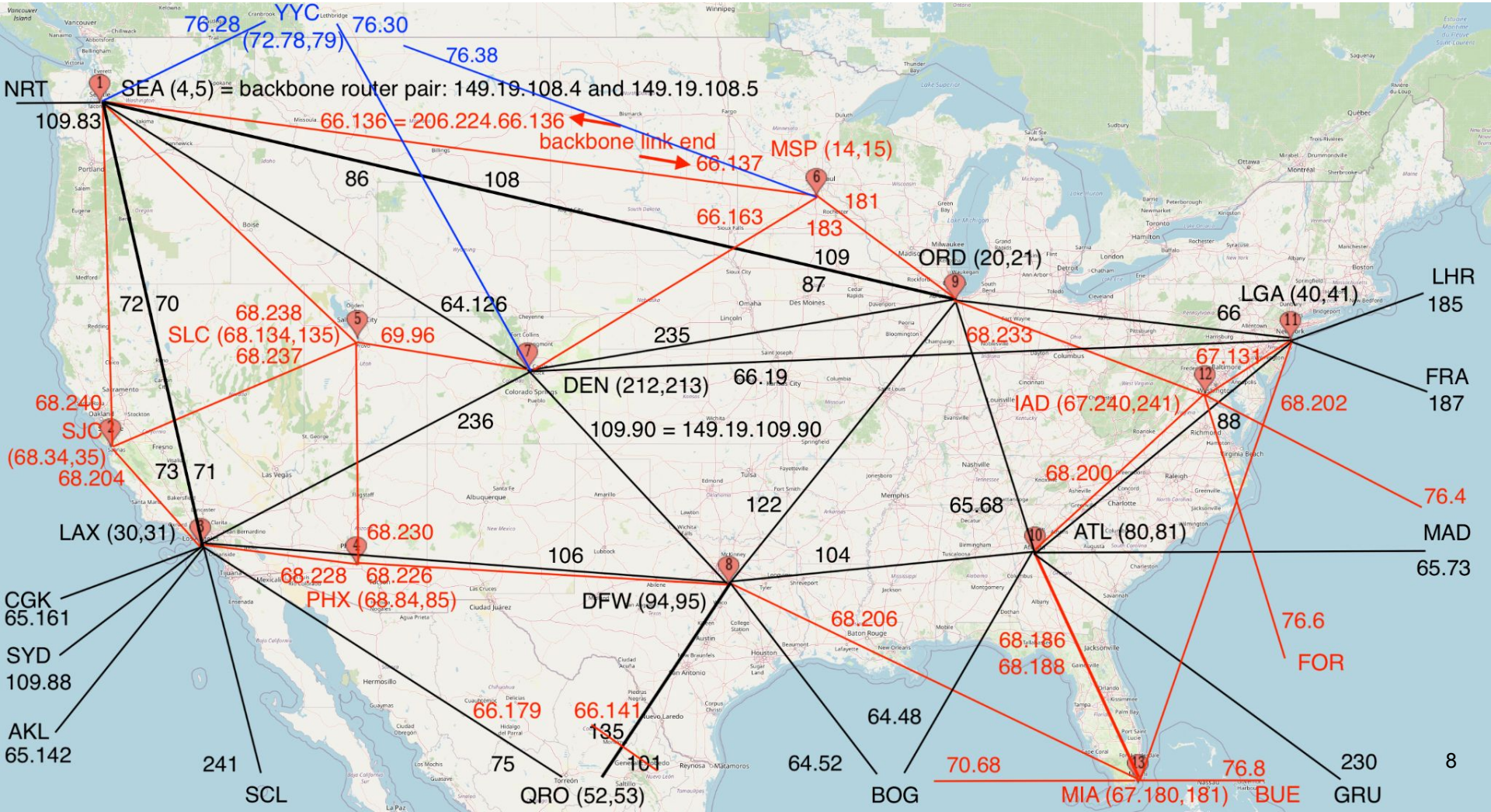
Routing on the ground

- Starlink **backbone** network
  - Starlink points of presence (PoPs)
    - http://peeringdb.com/asn/14593
    - Currently about 40 PoPs
    - Each PoP has at least two IXPs/locations
  - Outgoing Starlink user traffic
    - Exit at the source's home PoP ASAP
    - Unless the destination is within Starlink
      - Then through the Starlink backbone network
  - Incoming Starlink user traffic
    - Over the public Internet as much as possible
    - Enter Starlink near the destination's home PoP
  - Also connect the landing ground stations and home PoP
    - To tunnel the user traffic
  - Each PoP has at least two neighbor PoPs



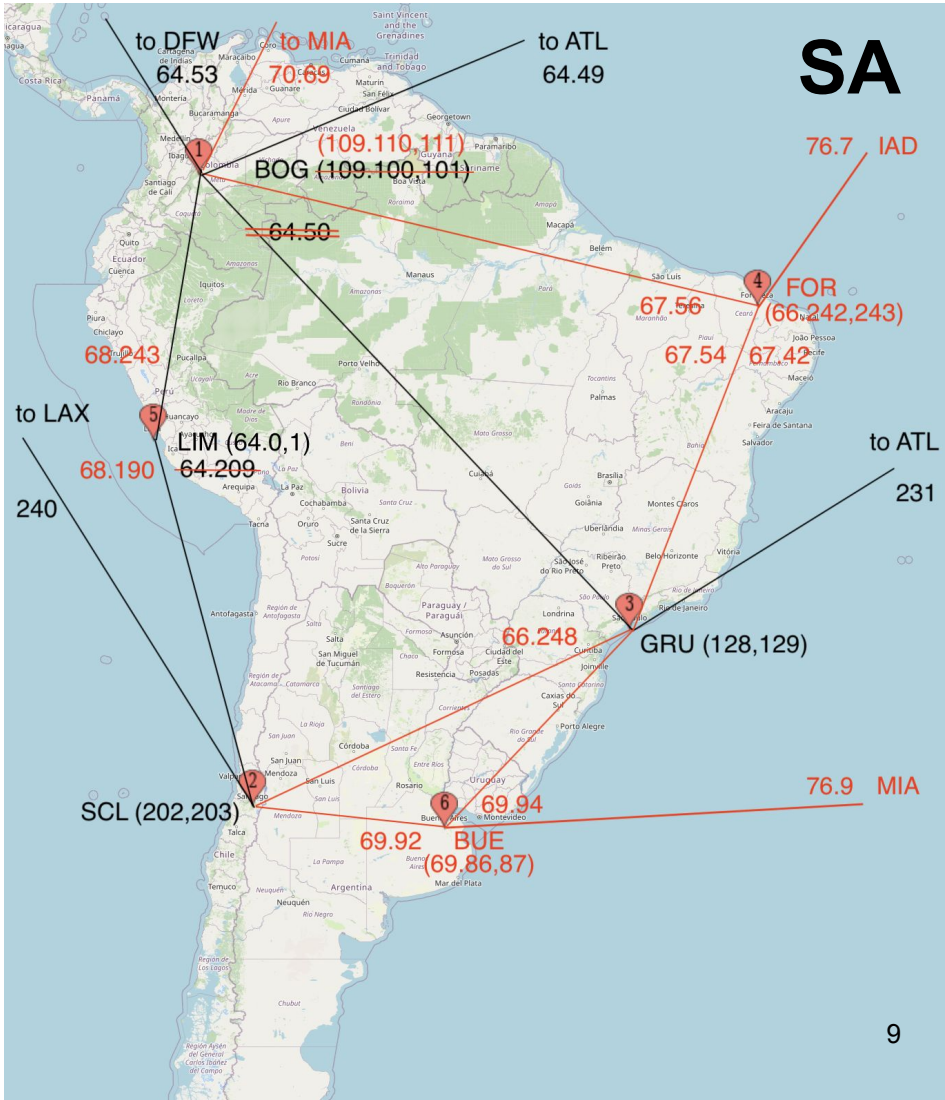
- Starlink PoPs in 2023
  - NA: SEA, ORD, LGA, DEN, LAX, DFW, ATL
  - SA: BOG, LIM, SCL, GRU
  - AP: SYD, AKL, NRT
  - EMEA: LHR, FRA, MAD, LOS

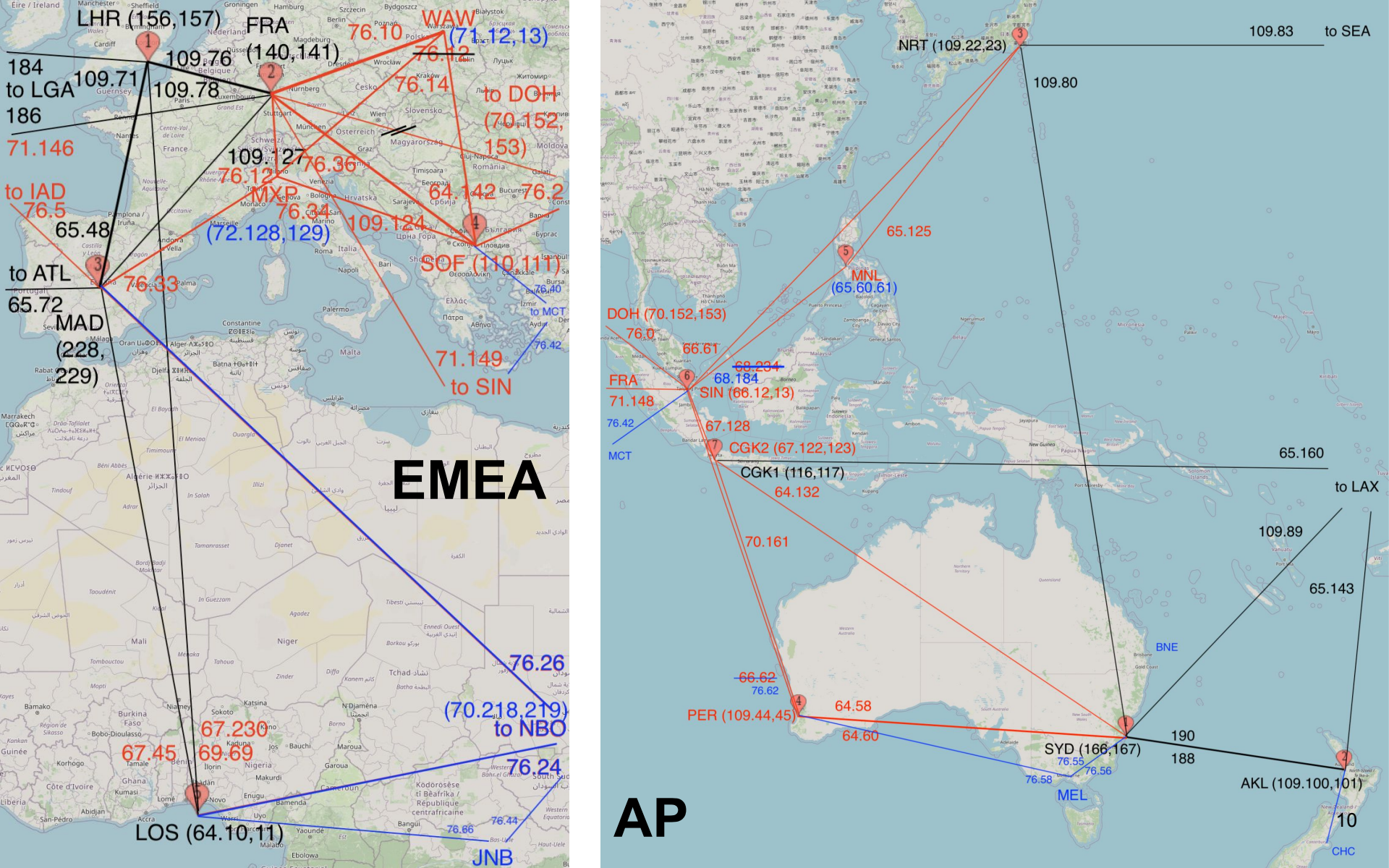
Starlink North America backbone (red: ’24; blue: ’25)



Starlink global backbone

- To discover the Starlink backbone
  - traceroute from Starlink users
    - Scripts, probes, VMs, etc
  - traceroute from the Internet VMs
    - Near Starlink PoPs
- Similar to other global networks
  - MPLS-based tunnels
    - ICMP echo inflation
    - Toward Starlink users
    - But not to Starlink backbone
  - PoPs near top IXPs
    - Many other ISPs
    - Big content providers
    - Also CDN providers




LHR (156,157)
FRA
(140,141)
WAW
(71,12,13)
76.10
76.12
109.76
184
to LGA
186
109.71
109.78
76.14
to DOH
(70.152,
153)
71.146
109.27
76.36
76.12
MXP
64.142
76.2
to IAD
76.5
65.48
76.34
(72.128,129)
109.184
SOF (110,111)
to ATL
65.72
76.33
MAD
(228,
229)
76.40
to MCT
76.42
71.149
to SIN
EMEA
76.26
(70.218,219)
to NBO
67.230
67.45
69.69
76.24
LOS (64.10,11)
76.66
76.44
JNB
109.83
to SEA
NRT (109.22,23)
109.80
65.125
MNL
(65.60.61)
DOH (70.152,153)
76.0
66.61
68.234
68.184
FRA
71.148
SIN (66.12,13)
76.42
67.128
MCT
CGK2 (67.122,123)
CGK1 (116,117)
65.160
64.132
to LAX
70.161
109.89
65.143
BNE
66.62
76.62
PER (109.44,45)
64.58
64.60
190
188
SYD (166,167)
76.55
76.56
76.58
MEL
AKL (109.100,101)
AP
10
CHC

Suboptimal routing

HOST: administrator-virtual-machi	Loss%	Snt	Last	Avg	Best	Wrst	StDev	
1.|-- 192.168.1.1	0.0%	100	0.6	0.7	0.4	9.7	0.9	
2.|-- 100.64.0.1	2.0%	100	181.3	201.1	156.2	374.3	52.0	inte
3.|-- 172.16.249.14	1.0%	100	174.6	206.7	156.4	377.1	54.7	
4.|-- 206.224.64.10	1.0%	100	181.6	202.4	158.4	374.2	51.7	LOS
5.|-- 206.224.64.205	1.0%	100	267.0	297.7	252.1	463.2	51.5	LHR
6.|-- 149.19.108.184	2.0%	100	330.7	363.6	320.5	534.3	51.2	LGA
7.|-- 149.19.108.41	2.0%	100	335.0	364.4	314.9	533.0	51.4	LGA
8.|-- 206.224.66.19	1.0%	100	399.0	423.1	381.4	778.7	58.9	DEN
9.|-- 149.19.108.237	1.0%	100	415.8	447.5	395.9	714.8	57.5	LAX
10.|-- 149.19.108.31	1.0%	100	423.6	446.5	394.6	651.0	54.2	LAX
11.|-- 149.19.109.88	1.0%	100	568.5	596.3	553.5	760.6	49.4	SYD
12.|-- 206.224.64.60	2.0%	100	607.3	640.1	595.9	807.8	49.3	PER
13.|-- 149.19.109.44	2.0%	100	614.7	639.3	592.4	820.4	50.3	

- Currently **home PoP** centric
  - Route toward the home PoP first
    - UT-SAT*-SAG
    - Space and ground tunnel
    - Home PoP
  - Regardless the destination
    - Exit home PoP ASAP for non-Starlink destinations
  - In 2023, from Starlink West to Starlink East Indian Ocean
    - Inter-sat links to Lagos (LOS)
    - Lagos to London (LHR)
    - London to New York City (LGA)
    - New York City to Denver (DEN)
    - Denver to Los Angeles (LAX)
    - Los Angeles to Sydney (SYD)
    - Sydney to Perth (PER), ~600ms RTT
- In 2024
  - LOS-LHR-FRA-**SIN**-PER
  - Better than 2023 above
  - ~300ms RTT
- Hopefully in near future
  - **Direct** inter-sat links
  - Across the Indian Ocean
  - ~100ms RTT

Other routing issues

- Still **limited** PoP Locations
  - Two (side-by-side) Starlink users in Alaska
    - Exchange traffic at Seattle PoP
- **Mismatch** between PoP and content
  - Ping-to-PoP vs ping-to-content dilemma
  - E.g., a Starlink user in Africa with a PoP in Europe
    - High ping-to-PoP due to inter-sat links
    - But ping-to-content just a little bit extra
    - May receive geo-irrelevant content (by PoP)
  - Later moved to a PoP in Africa
    - Much lower ping-to-PoP with nearby GS/PoP
    - But ping-to-content even higher for some content
    - Congested PoP, fiber, limited content in Africa
    - Some content (e.g., game servers) still in Europe
- Starlink moves a lot
  - In addition to its satellites
  - Global expansion
    - now 125+ countries
  - Address allocation
    - **Reshuffling**
  - GeoIP *manually* updated
    - Auto exported
    - Without timestamp
    - Or time-to-live, TTL
  - Content providers use
    - an *outdated* copy
  - Starlink customers see
    - Geo-irrelevant ads

Routing is *not* only in the network layer

- Content routing
  - A Starlink user in Zambia
  - Now associated with the Nairobi PoP
  - Traceroute to Cloudflare in Nairobi
    - As expected
  - HTTP served by
    - Nairobi
    - and Johannesburg, so >100ms extra RTT
    - In an almost interleaved way
  - Limited capacity/content at Nairobi?
  - Load balancing?
    - Shall be consistent for a user?
    - Or stateful applications may suffer?
  - Anyone from SpaceX or Cloudflare?

< CF-RAY: 9220830bea799e94-JNB
real 0m0.224s
< CF-RAY: 9220830d992e73fa-JNB
real 0m0.264s
< CF-RAY: 9220830e99a68a47-NBO
real 0m0.124s
< CF-RAY: 9220830f69a98a41-NBO
real 0m0.121s
< CF-RAY: 92208310cce99e94-JNB
real 0m0.262s
< CF-RAY: 92208311daba8a47-NBO
real 0m0.120s
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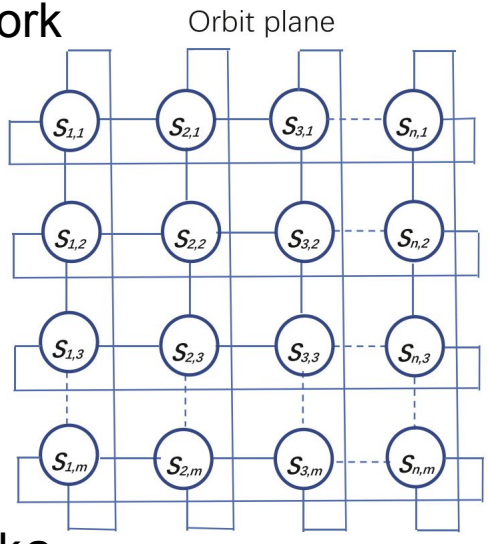
real 0m0.270s
< CF-RAY: 922083173d6c73fa-JNB
real 0m0.263s

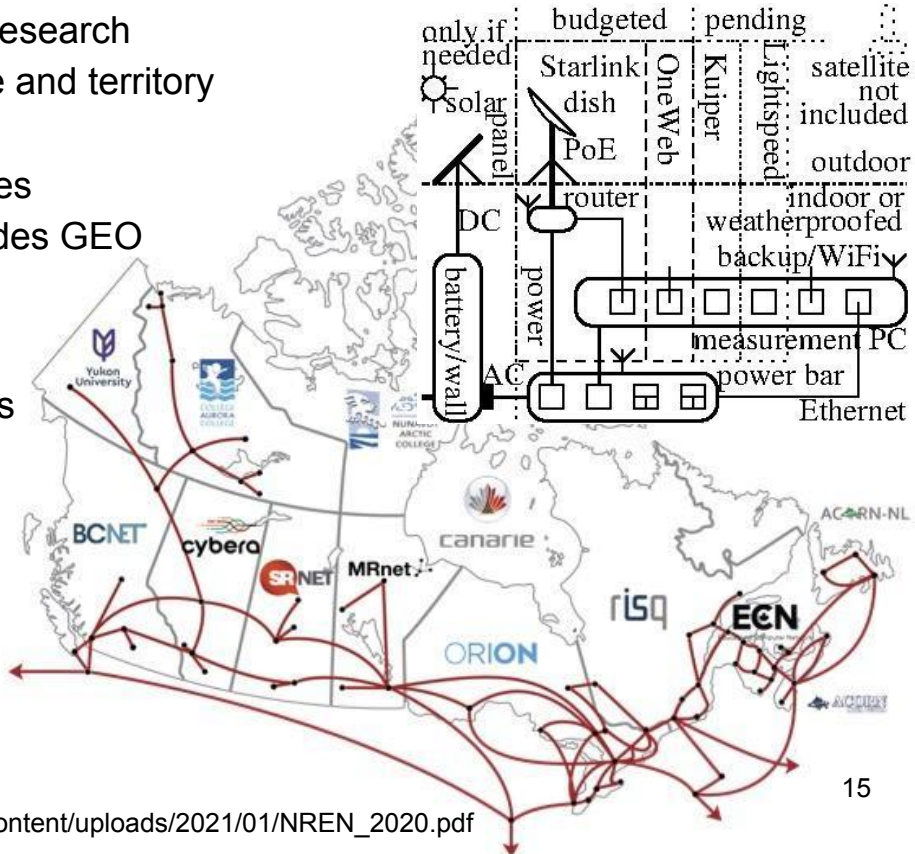
Routing is a ***central*** function of any networks

- No exception for **a** large-scale low-earth-orbit satellite network
  - How to route among satellites
    - Same orbital plane?
    - Neighbor orbital planes?
    - Intersecting orbital planes?
  - How to route between satellite and ground
    - Where is the landing ground station?
    - How to exit to the Internet ASAP?
  - How to route on the ground
    - Tradeoff between space and ground?
- No exception for large-scale low-earth-orbit satellite network***s***
  - Peering in space?
  - Peering at ground station?
  - Peering on the ground?



Why a cross-country/global 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



Also https://leoscope.surrey.ac.uk/

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

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
  - DRDC **PolarLink** (**selected**), etc