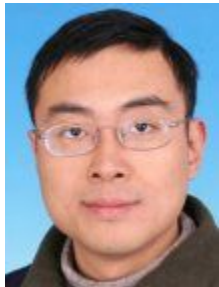
Handover behaviors of LEO satellite networks and impacts on the transport-layer protocols of the Internet

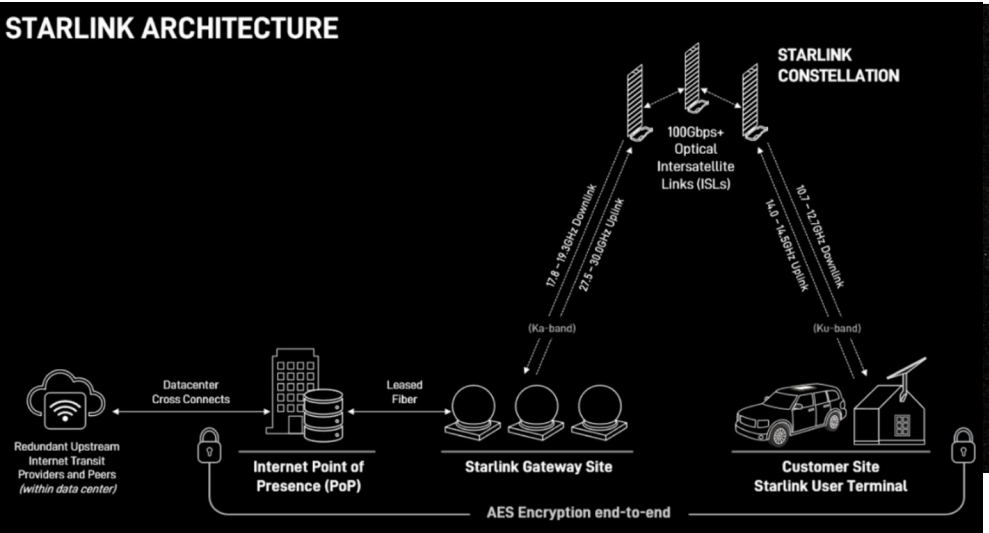
Jianping Pan
University of Victoria, BC, Canada
Pan@UVic.CA

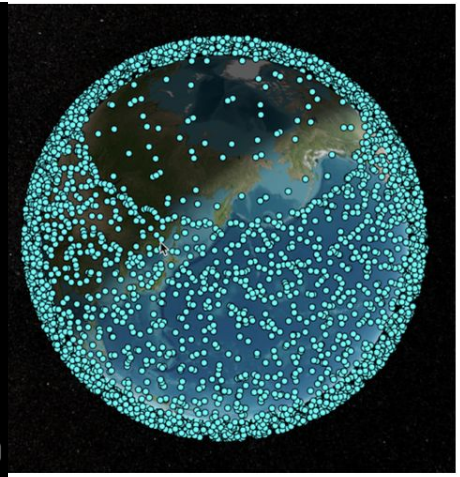


PANDALAB
Parallel, Networking and Distributed Applications Laboratory

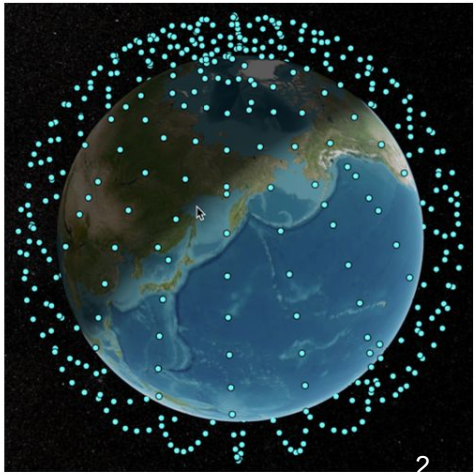
Layer 0: Architecture and topology (geometry layer)

- 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)





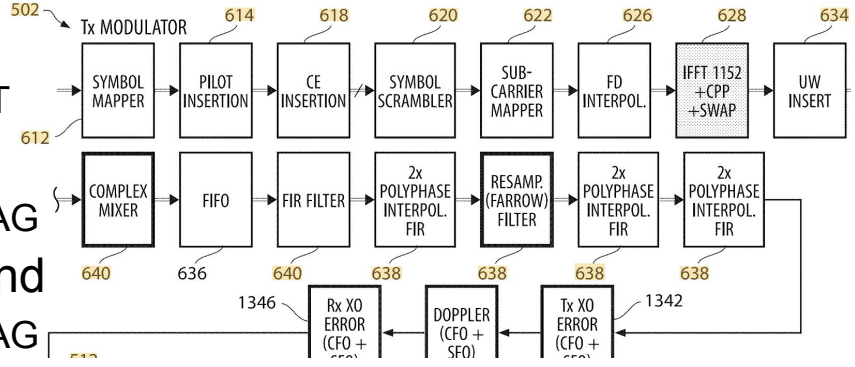
(a) Starlink

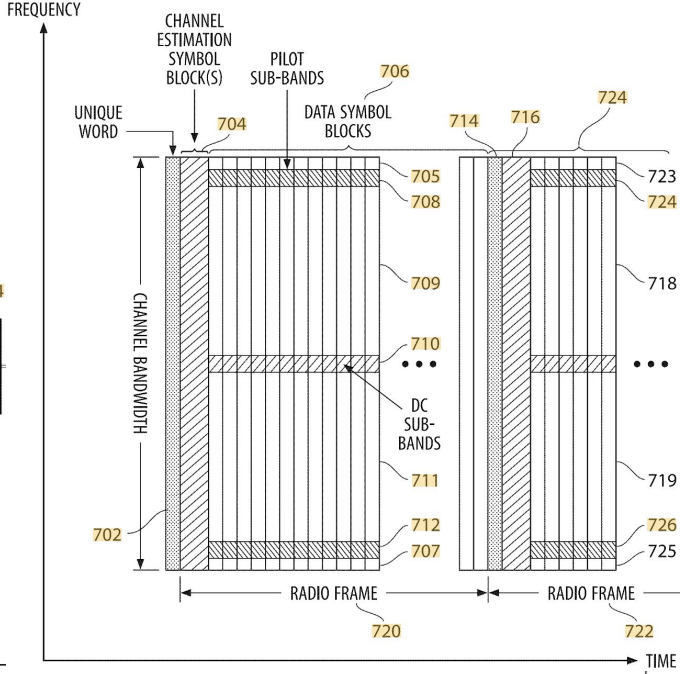


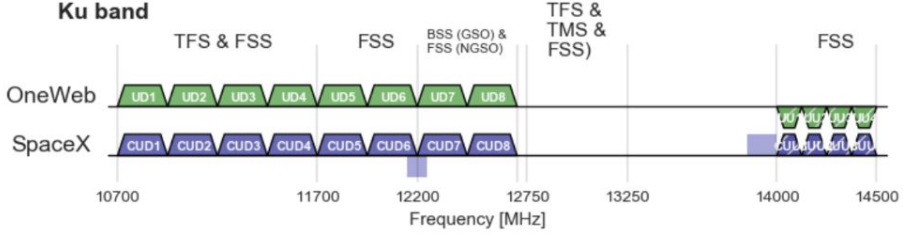
(b) OneWeb

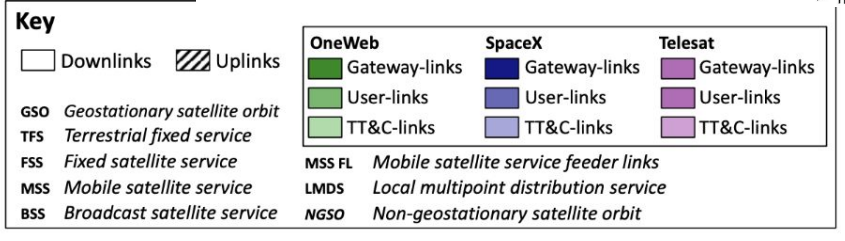
Layer 1: Physical layer (OFDM)

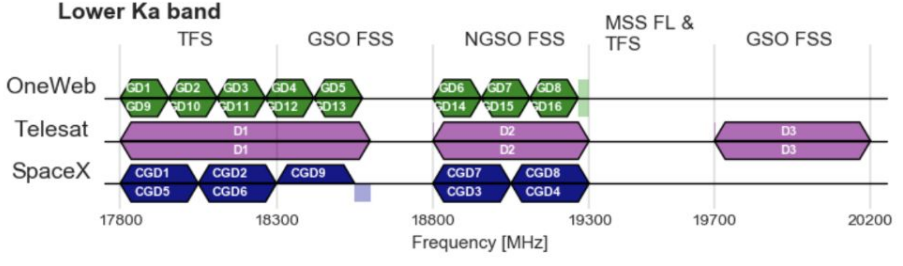
- Ku-band
  - UT-SAT
- Ka-band
  - SAT-SAG
- Also E-band
  - SAT-SAG

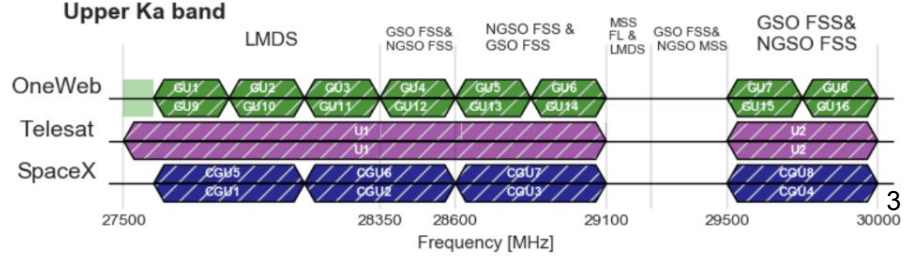






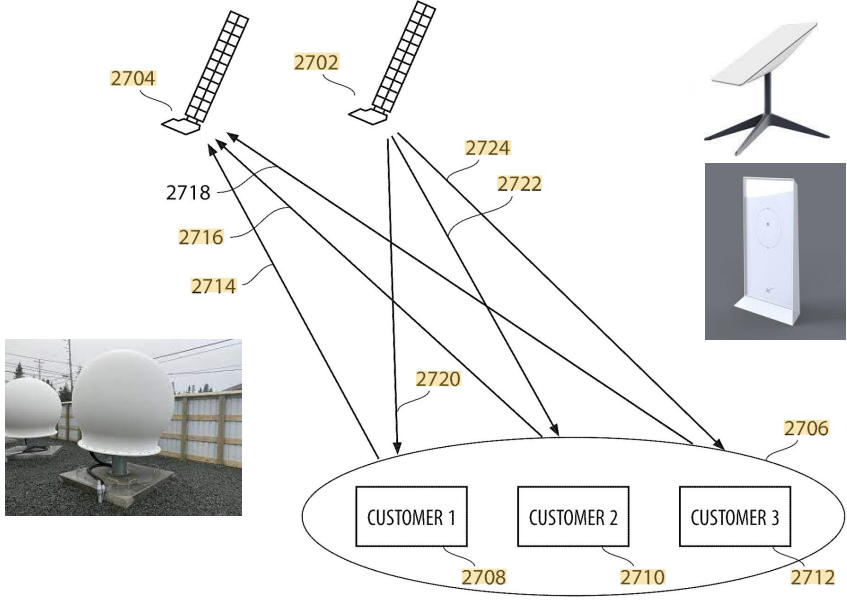


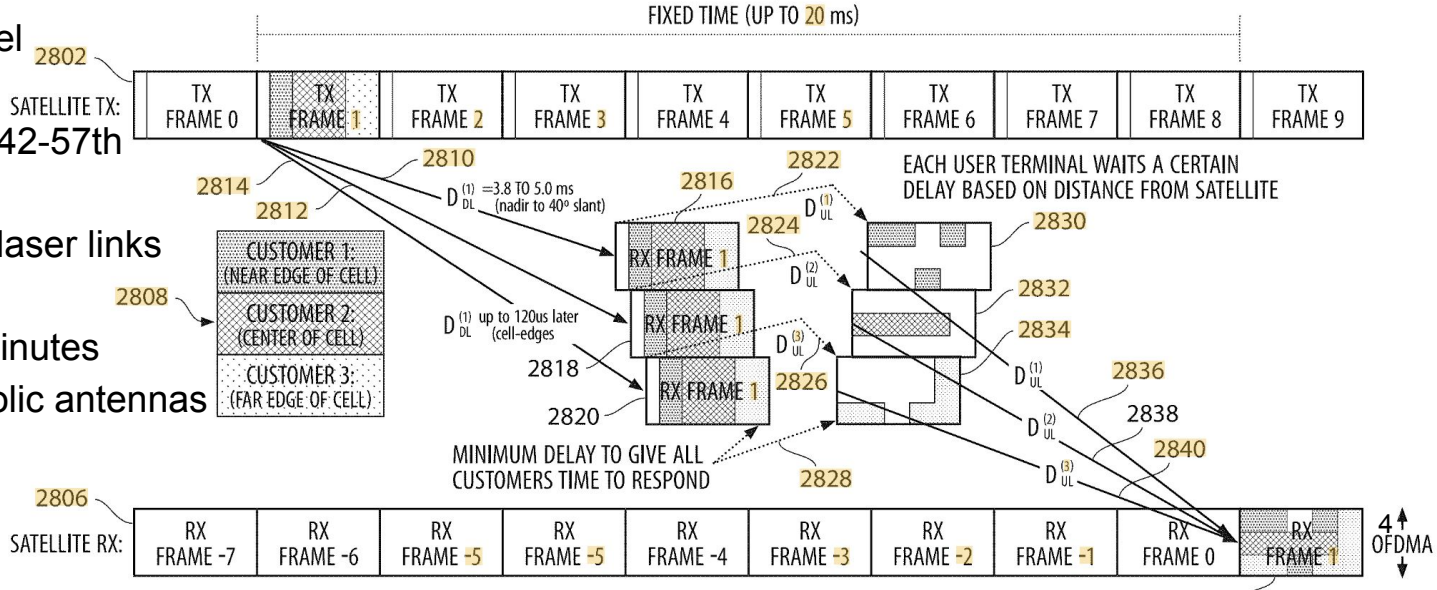




Layer 2: Link layer (tunnels)

- Media access control
  - Users are grouped into service cells
  - User downlink: Broadcast by nature
    - User traffic UT-PoP encrypted
  - User uplink: Poll-randomize-grant
- **Link-layer handovers**
  - UT-SAT panel
    - 15-sec
    - 12-27-42-57th
  - SAT-SAT
    - Three laser links
  - SAT-SAG
    - Few minutes
    - Parabolic antennas



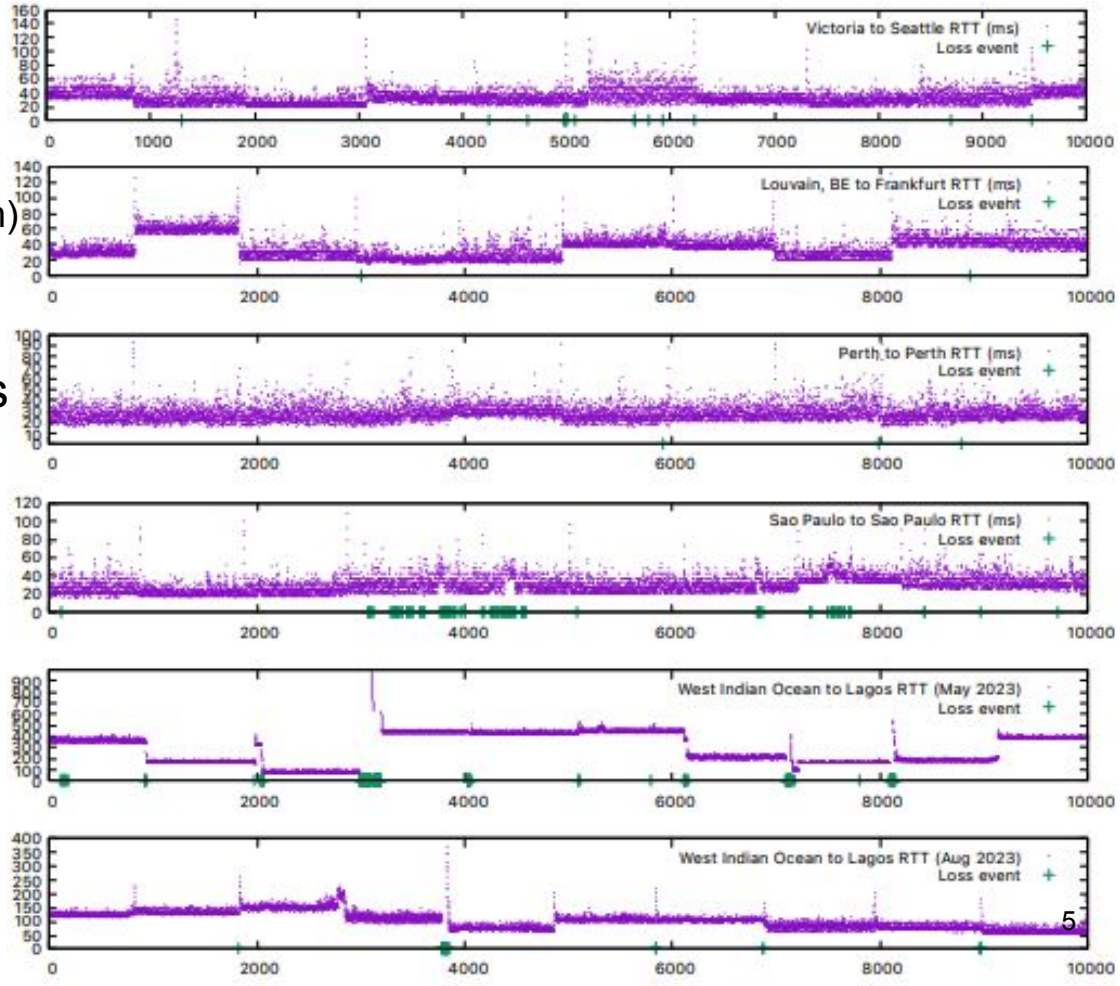


Layer 3: Network layer (Starlink: both IPv4 and IPv6)

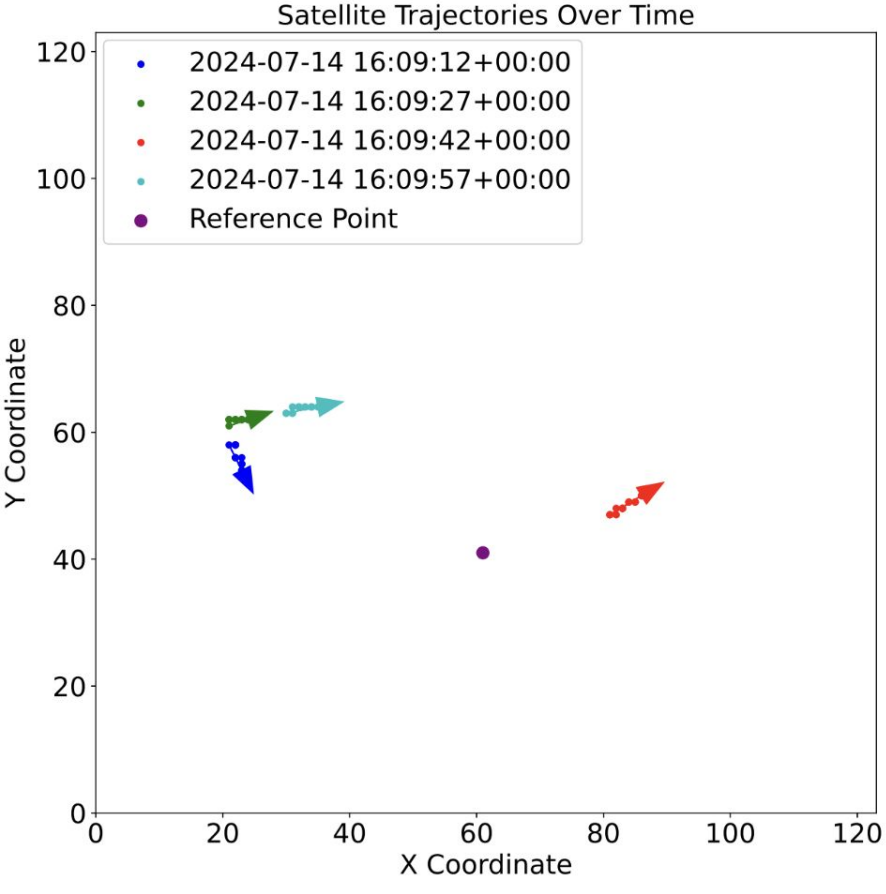
- User terminal router (UTR)
  - LAN: 192.168.1.1 by default
  - WAN: 100.x.y.z/10 (unique hash)
- User terminal antenna (UTA)
  - 192.168.100.1: Web and gRPC
- Satellites and ground stations
  - Invisible at IP layer by users
  - Latency (min-RTT) can infer
- Point-of-presence
  - 100.64.0.1 for CGNAT users
  - fe80::200:5eff:fe00:101 for IPv6
- **So the “access hop” in IP**
  - Ping between UTR and PoP

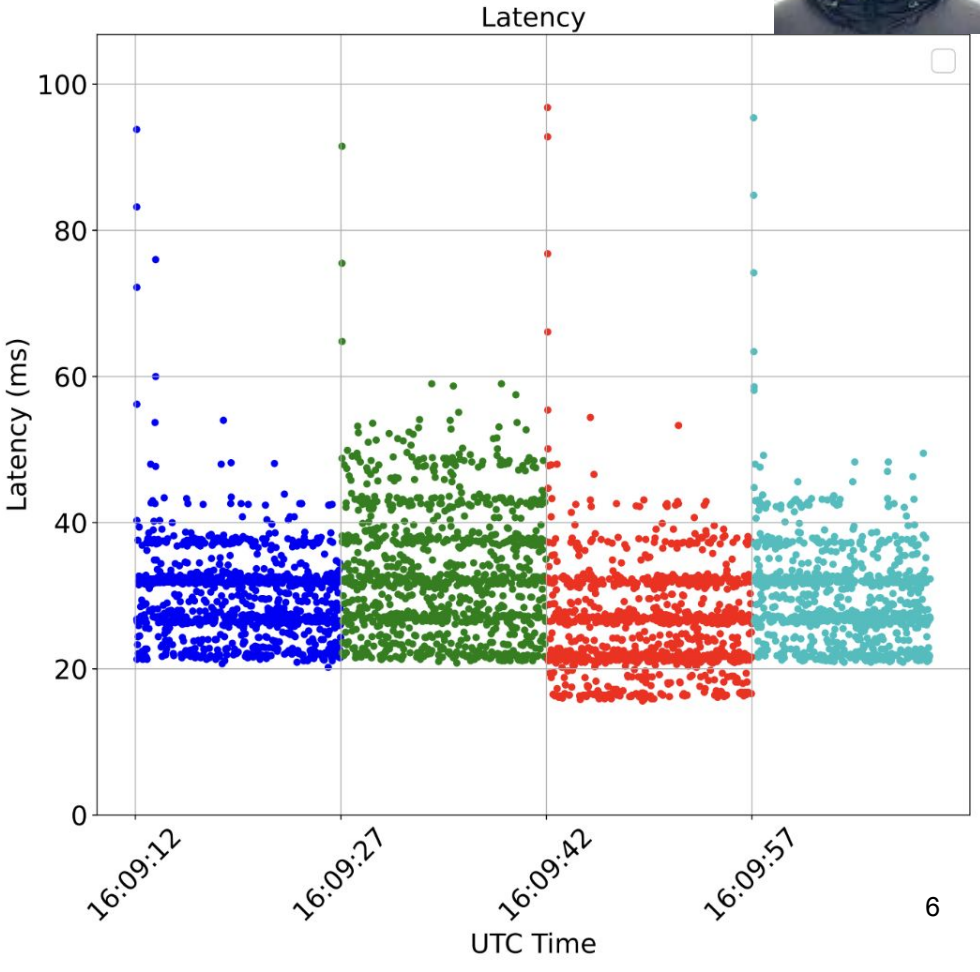
1 IP hop

```
traceroute to 100.64.0.1 (100.64.0.1)
 1  192.168.1.1  0.254 ms  0.261 ms  UTR
 2  100.64.0.1  26.708 ms  38.670 ms  NATi
 3  100.64.0.1  38.620 ms  38.609 ms  NATe
```



Satellite handover and link **latency** performance

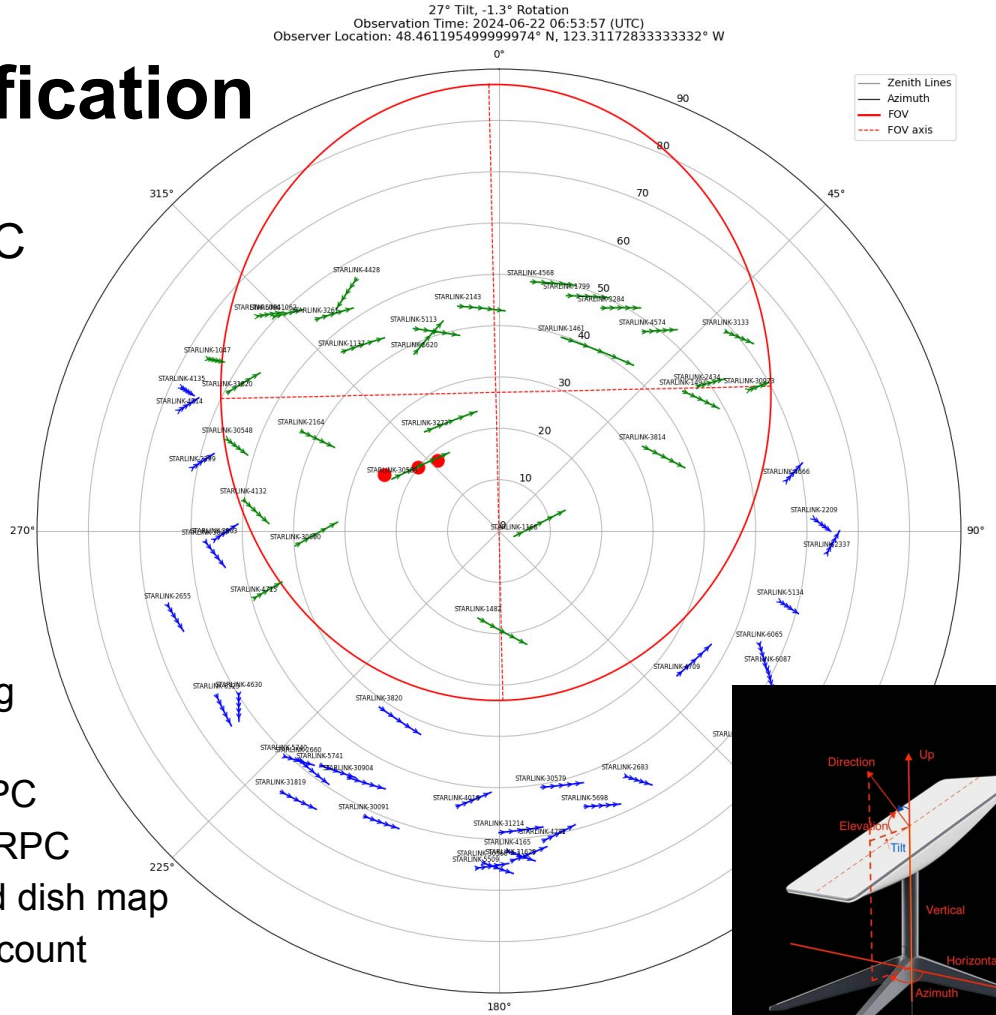




* ACM LEONET 2024; available on GitHub

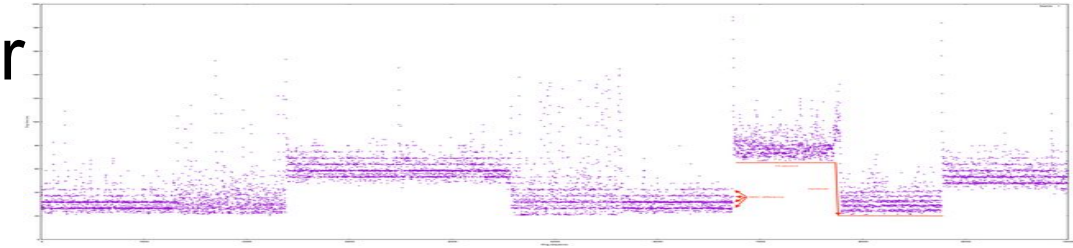
Starlink satellite **identification**

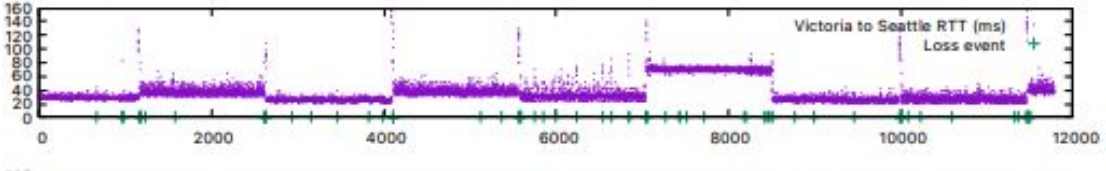
- Starlink used to export by gRPC
  - Satellite ID
  - Cell ID
  - Gateway ID
- No longer anymore
  - For whatever reason
- Identification is very important
  - For research purposes
    - TLE data from CelesTrak.org
    - Dish GPS location by gRPC
    - Dish orientation data by gRPC
    - Dish “obstruction” map by gRPC
  - Correlation between TLE data and dish map
    - With trajectory taken into account

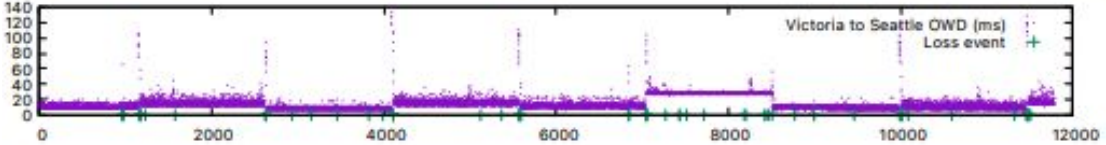


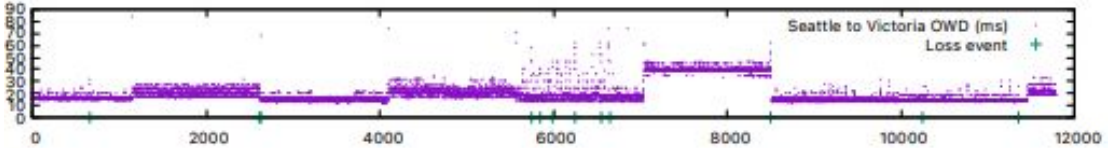
Layer 4: Transport layer

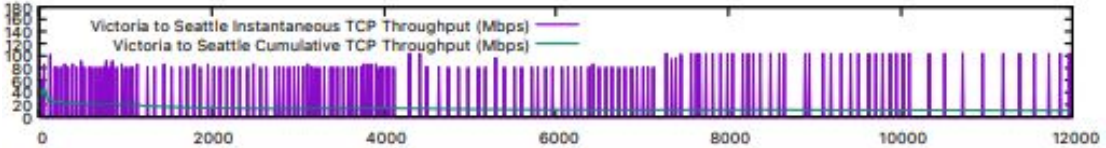
- Most common nowadays
  - TCP with congestion control
    - Reno, CUBIC, BBR, etc
    - Loss = congestion
    - Reordering = loss
  - UDP
- Emerging one
  - QUIC based on UDP
- **TCP/IP over Starlink**
  - Handover delay spike
    - Up: premature timeout
    - Down: thus reordering
  - Mistaken as network congestion
    - → much lower throughput

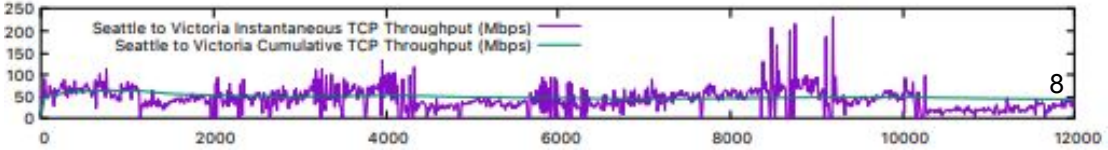






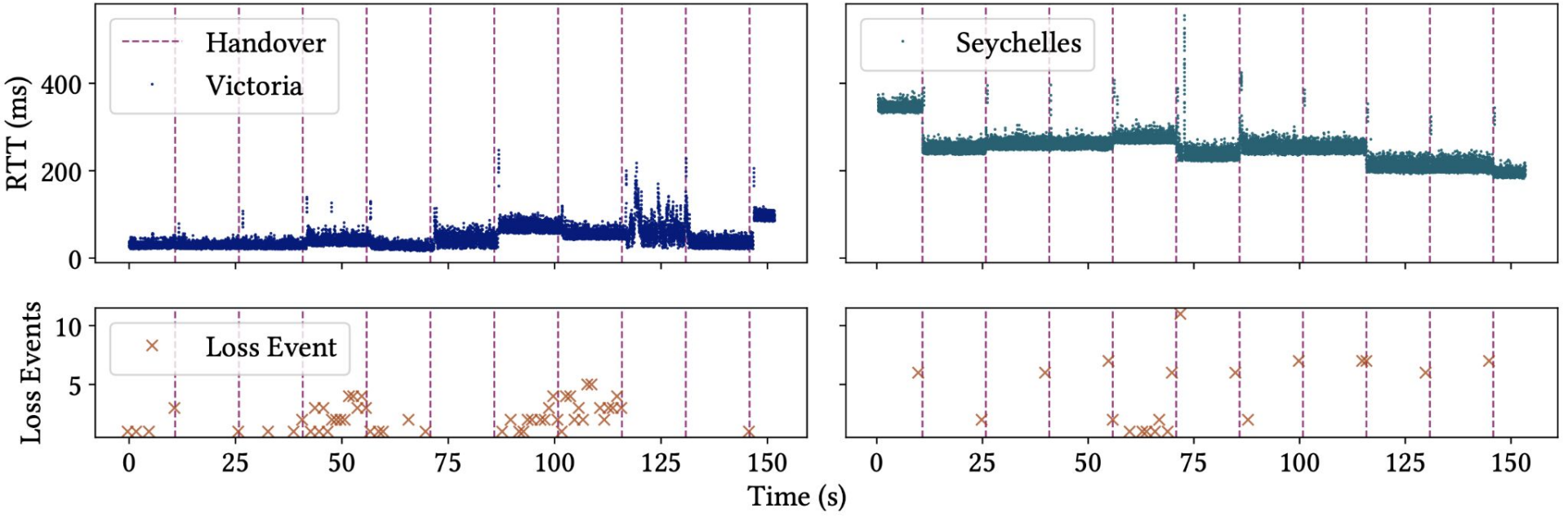






Satellite handover and **loss** event behaviors

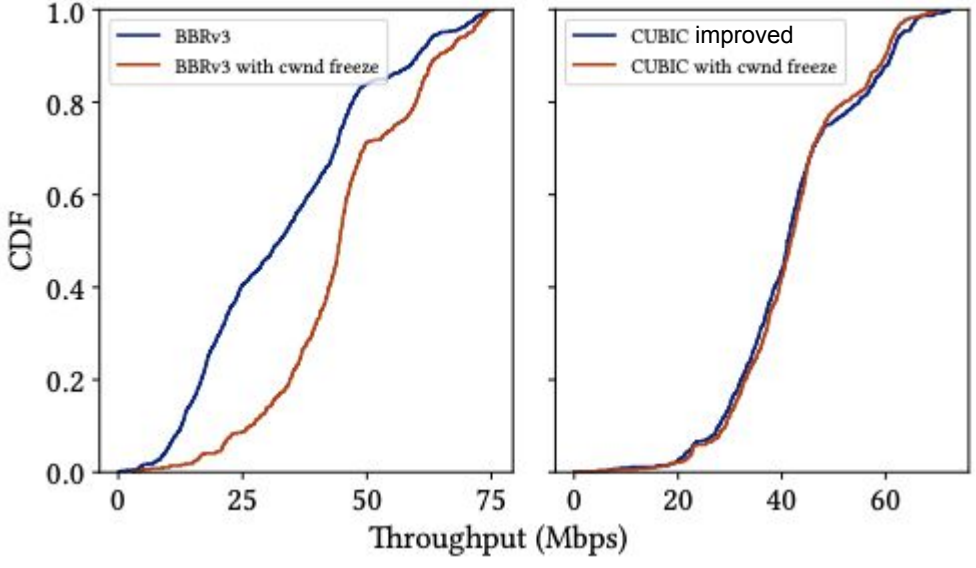
- Loss-sensitive congestion control in TCP and QUIC
  - congestion vs handover loss

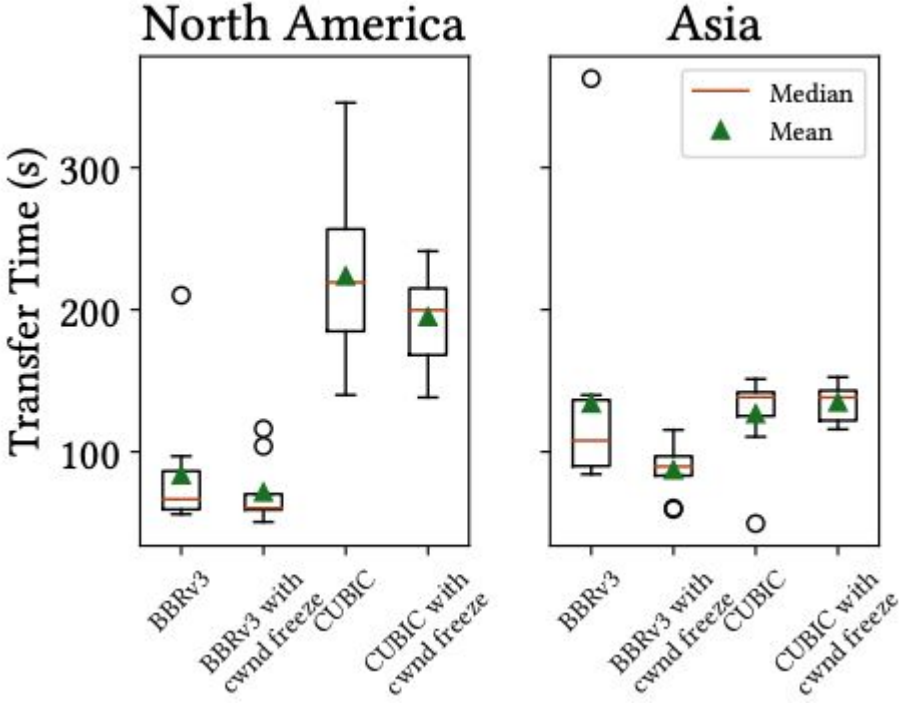


* ACM LEONET 2024; available on GitHub

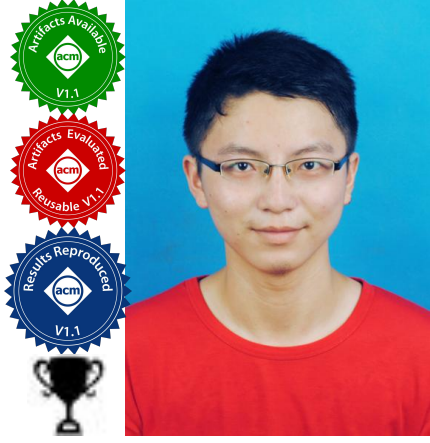
Handover-aware congestion control

- Congestion window freeze at handover
  - Mininet emulation (left)
  - Live Starlink network (right)

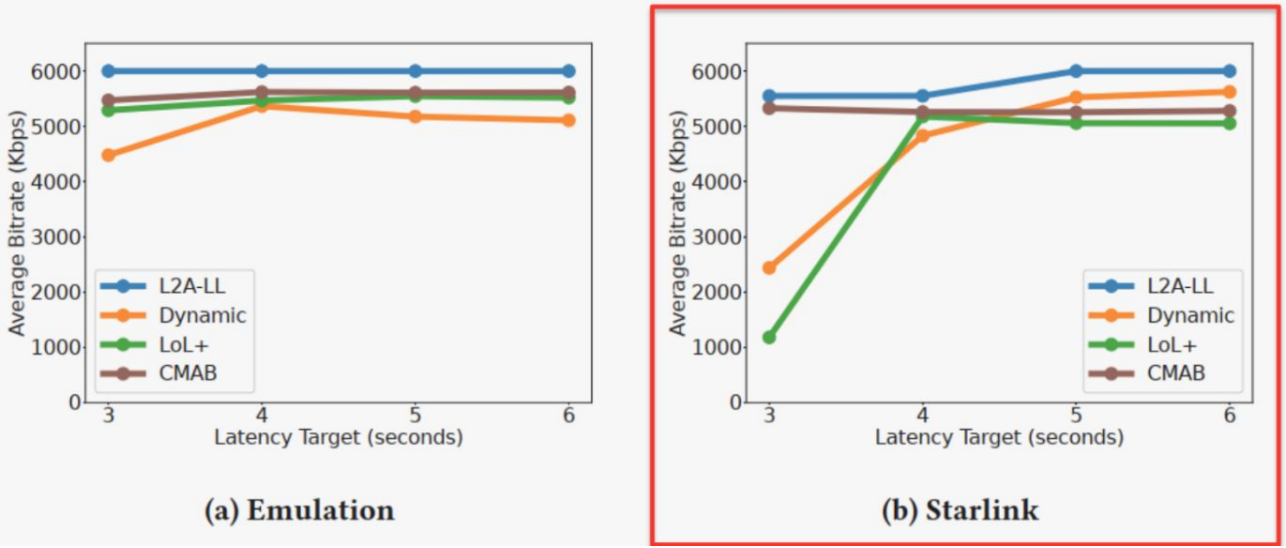




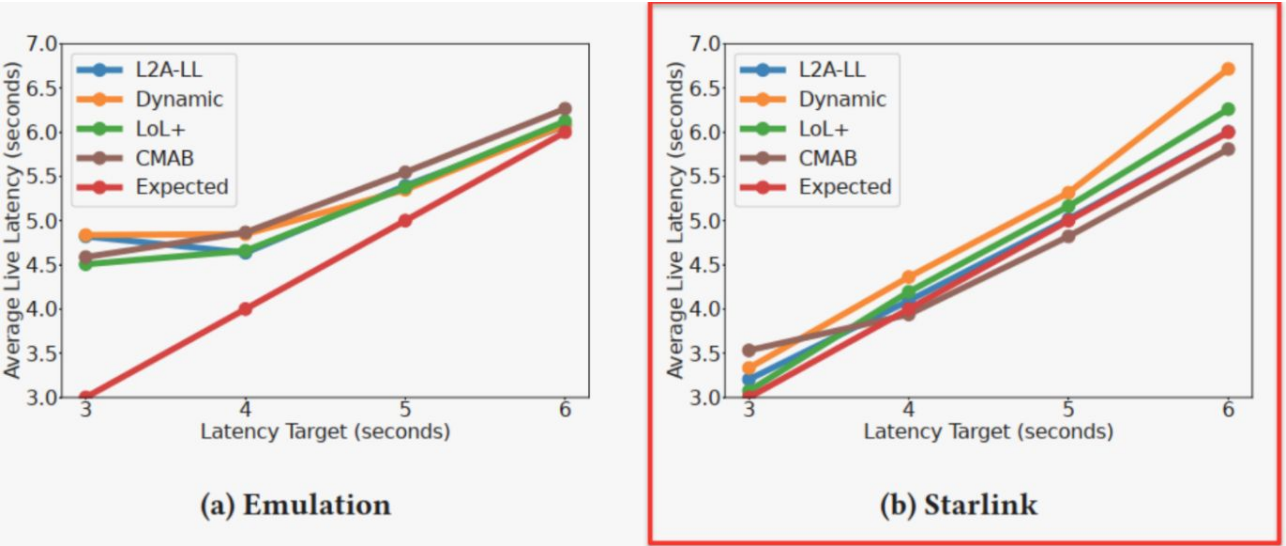
Adaptive video streaming over Starlink

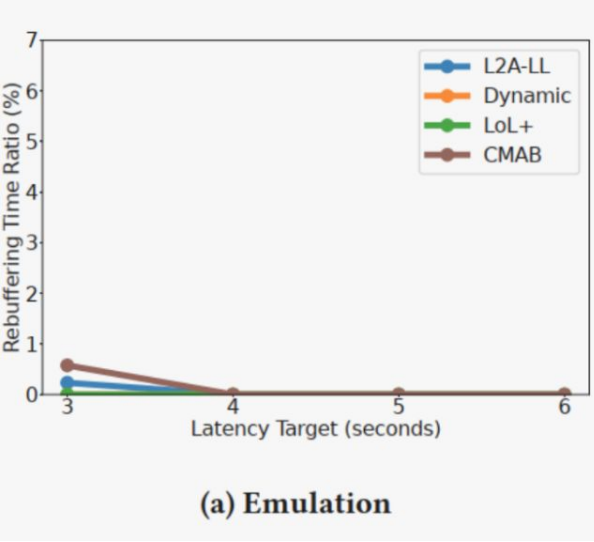


* ACM MMSys 2024; available on GitHub; DASH Prize

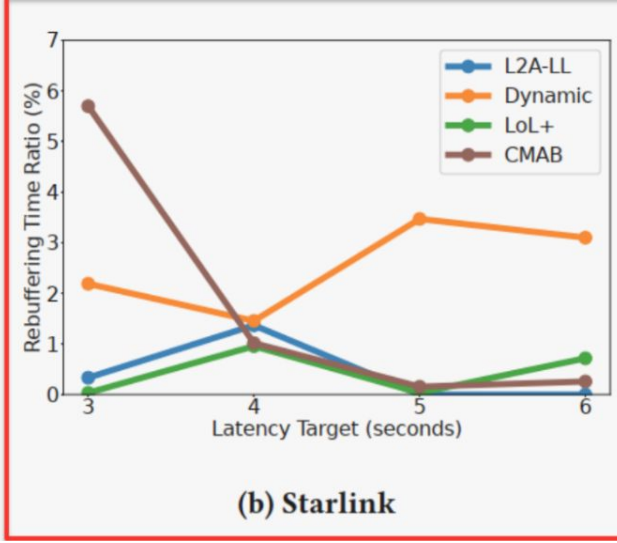


Average bit rate (^) and live latency (v)

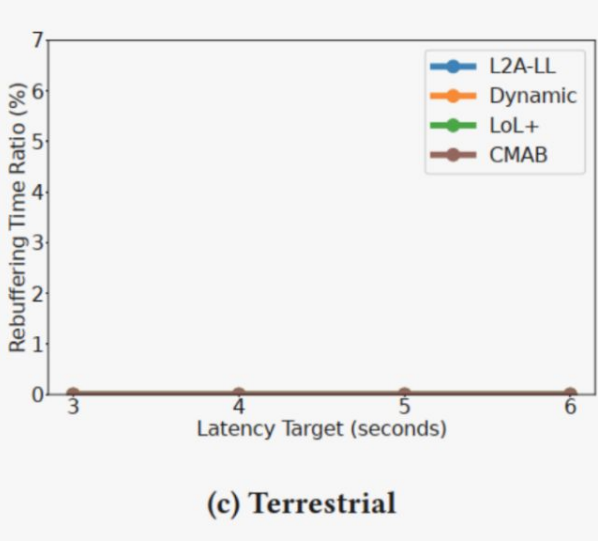




(a) Emulation

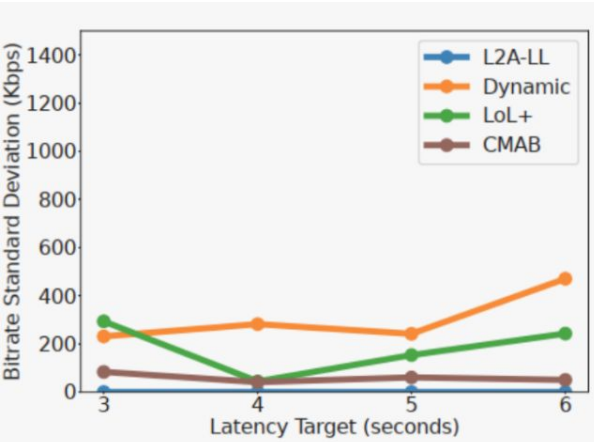


(b) Starlink

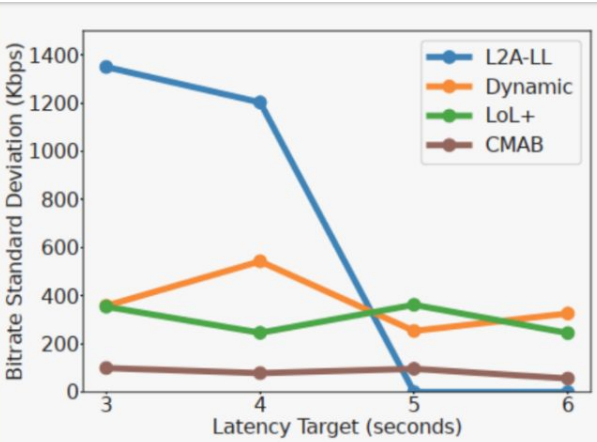


(c) Terrestrial

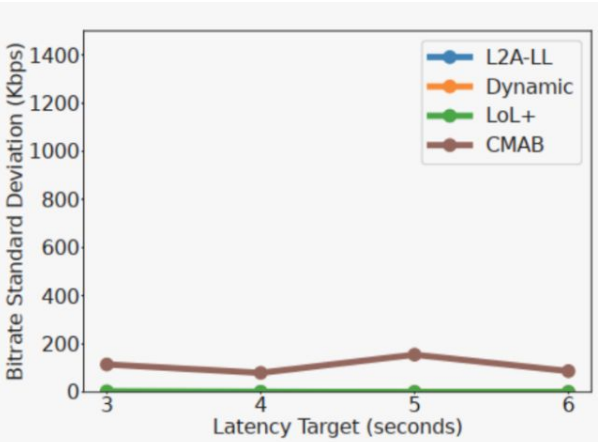
Rebuffering ratio (^) and bitrate deviation (v)



(a) Emulation



(b) Starlink



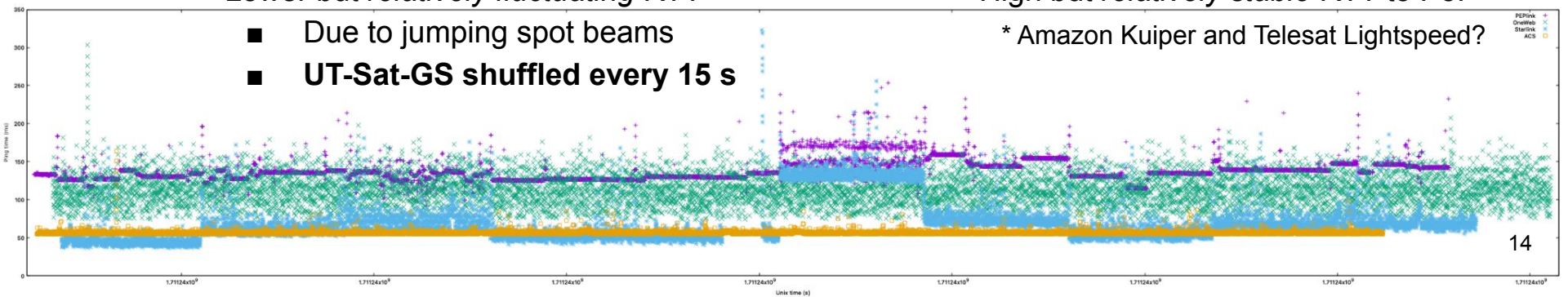
(c) Terrestrial

Comparing two LEO satellite networks

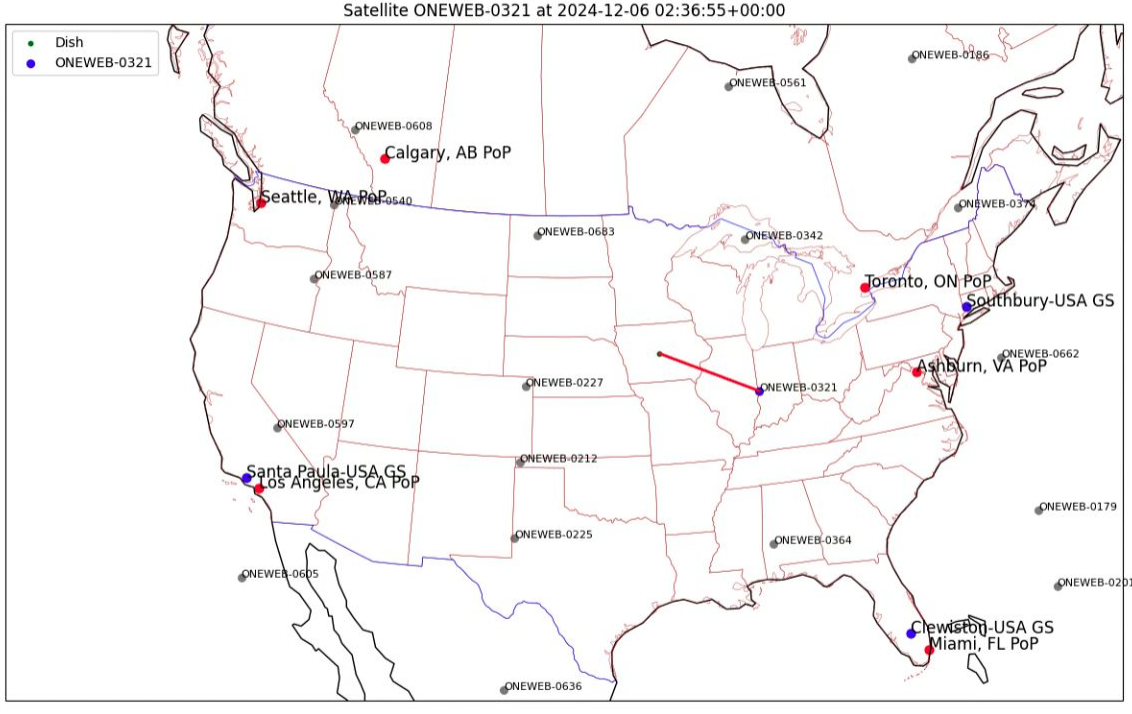
- **Starlink**
  - Initially target *consumer* users
  - Mostly 53° inclination
  - Mostly 550km above the Earth
  - **Spotting** beams for individual dishes
    - Ku for UT and Ka for GS
  - Currently >6000 active satellites
    - All launched by SpaceX
  - Currently >300x ground stations
  - Many PoPs around the world
  - Lower but *relatively fluctuating* RTT
    - Due to jumping spot beams
    - **UT-Sat-GS shuffled every 15 s**

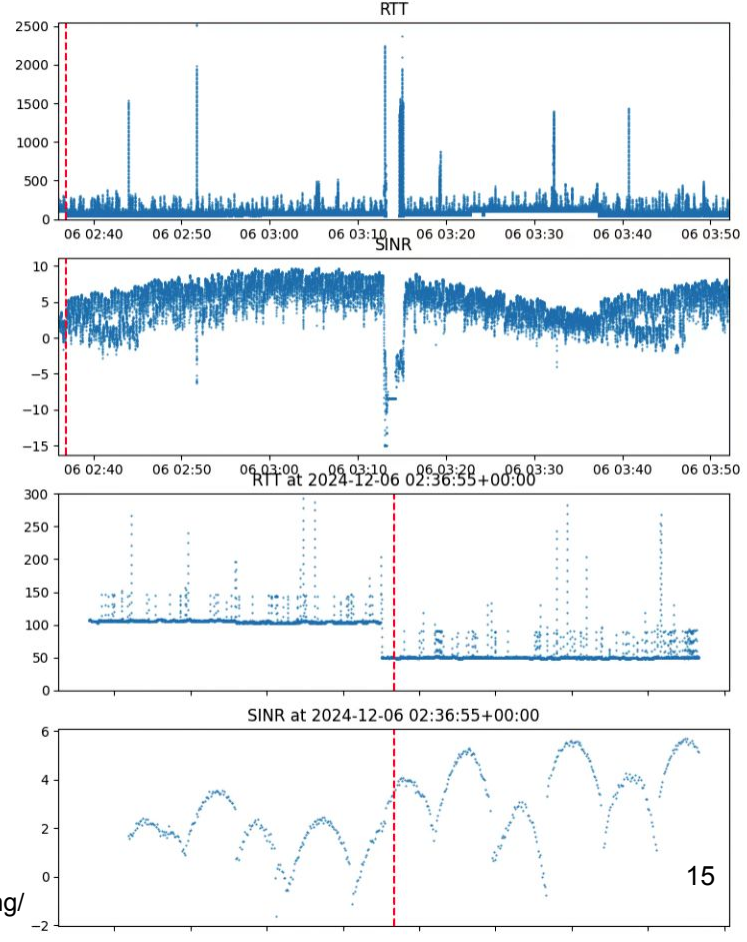
- **OneWeb**
  - Currently target *enterprise* users
  - Polar orbits
  - Around 1200km in altitude
  - **Sweeping** beams for community dishes
    - Similarly Ku and Ka
  - Currently ~600 active satellites
    - Limited 3rd-party launch capacity
  - Currently ~30x ground stations
  - Very few customer PoPs now
  - High but *relatively stable* RTT to PoP

* Amazon Kuiper and Telesat Lightspeed?



Handover behaviors in OneWeb: UT-SAT-SNP/SAG





https://www.reddit.com/r/OneWeb/comments/1hcpabo/the_video_impact_of_satellitebeam_and_landing/

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