Large Scale LEO Satellite Network for Future Internet - Routing and Solution

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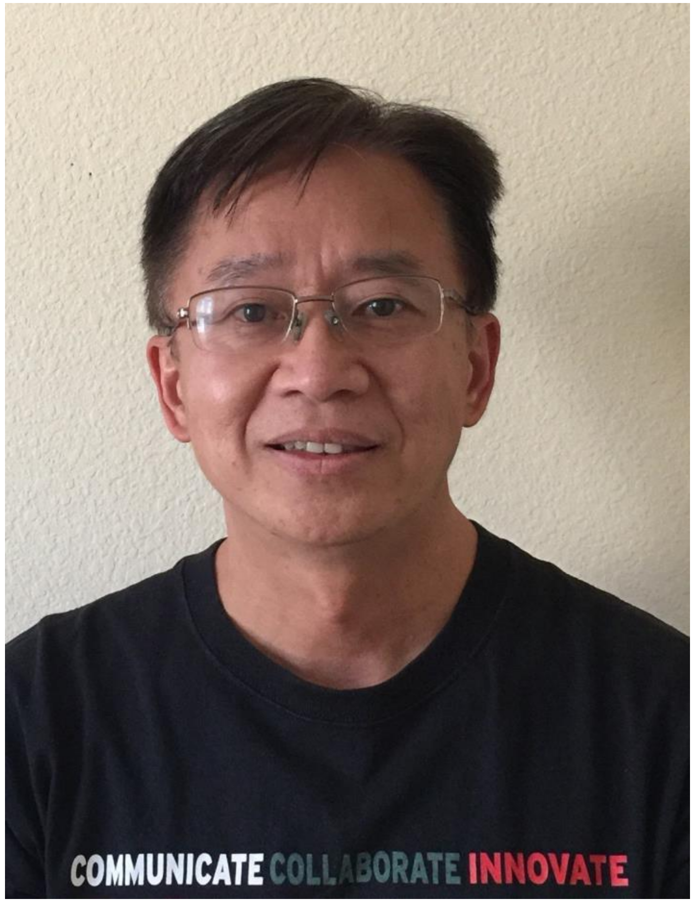
Bio

- Professional Experience
  - Distinguished Engineer, Futurewei Technologies, U.S.A (2019-Present)
  - Principal Engineer, Huawei U.S.A (2011-2019)
  - Technical Leader, Cisco Systems, U.S.A (1999-2011)
  - Software Engineer, Newbridge Network, Canada (1996-1999)
  - Engineer, Electronics Research Institute, Southeast Univ., China (1988-1994)
- Research Interest
  - Explore new network technologies for future Internet, including architecture, protocol, 5G and beyond, NTN integration, satellite networking.
- Activities
  - Work for “Focus Group on Technologies for Network 2030” in ITU, 2019
  - Rapporteur of ETSI NGP “Network Layer Multi-Path” WI, 2018
  - Rapporteur of ETSI NGP “New Transport Technology” WI, 2017
  - Papers for IEEE conference and More than 20 USA Patents
- Education
  - Master in Science, EECE, University of Toronto, Canada (1996)
  - Master in Electronics, EE, Southeast University, China (1988)



Agenda

- Satellite Networking: History and Current State
- NTN Integration: 3GPP Study and Technology Challenges
- Satellite Networking: IP Routing and Existing Research
- Our solution
  - Semantic Addressing
  - Control plane: Modified OSPF
  - Data Plane: Instructive Routing
- Modeling and Experiments
- Conclusions

History of Satellite Service

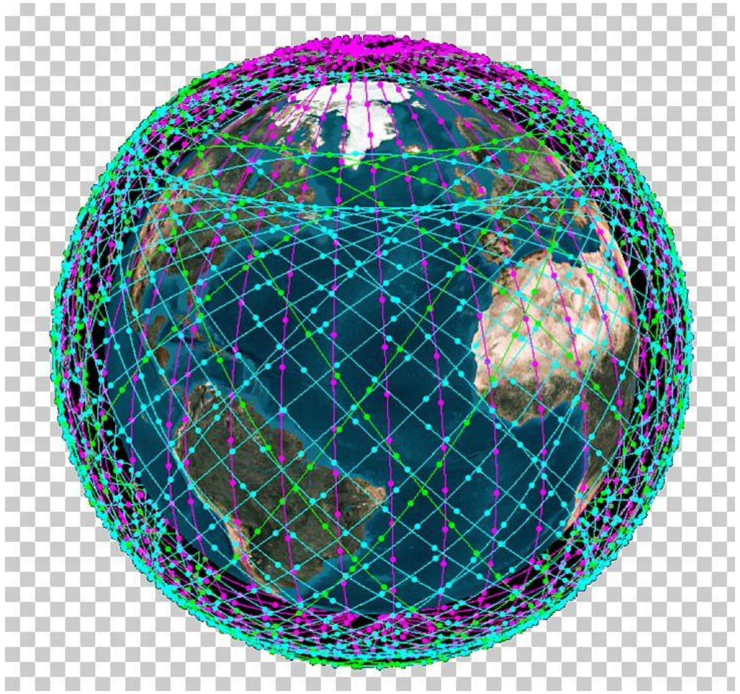
- Tradition satellite service:
  - GEO, 36000km,
  - Dish antenna
  - Broadcasting (TV) service
- Traditional satellite telecom service:
  - Voice + data
  - Use GEO, MEO
  - Very low rate ~10kbps
- LEO for Internet access:
  - < 2000km
  - Moves fast at 7.x km/s and
  - Number is high to cover the earth (>1000)
  - Broadband Internet service, ~100M bps

https://en.wikipedia.org/wiki/Low_Earth_orbit

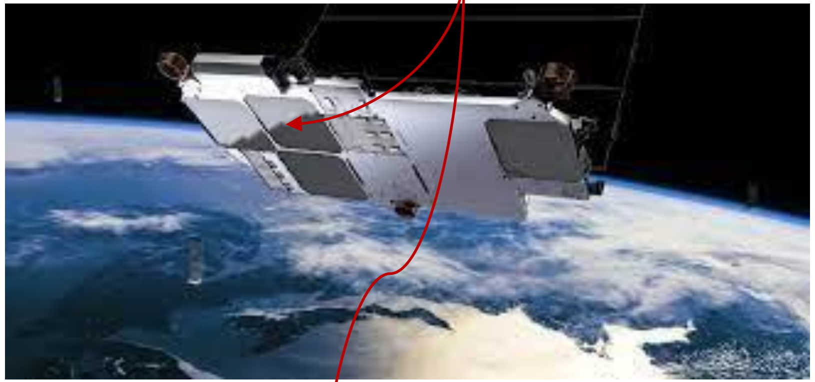
Current state - StarLink

- As of February 2023, Starlink consists of over 3,580 LEO satellite In total, nearly 12,000 satellites are planned to be deployed, with a possible later extension to 42,000
- Over 1M subscribers

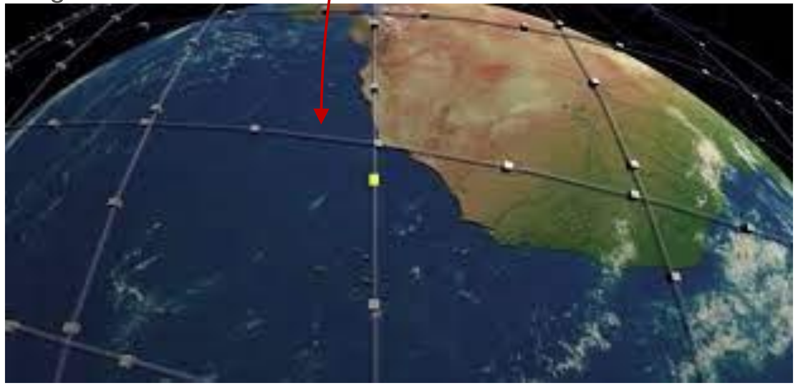
- phased array beam-forming
- Inter-satellite links



https://favpng.com/png_view/politifact-low-earth-orbit-satellite-internet-access-starlink-oneweb-satellite-constellation-png/TMgy2qS4

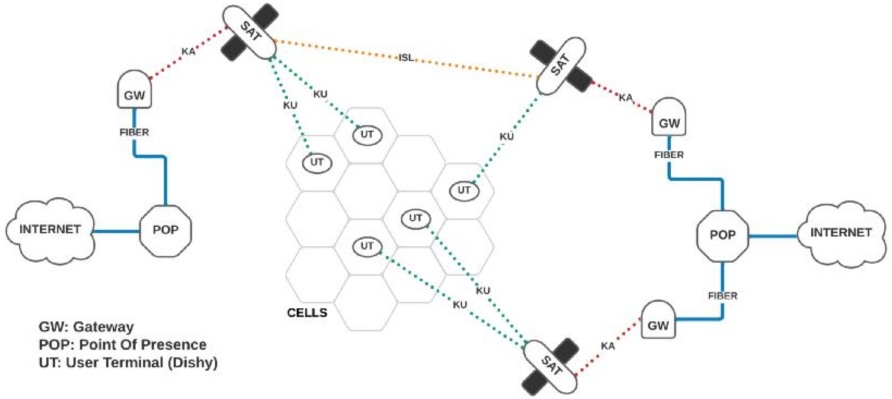


https://www.teslarati.com/spacex-next-starlink-launch-worlds-largest-constellation/



https://www.satellitetoday.com/launch/2019/04/29/fcc-approves-lower-orbit-for-spacex-starlink-satellites/

https://mikepuchol.com/modeling-starlink-capacity-843b2387f501



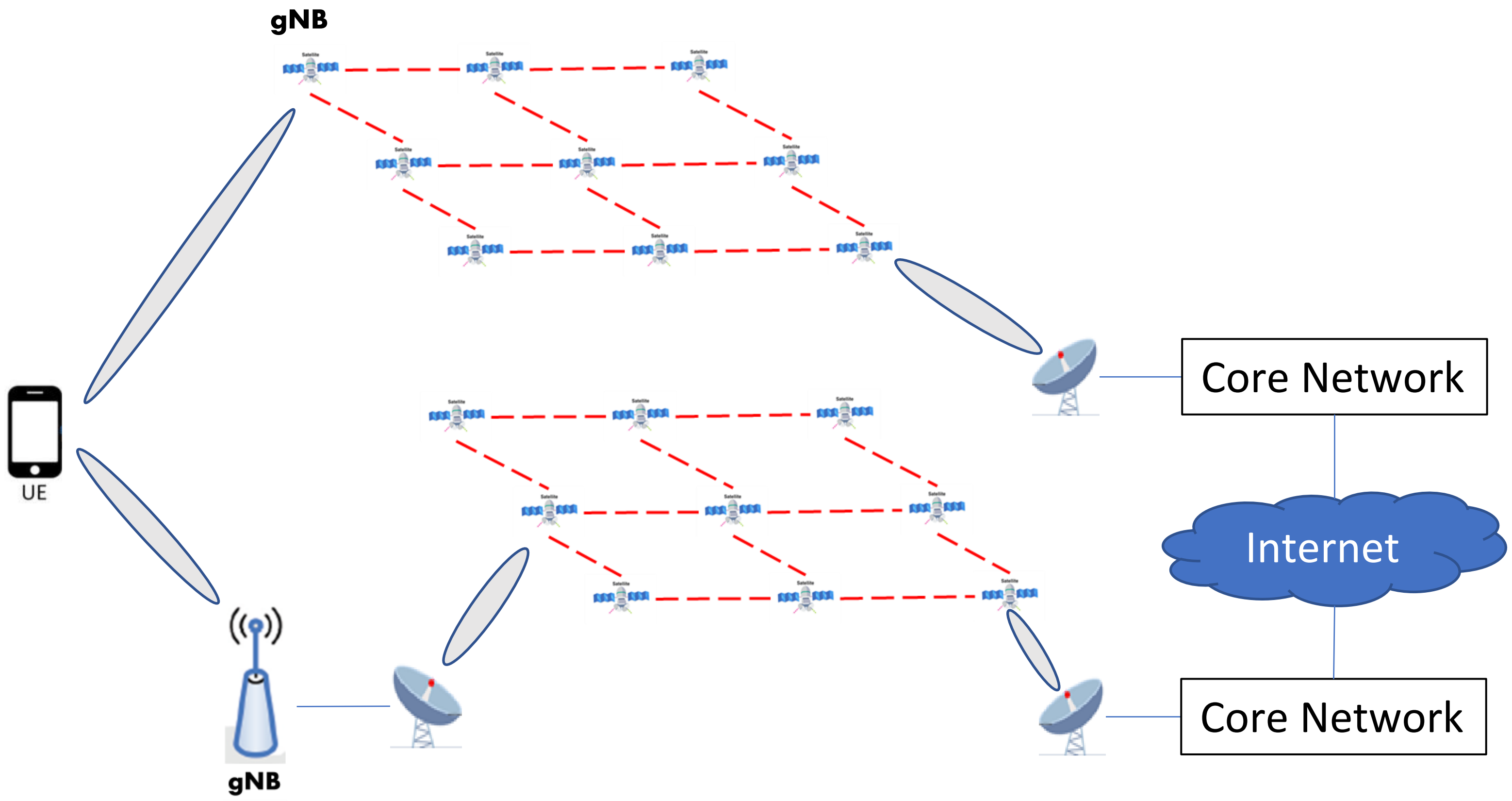
https://circleid.com/posts/20230104-spacex-launches-second-generation-starlink-satellites

Quarterly Starlink speeds, U. S.				
Date	Downlaod	Upload	Latency	
Oct 2020	79.5	13.8	42	beta
q4 2020	104.97	12.04	40	
q1 2021	65.72	13.77	40	
q2 2021	97.23	13.8	45	
q3 2021	87.25	13.54	44	
q4 2021	104.97	12.04	40	
q1 2022	90.55	9.33	43	
q2 2022	62.53	7.24	48	
q3 2022	53	7.22	67	

Current state - Industry

- Apple has started to provide emergency service for iphone14 by Globalstar LEO
  - Short msg with very low rate (<10k bps), sending only
  - Globalstar LEO is very small and early stage: (8 orbit planes) x (6 satellites/per orbit plane) at 1414 km altitudes, inclination 52°.
- Huawei has started to provide short msg service for new phone Mate50 by China GPS Beidou system
  - Limited size of msg with very low rate (~9.6k bps), sending only
  - Using Beidou GPS satellites
  - 30 satellites: 3 GEO satellites + 3 IGSO satellites(36000km) + 24 MEO satellites(21500km)
- T-mobile and StarLink will collaborate to provide service from 2023
  - Use existing midband PCS spectrum and existing mobile devices
  - Messaging service first, then voice and limited data, rate 2~4 Mbps
  - Satellite (7m long) with antenna 25 m^2

3GPP: NTN integration for 5G+ and 6G



TR38.821, Rel 16

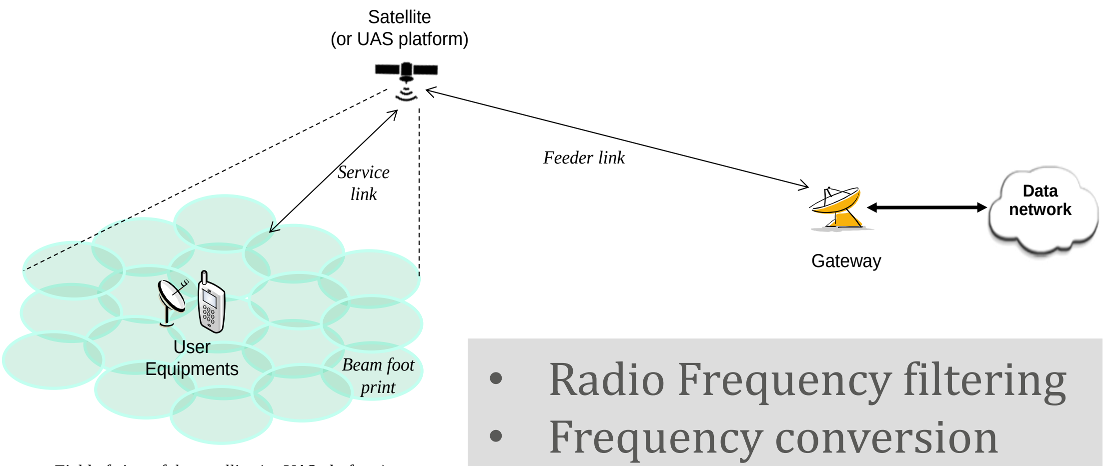
LEO satellite network as 5G Access Network
- gNB on satellite
- DU and CU can be separated on satellite and ground respectively
- CN can be completely or partially (i.e, UPF) on satellite
- RAN: TR38.811(Rel15), TR38.821(Rel17)
- Architecture: TR22.822(Rel16), TR23.737(Rel17) TR28.808(Rel17)

TR23.700, to be in Rel 18

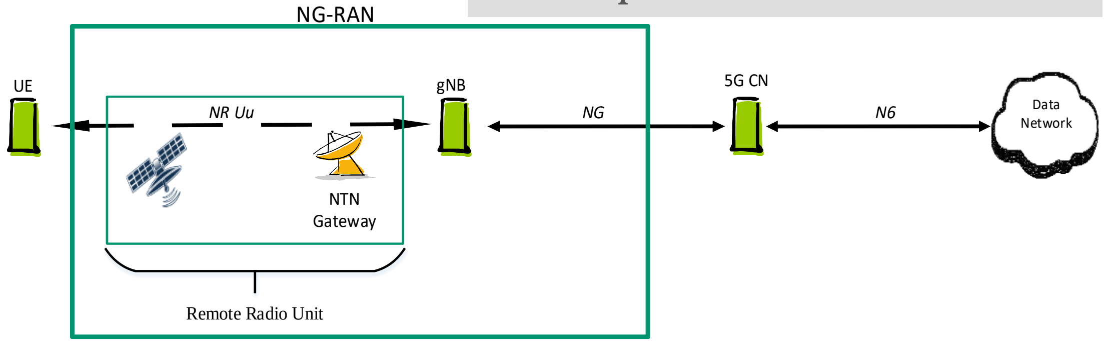
LEO satellite network as 5G Back haul
- gNB on ground
- CN can be completely or partially (i.e, UPF) on satellite
- Radio: 5G NR or other technologies
- Architecture: TR23.700(Rel18)

3GPP: Satellite-based NG-RAN architectures (TR38.821)

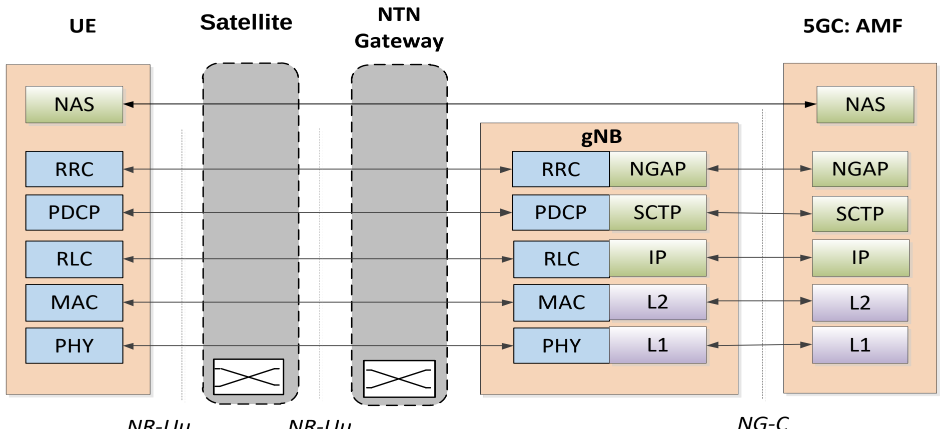
- Satellite with transparent payload

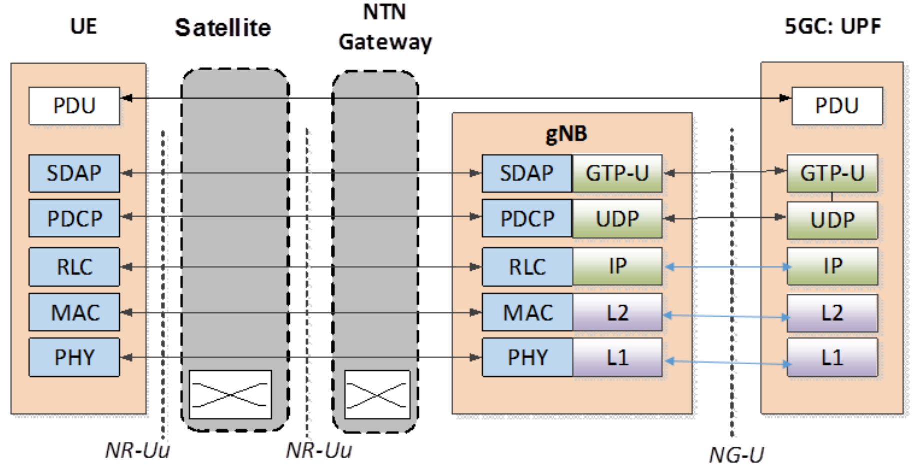


- Radio Frequency filtering
- Frequency conversion
- Amplification
- No packet work



- Control plane and user plane stack





- Simplest but Limited usage since the availability and distance between GS are limited

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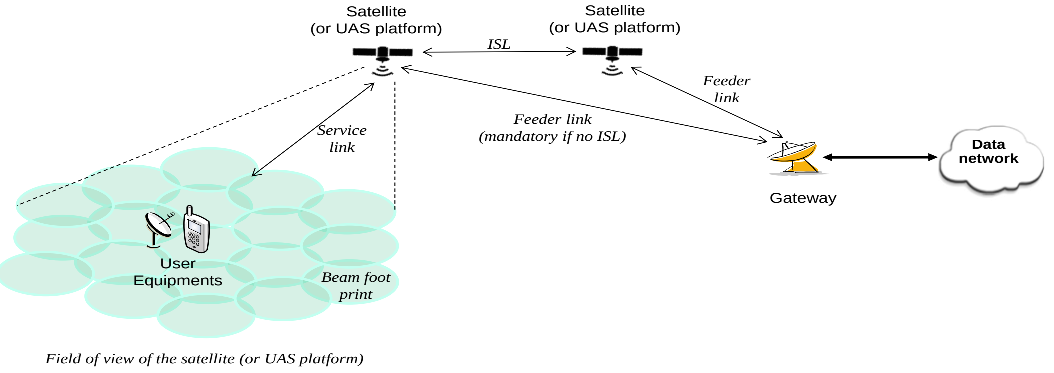
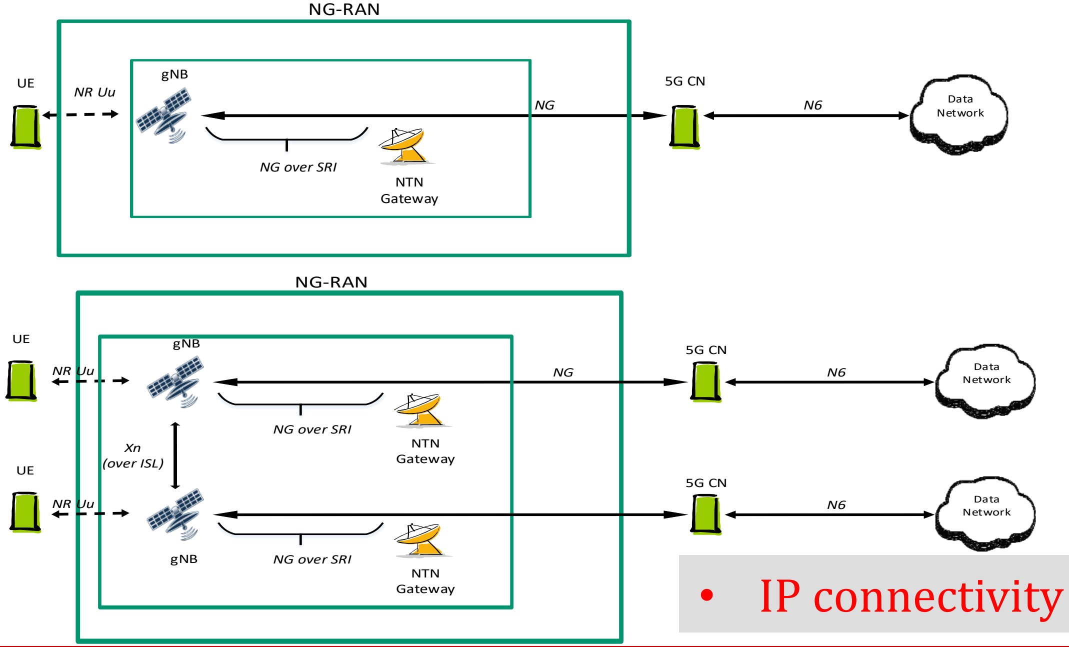
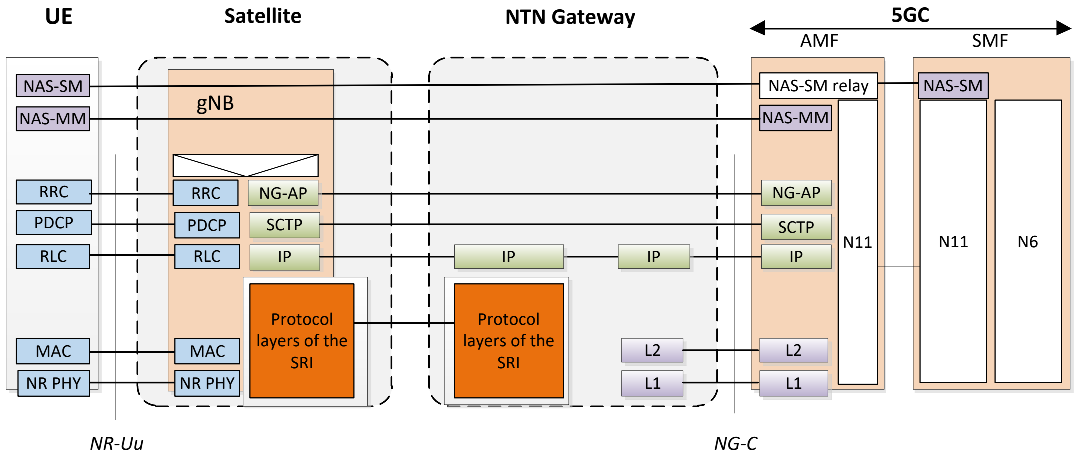
3GPP: Satellite-based NG-RAN architectures (TR38.821)

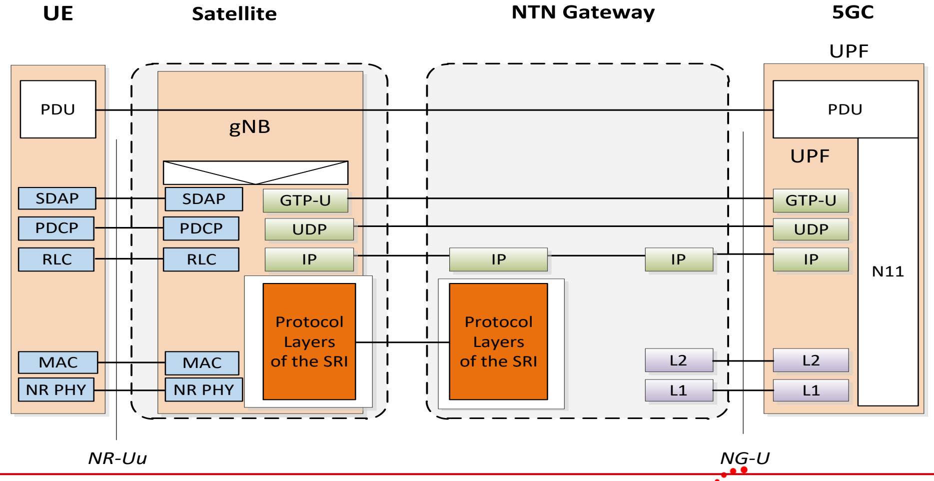
- Satellite with regenerative payload (gNB on board, with and without ISL)





- Control plane and user plane stack





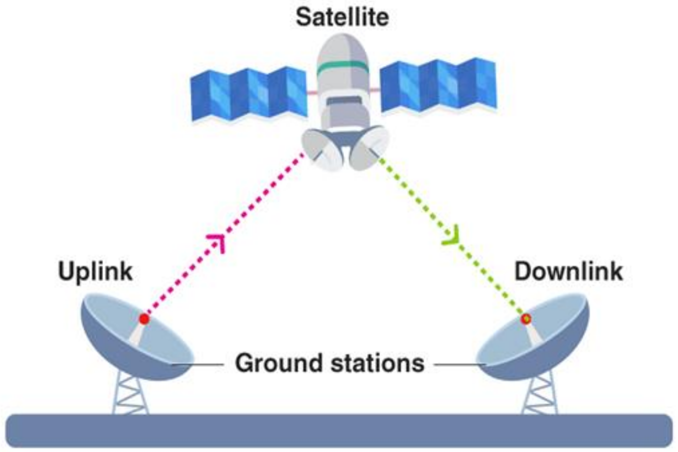
- IP connectivity is key requirements for infrastructure

NTN: Technology Challenges

- Mobile device
  - Antenna, beam forming, MIMO, Satellite tracking
  - Power/amplifier/etc. to achieve the enough gain
    - StarLink UT: 50x30cm, 50-75W, ~1.2k TX/RX,
- Satellites
  - Power management
  - Antenna, beamforming, MIMO
  - Optical inter-satellite-link
  - Satellite tracking, user tracking
  - Connectivity between satellites and ground-stations, satellite networking
- Integration
  - Architecture: any simplification or enhancement?
  - Security: radio, ISL, signal, data
  - Handover: inter-beam, inter-gNB
  - Satellite network sharing
  - Integration with internet

Note: All Starlink data are from public Internet

Satellite Networking Types: Tradition and Future

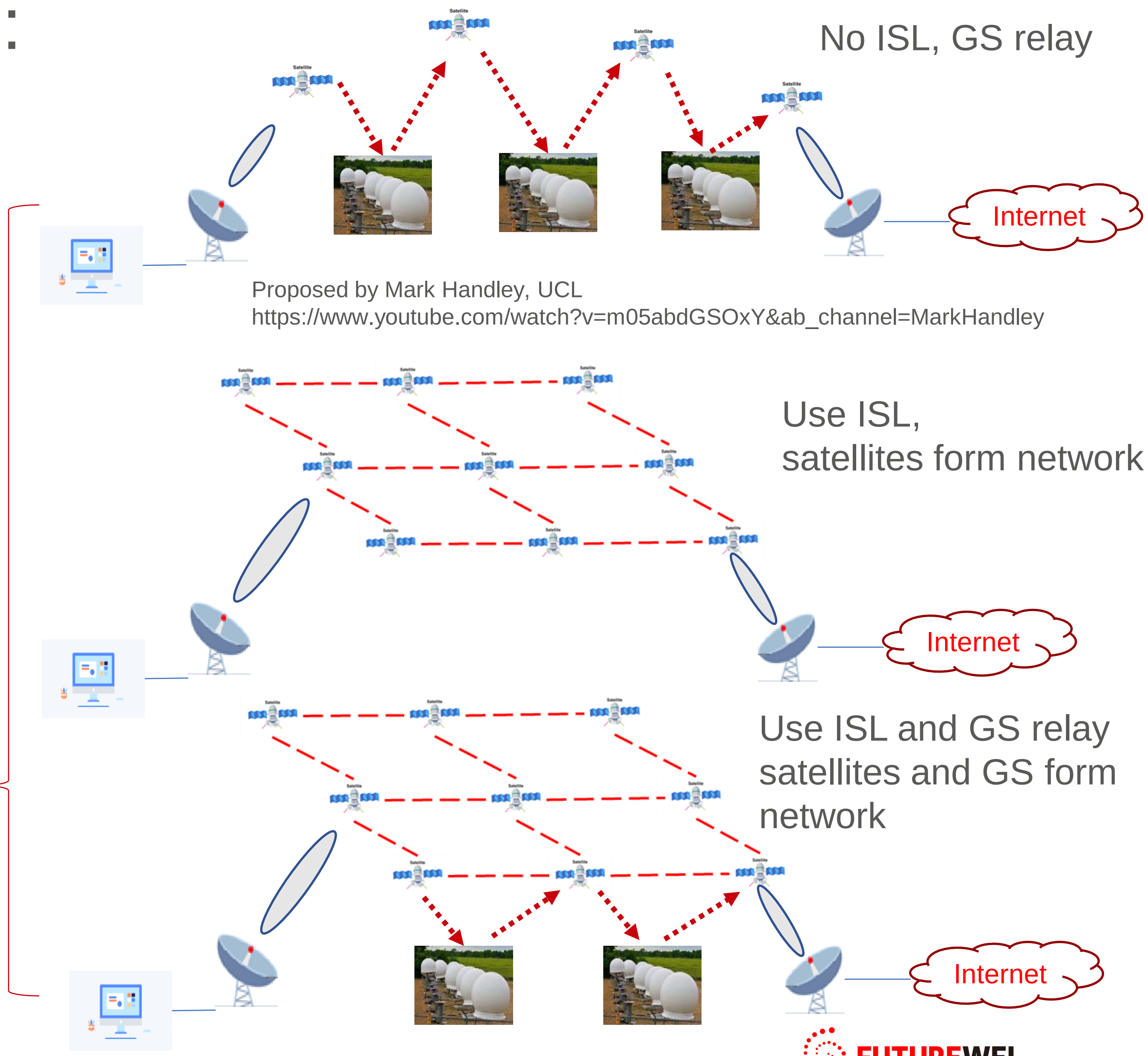


Traditional way, bent pipe

- Radio Frequency filtering
- Frequency conversion
- Amplification
- No packet work
- No global coverage

Future way, networking

- Regenerative payload
- Packet processing
- L2 or L3 networking
- Large scale networking



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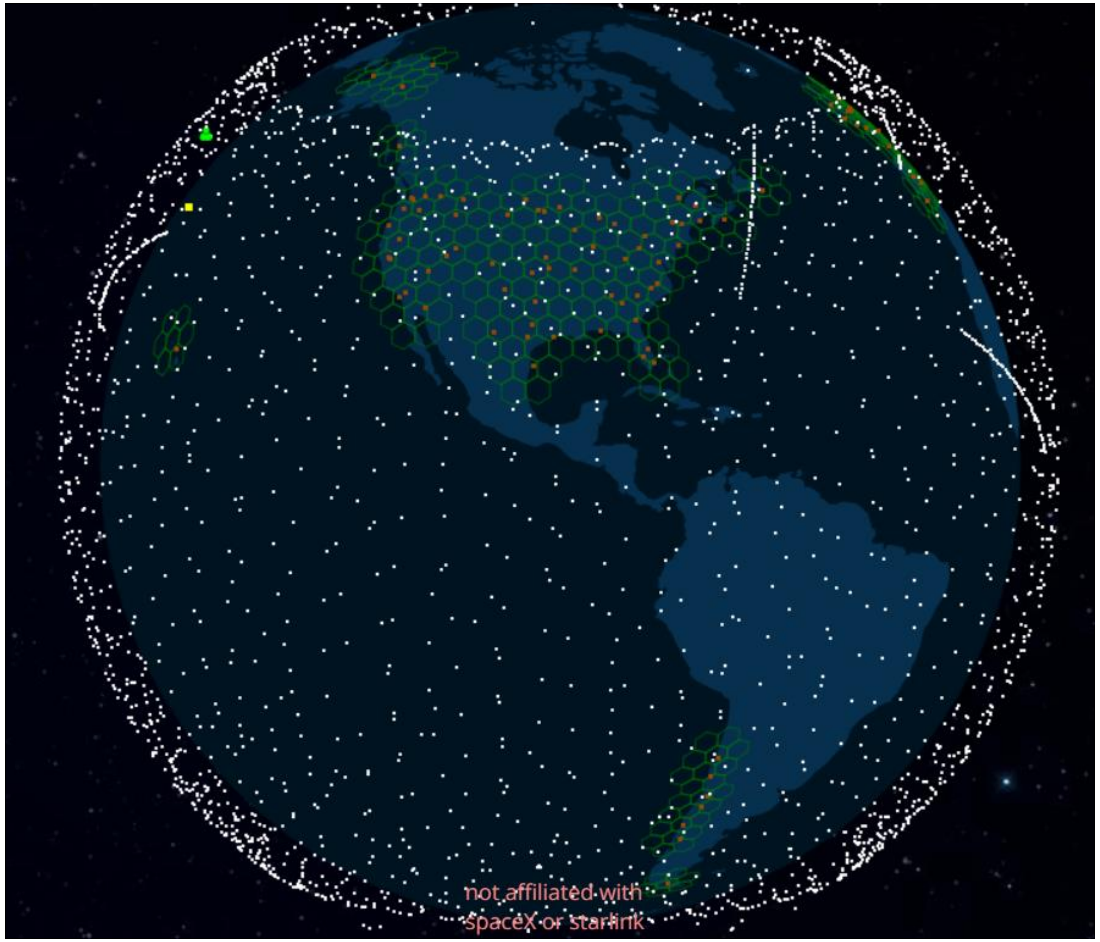
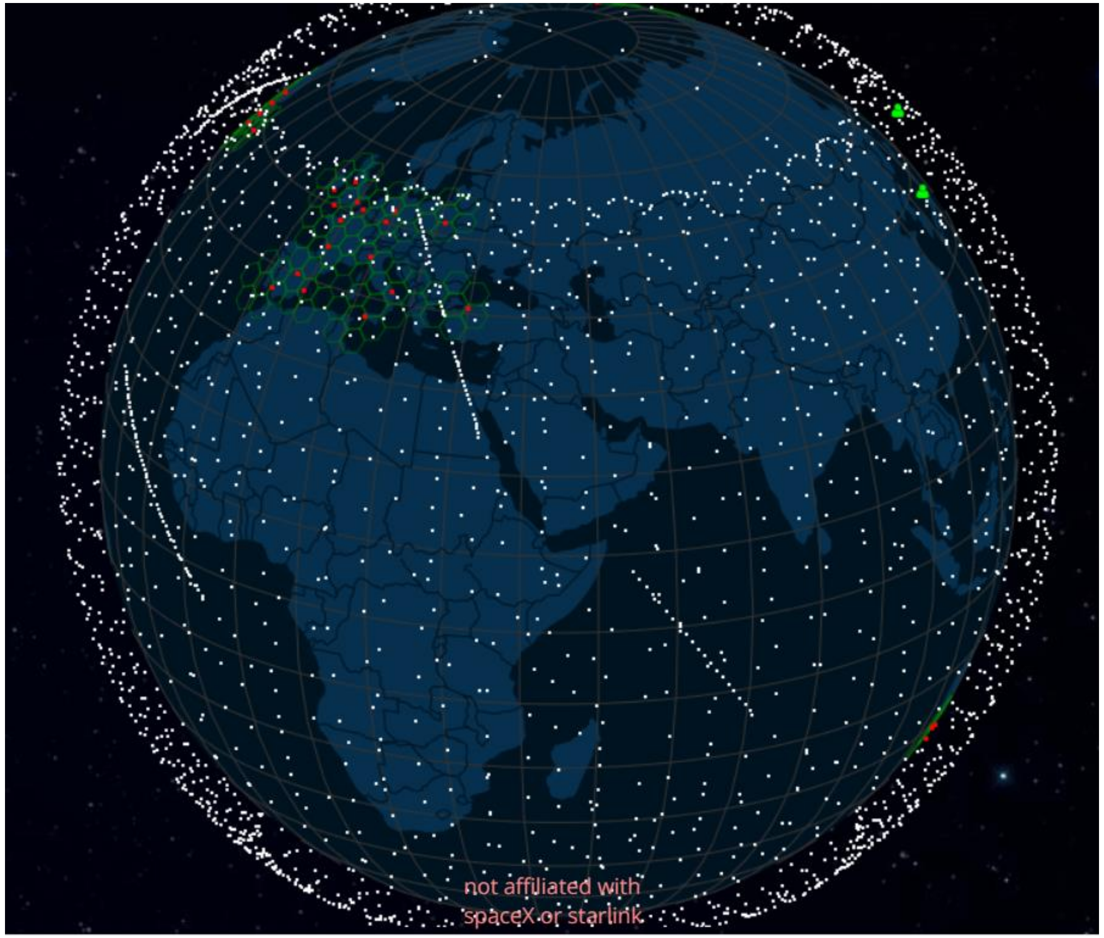
ISL and Networking for Large LEO constellation are Key: Global Coverage, Most Economical



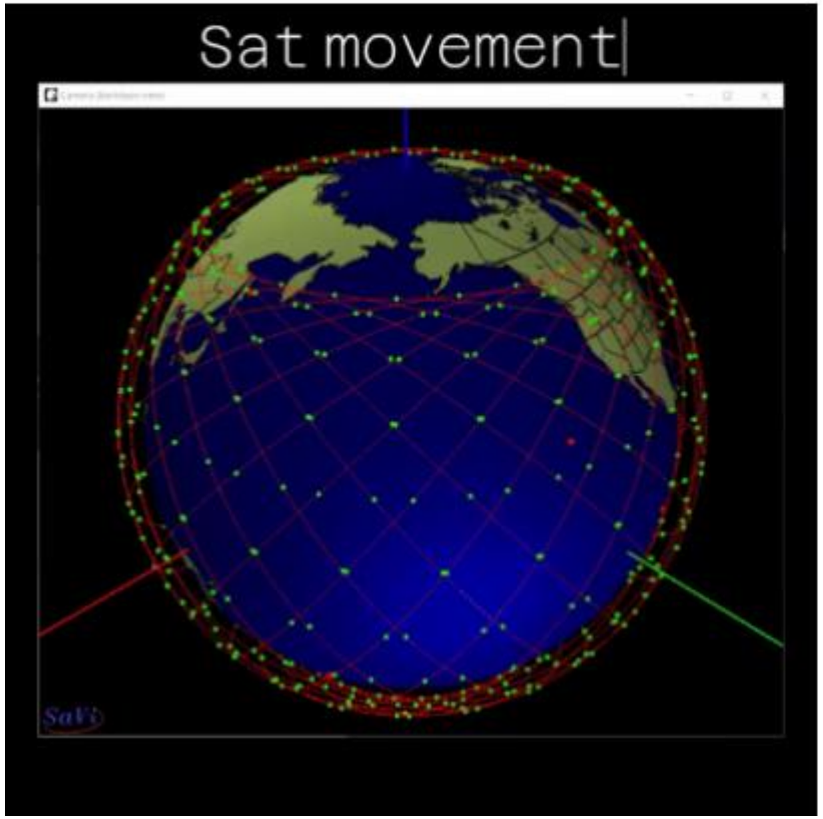


https://satellitemap.space/?constellation=starlink
https://starlink.sx/

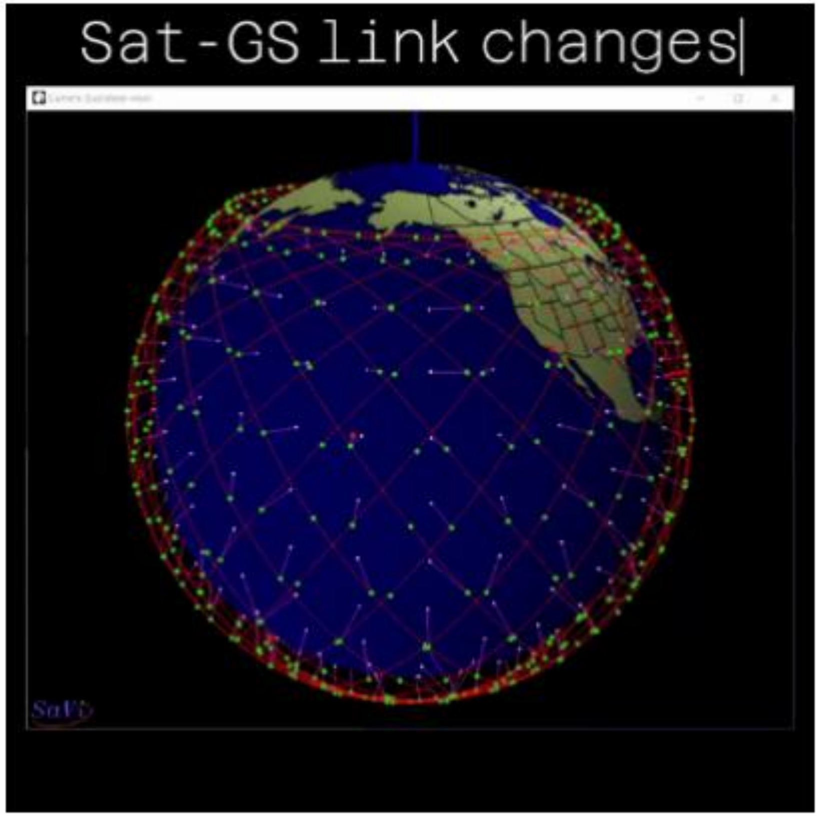
Why IP networking is required for LEO with ISL

- Why L3 networking is needed
    - Large scale network with over 10k nodes connected by ISL and million sat-ground-station links
    - Interworking with other networks in Internet for NTN integration
    - 3GPP expected satellite network as part of wireless access or back haul, must support IP and 5G functions (i.e, UPF distribution in satellites)
- Problems for current IP networking technologies for LEO
    - Addressing, Routing, Traffic Engineering, Multi-path, Mobility
    - All current protocols will experience the issues when used for LEO (OSPF, IS-IS, BGP, MPLS, TE, MIPv6, DTN, etc.)
    - ISL link bandwidth is very precious (< tens of Gbps dependent on the distance), needs to save it as much as we can.
    - The most fundamental problem is routing. Without solving this, all other protocols, both from IETF and 3GPP, cannot work properly.
        - The usability of IGP will be dramatically reduced (<20%) due to the frequent LSA update caused by link flipping.
        - The BGP is hard to converge due to the frequent BGP update caused by link flipping.
        - The un-converged network can lead to IP routing table un-stable and un-usable. Thus, the IP packet forwarding is not reliable (packet loop or drop).

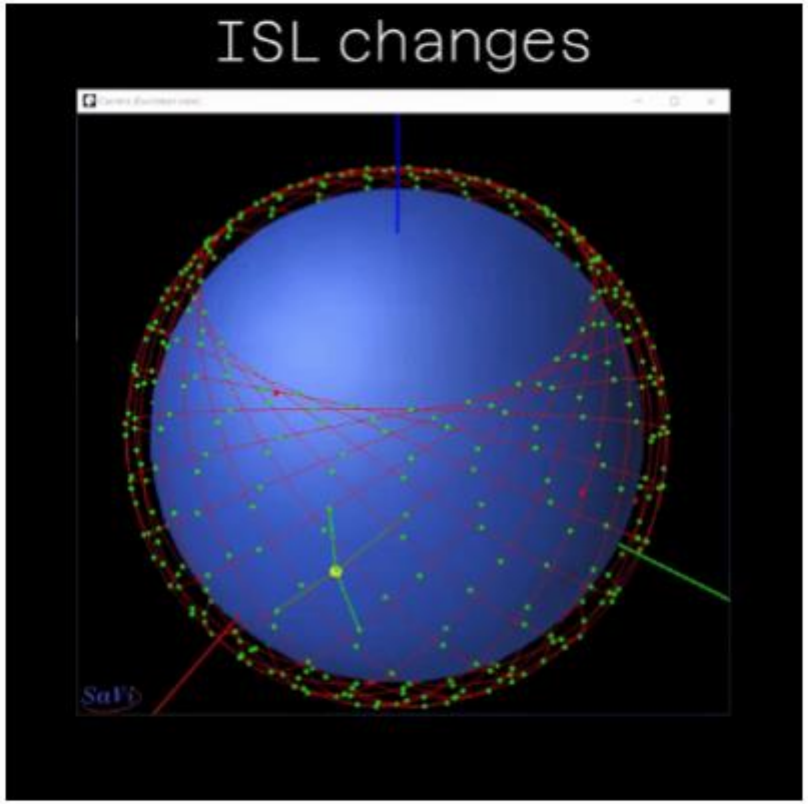
Large Scale LEO Constellation- Challenges to the current IP networking technologies



- LEO satellites move at ~7.x km/s with ~100min period
- 50% satellites move on different direction with another 50% satellites and form a dynamic interleaved network
- Earth is self-rotating at ~463m/s



- links between satellites and ground station (GS) will flip every ~5min for LEO satellites (~550 km altitude), distance keeps changing
- One satellite has multiple GS connected
- One GS has multiple satellites connected
- Huge number of Sat-GS links (> million)



- ISL distance for satellites on adjacent orbits keep changing
- ISL direction swaps on polar areas

Simulation is by savi: https://savi.sourceforge.io/

Research and Current Works for Satellite Routing

- Very challenging issue, many works since 90s.
- Current IETF work but not fitting to LEO used for NTN integration
  - MANET WG – for Mobile ad hoc Network, different as LEO satellite network
  - DTN WG – for Delay/Disruption Tolerant Networking, performance issues
  - TVR WG – for Time-Variant Routing, information and data model, not routing solution
- Typical routing solutions in research
  - Connection-oriented (ATM) (based on discrete time, virtual node/topology, footprint handover)
  - Based on demand (AODV, DSR, DSDV)
  - Considering the Capacity, Congestion, QoS, Load Balance
  - Forwarding based on Geographic information
  - Based on SDN
  - Based on ML, MEC, AI for NTN integration

Solution Summary

- Balance in performance, complexity for scalability
- Only connectivity, no consideration for QoS, no handover, those issues will be resolved separately.
- Re-use the existing IETF solution (OSPF) as an instance for path determination

Purpose

- draft-lhan-satellite-semantic-addressing

Addressing method

- draft-lhan-satellite-instructive-routing

Forwarding method

- draft-retana-lsr-ospf-monitor-node

OSPF based
Path determination

Han, L., Retana, A., Westphal, . C., & Li, R. (2022). Large Scale LEO Satellite Networks for the Future Internet: Challenges and Solutions to Addressing and Routing. *Computer Networks and Communications*, *1*(1), 31–58. https://ojs.wiserpub.com/index.php/CNC/article/view/2105

More details

Not complete, many other issues need to solve

Future

IP Routing for LEO satellite network – Solution summary and Comparisons

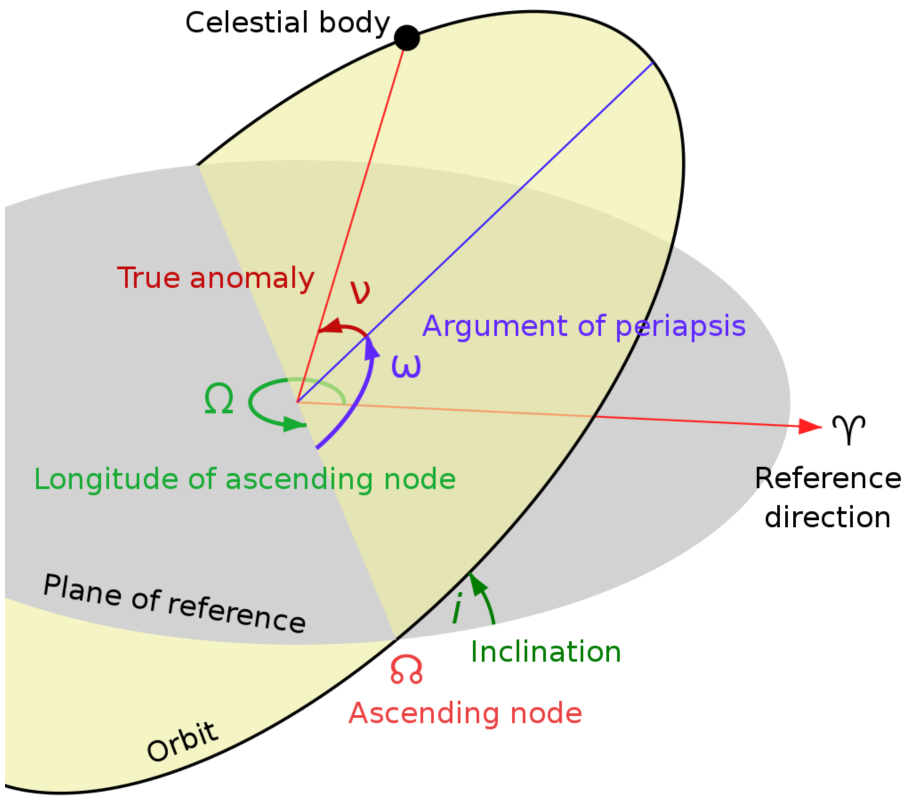
- Addressing: Semantic address
  - Simple mechanism to describe the relationship of satellite
- Control Plane: Modified OSPF + Ephemeris Table + Off-line Computation
  - Why use OSPF
    - Maximize the usage of existing technology since it was proven in Internet for long time
    - Don't recreate wheel
  - What we use from OSPF
    - Messaging exchanging mechanism: Hello, LSA, DB
    - SPF algorithm (Dijkstra Algo)
  - What we change:
    - Suppress LSA and messaging, and SPF computation
- Data Plane: Instructive-semantics based routing
  - Instructions embedded into user packet to guide the routing

- Essence of ATM based solution has been taken into the consideration
  - Discrete time, virtual link/node/topology
  - Source routing (connection like without connection setup), overcome the problem of hop-by-hop routing
- Orthogonal to the Path determination algorithms
- QoS, Load balance, Capacity and Congestion are handled by separate protocol following the layered principal in Internet.
  - L4 protocol, traffic engineering
- ML, AI are not directly used for routing due to the performance but could be used for other aspects
  - Link/topology state prediction
  - Alternative or enhancement of Path determination
- SDN could be used for management and table (not forwarding) update

Semantic Address for LEO satellites (draft-lhan-satellite-semantic-addressing)

- All satellites in LEO constellation are organized by
  - Altitude, Inclination
  - Longitude of Ascending Node
  - True Anomaly
- A scheme to uniquely identify a LEO satellite
  - 3 indexes to indicate the relative sequence value of orbit parameters
  - Indexes values assigned never changes even satellite is moving
  - Shell_Index: related to the {Altitude, Inclination}
  - Orbit_Index: related to the Longitude of the ascending node (Ω)
  - Sate_Index: related to the True anomaly (ν)
- Not IPv4/IPv6 address or prefix

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Owner Code  |  Shell_Index  |  Orbit_Index  |   Sat_Index   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```



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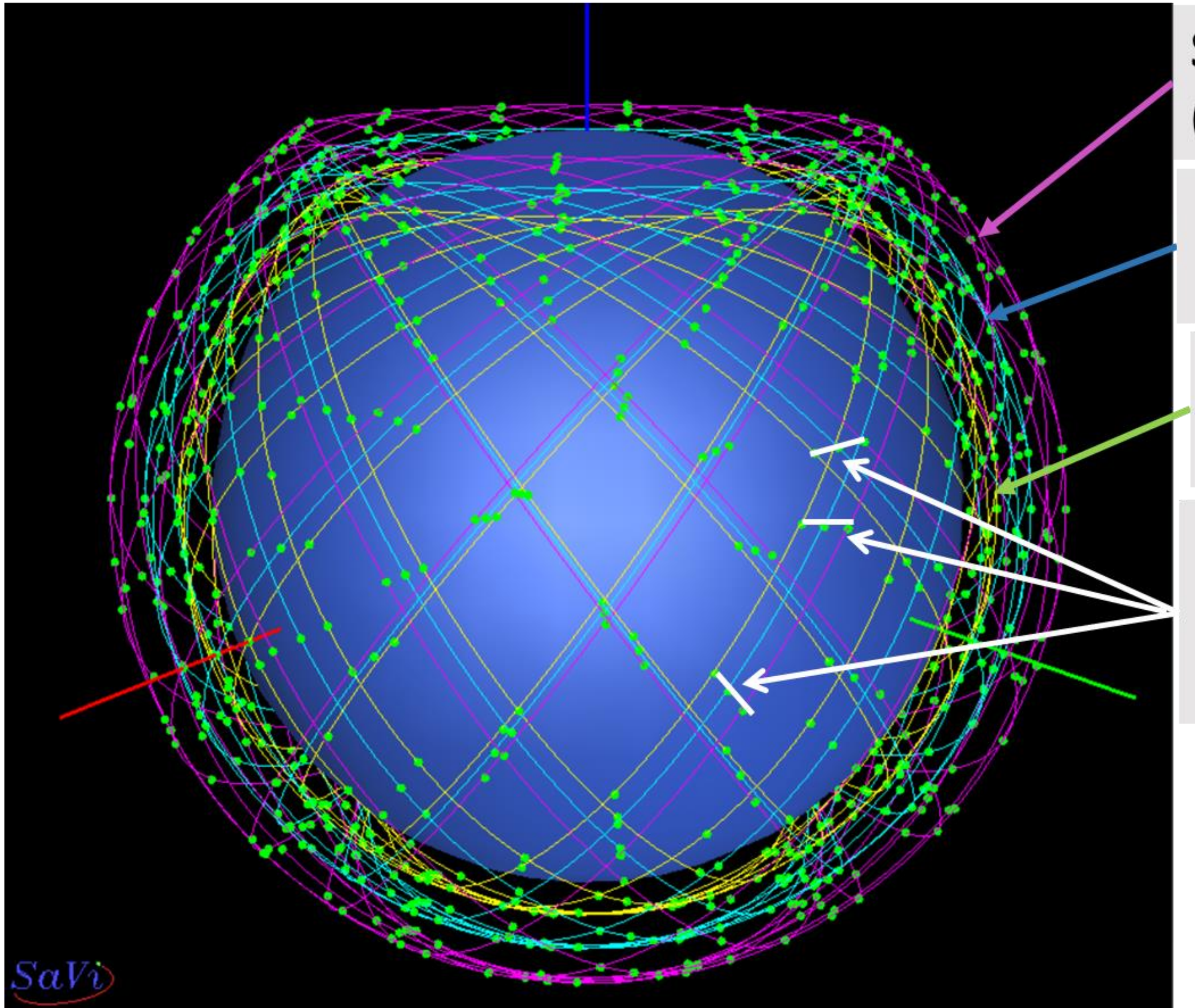
Shell_index and associated segment



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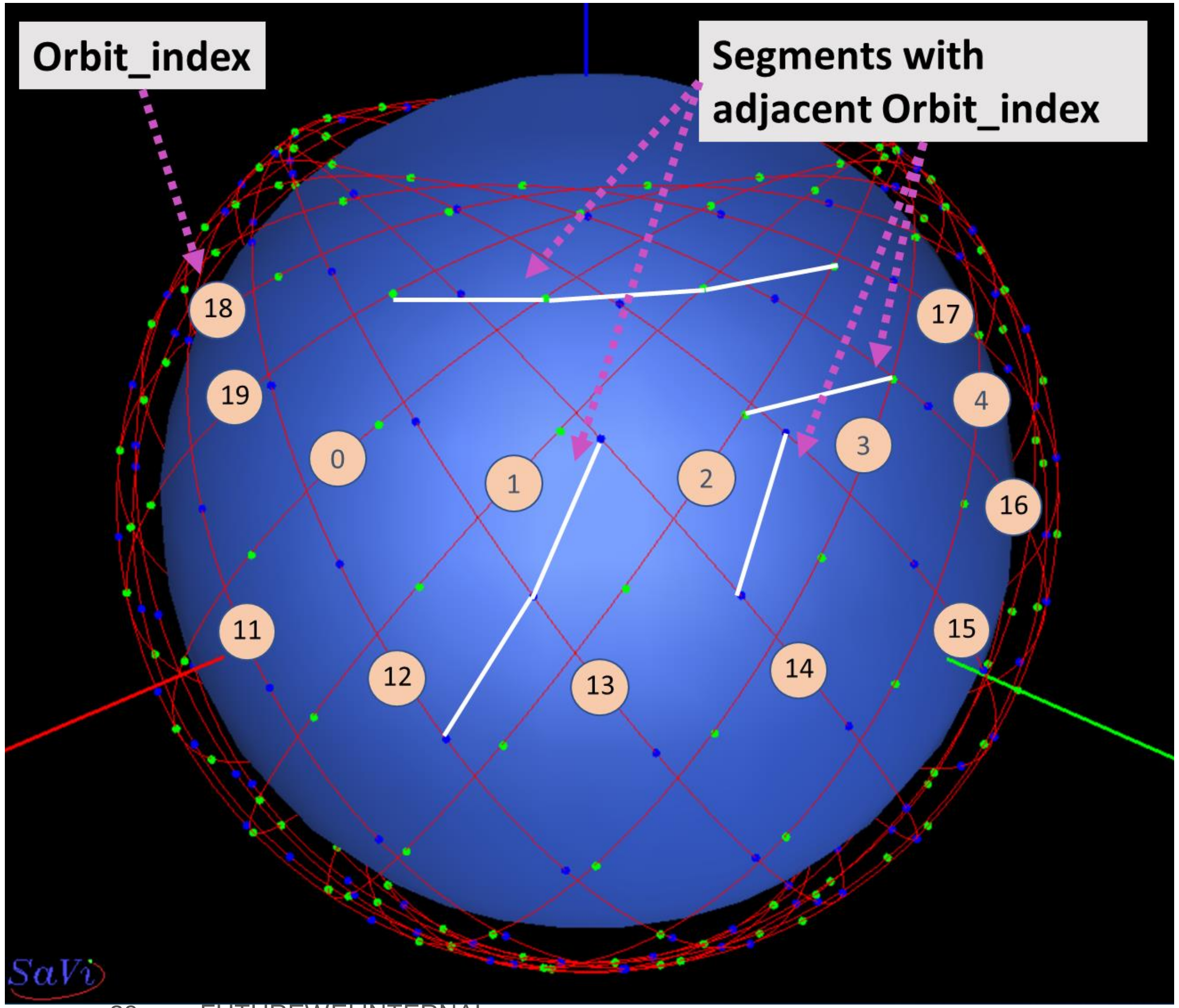
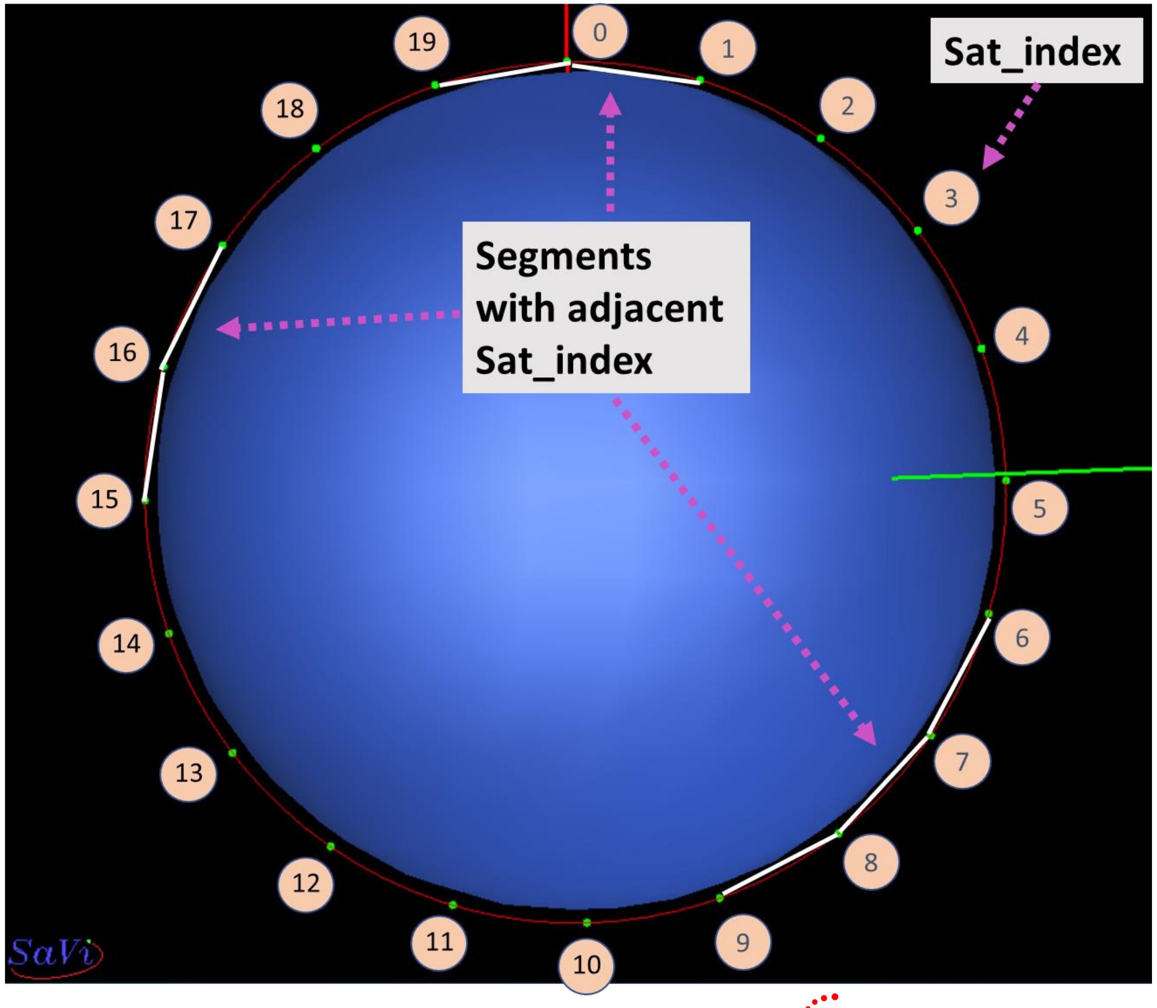
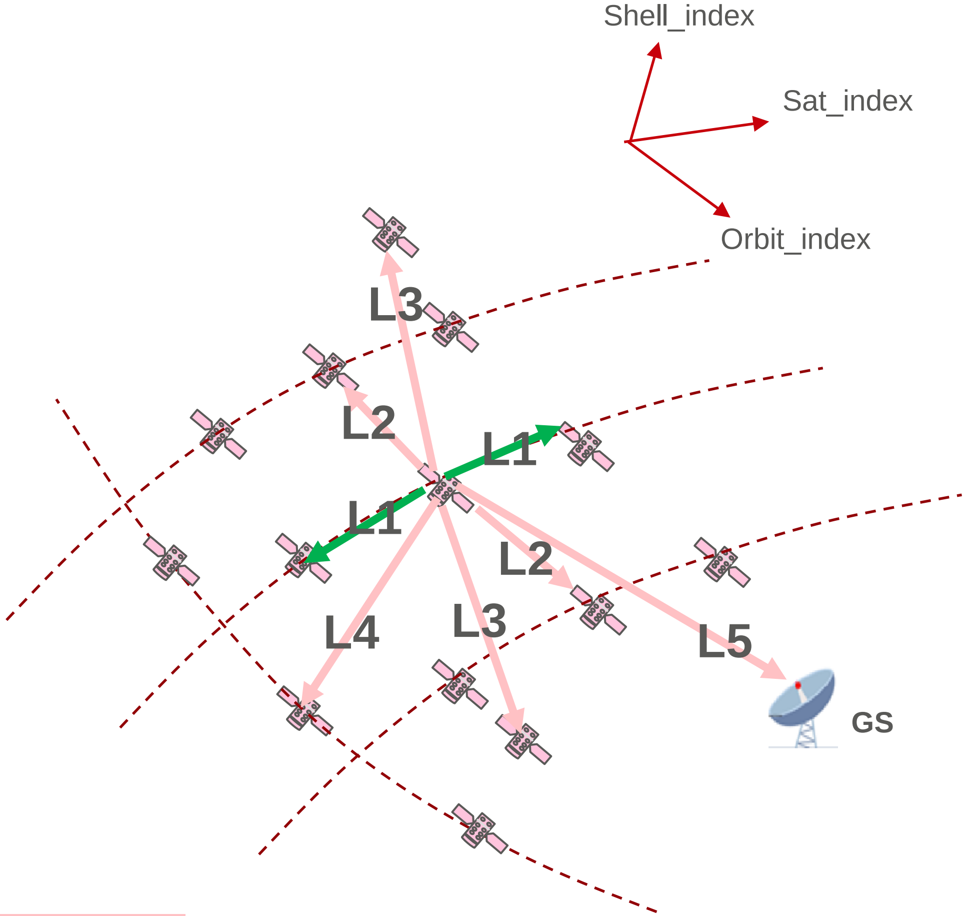
Orbit_index, Sat_Index and associated segment





Control Plane:
Routing: How to handle Links Life and Link Metrics?

Link type	Description	Link Life	Link Metrics
L1	Between adjacent satellites on the same orbit plane	Steady	Steady
L2	Between two satellites on the adjacent orbit	Unsteady, lasts tens of mins	Keep changing
L3	Between two satellites on the adjacent orbit shell	Unsteady, lasts tens of mins	Keep changing
L4	Between two satellites on the un-adjacent orbit	Unsteady, lasts couple of mins	Keep changing
L5	Between satellite and ground station	Unsteady, lasts couple of mins	Keep changing



Traditional routing protocol:
Detect the link state, and measure the link metrics, flood LSA update

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Control Plane:
Routing: How to quickly know the network topology and state

Computed and updated
in large period (off-line/real-time)

Ephemeris table

- A Table to store predicted link state changes with time
- Link types: L2 to L5
- What to store:
  - Each possible satellite-GS peer and state
  - Each L2 to L5 peer and state
- What we can:
  - Given a time, a satellite or a GS, we can find out
    - The “most likely” peer and its state
    - The estimated link metrics

Real-time running on
All satellites and GS

OSPF

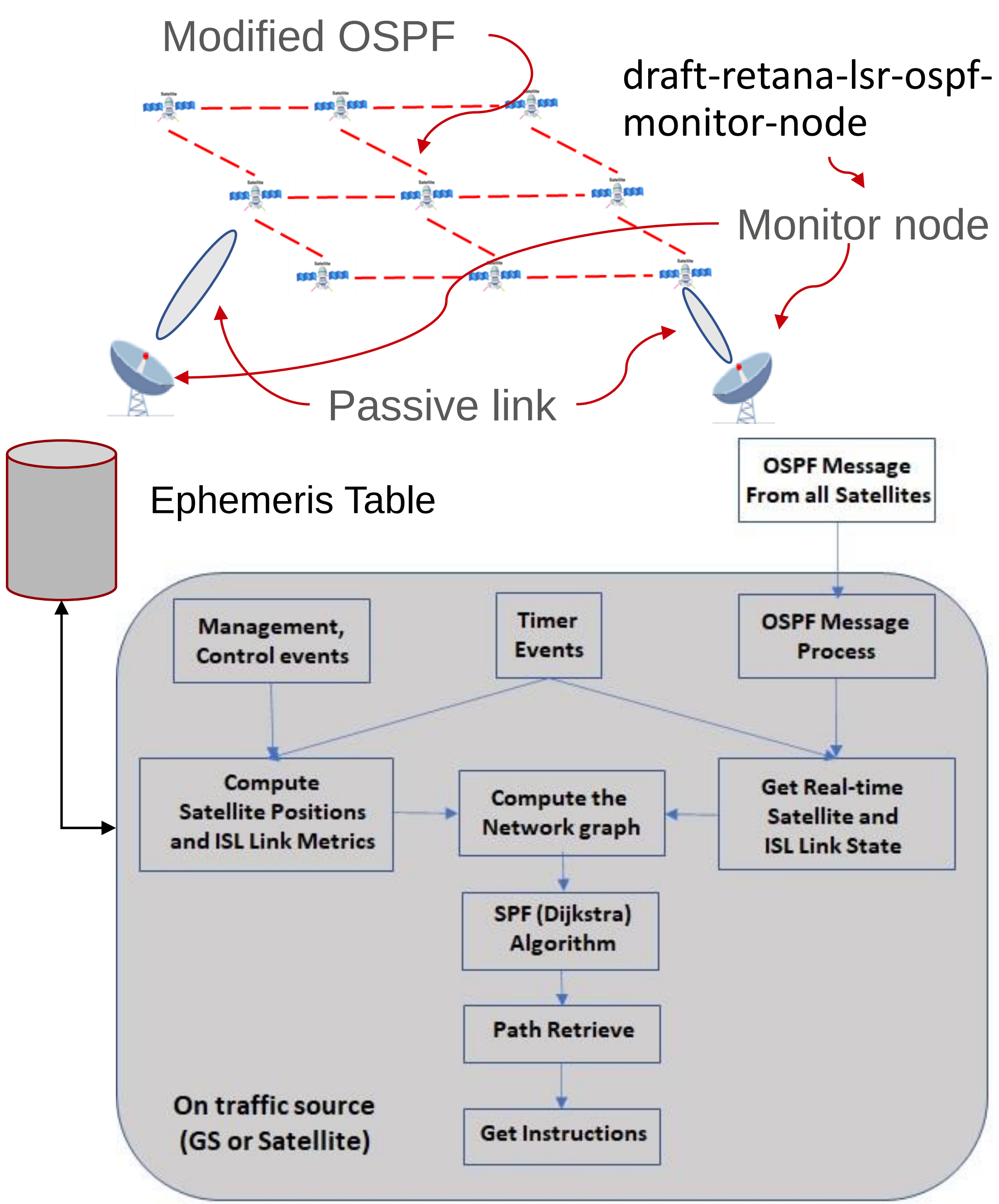
- Hello detects satellite and ISL state
- Limited LSA flooding tells the state of network
  - Router-LSA
  - Network-LSA
  - Intra-Area-Prefix-LSA
- Only flood when the satellite and ISL state changes
- SPF computation when necessary
- Path retrieve

Real-time packet detection

Real-time satellite network topology and state

Control Plane: Modified OSPF and Workflow

- Router ID = Satellite Semantic Address
- Satellites and ground-stations run OSPF
- Sat-Ground links are passive, its flipping does not trigger the LSA
- Ground stations receive LSA, but not advertise
- Only traffic source, i.e, GS, calculate SPF tree, satellites doe not unless send packets to others
- Periodically trigger OSPF at traffic source to compute all link metrics and SPF tree
- Retrieve the path info from SPF tree
- Path info -> segments-> instructions



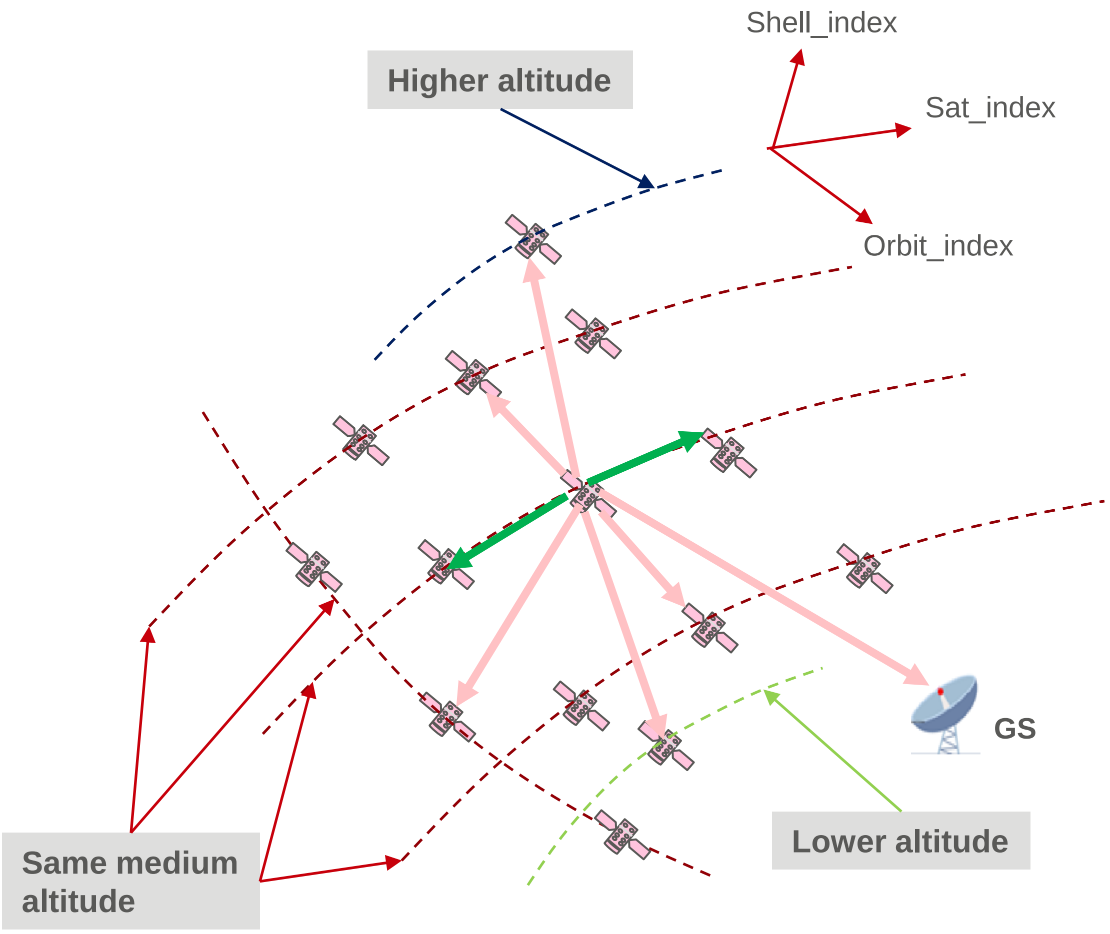
Data Plane:
Instructive Routing (draft-lhan-satellite-instructive-routing)

- Instructions embedded into user packet as Extension Hdr for Routing
  - Subtype: Satellite Routing
  - List of instructions
  - Instruction = Function + Argument
  - Instruction tells hardware to forward packet to specified direction and where to stop.
- Routing is no longer controlled by distributed routing protocol, hop-by-hop and TCAM (Ternary Content Addressable Memory) lookup
- Other path determination algo. can also be used

Function Name/Hex Value	Arguments/Size (Octet)
Fwd.Inc.Sat_Index/0x01	Sat_Index/1
Fwd.Dec.Sat_Index/0x02	Sat_Index/1
Fwd.Inc.Orbit_Index/0x03	Orbit_Index/1
Fwd.Dec.Orbit_Index/0x04	Orbit_Index/1
Fwd.Inc.Shell_Index/0x05	Shell_Index/1
Fwd.Dec.Shell_Index/0x06	Shell_Index/1
End.Intf_ID/0x07	Intf_ID/1
End.Punt/0x08	0x0/1
End.Lookup/0x09	0x0/1
End.Lookup.IPv4/0x0A	IPv4_Addr/4
End.Lookup.IPv6/0x0B	IPv6_Addr/4
Fwd.Sat_Addr/0x0C	Sat_Addr/4
Fwd.Sat_MacAddr/0x0D	Sat_MacAddr/6

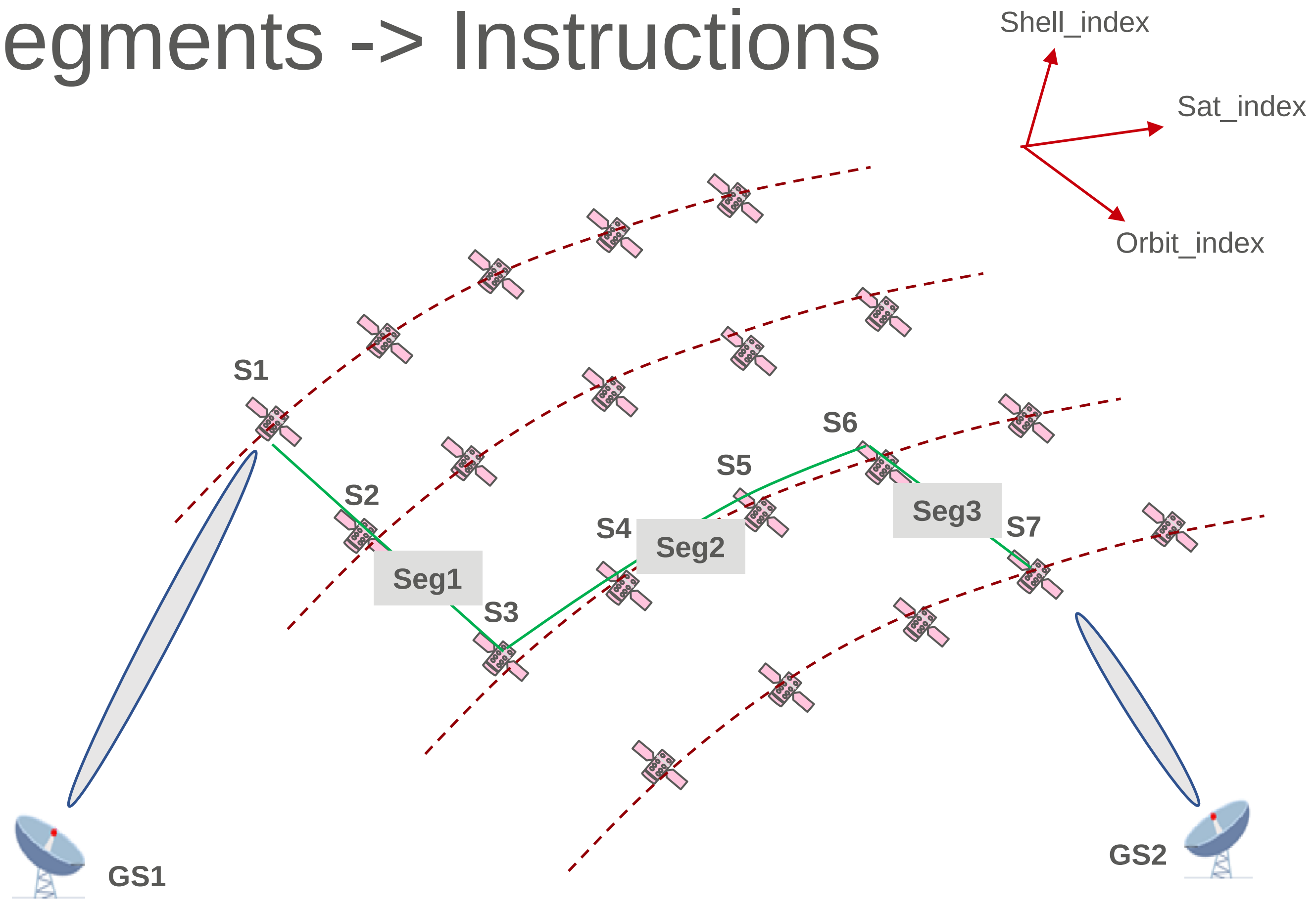
Data Plane:
Segments, Forwarding

- List of satellites, Used to compress the list of hops
- Four types:
  - Segment with adjacent Shell_Index,
  - Segment with adjacent Orbit_Index,
  - Segment with adjacent Sat_Index,
  - Segment with no-adjacent Index,
- Packet Forwarding and End Forwarding Processing:
  - Limited type of forwarding
    - Fwd to Incremental/Decremental direction of three indexes (6)
    - Fwd to un-adjacent satellite (1)
    - Fwd to ground station (1)
  - Limited type of End processing
    - Punt to CPU
    - Lookup specified address
    - Send to specified interface



Data Plane: Example
SPF tree -> path info -> Segments -> Instructions

- GS1 run OSPF to get SPF tree from GS1 to all destinations
- GS1 obtain the path to GS2 from SPF tree,
- GS1 to GS2 path info:
  - S1->S2->S3->S4->S5->S6->S7
- Route to segments:
  - Seg1(S1,S3) -> Seg2(S2, S6) -> Seg3(S5,S7)
  - Seg1, Seg3: Segment with adjacent Orbit_index
  - Seg2: Segment with adjacent Sat_Index
- Segments to instructions
  - Inst1: Fwd pak to the direction of Orbit_index increment until reach S3
  - Inst2: Fwd pak to the direction of Sat_index increment until reach S6
  - Inst3: Fwd pak to the direction of Orbit_index increment until reach S7
  - Inst4: Fwd pak to GS2



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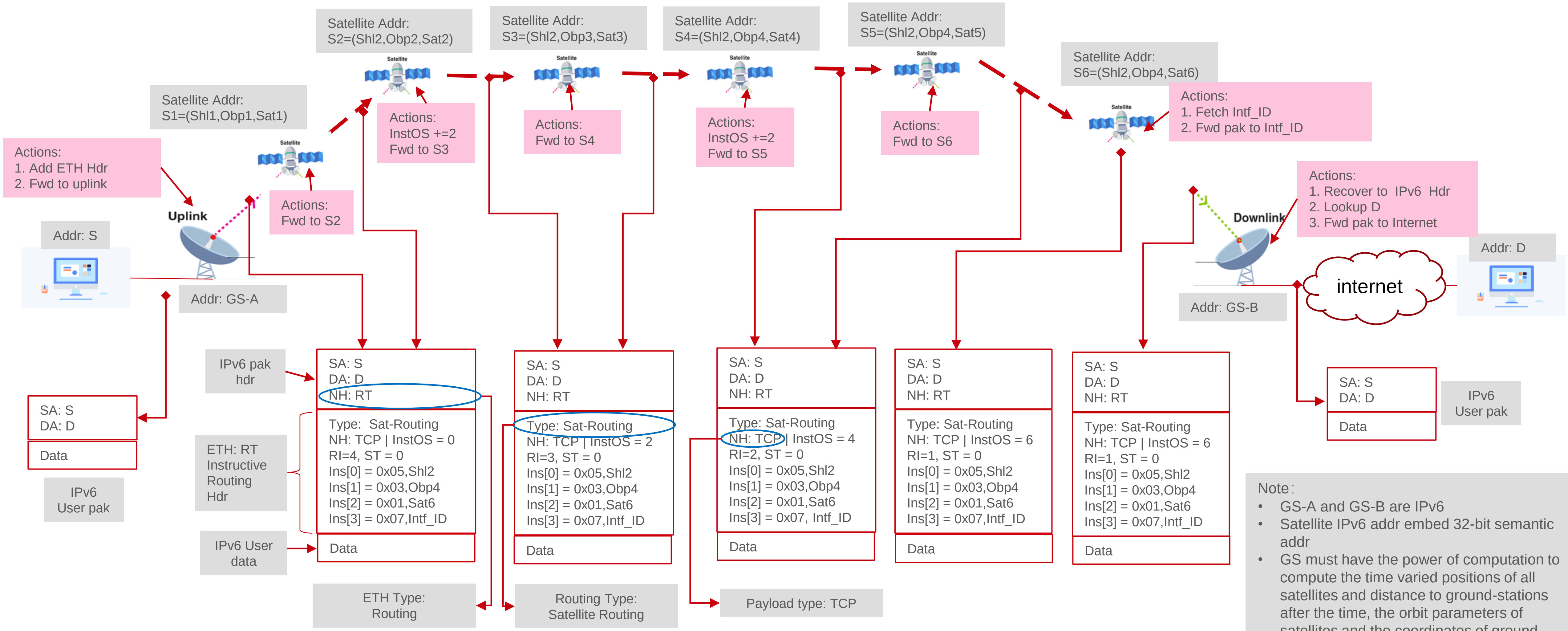
Data Plane:
Tunnel-less Mode Packet Format and Actions



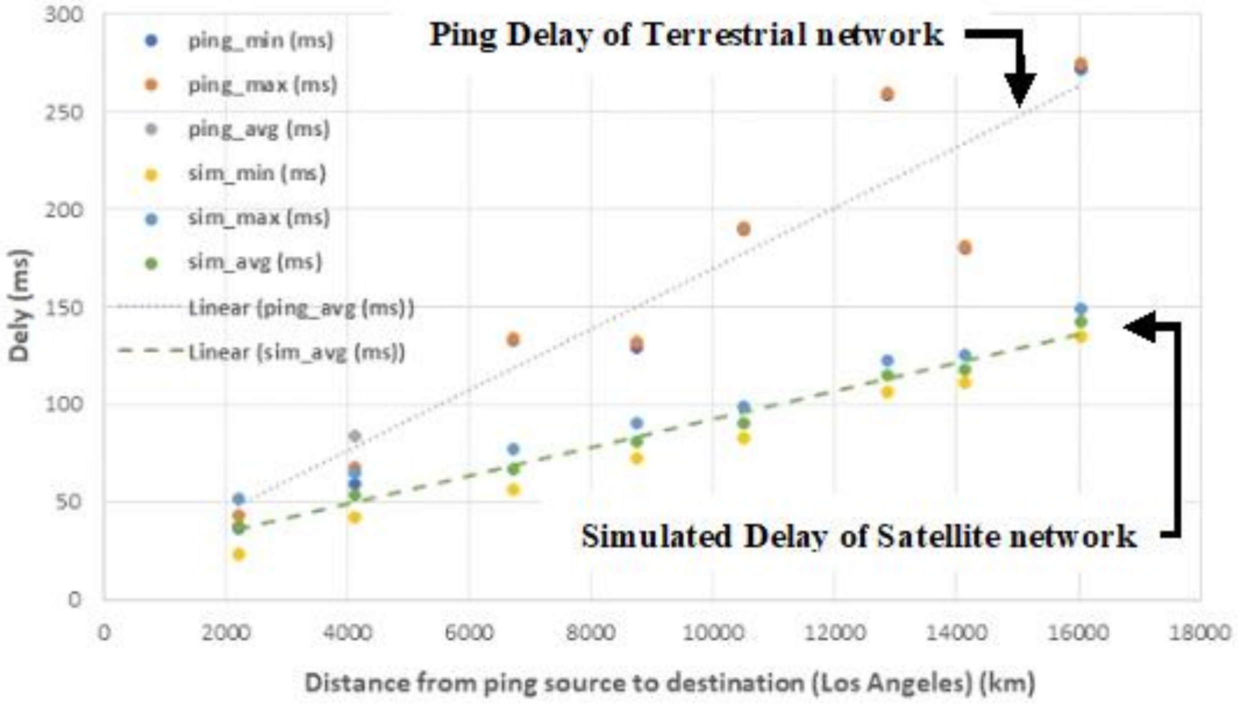
Note:
- GS-A and GS-B are IPv6
- Satellite IPv6 addr embed 32-bit semantic addr
- GS must have the power of computation to compute the time varied positions of all satellites and distance to ground-stations after the time, the orbit parameters of satellites and the coordinates of ground-station are given

Modeling and Experiments

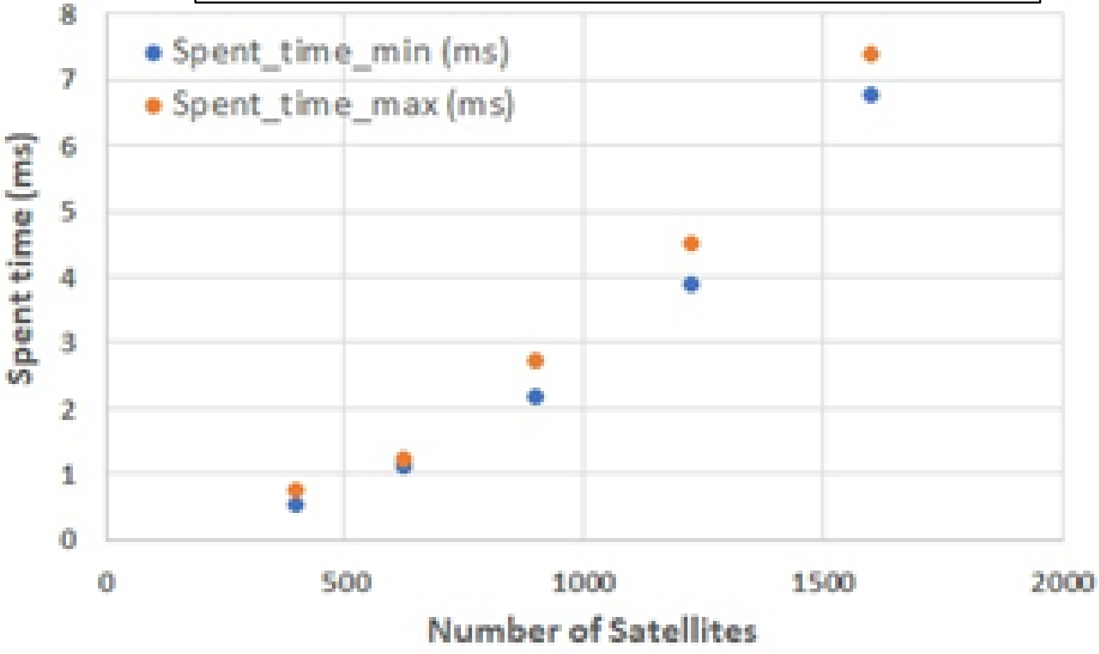
- Savi to simulate the LEO satellite network
  - 550km altitude; 53^o inclination; 30 orbit x 30 satellites/orbit
  - Five ISLs for each satellite (four for adjacent satellites and one for non-adjacent satellite)
  - Configurable number of Sat-GS links
- Link metrics ~ distance
- OSPF messaging to indicate the network topology and state
- OSPF SPF tree calculation and path retrieve
- Path verification, etc.

Delay, Performance, Salability

Simulated delay vs. Real ping delay of Internet



Time to compute SPF tree and routes



Num. of distinct path in 24 Hrs

Src City	Distance to LA (km)	Number of path
Houston	2207	1425
Honolulu	4117	1411
Lima	6727	1251
London	8758	1440
Auckland	10500	1307
New Delhi	12866	1394
Singapore	14129	1334
Cape Town	16056	1322

Number of hops, segments and packet overhead

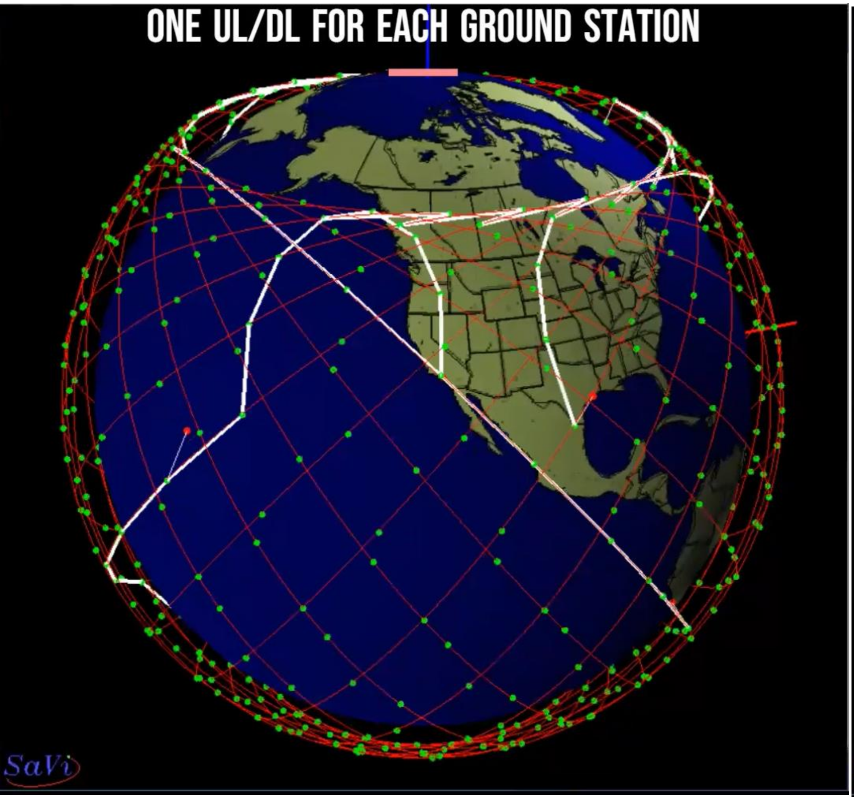
Src City	Distance to LA(KM)	Hops No. (min/max)	Segment No. (min/max)
Houston	2207	3/7	2/3
Honolulu	4117	5/9	2/4
Lima	6727	6/9	1/4
London	8758	10/13	2/7
Auckland	10500	8/12	1/4
New Delhi	12866	12/16	2/6
Singapore	14129	12/15	1/4
Cape Town	16056	12/18	2/4

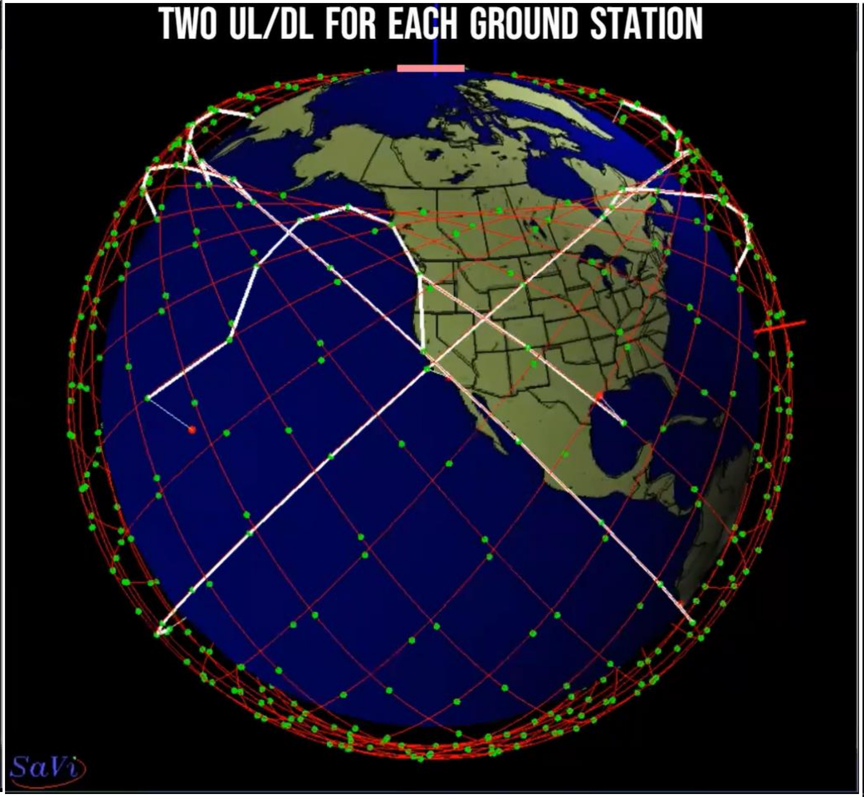
Number of Hops and Segments from LA to Different City (for 24 hour simulation)

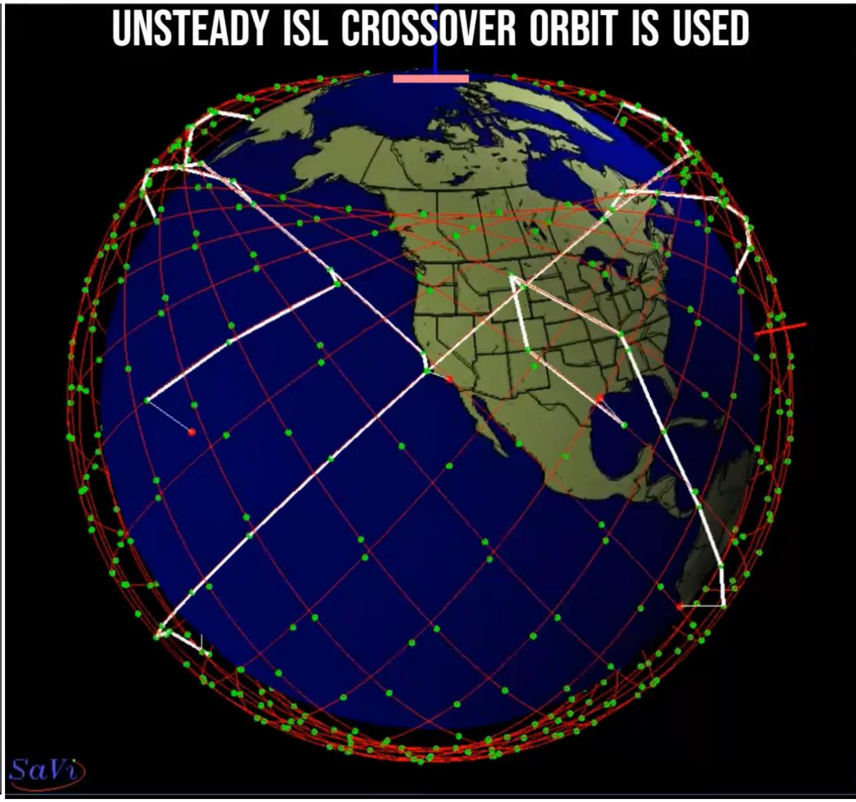
Src City	Our method	SRv6
Houston	6/8	32/48
Honolulu	6/10	32/64
Lima	4/10	16/64
London	6/16	32/112
Auckland	4/10	16/64
New Delhi	6/14	32/96
Singapore	4/10	16/64
Cape Town	6/10	32/64

Packet header overhead (min/max, in octets) for different path (for 24 hour simulation)

Key factors to achieve the shorter path







25 orbit x 25 satellites/orbit = 625 satellites

Conclusion

- LEO satellite networking is key for NTN integration for 6G
- Routing for large scale LEO satellite constellation, feasible solutions are needed for industry
- Proposed solution can provide the routing for very dynamic topology with scalability
- Experiment has validated the solution
- More research for security, path switchover, internet integration, etc.

Thank You.

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