New IP based semantic addressing and routing for LEO satellite networks

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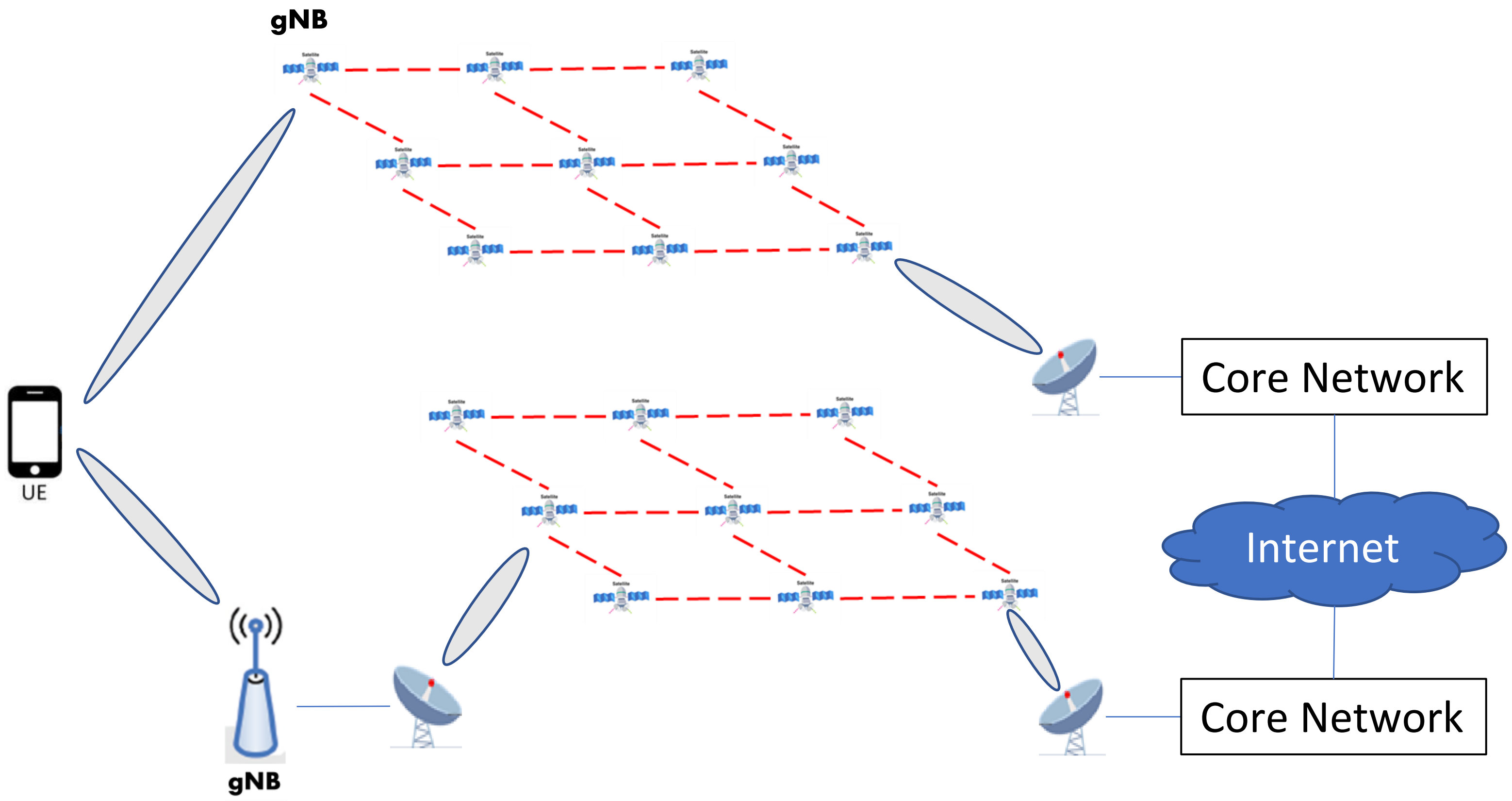
Agenda

- LEO Satellite Network Status in Industry and SDOs
- IP networking for LEO in the future
- Challenging to the current IP networking technologies
- New IP based solution:
  - New IP review
  - Addressing
    - Semantic address for LEO Satellite
  - Routing
    - New solution summary
    - Control Plane: New IP based OSPF
    - Data Plane: Instructive routing
- Experiments
- Summary: IPv6 Solution vs New IP Solution

LEO satellite network status – Industry

- StarLink
  - As of September 2022, over 2,300 functioning satellites, over 500,000 active subscribers
  - has started the ISL experiment from 2022. and provide service for polar area soon.
- 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, sending only
  - Using GEO/MEO (3600km/21500km) from Beidou satellites (GPS satellites)
  - Is working to provide dual-directional messaging
- T-mobile and StarLink will collaborate to provide service from 2023

LEO satellite network status –3GPP
LEO satellite network for NTN integration, Key for 5G+ and 6G



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
- Radio: Based on 5G NR for Ku, Ka band
- Architecture: SBA with enhancements
- Satellite network:
  - IP network to support 5G functions and interworking with other network in Internet

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
- Satellite network:
  - If want to support 5G functions and interworking with other networks in Internet, must be IP network

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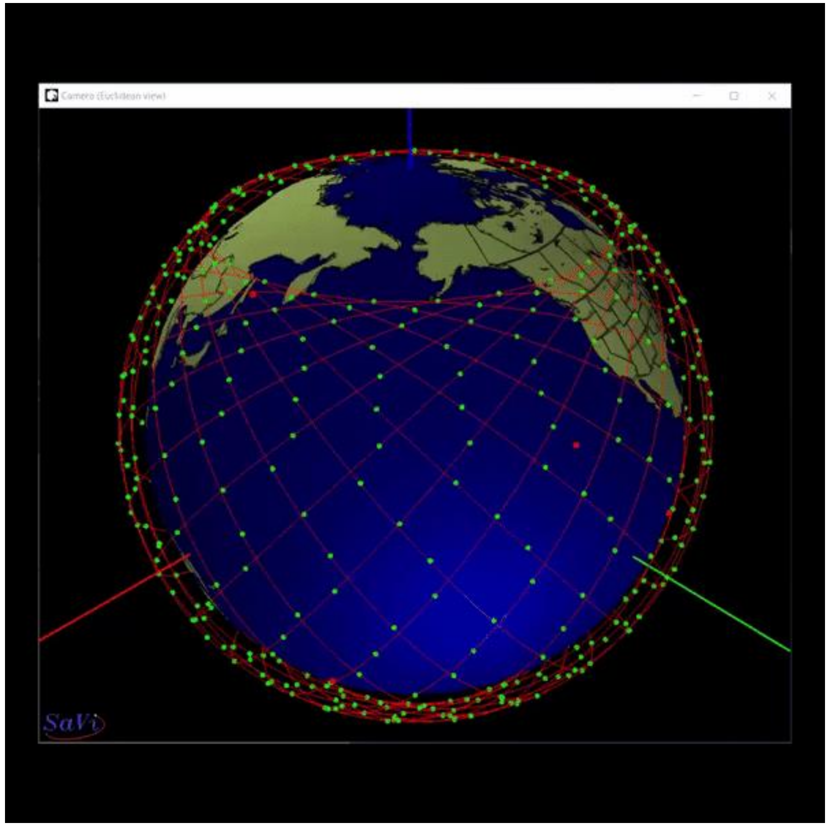
LEO satellite network status – IETF
Slow but Start work for LEO satellites

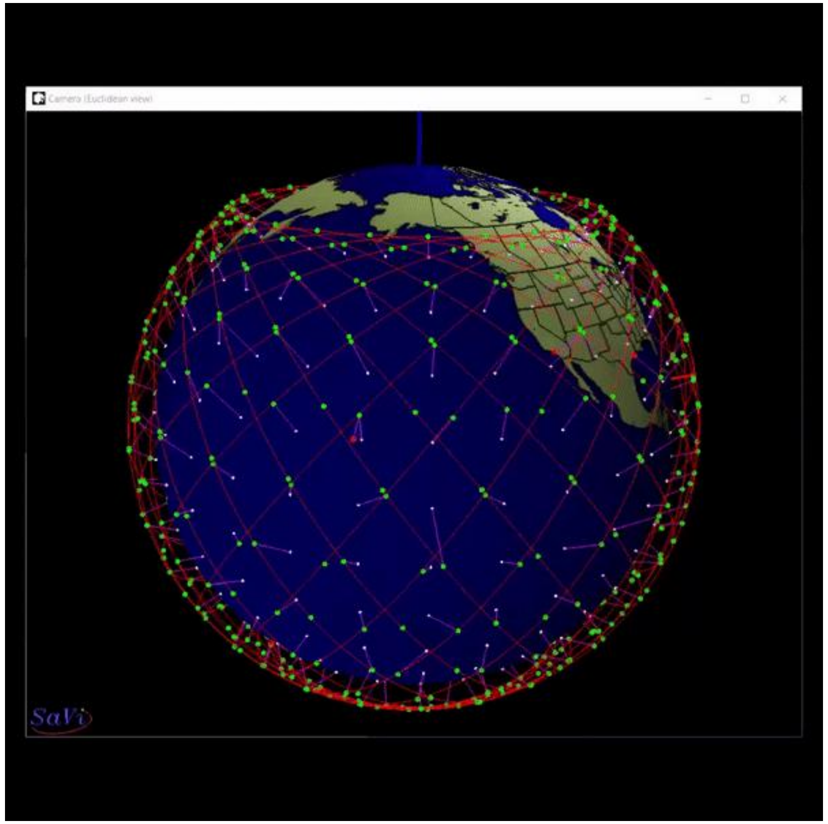
- IP over Satellite Links (ipsat) WG: IP over GEO, closed for unknown reason, and no output.
- Delay/Disruption Tolerant Networking (DTN WG): for GEO and inter-planetary communication, not fitting for LEO (due to short delay, less tolerance for disruption)
- L4 work
  - TCP Over Satellite (TCPSAT WG)
  - RFC2488, RFC2760,
- Network Coding for Satellite System: RFC8975
- SATCOM side meeting on IETF111
- Current drafts related to satellite network not belonging to any existing WG:
  - draft-li-istn-addressing-requirement
  - draft-jliu-istn-savi-requirement
  - draft-lai-bmwg-istn-methodology
  - draft-lhan-problems-requirements-satellite-net
  - draft-retana-lsr-ospf-monitor-node
  - draft-lhan-satellite-semantic-addressing
  - draft-lhan-satellite-instructive-routing
  - draft-kw-rtgwg-satellite-rtg-add-challanges-00

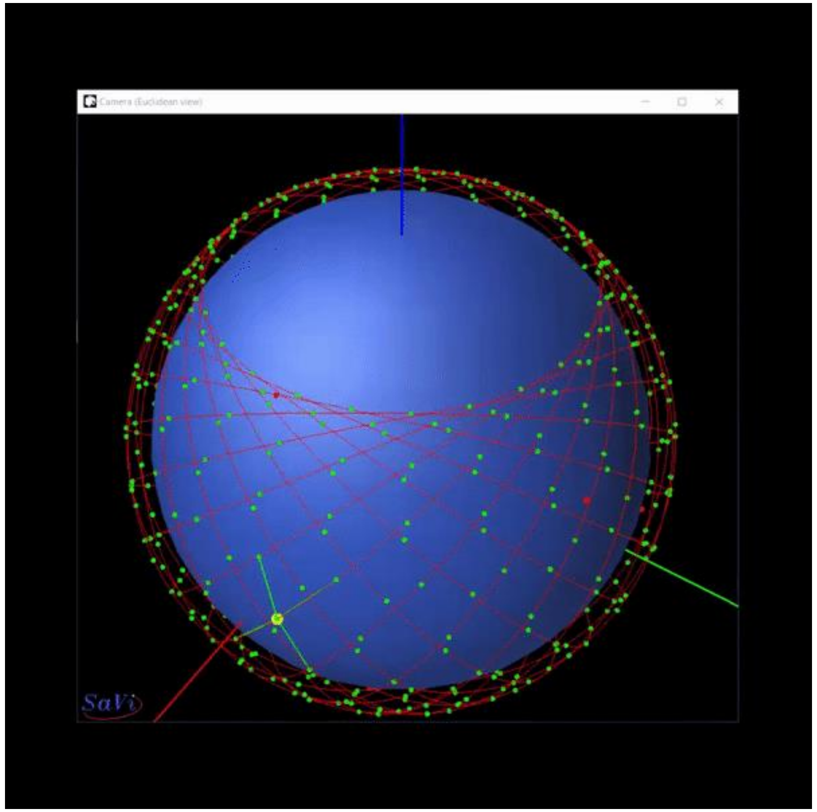
IP networking for LEO in the future

- Why IP 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).

LEO satellite constellation- Challenging 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

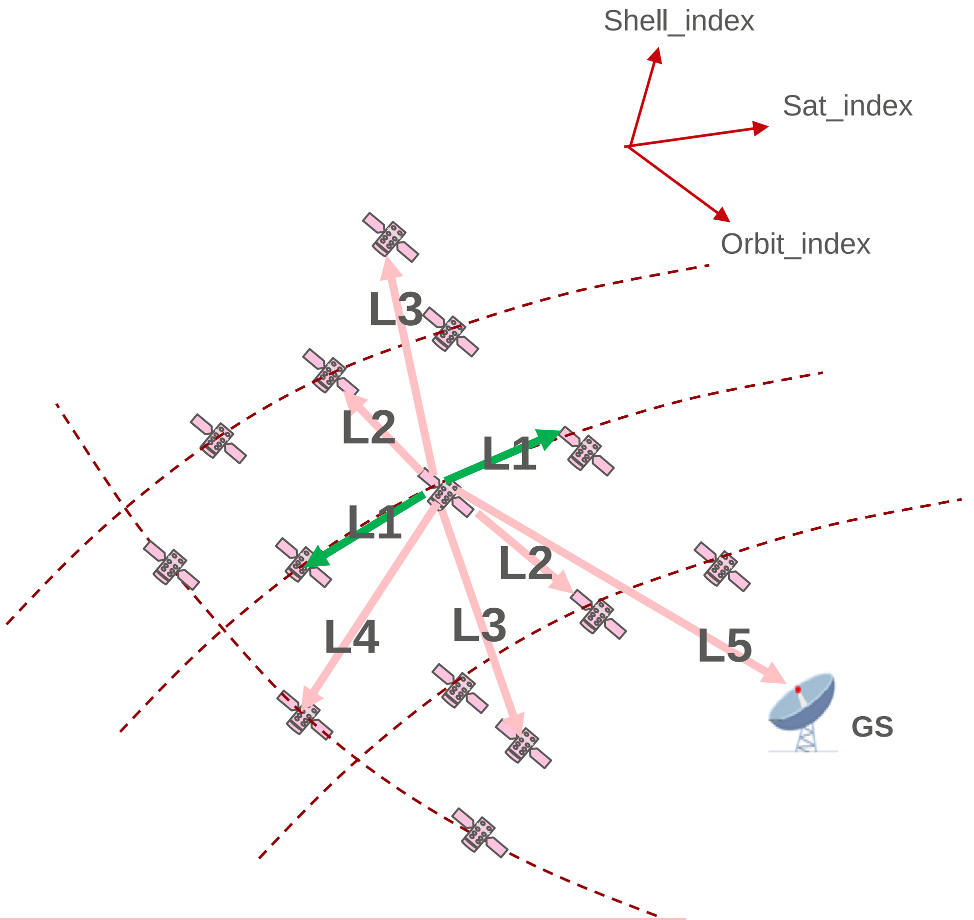
- links between satellites and ground station (GS) will flip every ~5min for LEO satellites (~550 km altitude), distance keeps changing
- One satellite has multiple GS connected
- One GS has multiple satellites connected
- Huge number of Sat-GS links (> million)

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

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

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, populate LSA update
New IP routing protocol: only detect the link state and populate the LSA update, link metrices are calculate periodically when necessary.

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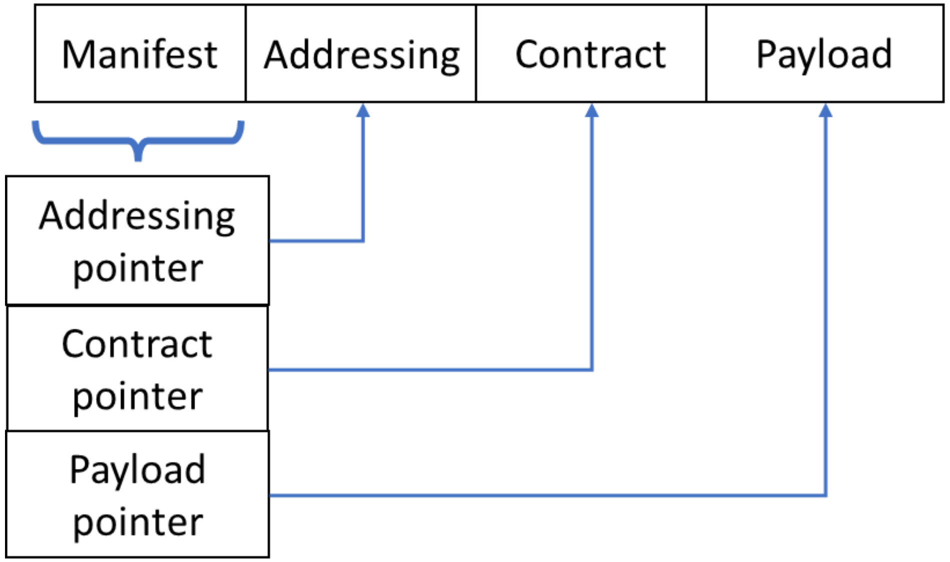
New IP review
a new protocol for LEO satellite routing solution



Addressing (for Omni-Convergence)
- Free Choice Addressing
  IPv4, IPv6, Lisp, Flexible Addressing System, Others
- Mix and Match

Contract
- KPI guarantee
  - In-time guarantee
  - On-time guarantee
  - Lossless networking
- User Programmable networking

Payload
- Native stream of Bits and Bytes
- Qualitative Payload
- Semantic Payload

- Routing protocol packet hdr use Non-IP satellite address
- 32-bit length
- LEO specific semantics

- User packet use Programmability for routing
- Instructive semantics
- Agnostic to address of user src/dest

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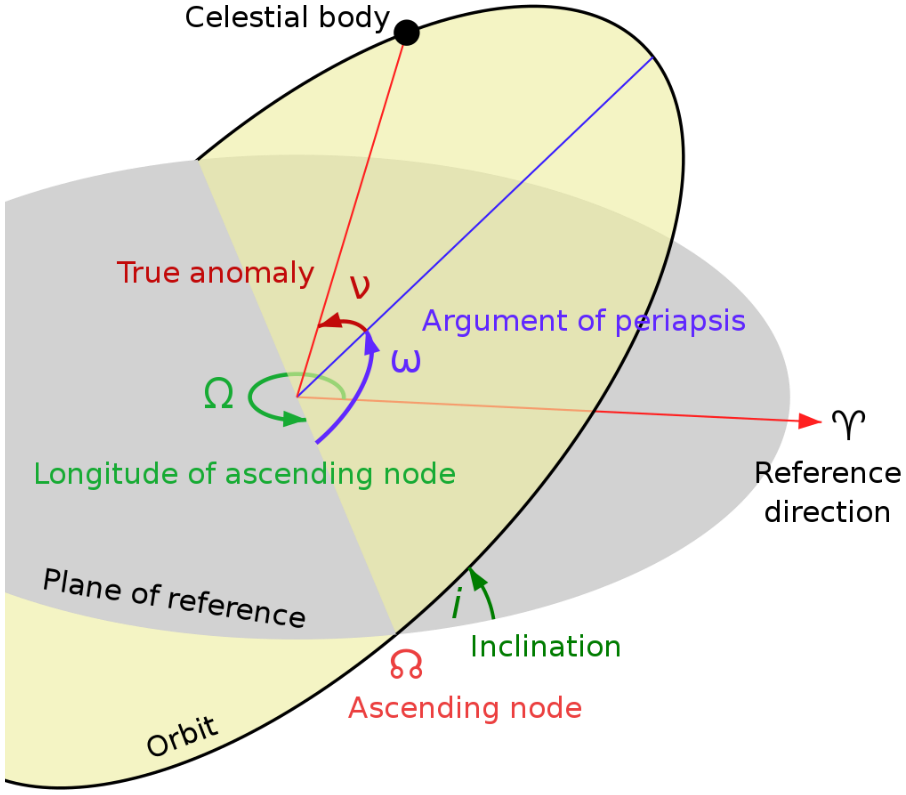
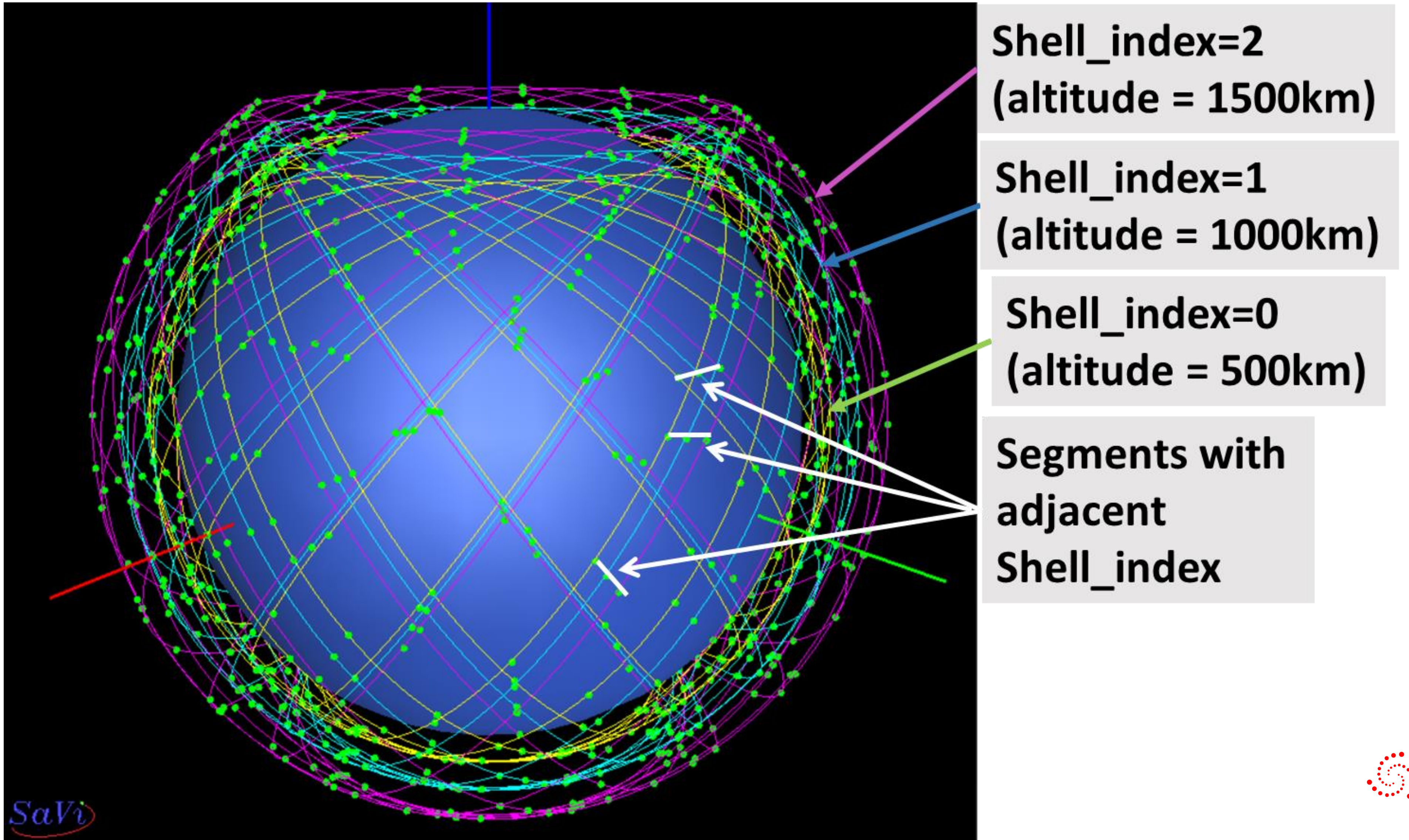
Semantic Address for LEO satellites

- 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   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Shell_index and associated segment



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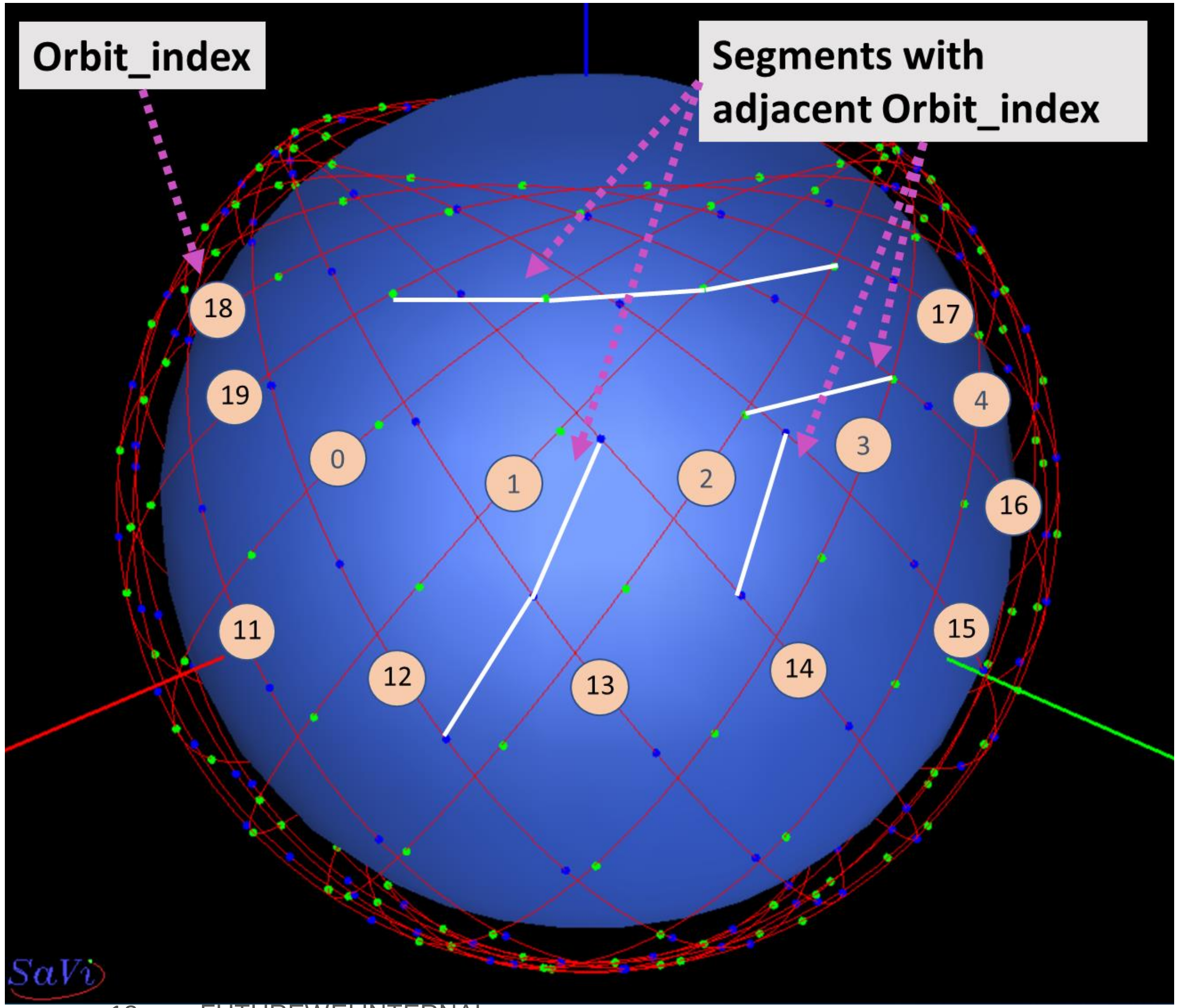
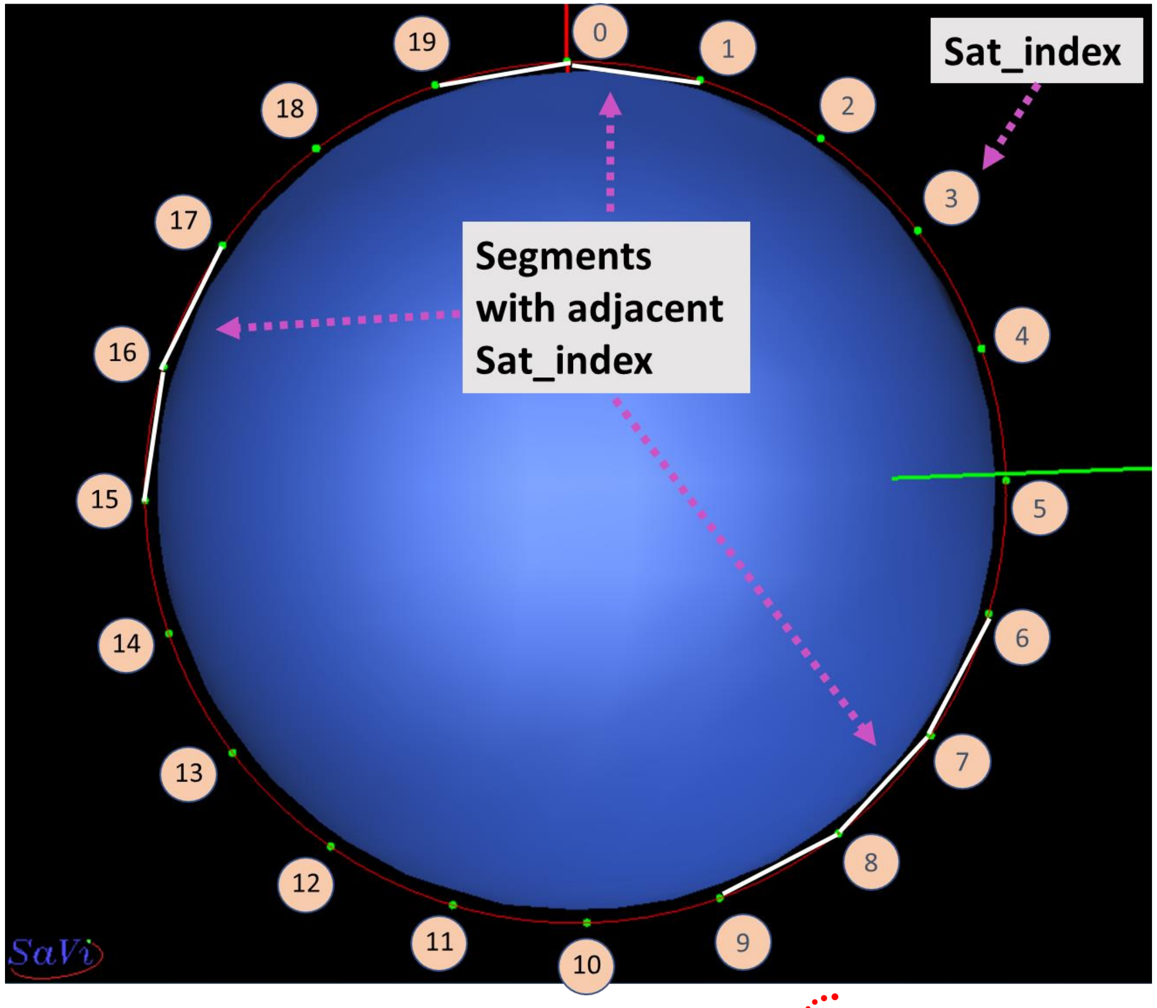
Orbit_index, Sat_Index and associated segment





Routing – New solution summary

- Control Plane: New IP based OSPF
  - New IP address family (address is TLV defined)
  - Router ID = Satellite Semantic Address
  - Satellites and ground-stations run OSPF
  - All nodes only populate Router LSA and attached network LSA
  - 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 does the SPF calculation unless it will send packets to others.
  - Path info (IP hop list) is retrieved from SPF tree.
- Data Plane: Instructive-semantics based routing
  - Periodically trigger OSPF at traffic source to calculation link metrics and SPF tree. retrieve the path info.
  - From path info -> segments-> instructions
  - Instructions embedded into user packet

Control Plane:
New IP based OSPF

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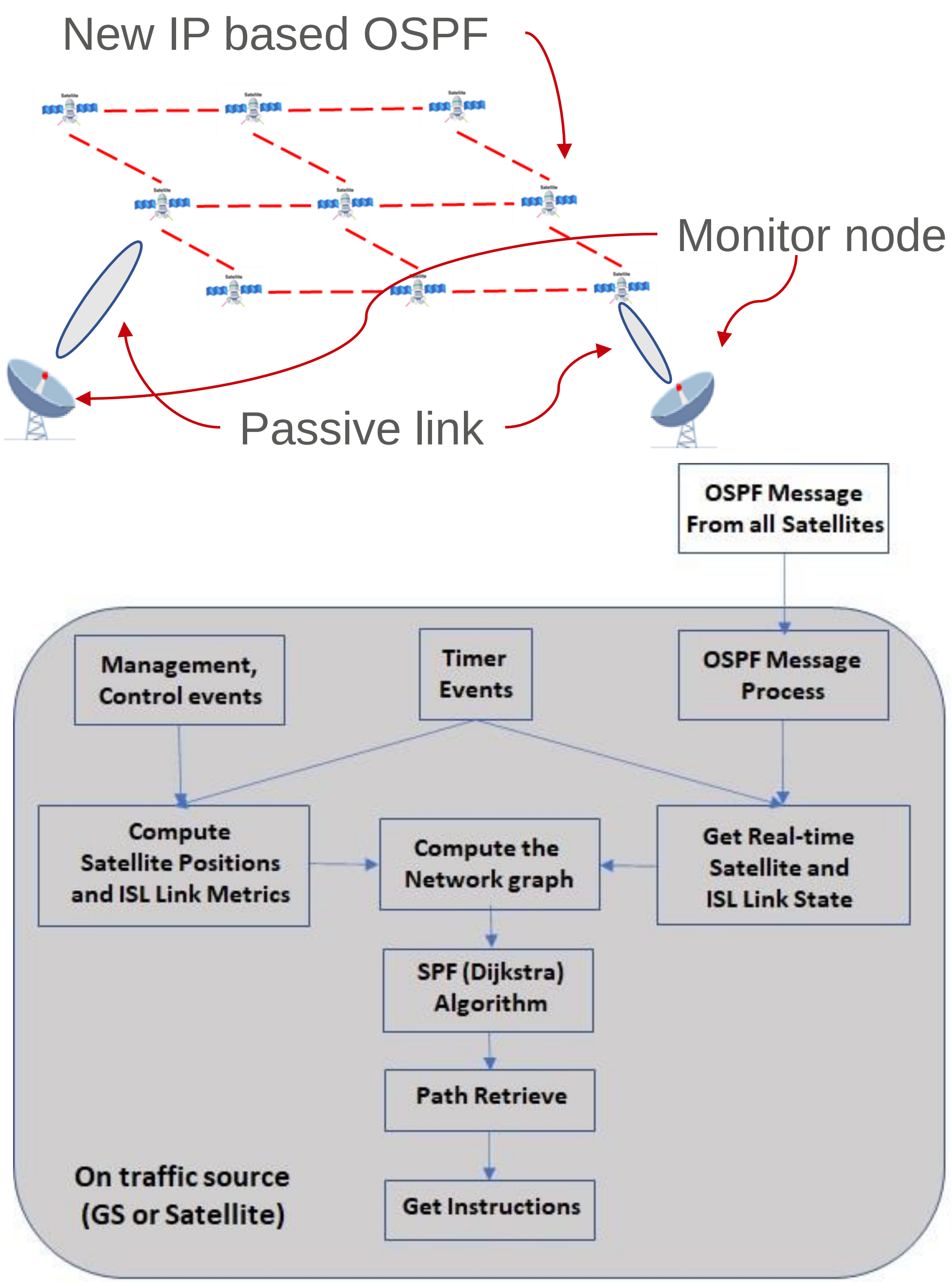
- Only traffic source, i.e, GS, calculate SPF tree, satellites doe not unless send packets to others
- Periodically trigger OSPF at traffic source to calculation all link metrics and SPF tree
- Retrieve the path info from SPF tree
- Path info -> segments-> instructions



Data Plane:
Instructive Routing

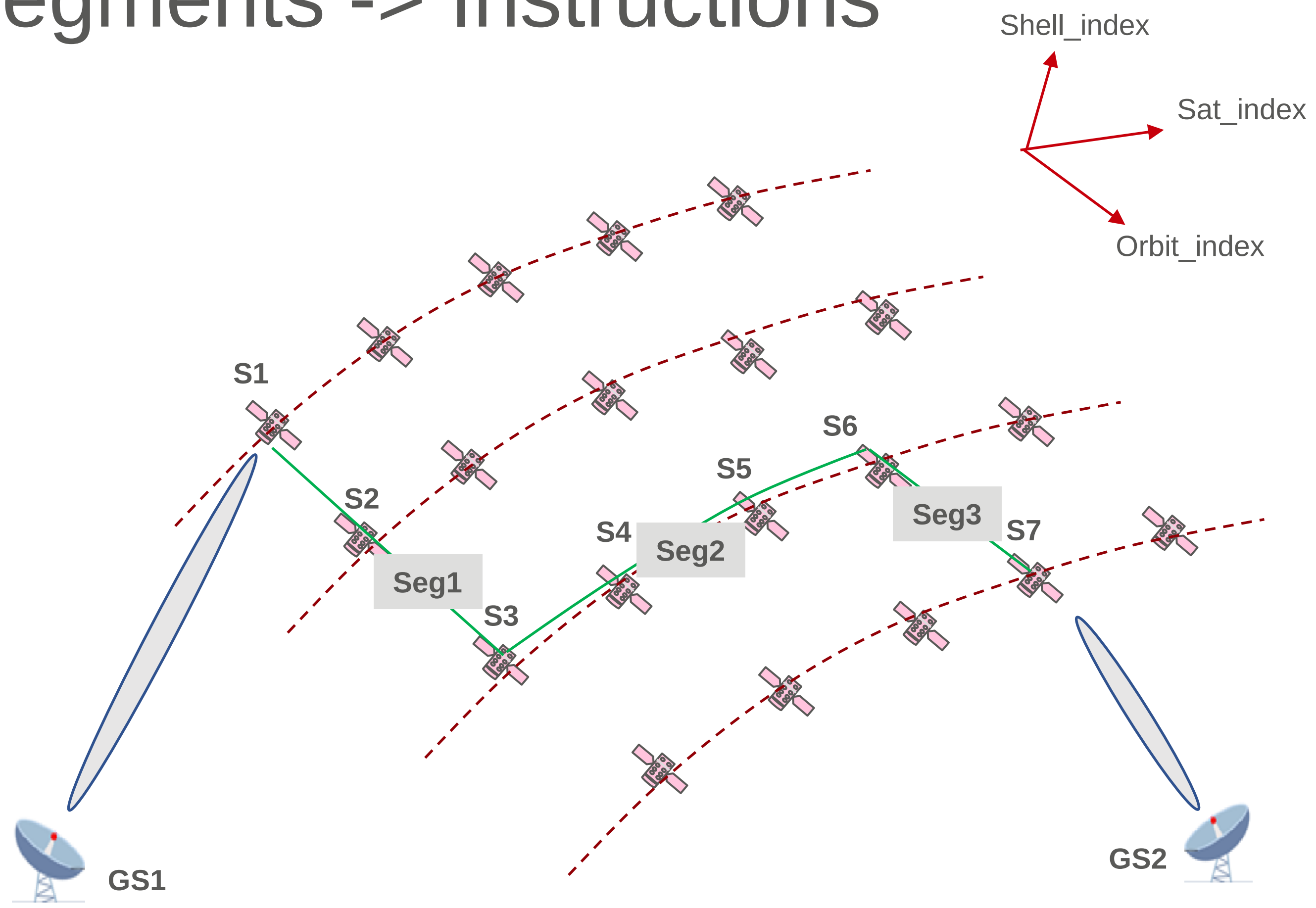
- Instructions embedded into user packet as Contract part
- Subtype Routing Programmability
- List of instructions
- Instruction = Function + Argument
- Instruction tells hardware to forward packet to specified direction and where to stop.
- Routing is no longer done by distributed routing calculation and TCAM lookup!

```
<Contract> := <Contract Clause>
            | <Contract Clause> AND <Contract>

<Contract Clause> := <Contract ECA> OR <Contract NP>

<Contract NP> := <Sat_Routing Contract>
            | <Sat_Routing Contract> AND <Contract NP>

<Sat_Routing Contract> := <Instruction>
            | <Instruction> AND <Sat_Routing Contract>

<Instruction> := <Func. Code> AND <Arguments>
            | <Func. Code> AND <Arguments> AND
              <Instruction>
```

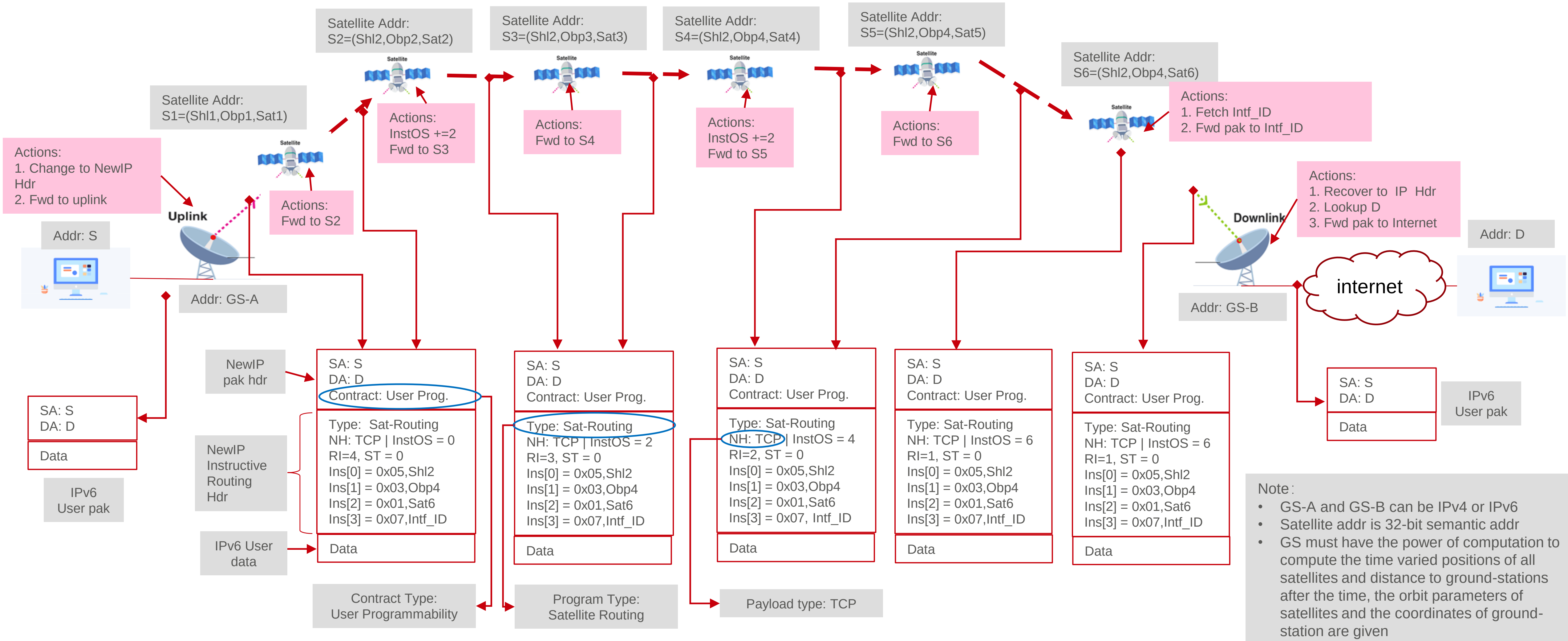
Function Name/Hex Value	Arguments/Size (Octet)
Fwd.Inc.Sat_Index/0x01	Sat_Index/1
Fwd.Dec.Sat_Index/0x02	Sat_Index/1
Fwd.Inc.Orbit_Index/0x03	Orbit_Index/1
Fwd.Dec.Orbit_Index/0x04	Orbit_Index/1
Fwd.Inc.Shell_Index/0x05	Shell_Index/1
Fwd.Dec.Shell_Index/0x06	Shell_Index/1
End.Intf_ID/0x07	Intf_ID/1
End.Punt/0x08	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

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



New IP Instructive Routing for Satellite – Tunnel-less Mode Packet Format and Actions



Note :
- GS-A and GS-B can be IPv4 or IPv6
- Satellite addr is 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

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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 UL/DL: one, two, as many as possible (GS is in the coverage)

GS-to-GS Delay estimation

$$\boldsymbol{Delay = D_P + D_{ISL}^S + D_R^S + D_{pak}^p} \quad \textbf{(1)}$$

$$\boldsymbol{D_P = Dist/S_l} \quad \textbf{(2)}$$

$$\boldsymbol{D_{ISL}^S = N_{ISL} * \frac{P_S}{S_{ISL}} = (N_{Sat} - 1) * \frac{P_S}{S_{ISL}}} \quad \textbf{(3)}$$

$$\boldsymbol{D_R^S = N_R * \frac{P_S}{S_R}} \quad \textbf{(4)}$$

$$\boldsymbol{D_{pak}^p = (N_{Sat} + 2) d_{pak}^p} \quad \textbf{(5)}$$

$Delay$	Total delay from src-GS to dst-GS
D_P	Laser propagation delay in free space
D_{ISL}^S	Packet transmission delay at all ISL links
D_R^S	Packet transmission delay at all radio links
D_{pak}^p	Total Packet processing delay at all satellites and GS
$Dist$	Distance of the path from Src-GS to Dst-GS, obtained from simulation
S_l	Speed of light in free space, $S_l = 300{,}000 km/s$
N_{Sat}	Number of satellites on the path, obtained from simulation
N_{ISL}	Number of ISL links on the path, obtained from simulation
P_S	Packet Size, assume $P_S = 1500 bytes$ in simulation
S_{ISL}	ISL speed, assume $S_{ISL} = 10G\ bps$ in simulation
N_R	Number of Radio Links, $N_R = 2$ in simulation
S_R	Radio Link Speed, $S_R = 100\ Mbps$ in simulation
d_{pak}^p	Packet processing delay at each hop, assume $d_{pak}^p = 100us$ in simulation

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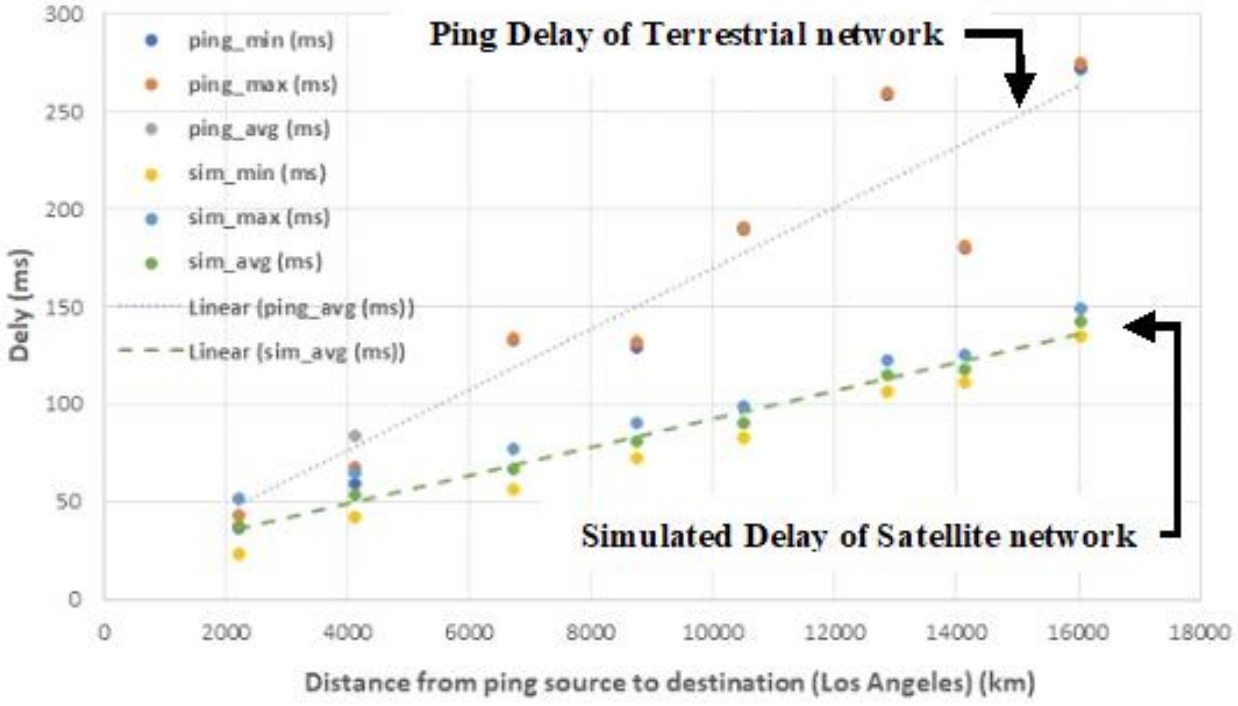
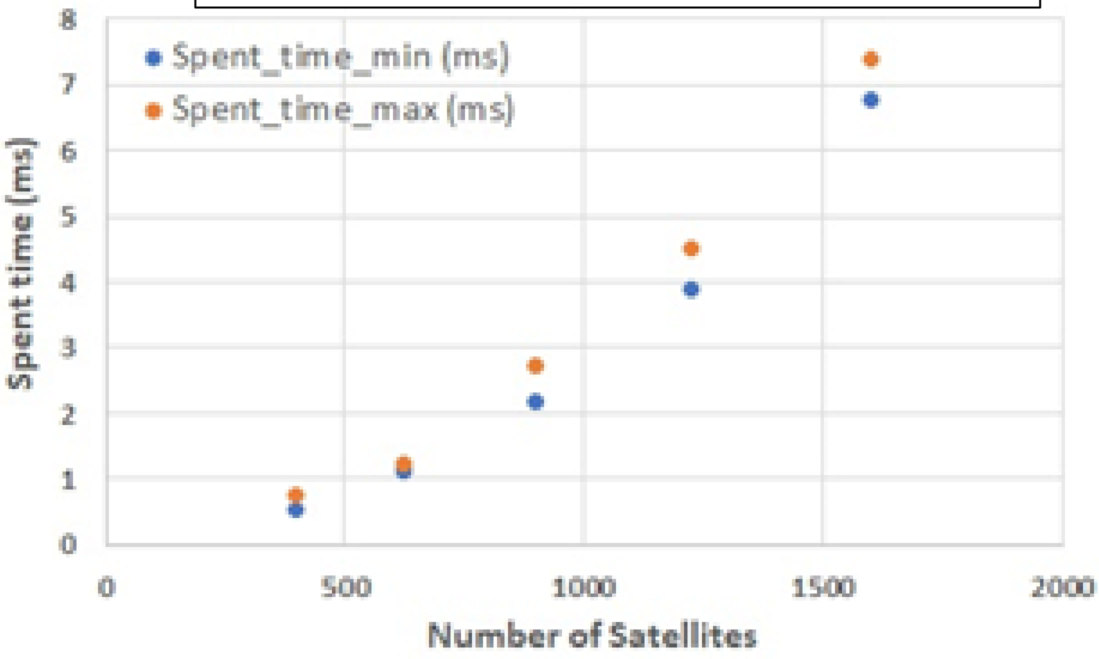
Delay, Performance, Salability

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, 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 & SEGMENTS FROM THE DIFFERENT SOURCE CITY TO LA (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)

Summary: IPv6 Solution vs New IP Solution

Items	IPv6	New IP	New IP Benefit
Control Plane: Network state and topology detection	• Use Modified OSPF for IPv6 (RFC5340)	• Use the OSPF that is designed for New IP address family; • Similar modification should be done like Modified OSPF for IPv6;	• New IP OSPF messages have shorter size; saving link bandwidth
Control Plane: Source routing instruction	• Use New Routing subtype in IPv6 Extension Header	• Use New IP Programmability subtype in Contract Field	
Data Plane: User address type	• IPv6	• IPv4 • IPv6 • Other address type	• New IP supports more type of user addresses

Thank You.

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