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


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

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

<table>
<thead>
<tr>
<th>Quarterly Starlink speeds, U.S.</th>
<th>Date</th>
<th>Download</th>
<th>Upload</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 2020</td>
<td>79.5</td>
<td>13.8</td>
<td>42</td>
<td>beta</td>
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<tr>
<td>q4 2020</td>
<td>104.97</td>
<td>12.04</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>q1 2021</td>
<td>65.72</td>
<td>13.77</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>q2 2021</td>
<td>97.23</td>
<td>13.8</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>q3 2021</td>
<td>87.25</td>
<td>13.54</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>q4 2021</td>
<td>104.97</td>
<td>12.04</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>q1 2022</td>
<td>90.55</td>
<td>9.33</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>q2 2022</td>
<td>62.53</td>
<td>7.24</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>q3 2022</td>
<td>53</td>
<td>7.22</td>
<td>67</td>
<td></td>
</tr>
</tbody>
</table>
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

**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)

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

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**TR38.821, Rel 16**

- LEO satellite network as 5G Access Network
- gNB on satellite
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- 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 Backhaul
- 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

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

Proposed by Mark Handley, UCL
https://www.youtube.com/watch?v=m05abdGSOxY&ab_channel=MarkHandley
ISL and Networking for Large LEO constellation are Key: Global Coverage, Most Economical
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

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Addressing method</th>
<th>Forwarding method</th>
<th>OSPF based Path determination</th>
<th>More details</th>
<th>Future</th>
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<tbody>
<tr>
<td>draft-lhan-satellite-semantic-addressing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>draft-lhan-satellite-instructive-routing</td>
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<td>draft-retana-lsr-ospf-monitor-node</td>
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</table>


Not complete, many other issues need to solve
IP Routing for LEO satellite network – Solution summary and Comparisons

<table>
<thead>
<tr>
<th>Addressing: Semantic address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple mechanism to describe the relationship of satellite</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Control Plane: Modified OSPF + Ephemeris Table + Off-line Computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why use OSPF</td>
</tr>
<tr>
<td>Maximize the usage of existing technology since it was proven in Internet for long time</td>
</tr>
<tr>
<td>Don’t recreate wheel</td>
</tr>
<tr>
<td>What we use from OSPF</td>
</tr>
<tr>
<td>Messaging exchanging mechanism: Hello, LSA, DB</td>
</tr>
<tr>
<td>SPF algorithm (Dijkstra Algo)</td>
</tr>
<tr>
<td>What we change:</td>
</tr>
<tr>
<td>Suppress LSA and messaging, and SPF computation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Plane: Instructive-semantics based routing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instructions embedded into user packet to guide the routing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Essence of ATM based solution has been taken into the consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete time, virtual link/node/topology</td>
</tr>
<tr>
<td>Source routing (connection like without connection setup), overcome the problem of hop-by-hop routing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orthogonal to the Path determination algorithms</th>
</tr>
</thead>
<tbody>
<tr>
<td>QoS, Load balance, Capacity and Congestion are handled by separate protocol following the layered principal in Internet.</td>
</tr>
<tr>
<td>L4 protocol, traffic engineering</td>
</tr>
<tr>
<td>ML, AI are not directly used for routing due to the performance but could be used for other aspects</td>
</tr>
<tr>
<td>Link/topology state prediction</td>
</tr>
<tr>
<td>Alternative or enhancement of Path determination</td>
</tr>
<tr>
<td>SDN could be used for management and table (not forwarding) update</td>
</tr>
</tbody>
</table>
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 (\(\nu\))

• Not IPv4/IPv6 address or prefix

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
| +------------------------------------------------------------------+
| Owner Code | Shell_Index | Orbit_Index | Sat_Index |
| +------------------------------------------------------------------+
Shell_index and associated segment

- \texttt{Shell\_index=2} (altitude = 1500km)
- \texttt{Shell\_index=1} (altitude = 1000km)
- \texttt{Shell\_index=0} (altitude = 500km)

Segments with adjacent \texttt{Shell\_index}
Our solution: Addressing Orbit_index, Sat_Index and associated segment
### Control Plane: Routing: How to handle Links Life and Link Metrics?

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

**Traditional routing protocol:**
Detect the link state, and measure the link metrics, flood LSA update
Control Plane: Routing: How to quickly know the network topology and state

**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

**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 running on All satellites and GS

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

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 do 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

<table>
<thead>
<tr>
<th>Function Name/Hex Value</th>
<th>Arguments/Size (Octet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fwd.Inc.Sat_Index/0x01</td>
<td>Sat_Index/1</td>
</tr>
<tr>
<td>Fwd.Dec.Sat_Index/0x02</td>
<td>Sat_Index/1</td>
</tr>
<tr>
<td>Fwd.Inc.Orbit_Index/0x03</td>
<td>Orbit_Index/1</td>
</tr>
<tr>
<td>Fwd.Dec.Orbit_Index/0x04</td>
<td>Orbit_Index/1</td>
</tr>
<tr>
<td>Fwd.Inc.Shell_Index/0x05</td>
<td>Shell_Index/1</td>
</tr>
<tr>
<td>Fwd.Dec.Shell_Index/0x06</td>
<td>Shell_Index/1</td>
</tr>
<tr>
<td>End.Intf_ID/0x07</td>
<td>Intf_ID/1</td>
</tr>
<tr>
<td>End.Punt/0x08</td>
<td>0x0/1</td>
</tr>
<tr>
<td>End.Lookup/0x09</td>
<td>0x0/1</td>
</tr>
<tr>
<td>End.Lookup.IPv4/0x0A</td>
<td>IPv4.Addr/4</td>
</tr>
<tr>
<td>End.Lookup.IPv6/0x0B</td>
<td>IPv6.Addr/4</td>
</tr>
<tr>
<td>Fwd.Sat.Addr/0x0C</td>
<td>Sat.Addr/4</td>
</tr>
<tr>
<td>Fwd.Sat_MacAddr/0x0D</td>
<td>Sat_MacAddr/6</td>
</tr>
</tbody>
</table>
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

Our solution: Data Plane
Data Plane: Tunnel-less Mode Packet Format and Actions

Our solution: Data Plane
Modeling and Experiments

• Savi to simulate the LEO satellite network
  • 550km altitude; 53° 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

Ping Delay of Terrestrial network

Simulated Delay of Satellite network

Time to compute SPF tree and routes

Num. of distinct path in 24 Hrs

<table>
<thead>
<tr>
<th>Src City</th>
<th>Distance to LA (km)</th>
<th>Number of path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston</td>
<td>2207</td>
<td>1425</td>
</tr>
<tr>
<td>Honolulu</td>
<td>4117</td>
<td>1411</td>
</tr>
<tr>
<td>Lima</td>
<td>6727</td>
<td>1251</td>
</tr>
<tr>
<td>London</td>
<td>8758</td>
<td>1440</td>
</tr>
<tr>
<td>Auckland</td>
<td>10500</td>
<td>1307</td>
</tr>
<tr>
<td>New Delhi</td>
<td>12866</td>
<td>1394</td>
</tr>
<tr>
<td>Singapore</td>
<td>14129</td>
<td>1334</td>
</tr>
<tr>
<td>Cape Town</td>
<td>16056</td>
<td>1322</td>
</tr>
</tbody>
</table>
## Number of hops, segments and packet overhead

<table>
<thead>
<tr>
<th>Src City</th>
<th>Distance to LA (KM)</th>
<th>Hops No. (min/max)</th>
<th>Segment No. (min/max)</th>
<th>Our method</th>
<th>SRv6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston</td>
<td>2207</td>
<td>3/7</td>
<td>2/3</td>
<td>6/8</td>
<td>32/48</td>
</tr>
<tr>
<td>Honolulu</td>
<td>4117</td>
<td>5/9</td>
<td>2/4</td>
<td>6/10</td>
<td>32/64</td>
</tr>
<tr>
<td>Lima</td>
<td>6727</td>
<td>6/9</td>
<td>1/4</td>
<td>4/10</td>
<td>16/64</td>
</tr>
<tr>
<td>London</td>
<td>8758</td>
<td>10/13</td>
<td>2/7</td>
<td>6/16</td>
<td>32/112</td>
</tr>
<tr>
<td>Auckland</td>
<td>10500</td>
<td>8/12</td>
<td>1/4</td>
<td>4/10</td>
<td>16/64</td>
</tr>
<tr>
<td>New Delhi</td>
<td>12866</td>
<td>12/16</td>
<td>2/6</td>
<td>6/14</td>
<td>32/96</td>
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<tr>
<td>Singapore</td>
<td>14129</td>
<td>12/15</td>
<td>1/4</td>
<td>4/10</td>
<td>16/64</td>
</tr>
<tr>
<td>Cape Town</td>
<td>16056</td>
<td>12/18</td>
<td>2/4</td>
<td>6/10</td>
<td>32/64</td>
</tr>
</tbody>
</table>

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

**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.