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Problems and Requirements of Addressing in Integrated Space-Terrestrial Network

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Abstract

This document presents a detailed analysis of the problems and requirements of network addressing in "Internet in space" for terrestrial users. It introduces the basics of satellite mega-constellations, terrestrial terminals/ground stations, and their inter-networking. Then it explicitly analyzes how space-terrestrial mobility yeilds challenges for the logical topology, addressing, and their impact on routing. The requirements of addressing in the space-terrestrial network are discussed in detail, including uniqueness, stability, locality, scalability, efficiency and backward compatibility with terrestrial Internet. The problems and requirements of network addressing in space-terrestrial networks are finally outlined.

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1. Introduction

The future Internet is up in the sky. We have seen a rocket-fast deployment of mega-constellations with 100s-10,000s of low-earth-orbit (LEO) satellites, such as Starlink [STARLINK], Kuiper [KUIPER] and OneWeb [ONEWEB]. These constellations promise competitive low latency and high capacity to terrestrial networks. They expand global high-speed Internet to remote areas that were not reachable by terrestrial networks, resulting in a tens-of-billions-of-dollar market with 2.7 billion users in rural areas[ITU-Measure], developing countries, aircraft, or oceans.

A salient feature for LEO mega-constellations is their high relative motions to the rotating earth. Unlike geosynchronous satellite or terrestrial networks, each LEO satellite moves fast (e.g., 28,080 km/h for Starlink), causing short-lived coverage for terrestrial users (less than 3 minutes). This yields diverse challenges for the traditional network designs.

This memo outlines the problems and requirements of addressing in integrated space-terrestrial network. It starts with the basics of satellite mega-constellations, terrestrial ground stations/terminals, and their inter-networking. It analyzes how multi-dimensional physical dynamics yields challenges for logical topology, addressing and their impacts on routing. Then it discusses the requirements of network addressing in space-terrestrial network for uniqueness, stability, locality, scalability, efficiency and backward compatibility with terrestrial Internet.

2. Terminology

GSO: Geosynchronous orbit (at the altitude of 35,786 km).

NGSO: Non-geosynchronous orbit.

LEO: Low Earth Orbit (at the altitude of 180-2,000 km).

MEO: Medium Earth Orbit (at the altitude of 2,000-35,786 km).

ISL: Inter Satellite Link.

NAT: Network Address Translation.

GS: Ground Station, a device on ground connecting the satellite.

FIB: Forwarding Information Base.

3. Basics of Space-Terrestrial Network

As shown in Figure 1, a space-terrestrial network for terrestrial users consists of the satellite or constellations, terrestrial terminals, and ground stations.

3.1. Satellites and Mega-Constellations

Satellites can be classified based on their relative motions to the earth. A satellite can operate at the geosynchronous orbit (GSO, at about 35,786 km altitude) or non-geosynchronous orbits, such as low earth orbits (LEO, <=2,000km) and medium earth orbits (MEO, between 2,000 km and 35,786 km). Satellites at higher altitudes offer broader coverage, while satellites at lower altitudes move faster.

Historically, communications in space were dominated by GSO satellites. As shown in Table 1, GSO offers excellent coverage at high altitudes, but at the cost of long space-terrestrial RTT (>=200ms) and low bandwidth (<=10Mbps, due to bit errors in long distance transmission). Instead, recent efforts seek to adopt satellites at lower non-geosynchronous orbits, with a special interest in low-earth orbits. Together with Ku (1218 GHz) and Ka (26.540GHz) bands, these satellites promise competitive bandwidth and latency to terrestrial networks([LOWLATENCY-ROUTING-SPACE], [SPACE-RACE], [NETWORK-TOPO-DESIGN]). Due to low coverage for each LEO satellite, a mega-constellation is necessary to retain global coverage. Table 2 exemplifies popular LEO mega-costellations in operation. They are enabled by recent advances in satellite miniaturization and rocket reusability.

```
            +-----------+              +-----------+
            | Satellite |_______ISL_______| Satellite | (Space Segment)
         _ _|___________|           _ _|___________|
            /|            \              /|
           / |             \            / |
          /   (Bent pipe)  \ |         /
         /                _ _\|        /
   +---------+            +------------+
   |  Mobile |            |   Ground   |
   | Station |            |  Station   |         (Ground Segment)
   |_________|            |____________|
```

Figure 1: A simplified space-terrestrial network architecture

Orbit		Altitude (km)	RTT (ms)
GSO	GEO	35,786	240
NGSO	MEO	2,000-35,786	12-240
	LEO	500-2,000	2-12

Table 1: Differences between GSO and NGSO.

Constellation	Num. satellites	Num. orbits	Altitude (km)
Starlink	1584	72	550
	1584	72	540
	720	36	570
	348	6	560
	172	4	560
Kuiper	1156	34	630
	1296	36	610
	784	28	590
Telesat	351	27	1015
	1320	40	1325
Iridium	66	6	780

Table 2: Low-earth-orbit (LEO) satellite mega-constellations in operation.

3.2. Evolution of Space-Terrestrial Network

Terrestrial users access satellite networks via terminals (e.g., satellite phones, onboard dishes, IoT endpoints) or ground stations. Ground stations can serve as network gateways (e.g., carrier-grade NAT in Starlink [STARLINK-CGNAT] and Kuiper [KUIPER-CGNAT]) and remote satellite controllers (e.g., telemetry, tracking, orbital update commands, or centralized routing control).

3.2.1. "One-to-one" satellite communication

Early satellite communications favor the simple "bent-pipe-only" model (Figure 1), i.e., satellites only relay terrestrial users' radio signals to the fixed ground stations without ISLs or routing. This model has been popular in GSO satellites with broad coverage (2G GMR [GEO-MOBILE-RADIO-INTERFACE] [ETSI-TS-101], 3G BGAN [BGAN] [ETSI-TS-102], and DVB-S [SATELLITE-COMMUNICATIONS]), and recently adopted by LEO satellites in OneWeb (4G) [ONEWEB] and 5G NTN [STUDY-NR-SUPPORT] [SOLUTION-NR-NTN]. However, this model suffers from low LEO satellite coverage. To access the network, both terrestrial users and ground stations must reside inside the satellite's coverage. Due to each LEO satellite's low coverage, most users in remote areas with sparse or no ground stations cannot be served. As shown in Table 3, under current Starlink (no ISLs so far) and ground station deployments ([STARLINK-GS-FOUND], [AZURE-GS], [AWS-GS], [GOOGLE-DATA-CENTER], [AZURE-CLOUD-STARLINK], [STARLINK-GS-MAP]), 27%52% global populations cannot be served by the "one-to-one" model (depending on how many satellites each ground station can simultaneously associate to). Most under-served users are from remote areas (e.g., Africa), thus causing revenue loss for operators.

The ground station aggregates traffic from all satellite users and becomes the single-point bottleneck. In reality, Starlink' s LEO satellites generate 5 TB telemetry data per day for the ground stations to process [REDDIT]. With limited space-terrestrial radio link capacity, its ground stations have limited the LEO network' s total capacity [COMPARISON-THREE-CONSTELLATION]. Similarly, each OneWeb's ground station must process 10,000 terminal handovers per second [ONEWEB-GS]. Deploying dense ground stations in these remote areas could mitigate above two problems. However, it is expensive and lowers commercial competitive advantages to terrestrial networks.

3.2.2. "One-to-many" networked ground stations

To this end, networked space-terrestrial infrastructure is crucial for global coverage and single-point bottleneck elimination. To date, inter-satellite links (ISLs) are under early adoption([BEIDOU-TEST], [TheVerge-STARLINK-SPEED]). The recent "burn on re-entry" regulations from FCC also slows down the adoption of ISLs[SPACEX-CLAIM]. As a near-term remedy, routing with distributed ground station networks is adopted. There are two variants. The ground station-as-gateway is adopted by Starlink and Kuiper. Each ground station is a carrier-grade NAT that offers private IP[RFC0791] for terrestrial users. The ground station-as-relay [USE-GROUND-RELAY] mitigates ISLs with ground station-assisted routing, but is vulnerable to intermittent space-terrestrial links in Ku/Ka-bands. Fundamentally, the "one-to-many" model heavily relies on global deployments of ground station networks, thus offsetting LEO satellites’ advantages and competitive edges to terrestrial networks.

3.2.3. "Many-to-many" networked satellites

To unleash LEO mega-constellations’ potentials and long-term success, the networked LEO satellites are under rapid deployments[KUIPER][STARLINK]. Today’s networked LEO satellites typically have a microwave space-terrestrial radio interface and 45 laser/microwave inter-satellite links (ISLs) [LOWLATENCY-ROUTING-SPACE][USE-GROUND-RELAY] (2 intra-orbit ISLs, 2 inter-orbit ISLs, and 1 optional inter-orbital-shell ISL). Starlink’s ISLs have started to operate for high latitude areas like Latin America [STARLINK-ISL-AMERICA], Antarctica [STARLINK-ISL-ANTARCTICA], and oceans [STARLINK-ISL-OCEANS]. With this capability, recent work has explored topology design [NETWORK-TOPO-DESIGN], low-latency routing [LOWLATENCY-ROUTING-SPACE][SPACE-RACE], inter-domain routing [Giuliari20Internet], orbital computing [ORBITAL-EDGE-COM][IN-ORBIT-COM], and security [ICARUS] in LEO networks. We take a forward-looking view to simplifying LEO networks in the first place and helps these efforts fulfill their merits in space.

	Global	Africa	Oceania	South America	Asia	European	North America
1-SAT association	48.71%	19.52%	42.85%	49.63%	43.49%	91.00%	87.50%
2-SAT association	57.30%	24.37%	56.58%	53.90%	55.91%	94.33%	91.23%
4-SAT association	67.04%	26.13%	60.31%	63.16%	71.34%	95.46%	95.04%
8-SAT association	73.04%	29.17%	60.68%	65.65%	80.28%	96.91%	98.86%

Table 3: Global population that could access Starlink in its current "bent- pipe-only" model.

4. Problems in Space-Terrestrial Network Addressing

In terrestrial and GEO satellite networks, the logical network topology, addresses, and routes are mostly stationary due to fixed infrastructure. Instead, LEO mega-constellations hardly enjoy this luxury, whose satellites move at high speeds (about 28,080 km/h). The earth’ s rotation further complicates the relative motions between space and ground. In this section, we will analyze how multi-dimensional dynamics within space-terrestrial networks challenges addressing due to topology instability, and its impact on routing [INTERNET-IN-SPACE][SHORT].

4.1. Multi-Dimensional Topology Dynamics

High physical mobility incurs frequent link churns between space and terrestrial nodes, thus causing frequent logical network topology changes. This topology dynamics is multi-dimensional, manifesting within a single orbital shell and interweaving across heterogeneous orbital shells.

4.1.1. Space-Terrestrial Dynamics

Unlike classic GEO satellites, LEO satellites’ GSLs are unstable due to their unavoidable complex asynchronous motions to Earth. The GSL changes are magnified with vast LEO satellites in the mega-constellation in Table 2. On average, the global GSL churn occurs every 1.463.98s. The link churn populates with more satellites and ground stations.

In terrestrial mobile networks (e.g., 4G/5G), such physical link churn can be masked by handoffs without incurring logical topology changes. This method works based on two premises. First, all link churns occur at the last-hop radio due to user mobility, without affecting the infrastructure topology. Second, all cellular infrastructure nodes are fixed, resulting in a stable logical topology as “anchors”.

However, neither premise holds in non-geosynchronous constellations. Instead, infrastructure mobility between satellites and ground stations becomes a norm rather than an exception. This voids cellular handoffs’ merits to avoid propagation of physical link churns to logical network topology: They are designed for user mobility only, and heavily rely on the fixed infrastructure as “anchors.” Therefore, 5G NTN lists satellite handoffs as an unsolved problem ([STUDY-NR-SUPPORT], [SOLUTION-NR-NTN]), and the latest 3GPP 5G release 17 defers its mobility support for satellites [TEC-SPECI-GROUP-MEETING] due to significant architectural changes. While Starlink uses handoffs to migrate physical links between satellites and ground stations (every 15s [STARLINK-CGNAT]), its logical topology and routing are still be repeatedly updated at high costs.

4.1.2. Intra-Orbital-Shell Dynamics

Topological dynamics between LEO satellites inside an orbital shell is milder than space-terrestrial dynamics but still alarming due to various practical factors. In Starlink, ISL churns in orbital shell 2 and 3 occur every 208.7 and 970.0s, respectively. In orbital shell 4, inter-orbit ISL churn occurs every 11.4s due to its partial deployment below.

There are three practical factors triggering intra-orbital-shell dynamics. First, orbital maneuvers cause repetitive ISL churns. To avoid collisions, a satellite should slightly raise/lower its altitude. This incurs relative motions to its neighboring satellites inside the orbital shell and prolongs their distances accumulatively. They can eventually disrupt laser ISLs if neighboring satellites’ distance is beyond their visibility [STARLINK-SELF-DRIVING] or change the intra-orbit satellite neighborship to force multiple ISL reconfigurations [NETWORK-AWARE-MANEUVERS]. Starlink’s maneuvers cause 48 ISL churns per day on average (up to 259 ISL churns/day) in shell 2 [SHORT]. Second, random satellite/ISL failures cause unpredicted ISL churns. LEO satellites operates in harsh outer space. Starlink’s official reports [STARLINK-REPORT-2021-1][STARLINK-REPORT-2021-2][STARLINK-REPORT-2022-1][STARLINK-REPORT-2022-2][STARLINK-REPORT-2023-1] show that, by May 2023, every 1 out of 13 Starlink satellites has failed due to disposal, geomagnetic storm, flight control failures, hardware failures using commodity CPUs, and others. Third, partial deployments cause more frequent ISL churns. An orbital shell cannot be deployed all at once, thus causing partial deployments. As of 2025.06, Starlink’ s shell 3 and 4 in Table 2 are still unfinished. Even so, these partial shells already offer services using ISLs in areas like Antarctica (via shell 4, Starlink’ s only shell covering Antarctica). Partial deployments result in sparser satellites and more frequent ISL churns. Starlink’ s shell 4 has 18.3× more ISL churns than shell 2 (almost completed) [SHORT].

4.1.3. Inter-Orbital-Shell Dynamics

Operational LEO networks adopt multiple orbital shells to match their satellite distribution and capacity with unevenly distributed users. For optimal coverage, the LEO network can use multiple shells with different inclinations and numbers of satellites, each primarily serving a subset of users at different latitudes. For instance, most Starlink satellites’ inclinations are 53-53.2 to serve most users in low-latitude areas. Its shells 3 and 4 use 70° and 97.6° inclination for high-latitude users, but have much fewer satellites due to the low population.

Different orbital shells have heterogenous altitudes and inclination angles (Table 2). Similar to space-terrestrial dynamics, such heterogeneity yields nonlinear, asynchronous, and accumulative motions between inter-orbital-shell satellites and hence ISL churns. Inter-orbital-shell dynamics is more dramatic than intra-orbital-shell dynamics but less critical for the basic functionality of LEO networking.

Inter-orbital-shell ISLs are nice to have for shorter paths but are not always as mandatory as other links. Inter-orbital-shell routing must occur only when the source (destination) resides in the high latitude areas where the destination’s (source’s) orbital shell cannot cover. This scenario is rare in practice due to the low populations in high-latitude areas. Even without inter-orbital-shell ISLs, orbital shells can still be indirectly bridged by GSLs from ground stations in their overlapped terrestrial coverage.

4.2. Inconsistent “Locations” for Space/Terrestrial Nodes

Each space/terrestrial node has two notions of “locations”: The logical location in its topological address, and the physical location in reality. With repetitive topology changes, a static network address can hardly ensure its logical location in the topology is consistent with the fast-moving node’ s physical location in reality. Then to correctly forward data, a network should choose one of the following designs:

a. Dynamic address updates

A node can repetitively re-bind its physical location to its logical network address, thus incurring frequent address updates or re-binding. Under high mobility, this could severely disrupt user experiences or incur heavy signaling overhead. Table 4 and Table 5 project the address update frequency when using legacy IP addresses[RFC0791] for logical interfaces. In this scheme, the terrestrial users' logical IP[RFC0791] address changes if it re-associates to a new satellite (thus new interfaces and subnets) to retain its Internet access. Due to high LEO satellite mobility, each user is forced to change its logical IP address[RFC0791] every 133510s. Every second, we observe 2,0827,961 global users per second should change their IP addresses.

Starlink	Telesat	Kuiper	Iridium
Every 133s	Every 510s	Every 179s	Every 458s

Table 4: Frequency of each user's logical IP address update.

Starlink	Telesat	Kuiper	Iridium
7961	2082	5673	2379

Table 5: Number of terrestrial users that change logical IP address per second.

b. Static address binding to a fixed gateway

This is adopted by the cellular networks and Starlink [STARLINK-CGNAT] and Kuiper's[KUIPER-CGNAT] initial rollouts. Each user gets a static address from the remote ground station (via carrier-grade NAT), which masks the external address changes and redirects users' traffic. This mitigates user address updates, but cannot avoid gateway's external address updates when changing satellite interfaces (detailed below). It also incurs detours and long routing latencies for remote users from ground stations (e.g., 18,000 km detours and 370 ms extra delays in [lai2021icnp]).

4.3. Impact on Routing: Frequent Routing Updates

The inconsistent locations in addressing further impact the network routing. As space and terrestrial infrastructure nodes physically move fast, the logical routing in cyberspace expires frequently. It must be updated frequently, thus threatening various routing schemes:

a. Distributed routing: Repetitive re-convergence.

   In distributed routing, network nodes distribute topology information to others, locally compute forwarding tables, and eventually reach a global consensus on routing paths (i.e., convergence). Before global routing convergence, there is no guaranteed network reachability. With high mobility, each LEO satellite can only offer very short-lived access for a ground station(<=3 minutes in Starlink). Frequent topology updates cause repetitive routing re-convergence and thus lowing network usability. For intra-domain routing (e.g., OSPF[RFC2328], IS-IS[RFC1142], AODV[RFC3561], DSR[RFC4728]), most mega-constellations suffer from low network usability. Even the the size of constellation is small, the network needs more than fifty seconds to converge after each handoff while using OSPF[TIMESLOT-DIVISION]. For inter-domain routing (e.g., BGP[RFC4271]), [Giuliari20Internet] and [NETWORK-IN-HEAVEN] show frequent logical topology changes cause BGP[RFC4271] re-peering, thus sharpening the instability of global Internet routing.

b. Centralized routing: Repetitive global updates.

   In the centralized routing, a ground station predicts the temporal evolution of topology based on satellites' orbital patterns, divides it into a series of semi-static topology snapshots, schedules the forthcoming global routing tables for each snapshot, and remotely updates the routing tables to all satellites (e.g., via SDN[RFC7426], MPLS[RFC3031], or SRv6[RFC8754]). While helpful and can mitigate the impact of topology dynamics, prediction-based centralized routing does not suffice for two reasons: (1) Exhaustive computation: multi-level LEO dynamics in 4.1 interleave with each other to complicate overall predictions and result in routing/switch table explosion; (2) Inaccurate prediction: Chaotic orbital maneuvers, random failures, and partial deployments in 4.1.2 are less predictable and limit prediction-based routing's correctness and responsiveness. Moreover, every satellite should locally load these new FIBs upon snapshot changes, which is vulnerable to transient global routing inconsistencies and thus black holes or loops.

5. Requirements of Addressing in Space-Terrestrial Network

Except from the basic properties like clusterability, network addressing in space-terrestrial network should also meet the following requirements:

5.1. Uniqueness

In integrated space-terrestrial networks, each user’s L2/L3 address should be globally unique. This property calls for address allocation and duplicate address detection mechanisms.

5.2. Stability

Each terrestrial node’s address should stay unchanged despite LEO satellite mobility and Earth’s rotations. With this property, location-based routing will be more stable, avoiding routing convergence caused by the high dynamics of integrated space-terrestrial network. The stability of the address also reduces the impact on users’ network services.

5.3. Locality

For any two users or satellites, if their addresses are closer, their actual physical distances should also be closer. Locality not only guarantees the unified logical and physical locations, but also simplifies the design and implementation of location-based routing.

5.4. Scalability

The address space should scale to numerous terrestrial nodes and LEO satellite mega-constellations. Hierarchical addressing will be more scalable. By organizing the entire network into hierarchical routing domains, hierarchical addressing can localize topology/routing changes inside each domain, thereby facilitating the scaling to extensive space-terrestrial networks.

5.5. Efficiency

The addressing of integrated space-terrestrial network should be spatially compact and computationally lightweight to process. It should ensure consistent cyber-physical locations, thus easing physically shortest paths without detours.

5.6. Backward Compatibility with Terrestrial Internet

The addressing of integrated space-terrestrial network should be compatible with state-of-the-art terrestrial network addressing. For example, it should be compatible with the standard IPv6 addressing formats and facilitates inter-networking to external networks without modifying terrestrial infrastructure. For backward compatibility with IPv4, we recommend adopting a 4over6 transition for integrated space-terrestrial networks.

6. IANA Considerations

This memo includes no request to IANA.

7. Security Considerations

The present memo does not introduce any new technology and/or mechanism and as such does not introduce any security threat to the TCP/IP protocol suite.

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