×Grid: A Location-oriented Topology Design for LEO Satellites

Joseph McLaughlin
jmclaug2@uoregon.edu
University of Oregon

Jee Choi
jeec@uoregon.edu
University of Oregon

Ramakrishnan Durairajan
ram@cs.uoregon.edu
University of Oregon

ABSTRACT

The high frequency at which handoff occurs between interconnected low-earth orbit (LEO) satellites pose a significant challenge in successfully implementing a satellite-based global Internet service. This is primarily due to the fact that LEO satellites only remain in range for approximately 3 minutes at a time, resulting in client state handoffs occurring 20x per hour. In this paper, we propose ×Grid, a topology design for LEO satellites that leverages the predictability of satellite positions. Our design is *location-oriented*, allowing handoff to occur between satellites that share interconnected satellite links (ISLs). This approach contrasts with the current conventional topology designs, which require propagating client state information throughout the network and performing unnecessary computations to determine the appropriate return node for packets. Through simulations, we demonstrate that the ×Grid reduces the number of ISL hops between major population centers and decreases the occurrence of dropped messages during handoff compared to conventional topology designs.

1 INTRODUCTION

Recent advancements in satellite technology, combined with streamlined satellite launch processes pioneered by companies (e.g., SpaceX, Kuiper), have revitalized the research focus on satellite networks for both commercial and research applications. These networks would exist in low-earth orbit (LEO) at a height of between 500–1,500 km above the surface of the earth and with an orbital period of at most 100 minutes. These constraints mean LEO satellites move at approximately 7,500 m/s and are within the operational range of terrestrial ground stations for only minutes at a time. Their low altitude when compared with other satellite classes, e.g., geostationary orbit (GEO), minimizes the latency (e.g., round-trip times or RTTs) in over-the-air communication which can be considerable at greater altitudes. To compensate for their low orbit, satellites are organized in constellations where any number of satellites co-exist in coordinated patterns.

Several companies have recently filed constellation plans with the US FCC including SpaceX with two separate filings, one for 4,408 satellites, a second for 30,000 satellites, and OneWeb with 47,844 satellites [1–3]. Researchers from several domains have explored the impact that these constellations could have on astronomical observations and collision likelihood [11, 18]. We observe that these filings have become the basis for much of the contemporary research into interconnected LEO satellite networks for global Internet.

Several recent research efforts have supported our observation regarding the feasibility and challenges of interconnected LEO satellite networks, primarily based on a common network topology derived from SpaceX FCC filings. For example, [12] discusses how return packets may not route to the correct node if the satellite is not longer overhead. The authors use Dijkstra's algorithm on a model SpaceX network adapted to the estimated RTT to select the appropriate path [9]. However, RTT would have to be known for every route and at every time a packet was sent, as the physical orientation of the network evolves in space and in time. This also incurs additional computation that would likely occur on the (satellite) nodes themselves, draining precious resources, such as energy and computational power.

Since then, other researchers have explored the feasibility of interconnected satellite networks. [13] questioned the viability of Interconnected Satellite Links (ISLs), while [4] further investigated the duration of handoff sessions. Furthermore, studies have examined potential applications of LEO satellite networks, such as edge computing, load balancing, and network security [7, 8, 17, 20]. Additionally, models have been developed to characterize satellite features like latency, traffic, and routing [10, 16]. It is worth noting that *all* these studies have relied on the conventional SpaceX topology, which we believe does not fully leverage the unique

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Element	Altitude	Inclination	Number of planes	Satellites per plane	Total
1	550	53.0	72	22	1584
2	540	53.2	72	22	1584
3	570	70.0	36	20	720
4	560	97.6	6	58	384
5	560	97.6	4	43	172

Table 1: SpaceX April 2020 FCC Filing.

aspects of LEO satellites and incurs significant computational overheads.

To address these challenges, we introduce ×Grid, a novel topology design that takes advantage of the predictable nature of satellite movements and allows handoff to occur between satellites that share ISLs. At the core of ×Grid is the insight that the future positions of satellites are predictable—a significant departure from state-of-the-art. While previous studies (e.g., [12]) have also acknowledged this aspect, as noted above, their approach primarily relies on a SpaceX-based topology rather than fully leveraging the predictability of satellite positions. By adopting a "location-oriented" approach, ×Grid accommodates the satellite motion relative to a ground station (GS). This location-oriented design eliminates computational overheads in determining the return node, forming the basis for our low-cost routing scheme in ×Grid. Finally, SpaceX's recent progress in deploying LEO satellites equipped with laser communication terminals to establish inter-satellite links (ISLs), providing the necessary technology for the realization of ×Grid. As shown in [13], laser-based ISL is anticipated to deliver exceptionally low-latency performance (e.g., 10 ms).

We evaluate the efficacy of ×Grid by building a custom simulator using PyEphem [19] and TCP sockets to model the ×Grid network alongside a conventional network design. We also simulate the routing scheme supported by ×Grid. We demonstrate with simulation that ×Grid alone reduces the number of hops between major population centers, and that the routing scheme eliminates packet drops during client handoffs.

2 BACKGROUND AND MOTIVATION

In this section, we provide a brief background on satellite orbit geometry, followed by the assumptions we make in our work. We also review the limitations of the state-of-the-art.

2.1 Satellite orbits

The classical, *keplerian* model for satellite orbits is constructed from six parameters. We can eliminate some of these parameters for our purposes by assuming a near circular orbit. The *eccentricity*, e, describes the shape of an orbit, where $1 < e$ is a hyperbolic orbit and $0 < e < 1$ is an elliptical orbit. By fixing a small eccentricity ($e - \epsilon = 0$), we only consider the parameters describing the orbital plane, i.e., the path around the earth in which satellite travels.

- i – inclination, the angle between the path of the satellite and the equator.
- ω – right angle of the ascending node, the longitude where the orbit crosses the equator.
- θ – anomaly, a value describing the location of the satellite in its orbit.

Here, we exclude mean motion (revolutions per day) and altitude which are dependent upon each other. Instead, we fix mean motion such that it yields the appropriate altitude.

2.2 Constellations

Interconnected satellite networks are characterized by two common constellation designs. The first contains several concentric polar orbital planes (i.e., $i = 90°$) equally spaced around the equator. This design is notable for its vertical seam where the two adjacent planes have a high relatively velocity. It is expected that inter-satellite communication will be uniquely challenging if not impossible at this seam.

The second contains several concentric orbital planes with non-polar orbits $i < 90°$. This design concentrates more satellites in equatorial regions, i.e., population centers. FCC filings from SpaceX and OneWeb utilize delta pattern constellations and have thus become the standard when studying these networks.

SpaceX, OneWeb, and Kuiper have filed with the FCC to launch global-scale satellite constellations. Each of these constellations are comprised of several orbital shells that can each be considered a distinct delta configuration at different altitudes. It is likely that a single orbital shell will be insufficient to serve the global population thus the various orbital shells serve as redundancies. In practice, it will be operative for the ground station to select the shell with the least traffic as inter-shell ISL communication is likely infeasible. For our work, we consider a single orbital shell in a single FCC filing from SpaceX. The entire filing is listed in Table 1. To model our network, we consider only element 1 which we utilize as a backbone network connected to fixed GS terminals. We intend to explore others as part of future work.

2.3 Limitations of +Grid

The term "+Grid" was coined to formalize the delta constellation network topology used in the study of satellite networks [5]. This design is illustrated in Figure 1 with a staggered θ value. In +Grid, inter-satellite links (ISLs) are established between the leading and trailing satellites within the same orbital plane and between satellites on adjacent orbital planes. We refer to these as θ-neighbors and ω-neighbors, respectively. This configuration has become the default and state-of-the-art choice for modeling satellite networks. However, some researchers have demonstrated the limitations of +Grid and have proposed alternative configurations to reduce traffic and improve latency [5].

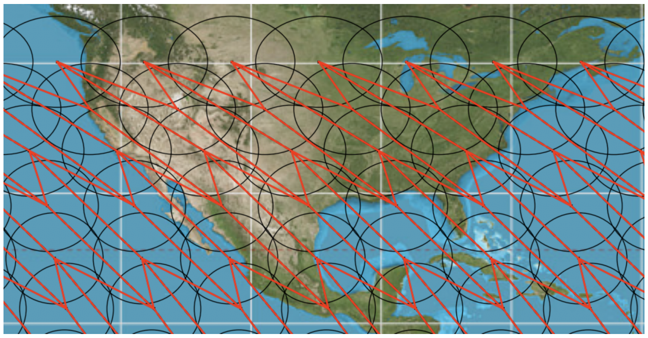

Figure 1: A staggered +Grid configuration plotted on an equirectangular projection. Connecting lines denote ISLs, circles denote satellite field-of-view. Direction of motion follows the connecting lines from top left to lower right. Ascending portions of the orbits are excluded. Propagated using pyephem [19].

The *staggered* +Grid construction offsets every other orbital plane to achieve a more consistent coverage geometry. This construction selects adjacent θ-neighbors and ω-neighbors for establishing ISLs. Intuitively, handoffs[1] could occur between adjacent satellites within the same plane. However, the field of view (FOV), defined by a 40° angle of elevation, does not overlap, necessitating handoffs between different orbital planes. Figure 2 illustrates this concept, oriented parallel to the motion of the satellite orbit (parallel to the orbital plane). In this figure, our orbit is inclined at 53°, causing the line connecting ω-neighbors to be non-perpendicular to the orbital plane, resulting in a jagged line due to the staggered construction. We observe that the handoff path can vary based on the ground station's location within a satellite's FOV. Furthermore, we notice that handoffs always occur between orbital planes and, in some cases, traverse multiple planes. Additionally, only 1/4 of all handoffs take place between satellites connected by ISLs.

3 DESIGN AND OVERVIEW OF ×Grid

In this section, we propose an alternative topology, ×Grid, which simplifies client handoff procedures using *pyephem's* kelperian orbit models [19], overcoming the limitations of the +Grid described above. Additionally, we describe a low-cost routing scheme atop ×Grid which selects the correct return node without computing the state of the network.

3.1 Key Insight

We recognize a pattern in Figure 2, namely for a satellite in a staggered delta pattern, handoff will occur between

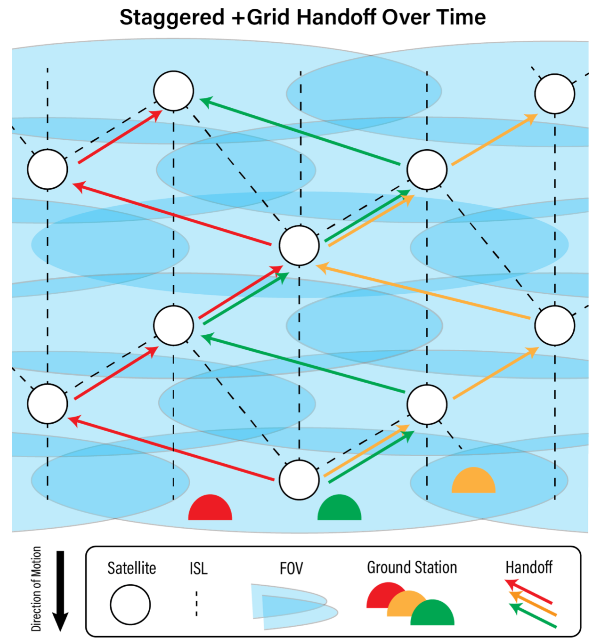

Figure 2: Illustration of staggered +Grid handoff. Due to a shallow FOV, the handoff flow does not map to the network topology, requiring multiple hops at most handoff. Orbital planes are compressed making the satellite FOV appear wide.

the trailing satellite two ω-neighbors away or the trailing satellite of the opposing ω-neighbor. In the latter instance, this alternates between the adjacent ω-neighbor and the ω-neighbor's θ-neighbor. This is illustrated in Figure 2 along the leftmost handoff path, where the second handoff occurs between ω-neighbors where there is a link, but the third handoff occurs between the ω-neighbor's θ-neighbor where there is not a link.

Using this information, we develop ×Grid, a network topology based on ISL for delta constellations, guaranteeing seamless handoff between satellites linked by an ISL. We project ×Grid onto a equirectangular map in Figure 3. For clarity, only the descending portions of the orbits are shown; the full constellation has ascending orbits that trail from the bottom rise from the southwest to the northeast.

We illustrate how ×Grid handles handoff in Figure 4. From this figure, we see that all GSs within the FOV of the current satellite are within the FOV of at least one ISL link. This is patterned, and remains true for all subsequent satellites. The handoff link can be determined by whether the node is above or below the orbital plane (right or left in Figure 4). This can be determined for future nodes, mapping the logical handoff path ahead of time.

3.2 Location-oriented Routing Scheme

Having designed a topology that harnesses the predictability of satellites' positions in the future, we now focus on a

[1]Handoff refers to a state transfer between two devices to maintain an uninterrupted connection and is necessary in most wireless networks. In LEO satellite networks, handoff refers to the migration of ground station state between satellites, and typically occurs on frequent and regular intervals.

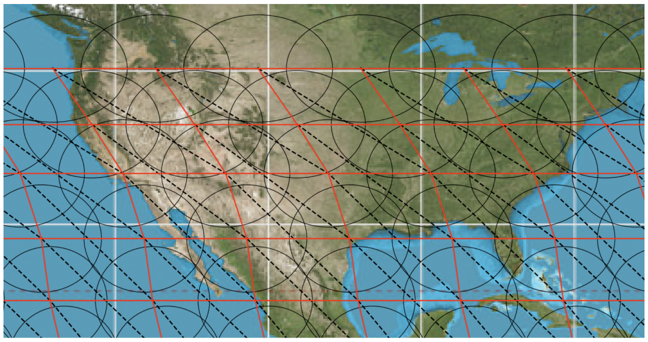

Figure 3: A ×Grid configuration plotted on an equirectangular projection. Solid lines denote ISLs, circles denote satellite FOV. Dotted lines denote orbital planes. Direction of motion follows orbital planes from top left to lower right. Ascending portions of the orbits are excluded. Visually, ×Grid orients half of ISLs parallel to the equator, where staggered +Grid (Figure 1) routes longitudinal traffic diagonally.

routing scheme atop the topology to select the correct return node without incurring computational overheads. Concretely, ×Grid allows us to consider a routing scheme that takes advantage of the guarantee of handoff occurring between connected satellites:

(1) Outgoing messages from ground stations are forwarded to the future handoff node, i.e., the forwarding node.
(2) Outgoing messages are tagged with the address of the edge node and the forwarding node.
(3) Incoming messages are routed through the forwarding node and back to the edge node.
(4) If the ground station is no longer in the FOV of the edge node, the forwarding node delivers the message.

This scheme ensures that the address of returning packet is known for the remaining of connectivity of with current node and the duration of connectivity of the future handoff node. For LEO satellites in this configuration handoff occurs approximately every 3 minutes. This scheme guarantees the return node is known for at least 3 minutes, though RTTs > 3 minutes would repeat this scheme using the selected forwarding node as the edge node. This allows for any arbitrary route between the forwarding node and the packet's destination as long as the route terminates in under 3 minutes.

4 EVALUATION

We built a custom simulator using PyEphem [19] with TCP sockets to measure the efficacy of our scheme during a handoff event. Our simulations consider five nodes: an echo server, three satellite nodes, and a ground station node. To approximate communication between a ground station and multiple satellites, we open a socket with each satellite from the ground station; the ground station sends its outgoing messages to every connected satellite and the satellite nodes

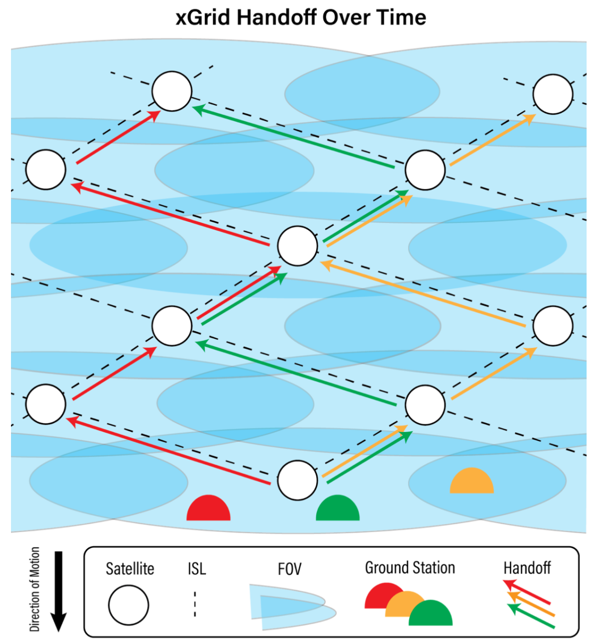

Figure 4: Logical illustration of ×Grid handoff. Handoff flow maps directly to the network topology despite a shallow FOV, requiring one hop at every handoff. Orbital planes are compressed making the satellite FOV appear wide.

themselves reject or accept the message. TCP is also used by the Hypatia software library [16] to model these networks.

We implement two routing schemes: **(1)** a simple routing scheme that immediately swaps connectivity between satellites at a given epoch for both +Grid and ×Grid and **(2)** an implementation of our proposed location-oriented routing scheme for our ×Grid. The simple scheme routes a message from the source node to its destination and if handoff occurs prior to a response it is routed inccorectly.

To approximate communication between destinations we find the average number of ISLs between locations and add a fixed a latency in the echo server. We add 2 ms of latency for every ISL and 10 ms for every GS-to-Sat and Sat-to-GS link. These valued approximate the latency of associated physical systems that are commonly used [12]. When determining the number of ISL hops for the simple scheme we consider both +Grid and ×Grid.

4.1 Results

We simulate three paths, Los Angeles to New York City, Seattle to Miami, and San Francisco to Washington D.C. Table 2 shows the average number of ISLs between locations. We fix the latency of the source to $2\times(2\text{ms})\times k+(10\text{ms})\times 3$ where k is the number of hops. As we are only seeking to characterize the efficacy during handoff, we evaluate the our network simulation over 10 seconds, executing client handoff half way through. Table 3 shows the total number of TCP TCP messages sent in each scheme. We find that ×Grid significantly reduced the number of hops and hence increased the total number of messages we sent. In both the schemes (+Grid and ×Grid) we observed that an average of three messages were routed back to the incorrect satellite after handoff occurred. We observed that no packets were dropped using our location-oriented routing scheme, while an average of 8 packets were lost in the simple routing scheme during the 10 s handoff epoch. In one case, the location-oriented scheme performs worse than the simple ×Grid scheme. This can be explained by the additional two hops via the forwarding node that the simple ×Grid scheme lacks.

Path	+Grid ISLs	×Grid ISLs
LA to NYC	12	6
SEA to Miami	7	7
SF to DC	12	4

Table 2: Average ISLs between locations in varying network topologies.

Path	+Grid	×Grid only	×Grid + LO routing
LA to NYC	174	245	211
SEA to Miami	197	201	208
SF to DC	171	223	238

Table 3: TCP messages sent during a fixed (10 s) period for the conventional +Grid model, an ×Grid with a conventional routing, and an ×Grid model with location-oriented routing.

5 DISCUSSION

The results of our network study suggest that ×Grid alone reduces the number of ISL hops by an average factor of two. This is explained by a simple property of ×Grid, that being that the second ω-neighbor is selected over the first. Traffic more commonly travels longitudinally so we benefit by reducing the short ISLs that span across longitude in +Grid. Additionally, the ×Grid topology more evenly distributes ISLs over both latitude and longitude when compared to +Grid or staggered +Grid.

5.1 Choosing the Forwarding Node

The choice of handoff node, i.e., forwarding node in the routing scheme, would be trivial for fixed GS's with a known position that are firmly within the FOV of a single satellite. This is illustrated by the red GS in Figure 4. However for satellites under the FOV of two candidate handoff nodes, we would likely select by the strong RF signals of the candidates. Juan et al. [14] implement a similar regimen for 5G intra-satellite RF handoff. In some of these less obvious cases, the connection duration may be smaller if the GS passes through the edge of the satellite's FOV. In these instances it may be necessary repeat the routing procedure on the handoff node to gain an extra forwarding node. This scheme assumes a GS has already selected a suitable satellite link, but for every shell there are typically 2 candidate links for every GS (ascending and descending), this work does not address that issue.

5.2 A Persistent Challenge

The problem of handoff in these has yet to be well studied or thoroughly characterized, despite the growing amount of application research in the area. There has been significant work in related networks such as LTE/5G communication [6, 14] and small satellite networks [15, 21]. Our simulation considered communication between two fixed ground stations at a short epoch around the time of handoff, though a larger network with several GS links could further illuminate the issues of the conventional +Grid paradigm.

6 SUMMARY

We presented a network topology for global constellations of interconnected LEO satellite internet networks that supports a low-cost, location-oriented routing scheme. We demonstrate that ×Grid has fewer hops between common routes than conventional +Grid configurations. The ×Grid topology orients ISLs to the direction of motion, allowing client state information to be handed off to direct neighbors. Additionally, the routing scheme atop ×Grid facilitates the selection of appropriate return node knowing only the estimated RTT. We demonstrate efficacy of ×Grid and the routing scheme through simple simulations. In this simulation we show that ×Grid alone delivers approximately 20% more packets due to reduced latency in the number of hops, and that our routing scheme performs similarly to plain ×Grid while never dropping packets due to handoff.

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