A Roadmap for the Democratization of Space-Based Communications

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ABSTRACT

The Internet today is owned, managed and controlled by a heterogeneous mix of autonomous systems. As a result, there's no one single entity that holds the "Internet kill switch". However, for emerging Low-Earth Orbit satellite Internet services, few gatekeepers control access globally, going against the fundamental principle of the Internet as a distributed and decentralized system. While satellite Internet remains a small part of the Internet today, it is growing exponentially and is often the only connectivity option for regions that are sparsely populated, experience political instability, or are prone to natural disasters that are likely to damage equipment. We first discuss why the satellite Internet world is ripe for monopolies, global ownership, and vertical integration. We then lay out OpenSpace, an architectural roadmap for a more open and heterogeneous satellite Internet paradigm, where many players build, launch, and manage satellites that communicate, to collectively deliver a reliable Internet service. We also discuss several open problems and research challenges in making satellite Internet more interoperable and heterogeneous, facilitating accessibility for big and small firms alike.

CCS CONCEPTS

• **Networks** → *Network design principles*; • **Hardware** → *Communication hardware, interfaces and storage*; • **Computer systems organization** → *Distributed architectures*.

HOTNETS '24, November 18–19, 2024, Irvine, CA, USA

ACM ISBN 979-8-4007-1272-2/24/11
https://doi.org/10.1145/3696348.3696866

KEYWORDS

Satellite Networks, Distributed Systems, Communication Interfaces, Network Design

ACM Reference Format:
Veronica Muriga, Swarun Kumar, Akshitha Sriraman, and Assane Gueye. 2024. A Roadmap for the Democratization of Space-Based Communications. In *The 23rd ACM Workshop on Hot Topics in Networks (HOTNETS '24), November 18–19, 2024, Irvine, CA, USA.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3696348.3696866

1 INTRODUCTION

Satellite Internet powered by large constellations of Low-Earth Orbit (LEO) satellites, such as Starlink [5] and OneWeb [1], have revolutionized access to the Internet. However, in the current global satellite communications landscape, a few players collectively have disproportionately large control over service [17]. In particular, Starlink is presently the only viable Internet option for many regions of the world, especially for remote communities and parts of the developing world where cellular infrastructure is not commercially viable [27]. It has frequently been the only option for communities in politically unstable situations, or those in areas affected by natural disasters [10], leaving Internet access in these regions in the hands of a single individual and company.

For the rest of the Internet, however, the spirit of decentralization and distributed control, ownership, and management have long been the guiding principles. Thus, by design, no single individual/company/government truly holds the global "Internet kill switch." Rather, the Internet consists of autonomous networks that voluntarily link together to provide connectivity [6]. A major contributor to this decentralization has been the development of open protocols, layers, and interfaces between diverse technologies allowing for them to inter-operate while being independently managed, such as BGP [9]. Indeed, this form of democratized inter-operable systems has been the hallmark of various networks [7, 14].

Space-based Internet has evaded such standardization and collaboration, primarily due to the huge up-front investment and high barrier to entry. For example, Starlink invested billions of dollars up-front and launched over 6000 satellites before offering any meaningful global service [25]. In traditional networks, a small town ISP or regional cellular service could exist and then aspire to organically grow its service area. However, LEO satellites have an all-or-nothing business model, where a constellation needs wide geographical coverage from the start to achieve reliable connectivity [22]. To this end, the whole constellation must be up and running for the satellite system to provide commercially viable connectivity. These constraints are driven by LEO satellite dynamics, where due to their altitude and speed, their range is limited relative to other higher-orbit satellites. This high bar for entry has led to the LEO satellite communications field being ripe for global monopolies rather than the heterogeneous mix of big and small businesses that serve the rest of the Internet. If unchecked, these technical and market forces will only worsen, leading to even more domination of the LEO satellite connectivity market by a small number of firms that gate-keep Internet access.

This paper presents *OpenSpace*, an architecture for an open and inter-operable LEO space-based Internet service that is owned, controlled, and managed by distributed entities and can be scaled to offer reliable service globally. Unlike the presently exclusive, vertically-integrated, single-company-owned LEO Internet services, *OpenSpace* proposes networking satellites and ground platforms owned by a heterogeneous group of small, medium, and large firms. While these firms may individually not be capable of offering a connected global network, we envision connecting their satellites as well as ground infrastructure with communication links that together results in global coverage. *OpenSpace* designs a collection of interfaces and standards to enable such communication and coordination. We emphasize that *OpenSpace* is not a deployed system but simply an architectural roadmap that includes several open questions towards the design of a more open space-based Internet, with the objective of spurring discussion within the HotNets community on our role in shaping that future.

The rest of this paper discusses various design decisions in shaping *OpenSpace*. Section 2 addresses the technology and systems building blocks, such as the choice of spectrum and physical-layer technologies for communication. We emphasize that it is critical for disparate players to communicate effectively along both Inter-Satellite Links (ISLs) and ground infrastructure. In the current landscape, this communication is challenging without access to shared spectrum, interoperable network interfaces, and physical-layer protocols. Therefore, *OpenSpace* must have access to a shared ground infrastructure network that caters to the broadest possible class of overhead satellites with the necessary higher-layer protocols for interoperability and authentication.

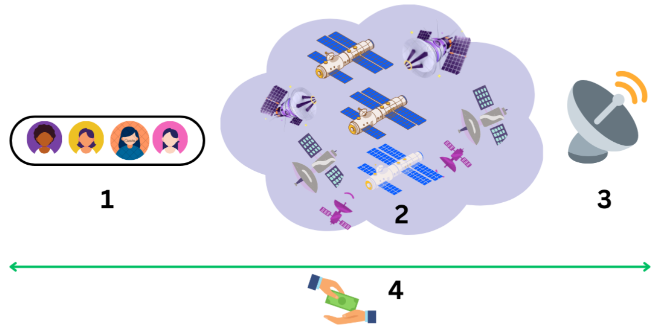


Figure 1: *Overview of* OpenSpace.
(1) We study how independent satellite providers can collaborate to connect users, initiate satellite pairing and handover.
(2) We discuss interoperability between heterogeneous spacecraft, including enabling inter-satellite communication, MAC protocols, and routing in a rapidly changing network topology.
(3) We discuss ground infrastructure.
(4) We present end-to-end cost models for OpenSpace.

In Section 3, we discuss *OpenSpace*'s pricing and economics, accommodating the proposed distributed ownership model, and with an eye on the disparate entities owning satellites and ground infrastructure. In Section 4, we discuss the performance of a system that has distributed ownership and contains satellites and ground-based systems that offer heterogeneous capabilities. We also study the critical mass needed for such a system to achieve global coverage and reliable performance through simulations, while offering pathways for incremental deployment. We conclude in Section 6 with a call to action to the research community to address important open questions towards enabling a truly democratized space-based Internet.

2 TECHNICAL DESIGN

We describe *OpenSpace*'s overall technical design and how it contrasts with that of a traditional and monolithic global LEO satellite firm. A typical LEO satellite network consists of ground users, satellites, ground stations, and the links between these entities (ground-to-satellite, satellite-to-satellite, and satellite-to-ground). For monolithic satellite providers working with standardized spacecraft, they can design these system components without concern for interoperability or standardization of individual blocks.

***OpenSpace*'s approach:** Unlike monolithic satellite systems, *OpenSpace* is built on interoperability between heterogeneous spacecraft, each launched by different players. Facilitating a competitive space communications landscape consisting of small and medium-sized satellite providers alongside mega-constellations requires collaboration between smaller firms, such that together they can provide comprehensive coverage to larger regions, even working towards global coverage. Without meaningful collaboration, many smaller satellite networks would simply have coverage for a patchwork of regions around the globe rather than continuous global coverage on their own. Furthermore, some satellites owned by a given firm may be completely disconnected from the rest of their infrastructure for significant periods of time as they orbit the Earth, should they choose not to collaborate with other players, therefore cutting them off from essential ground infrastructure that they require to provide connectivity to their users.

Facilitating interoperability among heterogeneous satellites requires building a cohesive network out of satellites that differ in energy budgets, hardware specifications, and missions, such that they work together to form an efficient and financially-viable routing network in space, to deliver packets between terrestrial users. The rest of this section describes the various solutions needed in enabling such an architecture across the network stack.

(1) Enabling standardized physical and link layers. First, *OpenSpace* providers must adhere to an open and standardized communication protocol for all spacecraft in the system to enable interoperability. This includes both standardized communication hardware, ISLs, and associated lower layers of the network stack. Unlike monolithic deployments, these standards must accommodate satellites with a wide variety of orbits and form factors.

(2) Enabling heterogeneity-aware routing. Next, *OpenSpace* must factor in the diversity of route ownership and technical ISL specifications that is present in a heterogeneous network. Inter-satellite communication in a monolithic network can be designed for standardized hardware whose exact specifications are known beforehand, and a common communication protocol can be defined well in advance given these known hardware specifications. However, in *OpenSpace*, packets can traverse satellites owned by different firms several times prior to being received on the ground. These links may differ based on physical layer specifications (RF or optical links), predefined agreements between providers, and ground station conditions. Given these complexities, satellites need to make quality-of-service-aware routing decisions that take into account the nature of the network, including available bandwidths of the ISLs. To address these requirements, we present methods to address hardware-level compatibility between spacecraft, communication protocols to standardize inter-satellite routing and handovers, and routing protocols that factor in satellite heterogeneity.

2.1 Standardizing Physical Links

Standardizing Inter-Satellite Links: One of the first steps in enabling communication between heterogeneous satellites is standardizing Inter-Satellite Links (ISLs). Differences in size, power capabilities, and inbuilt technology among *OpenSpace* satellites influence the type, number, and quality of their ISLs. To facilitate such links with a low entry-barrier, there needs to be a minimal hardware requirement for a satellite to join *OpenSpace*, as well as a protocol to allow satellites to both broadcast their presence, and share their ISL specifications.

Both RF and optical technologies have been used for inter-satellite communication in previously launched missions to LEO [23]. RF-based links have utilized the S- and UHF-bands, with these high frequencies offering the advantages of increased bandwidth capabilities and smaller, lighter transceivers. These high frequencies however come at a higher power cost. Laser technology offers a higher throughput than RF, with lower energy cost. However, they are more expensive due to their relative novelty in the market, estimating to cost about $500,000 per terminal and occupying 0.0234sq.m of volume and at least 15kg of weight [26]. These are infeasible specifications for smaller spacecraft that are lower in cost to launch and more accessible for small players.

To accommodate such small satellites, *OpenSpace* advocates for a common inter-satellite link paradigm, where satellites should be able to communicate through either RF signals or laser technology, depending on the specifications and current load of the spacecraft involved. We specify that *OpenSpace* satellites must permit RF-based communication links at a minimum and optionally also support standardized laser-based links, if laser terminals are part of the satellite's specifications. Given that S-band and UHF-band ISLs have been tried and tested in various missions [23], RF-based ISLs in *OpenSpace* can use the same spectra. The narrow transmission beam of laser links poses unique challenges in accurate data transfer. Pointing, acquisition, and tracking methods developed in prior work [16, 29] can be adapted for optical ISLs to maximize their throughput. We discuss the synchronization of ISL specifications during satellite association in section 2.2.

Prior research in Media Access Control (MAC) schemes for satellite constellations have shown that CSMA/CA allows for flexibility in synchronization between satellites, however is prone to higher overhead and corresponding larger latency due to Inter-Frame Spacing and backoff window requirements [23]. We leave the development of MAC methods more suitable for real-time communications to future work.

Establishing Inter-Satellite Links: Laser-links between satellites, even if available, are directional, which means that the satellites once paired, can re-orient (i.e., spin) to maintain a reliable link. While the information on when and how to spin is available up-front in monolithic networks, this information must be discovered on the fly in a heterogeneous network. All satellites in *OpenSpace* are at a minimum capable of RF-based inter-satellite connectivity, making the RF platform the best way for a pair of satellites to associate with each other. Furthermore, RF antennas are capable of broadcasting, which is ideal when the exact position of antennas is not known beforehand. When a satellite receives a beacon from another satellite, it can initiate pairing by broadcasting a pair request which contains its technical specifications (for example whether optical links are supported, and the exact position of its laser diodes) enabling laser beamforming if the two satellites have the capability and available bandwidth for optical links. The two satellites can then orient themselves such that their communication terminals are well positioned for data transfer.

Ground Infrastructure: We envision *OpenSpace* leveraging shared ground infrastructure, composed of distributed ground stations that have a reliable backhaul connectivity to the Internet. These ground stations operate on standardized radio links, much like those used for ISL as specified above, except for specific implementation details such as the exact spectrum bands used for ground uplink and downlink, which may differ due to factors such as atmospheric attenuation. Satellite providers today typically conduct ground communications in the Ku-band, which has been licensed in the US for satellite broadband companies [18]. *OpenSpace* providers can build ground stations and charge other providers for gateway services using methods discussed in section 3. These ground stations build on the pay-per-use ground-station-as-a-service model, much like today's AWS Ground Station [2], except that in *OpenSpace* ground stations could be owned by independent entities, which may price their services differently. Users in remote areas, where the nearest ground station could be several satellite hops away, may contend with lower performing Internet connectivity. However, we hope that the inroads into space connectivity facilitated by *OpenSpace* will lead to local providers in remote areas bringing ground station services closer to the remote user.

Standardizing Satellite to Ground Links: The specific frequencies that satellite-to-ground station transmissions or satellite-to-user transmissions will use is dependent on the region of operation, and satellites in the *OpenSpace* constellation should ensure their transciever radios have the ability to function over a wide range of frequencies to enable flexibility in the range of operational frequencies. A MAC protocol for satellite-to-user links is necessary, since it is likely that a single satellite will serve multiple ground users simultaneously. There are several promising options for such a scheme. For instance, existing satellite providers have employed OFDM in satellite-to-ground links [18], and this choice has shown to work well in efficiently utilizing the spectrum while minimizing interference with other users.

2.2 Enabling Network Connectivity

In this section, we study the operational elements needed to establish and maintain network connectivity between multiple end-users, ground infrastructures, and satellites.

Enabling Routing in *OpenSpace*: *OpenSpace* must support a diverse set of users connecting to multiple service providers that have access to satellites and ground infrastructure. Unfortunately, this makes connecting and routing data to/from users fairly complex. Unlike current vertically-integrated satellite networking systems whose routing protocols remain largely proprietary [15, 20, 28], not all satellites in the network are homogeneous. Further, routing solutions in many other mobile contexts such as mobile IP [30] require significant latency overhead for connection establishment and authentication.

Perhaps the closest approximate parallel to routing in *OpenSpace*'s context is to imagine it as a cellular service where a high degree of roaming occurs. Each end-user signs up for their own local Internet Service Provider (ISP) who have their own satellites launched, but "roams" when satellites owned by other ISPs overhead remain the best option for connectivity. However, unlike the cellular context, where roaming is occasional and occurs whenever the user exits a certain geographic region, in *OpenSpace* "roaming" may be quite rampant, since the best (or even only) satellite within range of the user may often not belong to their own ISP.

OpenSpace's approach to resolve this relies on the well-known orbital paths of satellites. For a user at any given geographical region, the set of overhead satellites and the times at which they will be available are entirely predictable. Even presently, the radar-tracked orbital paths of satellites are well-known and readily available on public websites [3, 8]. This means that all firms that contribute satellites to *OpenSpace* have a full public view of the topology of the entire network, including how it is likely to evolve over time. This significantly simplifies routing, given that the topology of the satellite network is both known and public, allowing for pre-computation of static routes between any set of satellites and fixed ground infrastructure.

For providers who own satellites with diverse technical specifications (for example some have laser terminals while others have RF terminals), using these known orbital configurations enables suitable distribution of satellites to meet the needs of a diverse user base, while also making it possible to preemptively adjust their QoS guarantees. For example, the provider can ensure the presence of laser-link-enabled spacecraft to handle traffic from users with more stringent QoS requirements. At the same time, in regions where routing paths will be bottlenecked by bandwidth-limited links, the provider can adjust advertised plans to reflect these looser QoS guarantees.

Such a proactive routing protocol will be effective for a beginner system. However, as more players join the network and the system scales both in size of the user base and infrastructure, there will be a need for routing protocols that take an end-to-end approach to determining a routing path, considering factors such as queuing delays at ISLs and at the ground station. In particular, although the locations of satellites can be determined in advance since their orbital paths are known, the cost of a path cannot be fully predicted since ISL congestion cannot be anticipated, and even ground station conditions may affect the cost or QoS guarantees of a link. For example, in the event that a ground station owned by a particular satellite provider is experiencing high traffic, that ground station may prioritize traffic coming from its users, and may place higher tariffs on 'visitor' traffic. In addition, given the power cost of executing rotations for ISLs and establishing those links, satellites may have power consumption constraints that limit the number of ISLs they can establish and the size of data transfers they can facilitate [12], increasing the complexity of proactive routing protocols.

Next, we discuss the association procedure for users, and give an overview of a potential satellite handover scheme.

User Association: Users in the satellite network are designed to simply associate with the available overhead satellite that supports *OpenSpace*. To make its initial selection of satellite and enable association at the link layer, all *OpenSpace* satellites advertise their presence via standardized periodic beacons that include orbital information. The user can evaluate received beacons to identify which satellite is in closest range, and request to associate with it. Upon initial association, the user device identifies its home ISP and proceeds to authenticate with it through a standardized protocol such as RADIUS [24]. This means that an association request from a user has to be authenticated by their home satellite provider, and this can be done through ISLs. The user's home provider should assign the user a digital certificate to inform other satellite providers that the user has been authenticated by their home network. After successful authentication, the user is fully associated with the satellite.

If a user changes their location such that they are no longer in the same physical region, they will have to go through the initial association and authentication process again. We note that while user positions may change, their speeds are several orders of magnitudes lower than that of satellites, meaning that re-authentication is a rare event relative to satellite handoffs. We discuss the design of a fast and smooth satellite changeover process below.

Satellite Handovers: Given their proximity to the earth relative to medium and geo-stationary satellites, LEO satellites provide lower latency but also only provide coverage to a small area of the earth's surface. They also travel at high speeds to maintain their orbit, meaning that frequent handovers between satellites is necessary to provide continuous connectivity. Starlink achieves continuous connectivity through sheer abundance, with satellite handover occurring every 15 seconds [13], necessitating the presence of many satellites over a given region.

In *OpenSpace*, the satellite uses advance knowledge of orbital trajectories to pick a successor, i.e., the satellite that it will hand over its connection to the ground user to, once the satellite is out of the ground user's line-of-sight. The satellite communicates specifics of its successor to the user, who establishes a new session with the successor. This eliminates the need run authentication and association protocols again, ensuring a smooth handoff.

3 COST MODELS

Manufacturing and launching satellites poses a significant cost, due to cost of materials, the expertise required for designing and building hardware and software systems, paying for licensing requirements, and launching and maneuvering satellites into the desired orbit [19]. As an example of licensing requirements, the FCC has proposed small satellite regulatory fees of about $12,145. These costs are all passed on to the user through the purchase and subscription costs. We investigate ways to minimize these startup costs for smaller satellite communications entities, exploring collaborations between different types of satellite missions as an alternative to independently sourcing capital, coming up with a more feasible and sustainable cost model.

Traditional cost models: The closest example of a heterogeneous distributed connectivity model that we can draw from is BGP, a standardized protocol that bridges independent Autonomous Systems (ASs) to provide routing paths for the Internet. The BGP cost model is a hierarchical relationship between different ASs which agree to route traffic through each other's infrastructure. Much of BGP involves providers (often larger ASes) charging customers (smaller ASes) with fees for bi-directional traffic, based on mutually agreed upon contracts.

Proposed cost model. While BGP offers a scalable, efficient and resilient routing mechanism and corresponding cost model, applying its architecture to *OpenSpace* is not straightforward, mainly because there is a less clear-cut separation between subsystems. For example, data may weave in and out of a user's home subsystem depending on the placements of its satellites in various orbits. This leads to a case where a *OpenSpace* subsystem could be both a provider and a customer, in BGP terms. Indeed, given this fluidity in routing protocols, the notion of a 'customer' and a 'provider' in BGP is not translatable to a meshed system like *OpenSpace* since the infrastructure that belongs to the different entities are mobile, even as the regions they provide coverage in persist between handovers.

Given this added layer of complexity, we propose a cost model building on the routing protocols discussed in Sec. 2.2, where a satellite home ISP has full knowledge and control of the topology of routes from its user through the network. This visibility allows for direct accounting and control of which other ISPs are engaged in the path between users and the Internet. The volume of traffic along this path is tracked by all parties involved to create an easily cross-verifiable account of the extent to which any given ISP's traffic was carried by the rest of the network. The precise monetary amounts that ISPs charge to carry said traffic is left to agreements between individual ISPs in *OpenSpace*, much like in BGP. The same model should can be used ground systems owned by individual providers. Ground stations should measure traffic through their gateways from users associated with different providers.

This cost model has the advantage of being adaptive to different technical specifications of the underlying satellite links, since awareness of hardware constraints of different satellites is inbuilt into the cost of a specific routing path. Since RF-based ISLs are likely to offer less bandwidth availability, these routes will likely be cheaper than laser-based ISLs, and will have looser QoS guarantees. In addition, this scheme allows for, and even promotes collaboration between providers. For example, if two providers realize they are routing similar amounts of traffic through each other's systems, and that their routing paths are heavily interdependent, they may decide to peer.

4 PERFORMANCE

In this section, we conduct a simulation study to evaluate the scale of *OpenSpace*'s deployments needed to offer reliable latency and coverage. Our objective is to understand how small initial deployments can be across a small number of initial players to achieve a starting point from which the system can scale, much like in the early days of the Internet.

The US Congressional Budget Office (CBO) estimates that 72 satellites in LEO, consisting of 12 satellites in 6 orbital planes at an inclination of 80 degrees, provides about 95% global coverage [19]. Iridium [4] fits within these estimates, comprising 66 satellites located at 780 km altitude at 8.4 degree inclinations in a Walker Star constellation [11]. Walker Star constellations are advantageous due to the relative simplicity in establishing ISLs both on the same orbital plane and adjacent planes, given the longitudinal distribution of satellites in the constellation. Given that Iridium's constellation provides global coverage, we use its specifications to demonstrate a hypothetical *OpenSpace* constellation of independently owned satellites and ground stations, illustrated in Figure 2(a). We use this simulation to show the cost and coverage benefits that satellite provider collaboration and interoperability can bring to a global user base.

We run a simplified simulation, fixing the user and ground station coordinates and randomly distributing satellites orbital paths. We then compute the shortest path between the satellite that picks up the user's signal, and the satellite that will relay that signal to the ground station, and use this path length to estimate latency. To get a realistic coverage estimate, we assume that if there is any overlap between a pair of satellite ranges, their effective coverage will be reduced to that of a single satellite- that is, we take the worst case where two satellites have completely overlapping ground coverage.

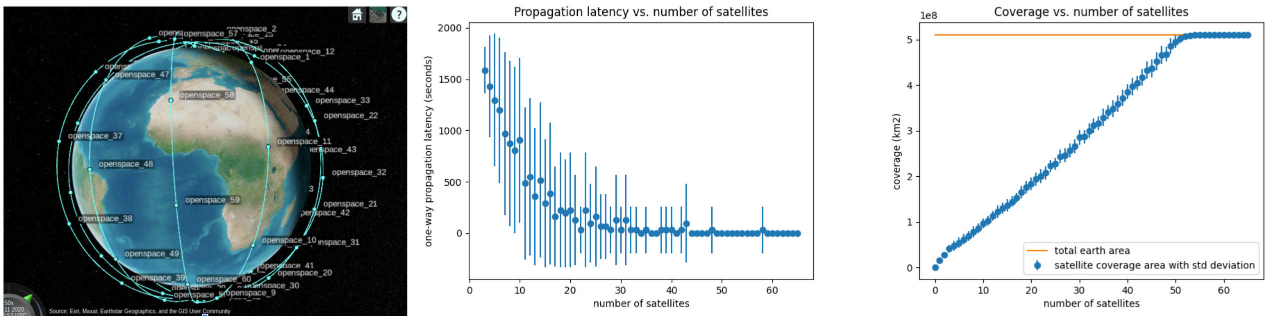
In latency evaluations shown in Figure 2(b), we find that increasing the number of satellites in the simulation dramatically reduces the inter-satellite latency up to about 25 satellites, after which latency values average about 30ms. In coverage evaluations shown in Figure 2(c), total earth coverage is achieved by about 50 satellites. The additional satellites ensure redundancy, such that operational failures, load balancing, and range cutoffs in particular geographical regions can be handled efficiently in the network.

5 DISCUSSION

We believe this paper raises provoking questions regarding the present and future state of space-based Internet, and provides a starting point to tackle these questions. We call the research community's attention to many research questions left undefined in this work, including:

(1) Diversity of Satellite Network Providers: What is the precise mix of small and big satellite players that are needed to realize *OpenSpace*? Defining these parameters requires simulating the different kinds of satellites that could be deployed as part of this system, including their technical diversity and hypothetical formations, and modelling a potential user base along with potential user traffic patterns. This would require extensive simulation tools not explored in this paper.

(2) Factors Impacting Satellite Routing: Can we design new routing protocols that factor in the more unpredictable components of user traffic, which cannot be accounted for by



(a) (b) (c)

Figure 2: ***(a) A simulated*** **OpenSpace** ***constellation.*** *This configuration achieves global coverage while maintaining inter-satellite distances and trajectories that allow for simple and sustained ISLs.*
(b) Propagation latency achieved by an increasing number of satellites in a constellation. *From the latency results, the constellation requires a minimum of about four satellites to guarantee that a satellite will orbit in range of the user's or ground station's location.*
(c) Coverage achieved by an increasing number of satellites in a constellation. *Additional satellites above the minimum for total earth coverage ensure fault tolerance, increased throughput and bandwidth capabilities, and increased availability in regions with signal-attenuating landscapes.*

proactive routing protocols computed based on known satellite trajectories? For example, peak loads at certain groundstations may necessitate re-routing of traffic to a ground station that is further away but is idle; in this case, a computation of the trade-off between longer routing distance vs queuing and job completion times is necessary at runtime.

(3) Impact of Regulation: How do we overcome the regulatory challenges in realizing a distributed and global satellite network? Different countries and regions have varying policies on satellite communications, such as different spectrum allocation policies, as well as independent licensing requirements [21]. The ability to use satellites located in some regions as relays for user traffic can also be impeded by diverse user data privacy regulations in different regions. In addition, there is the question of how to maintain a user's data privacy requirements when their traffic is routed to a groundstation outside their region.

(4) Creating Incentives for Collaboration: How can larger satellite provider companies be incentivized to join *OpenSpace* and collaborate with smaller providers? **We emphasize that the goal of *OpenSpace* is not to convince large satellite providers that are dominating the satellite internet market to cede space to and collaborate with smaller providers, but to create a platform for up and coming smaller satellite providers to collaborate with each other to better serve their users.** However, even on this platform, relatively larger providers may find that collaborating with smaller providers is not a net benefit for them, and it is worth expanding the cost model presented in Section 3 to include an incentive for this collaboration.

(6) Satellite Network Security: What security protocols can be enforced to ensure that a malicious provider does not take down the whole system? In addition to authentication of *OpenSpace* users as discussed in Section 2.2, it is worth exploring a security protocol to quickly identify and cut off bad actors in the network; such as attempts by non-*OpenSpace* agents to intercept user traffic, and a common baseline encryption scheme and security protocol implemented by all satellites to ensure secure end-to-end handling of user data.

6 CONCLUSION AND FUTURE WORK

In this work, we present an architectural roadmap for a heterogeneous Low-Earth Orbit satellite network that is launched by multiple collaborating players. We discuss the design of multiple elements of such an architecture, including satellite hardware, ground stations, routing protocols and cost models. We use simulations to chart the path for such a system to incrementally progress towards global coverage.

In summary, we believe the research community has a pivotal part to play in shaping the democratization of space-based Internet infrastructure, and that this paper presents first steps in realizing a more open and accessible satellite Internet landscape.

Acknowledgements: We acknowledge support from the NSF (2106921, 2030154, 2007786, 1942902, 2111751), ONR and the CMU-CIT Moonshot.

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