StarPerf: Characterizing Network Performance for Emerging Mega-Constellations

Zeqi Lai[‡*], Hewu Li[¶‡*], Jihao Li[†*]
Institute for Network Sciences and Cyberspace[‡], *Department of Computer Science and Technology*[†], Tsinghua University
Beijing National Research Center for Information Science and Technology (BNRist)[*], Beijing, China
zeqilai@tsinghua.edu.cn, lihewu@cernet.edu.cn, lijh19@mails.tsinghua.edu.cn

***Abstract*—“Newspace” mega-constellations, such as Starlink and OneWeb are gaining tremendous popularity, with the promising potential to provide high-capacity and low-latency communication globally. However, very little is known about the architecture and performance of such emerging systems, the workload they have to face, as well as the impact of topological options on the attainable network performance.**

This paper presents StarPerf, a mega-constellation performance simulation platform that enables constellation manufacturers and content providers to estimate and understand the achievable performance under a variety of constellation options. The proposed platform integrates two key techniques: (1) performance simulation for mega-constellation, which captures the impact of the inherent high mobility in satellite networks and profiles the area-to-area attainable network performance; (2) constellation scaling, which synthesizes various topological options by scaling the space resource and enables exploration on multiple operating conditions that can not be easily reproduced. To demonstrate the effectiveness of StarPerf on understanding and optimizing satellite networks, we leverage StarPerf to evaluate and compare the performance of several state-of-the-art low earth orbit (LEO) constellations and obtain insights on optimizing the architectural design to improve area-to-area network performance. Finally, to further show how applications can benefit from the proposed simulator, we propose an adaptive relay selection algorithm that can intelligently choose the optimal relay on cloud platforms and LEO satellites to achieve reduced latency. Evaluation results show that by properly selecting a relay in the satellite-cloud integrated infrastructure, end-to-end communication latency can be reduced by up to 62% for typical interactive traffic.

***Index Terms*—performance modeling and analysis, satellite constellations, network simulation, integrated satellite-terrestrial networks.**

I. Introduction

Constructing “NewSpace” satellite networks (SN) is gaining popularity in recent years, as SNs offer the promising potential to provide low-latency, high-throughput global Internet connectivity. We have witnessed a gold run to build constellations consisting of a large number of low earth orbit (LEO) satellites, namely “mega-constellations”, with players like OneWeb [7], Amazon [1] and SpaceX [12] entering the market. The latter one, which is the largest commercial satellite constellation operator in the world since January 2020, is actively constructing the Starlink constellation that consists of thousands of mass-produced small satellites in LEO, and will be initially available to customers in Canada and in the northern United States in 2020, with additional service expansion to other areas of the world throughout 2021 [11].

Fundamentally, mega-constellations facilitate the Internet by extending the connectivity of existing terrestrial networks (*i.e.,* integrated satellite-terrestrial networks), and breaking the inherently physical constraints in today’s Internet deployment. First, SNs expand the Internet coverage at broadband speeds to the remote area where access might be unreliable, expensive, or completely unavailable. Second, constellations with thousands of satellites working in LEO enable new opportunities for constructing a network in space to provide low-latency communication. Modern LEO satellites can equip optical inter-satellite links (ISLs) for inter-satellite communication. In the free-space, data packets can propagate in the speed of light in vacuum, which is much faster than that in the terrestrial fiber. Therefore the latency penalty in space might possibly be lowered by avoiding long-distance and meandering fiber routes. Finally, SNs are also expected to enhance the network throughput, since the rapid evolution of on-board technology and the increase in power generation have led to the evolution of high-bitrate satellite [39], which can provide tens and even hundreds of Gbps data rate.

While above exciting prospects depict a blooming picture of the future integrated satellite-terrestrial networks, the community still has very limited understanding of the topological characteristic and the attainable network performance of modern mega-constellations. Quantitatively profiling mega-constellations is meaningful for designing, using, and optimizing SNs, but it also faces a series of practical challenges: (i) currently emerging satellite constellations such as Starlink are still under heavy development, and the deployment of satellites is costly and time-consuming. It is thus difficult to directly measure the network performance from a completely deployed constellation system; (ii) SNs are fundamentally different from terrestrial networks. Emerging satellite networks inherently expose two particular features: only relatively nearby satellites can connect to each other due to the limited range of ISLs, and satellites are moving in high-speed with respect to ground stations and each other [19]. Such particular features make it difficult for existing network profiling methodologies to accurately characterize the

¶Hewu Li is the corresponding author.

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mega-constellations. Several existing works tried to model and analyze the characteristic of novel constellations but they mostly focus on modeling the system capacity under different physical layer payload decision [21], [43], which ignores the impact of using different constellation options or network policies on the user-perceived network performance.

In this paper we present the design and implementation of StarPerf, a performance simulation platform that helps constellation manufacturers and content providers to estimate and understand the achievable performance under a variety of constellation options. The two key techniques behind the proposed platform are: (1) performance simulation for mega-constellation, which captures the impact of the inherent high mobility in satellite networks and profiles the area-to-area attainable network performance; and (2) constellation scaling, which synthesizes various topological options by scaling the architectural capability (*e.g.,* number of satellite, link availability and capacity), and enables the exploration on multiple operating conditions that can not be easily reproduced.

To demonstrate the effectiveness of StarPerf on understanding and optimizing satellite networks, we then leverage StarPerf to evaluate and compare the performance of three state-of-the-art LEO constellations: Starlink, OneWeb and TeleSat, and perform *what-if* analysis, such as: what is the achievable latency between hosts located in London and NewYork respectively, if high-bitrate ISLs are fully deployed? The benchmark reveals a number of insights on using and optimizing existing mega-constellations like: emerging mega-constellations indeed offer low-latency opportunities for long-distance communications if ISLs are deployed, especially for communications between different continents. The constellation topology should be well designed to avoid high latency variation, as satellites move in high-speed and the path length in space is changing over time. The orbital decision and the scale of satellites can also significantly affect the resilience of the constellation.

Finally, to further show how applications or content providers can benefit from the proposed simulation platform, we illustrate StarPerf's ability on assisting a future satellite-cloud integrated infrastructure that offers low-latency relay for delay-sensitive real-time communications (RTC). StarPerf helps to intelligently choose the optimal relay located on either cloud platform or satellite to improve the quality of RTC. Evaluation results show that by properly selecting a relay in the satellite-cloud integrated infrastructure, end-to-end communication latency can be reduced by up to 62% for typical interactive traffic.

Conclusionally, this paper makes three key contributions:

- Presenting StarPerf, a simulation platform for profiling and understanding the network performance of mega-constellations under a diversity of architectural options and network policies. (§III)
- Leveraging StarPerf to benchmark three state-of-the-art mega-constellations and their possible topological extension, and highlighting insights on optimizing constellation designs to improve network performance. (§IV)

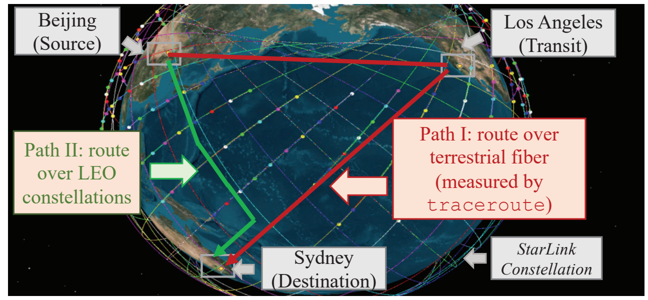

Fig. 1: The low-latency opportunity enabled by LEO satellite constellations. (I): the terrestrial route measured by `traceroute`; (II): route over Starlink constellation, with lower latency as it avoids long and meandering fiber routes.

- Quantifying the potential benefits of a satellite-cloud integrated infrastructure, and proposing a low-latency relay selection algorithm that can effectively reduce the latency of interactive video applications. (§V)

The implementation of StarPerf is mainly in Python and the code is open source[1]. To the best of our knowledge, StarPerf is the first open-source simulator for characterizing the network performance of emerging mega-constellations under various constellation options and network policies. Moreover, today's mega-constellations like Starlink are still evolving rapidly. As our future work, we will keep upgrading StarPerf to follow latest updates on Starlink and other emerging mega-constellations.

II. Why Profiling Satellite Networks is Important?

A. *Mega-constellations bring new opportunities for global low-latency and high-throughput communication.*

Quick primer for satellite networks: Typically, a satellite network (SN) built upon mega-constellations contains two primary components: (1) the *space section* which includes a large group of low-flying satellites running on low earth orbits (LEO), interconnected by inter-satellite links (ISLs); and (2) the *terrestrial section* that typically consists of a number of ground stations (GSes), which establish bidirectional satellite-to-ground links (SGLs) to connect the constellation in space.

New opportunities enabled by emerging constellations: The integration of satellite networks and the terrestrial Internet as a whole offers great new opportunities for improving the user-perceived network performance, which is not limited to broader Internet access. The rapid evolution of on-board technology has led to the development of the high-throughput satellites (HTS) [39], which promises to provide tens and even hundreds of Gbps transmission rate.

In addition to wider coverage and higher network capacity, mega-constellations also enables a promising potential for low-latency Internet communications. ISLs between satellites can use *free-space lasers* as the physical layer payload to communicate at the speed of light in a vacuum. Therefore, long-distance communications may attain lower latency via routing

[1] https://github.com/SpaceNetLab/StarPerf_Simulator

over LEO constellations [31]. Moreover, free-space mega-constellation breaks the *geographical routing constraints* that prolongs terrestrial paths. Figure 1 plots an example, showing the opportunity of leveraging inter-satellite links to reduce intercontinental communication latency. The `traceroute` result shows that current network deployments and routing policies forward data from Beijing to Sydney via Los Angeles by default. Such intercontinental detour incurs more hops and possibly larger delay than the shorter path built upon mega-constellations in space.

B. *Understanding satellite networks is challenging.*

While SNs offer promising opportunities on improving network performance, it is very challenging to understand SNs' architecture, network performance and the impact of various design options (*e.g.,* topological or routing potions).

First, SNs have the inherent *"high mobility"* property that differs from the terrestrial network, resulting in *dynamic* network topology and intermittent connectivity. In wired networks, network nodes such as routers and switches are typically *static*. Even in terrestrial Wi-Fi or cellular networks, mobile nodes (*e.g.,* mobile phones or vehicles) are not moving so fast as satellites. In SNs, potential network nodes are moving in high speed with respect to the Earth and other satellites, and ISLs are limited by range. Only those relatively nearby satellites can be connected, and thus routes over SNs should be updated timely to adapt the dynamic connectivity.

Second, the real deployment for mega-constellations are significantly cost-intensive and time-consuming, and thus it is very difficult to directly measure the performance of a fully deployed constellation system. Finally, the design of SN consists of a large number of architectural and routing options. Such diversity on design options makes it meaningful but difficult to estimate and understand the impact of various options on the corresponding network performance.

C. *Profiling mega-constellations is of significant importance.*

Summarily, when designing, operating and using emerging mega-constellations, it is often important and useful to profile the network performance of a constellation, specified by both the architectural options and network policies (*e.g.,* routing scheme). Therefore, the goal of this paper is to design and implement such a simulation platform to model, analyze and understand the network performance and design trade-space of emerging mega-constellations. The usage of our platform includes: (i) guiding constellation operators to attain a function of the network capacity of the constellation topology. Such a function can help to understand and optimize the design of constellations; (ii) guiding content providers who want to deploy their contents upon LEO satellites to provide low-latency services globally. Next we present the details of such a platform, STARPERF.

III. THE STARPERF PLATFORM

A. STARPERF *overview.*

System overview. Figure 2 plots the overview of our STARPERF platform. The STARPERF platform takes network topology, network policy and traffic pattern as the platform input. The input of STARPERF describes the composition and scale of the constellation, how satellites are connected to each other and ground stations, and how user requests are scheduled and forwarded over satellites. The main components inside STARPERF is a suit of models which quantitatively describe a LEO satellite constellation together with its performance estimation. At runtime, STARPERF loads the input and calculates the performance output based on the built-in models.

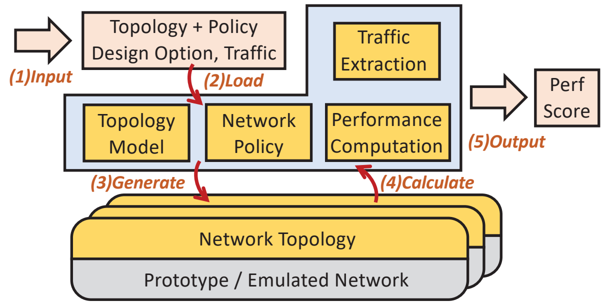

Fig. 2: The overview and workflow of STARPERF.

Collectively, STARPERF includes two key techniques: (1) performance simulation for mega-constellation, which captures the impact of inherent high mobility in satellite networks and profiles the area-to-area attainable network performance; (2) resource scaling, which synthesizes various constellation topologies and network policies by scaling the space resource (*e.g.,* number of satellite, link availability and capacity), and enables exploring multiple operating conditions that can not be easily reproduced.

Runtime workflow. To evaluate a satellite constellation by STARPERF, first the user specifies the constellation options and network policy (*e.g.,* traffic scheduling or routing strategy), together with a configured traffic pattern. The input is then loaded by the STARPERF platform and is used to generate a simulated satellite network according to the built-in model inside the platform. The traffic pattern is then loaded and applied in the network. Performance metrics such as network latencies are measured and finally used to compute and quantify the network performance.

B. *Characterizing network topology.*

Our STARPERF platform profiles the network topology of a LEO satellite constellation by modeling three primary aspects: (1) orbit property; (2) ground station distribution; and (3) link type and connectivity among satellites.

Orbit and constellation elements. The design option for constellation orbit can significantly affect the coverage and route stability in SNs. STARPERF leverages five primary continuous parameters to describe the orbit design: (1) *Inclination (`Inc`)*, which is the angle between an orbit and the Equator as the satellite travels northward. The value of Inclination for polar orbits is 90°; (2) *Altitude(`Alt`)*, which is measured over sea level and it determines the orbital velocity. Recent constellations typically consist of low-flying satellites with an altitude of 2,000 km or less; (3) *Orbit phase shifts(`OPS`)*, which

TABLE I: Design options for LEO mega-constellations.

Decision	Options and range of values
`Inclination`	inclination of orbit i (Inc_i)
`Altitude`	altitude of orbit i (Alt_i)
`Phase shift`	phase shift of orbit i (Pha_i)
`# of orbit`	total number of orbits (Num_{orb})
`# of satellite`	number of satellites in ith orbit ($SatN_i$)
`# of GS`	total number of ground stations
`Location of GS`	location distribution of GS
`Link band`	band range: S/X/Ku/Ka/optical
`Link type`	type range: bent-pipe, circuit- or packet-switched

capture the relative placement of satellites in a constellation. The orbit phase offset between orbital planes indicates when satellites in consecutive orbits cross the equator; (4) *Number of orbits(`NoO`)*; and (5) *Number of satellites(`NoS`)* in each orbit.

Link options. The link options include both the band allocation and payload type of inter-satellite and satellite-to-ground links. The link band is very critical to the network performance, as the link data rate largely depends on the band selected. For instance, data rate higher than 512Mbps is only doable if high bands (like Ka- or higher) are used. STARPERF describes the link type between arbitrary two nodes in the SN as one option selected form S-band, X-band, Ku-band, Ka-band or optical. In addition, the payload type refers to the type of architecture implemented, which includes bent-pipe, circuit-switched or packet-switched.

Satellite connectivity pattern. Satellites connect to GSes and other satellites. The connectivities are mainly limited by the visibility and power supplement, as well as the ability to quickly establish links between fast-moving satellites via radio or laser alignment. The approach of establishing connectivities in satellite constellation also significantly affects the network performance, as it determines the basic network topology. In particular, existing non-GEO constellations like Iridium use a grid-like approach for their ISLs. Recently works have proposed a Grid+ [19] connectivity pattern, in which each satellite has four bi-directional ISLs with its nearby neighbors, two in the same orbit, and other two with immediate neighbors in the 2 adjacent orbits. STARPERF supports grid and Grid+ connectivity pattern by default, and also allows customized connectivity design as the platform input.

Table I summarizes the design options for LEO mega-constellations supported by the STARPERF platform.

C. Options for routing strategy.

The network performance over SNs is affected not only by the design of constellation, but also by the network policies running on SNs. In order to accommodate all expected customers, a LEO satellite network has to determine how to optimally (if possible) route and forward demand traffic. Typically, we define such routing and forwarding strategies as the *routing policy*, which will significantly affect the path performance including latency, throughput, reachability and resilience in SNs.

By default, STARPERF models two kinds of routing strategies: (1) distributed routing strategies, such as OSPF and GPSR [36] which leverage the local information obtained on each node (*i.e.,* satellite) to calculate the routing table (*e.g.,* using djisktra); and (2) centralized routing strategies, like Dynamic Source Routing (DSR) [31], [35].

D. Characterizing network performance.

STARPERF characterizes three key performance metrics of a certain constellation system: 1) *Coverage rate*, which indicates the available range covered by satellites; (2) *Latency*, which is defined as the delay of sending a small packet from a source to its destination via satellites; and (3) *Throughput*, showing the ability of delivering content via the LEO constellation. Since the ultimate goal of a mega LEO constellation is to provide better Internet accessibility and communication quality, these metrics can quantify the main network aspects concerned by both constellation designers and content providers who aim to deploy on-satellite contents.

Further, to model the network performance geographically, STARPERF builds a grid systems upon the Earth surface for modeling and analyzing geographic information to measure the coverage, latency and throughput. The grid system used in STARPERF buckets user requests and satellites into hexagonal areas based on H3 [5]. STARPERF discretizes the Earth surface into hexagonal areas for several reasons: (1) Satellites in LEO are often in high-speed motion, and hexagons minimize the quantization error introduced when satellites moves in high speed. (2) Hexagons have good scalability, since the size of a hexagon can be dynamically adjusted by setting its *resolution*. A higher resolution indicates a smaller hexagon. (3) It is easy to use hexagonal areas to approximate radiuses, since they well fit the circle coverage of satellites. Using the hexagonal hierarchical grid system, STARPERF groups a set of nearby locations into a hexagonal area, and maps a certain location (specified by its latitude and longitude) to a 64-bit area index.

We denote A_i^R as the ith area in STARPERF, under a certain resolution R, and the total number of hexagonal area is denoted as Num_{area}^R. Next we formulate the network performance upon the grid system.

Coverage. Given a LEO constellation containing a number of satellites in high speed motion, the coverage is time-varying and depends on the constellation topology. Let c_{it} denote a binary parameter and is set to true if area A_i^R is covered by the satellite constellation. We then define the coverage of the constellation in slot t as the fraction of covered area: $\frac{\sum_{i=1}^{Num_{sat}} c_{it}}{Num_{area}}$. Thus, the coverage rate of constellation C over a period T can be formulated as CR_T^C:

$$CR_T^C = (\frac{\sum_{t=1}^{T}\sum_{i=1}^{Num_{area}} c_{it}}{Num_{area}})/T \tag{1}$$

The above equation quantifies the fraction of covered area. However, many areas on the Earth are built on ocean and mountains with rare communication requirements. To model the ability of providing services for "necessary" areas, we use binary parameter h_{it} to indicate whether there is at least one communication request in ith area in t time slot. Then the hotspot coverage rate can be formulated as:

$$HCR_T^C = (\sum_{t=1}^{T} \frac{\sum_{i=1}^{Num_{area}} c_{it} * h_{it}}{\sum_{i=1}^{Num_{area}} h_{it}})/T \quad (2)$$

Equation 2 captures the coverage rate of hotspot areas, and a higher value of HCR_T^C indicates better satellite accessibility of the constellation during the period T.

Area-to-area latency. StarPerf focuses on the attainable latency via routing over SNs, which is mainly constrained by the network topology and the speed of light. Therefore, in the design of StarPerf we refrain other impacts on the latency (*e.g.,* packet processing time, encoding/decoding time) and assume the latency here is dominated by the propagation latency. Moreover, note that the prior work [38] has shown that Internet latencies to any particular data center are similar from users in the similar location. Users in the same area have nearby locations and similar distance from the user terminals to the connected LEO satellite. Hence we assume that the end-to-end delays via the LEO constellation are similar for the same area pair, and we do not add an excessive constraint on latencies of all paths of the same area pair. StarPerf then formulates the area-to-area latency from ith area to jth area in slot t as:

$$L_{ij} = f_L(Tpl, RS, t) \quad (3)$$

where Tpl is the network topology of the LEO constellation and RS is the routing strategy used to route packets from the source area to the destination area. Once the area-to-area path is determined by the given routing strategy, the latency is estimated as the length of the path divided by the $2c/3$, where c is the light speed in space. The value of area-to-area latency suggests the ability of providing low latency communication of a LEO constellation, which is useful for delay-sensitive interactive applications, as we will show in later sections.

Area-to-area throughput. Another important performance metric is the area-to-area throughput. The rapid evolution of on-board technology and an increase in power generation led to the development of high-throughput satellites, which are able to provide tens and even hundreds of Gbps bandwidth. Therefore, the area-to-area throughput which indicates the achievable rate of successful data delivery between two areas over the SN, is critical for content providers who leverage satellites to distribute important content in real time. Particularly, we define the area-to-area throughput B_{ij} between area i and j as the total throughput of all paths that have the similar latency with the shortest path. Therefore, B_{ij} quantifies the ability of a certain constellation topology to deliver contents from i to j by routing traffic without congestion and with low latency. The function of B_{ij} is denoted as:

$$B_{ij} = f_B(Tpl, RS, t, \beta) \quad (4)$$

where Tpl and RS are the network topology and routing strategy respectively. β is a parameter to represent the latency requirement [30]. Calculating the area-to-area throughput provided by a certain constellation design follows the next stages. First, building a network with users in the source and destination areas, and all visible satellites. Second, running the routing algorithm to obtain the shortest path which consists of a set of sequential ISLs and satellite-to-ground links. Third, calculating the latency of the shortest path, denoted as D_{min}. Then identify all similar paths with the same source and destination that have latency $< \beta * D_{min}$. Finally, constructing a sub-network that includes all those similar paths and compute the max-flow from the source to the destination.

Resilience. Resilience indicates the ability of mega-constellations to provide and maintain an acceptable level of service in the face of faults and challenges to normal operation. When using SNs to extend terrestrial networks and support Internet service, constellation operators have to consider the vulnerabilities and resilience of the proposed constellations. The constellation topology should be reasonably designed to provide resilient and affordable capabilities to preserve stable connectivity in space. StarPerf uses the *betweenness centrality* [2] from graph theory to quantify the resilience of a constellation. Betweenness is a metric that describes the centrality in a graph based on shortest paths, and it is widely used in telecommunications networks, *e.g.,* a node with higher betweenness centrality would have more traffic passing through that node. Moreover, a node with a high betweenness centrality may also be a potential bottleneck node, since the failure of this node will affect all flows relying on it. Specifically, the betweenness of a satellite sat which works as a node in the SN is calculated as:

$$betweenness(sat) = \sum_{s \neq d \neq sat} \frac{p_{sd}(sat)}{p_{sd}} \quad (5)$$

where p_{sd} is the total number of the shortest paths from source s to destination d in the SN, and $p_{sd}(sat)$ is the number of those paths that pass through sat.

E. Characterizing user requests.

Typically, in satellite network, user handsets can connect to satellites directly (*e.g.,* like Iridium) or connect by very-small-aperture terminal (VSAT), which is a two-way satellite ground station with a small dish antenna. Emerging constellation systems like Starlink claim that it will be linked to flat user terminals in the size of a pizza box which will have phased array antennas and track the satellites. The terminals can be mounted anywhere, as long as they can observe the sky. Therefore, StarPerf assumes each end user can connect to satellites directly or connect via a pre-purchased VSAT, if the user is in the sight of view of the satellites.

User requests are formulated as a traffic matrix in the grid system. Let R_{ijt} denote a transfer task that requires to send R_{ijt} bytes data from ith area to jth area in slot t. Thus R_{ijt} describes the traffic distribution between different areas. In particular, the traffic distribution can be estimated by the population of different cities, or generated according to dedicated applications.

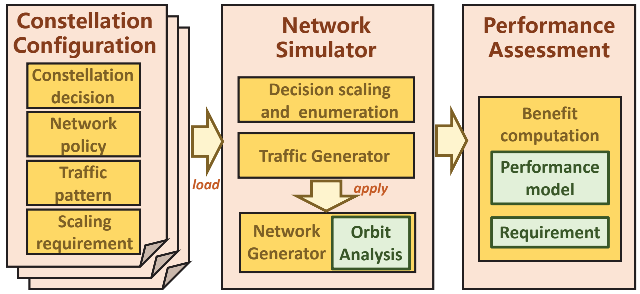

Fig. 3: Implementation of StarPerf. StarPerf loads configuration files which specific the key parameters of mega-constellation. StarPerf then simulates the network topology, and applies user traffic on it to calculate network performance.

F. Constellation scaling.

Constructing and deploying mega-constellations is cost-intensive and time-consuming. Therefore, in addition to study on a certain constellation pattern, it is meaningful but difficult to explore the impact of various architectural design decisions on the achievable network performance. The StarPerf platform has the capability of automatically scaling and enumerating all the possible design options outlined in previous sections. For example, the user can increase the number of satellites in the constellation, or enable/disable ISLs, by tuning the configuration files of StarPerf. All possible topologies and routing policies can be automatically enumerated and evaluated using this platform, by iterating the Cartesian product of all options in the trade-space listed in Table I.

G. Implementation of StarPerf platform.

Figure 3 plots the key components in the implementation of StarPerf. The StarPerf platform loads input manifest which describes network topology, flow scheduling policy, and traffic pattern to generate a satellite network graph. The constellation simulation is partially implemented based on third-party orbit analysis tools (*e.g.,* STK [8]), which help to simulate the movement of satellites over time. For each constellation, StarPerf calculates the constellation decisions and orbit parameters. Once all the nodes of the network have been loaded and scaled to the desired size, user traffics are generated and applied to the network and finally StarPerf calculates the corresponding network performance. As emerging constellations like Starlink are still under heavy deployment and it is difficult to collect the real number of its users, we follow the approach used in [21] to estimate the geo-distributed user requests, based on the real population in different areas. Specifically, the user requests are generated according to the Gridded Population of the World v4 dataset [4]. We assume that a satellite network operator will capture about 5% of the total Internet traffic of each area, and each user in an area has a 500Kbps data rate requirement.

IV. Benchmarking “NewSpace” Constellations

In this section we demonstrate the effectiveness of StarPerf on characterizing and understanding emerging state-of-the-art LEO mega-constellation systems.

TABLE II: Primary constellation parameters for three state-of-the-art mega-constellation systems in our benchmark.

Design Options	Starlink (Phase I)	OneWeb	TeleSat (Polar/Inclined)
Inclination	53°	87.9°	99.5°/37.4°
Altitude	550km	1200km	1000km/1200km
Phase shift	1	0	0/0
# of orbit	24	18	6/5
# of satellites	66	40	12/10

A. Benchmarking constellation systems by StarPerf.

Benchmark setup. In order to understand the architecture and performance of current mega-constellations, we leverage StarPerf to benchmark three state-of-the-art commercial mega-constellations, Starlink [12], OneWeb [7] and TeleSat [14]. In addition, we also scale the topological resource of each constellation (*e.g.,* enabling ISLs) to exploit the impact of diverse design options on the network performance. In each experiment we simulate a three-day duration for mega-constellations to get the result.

Table II shows the primary constellation parameters of the mega-constellation selected in the benchmark. Starlink Ku + Ka constellation comprises 1584 satellites that are distributed across several sets of orbits. Similarly, OneWeb Ku + Ka-band constellation comprises 720 satellites in 18 circular orbital planes at an altitude of about 1200km, each plane inclined at 88°. TeleSat is a constellation working in Ka-band, and it plans to comprise about 120 satellites flying in two groups of orbits: polar orbits and inclined orbits. The former group including six circular orbital planes will be at an altitude of about 1000km and 99.5° inclination. For each orbital plane, there will be at least 12 satellites. The latter group contains about 5 orbital planes in an altitude of about 1200km and 37.4° inclination. There are about 10 satellites in each orbital plane.

Results of coverage. We first examine the coverage of different constellations. First, the coverage (as defined in Equation (1)) of Starlink, OneWeb and TeleSat are 87%, 100% and 100% respectively. OneWeb and TeleSat achieve higher coverage rate as their constellation contains Polar orbits that extend the connectivities in polar region. Second, since one of the primary goal of building SNs is to connect key population centers with satellite paths that run close to the great circle route, we then explore coverage for cities with high population density. Figure 4 depicts the hot coverage rate of different constellations, aggregated by latitude and longitude respectively. The global population distribution is extracted from the Gridded Population of the World (GPW) version 4 [4]. We calculate the hot coverage rate of various constellation patterns. An area with population higher than the threshold is marked as “hot” area, and is eager to be covered by satellites. As shown in Figure 4, all constellations can cover large population centers (population $>$ 57 million). Finally, Figure 5 shows the number of satellites in line of sight per million population, aggregated by latitude or longitude respectively. This metric indicates the geo-distributed coverage rate in different areas, and Starlink has

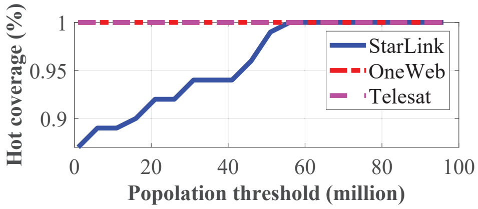

Fig. 4: Hot coverage rate.

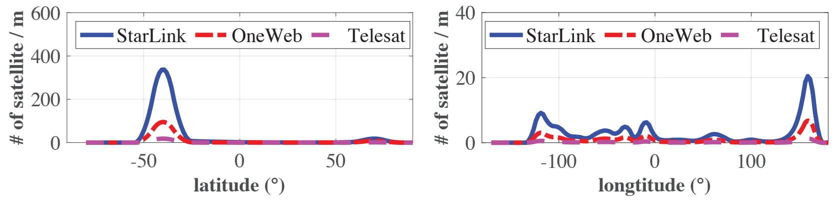

Fig. 5: Coverage aggregated by latitude and longitude respectively.

the largest number of satellites per million population around the -45° latitude band.

Results of latency. We then examine the latency distribution obtained in different constellations. Figure 6 plots the area-to-area latency via various constellation patterns among four big cities located in four continents. More detailed results containing other "hot areas" can be found in our technical report [13]. The route is calculated by Dijkstra's algorithm in every second, using link latency as the network metric to attain the path with shortest latency in every second. Several interesting findings can be observed from the results: (i) emerging mega-constellations can provide routes with lower latency for long-distance inter-continent communication, as compared to the terrestrial Internet. Our experiments show that such a latency reduction is caused by the higher transmission speed in free-space laser, and by avoiding transmission over meandering path (example in Figure 1); (ii) routes over SNs suffer from high latency variation. The root cause for such high variations is three-fold. First, as satellites move in high-speed, the physical distance between two nodes is elongated and shorten over time, resulting the latency change. Second, the variation is highly affected by the topology design of the constellation. An even constellation pattern like Starlink can obtain lower latency jitter as compared to TeleSat. Finally, routing packets via satellites that fly in different directions can also involve additional latency. For example, satellites in Starlink can be divided into two groups based on their direction: one runs in the south-west to north-east direction, and the other group runs in the north-west to south-east direction. The total path latency is prolonged if the source and destination connect to satellites in different direction group. Such a finding indicates an important suggestion for the topological design of constellation: a constellation can attain low latency and low latency variation, if both the source and destination area are covered by satellites working in the same direction, during the communication period.

Note that the previous study in [31] also performed an estimation on the round trip time between big cities via the Starlink constellation. The latency estimated here by StarPerf is slightly lower than the results in [31]. This is because in the prior work, latencies are estimated based on SpaceX's original plans with satellites orbiting at an altitude of about 1100km. Latency results calculated by StarPerf is based on the latest FCC, revised in November 2018 by SpaceX, and the revised constellation lowers the altitude of satellites from 1100km to 550km, resulting in reduced propagation latency. Moreover, if we adjust the constellation options to the original Starlink phase, latency results aligned to [31] can be obtained.

Results of throughput. The result of area-to-area achievable throughput is jointly affected by the constellation topology, routing scheme and the user traffic. Figure 7 shows the area-to-area throughput between four populated areas under different constellation patterns. In this experiment we use $\beta = 1.1$ and the capacity of ISLs are set to about 5Gbps according to [21]. $\beta = 1.1$ indicates that all paths with latency less than $1.1\times$ delay of the shortest path can be used for transferring data of the same user demand. On average, Starlink, OneWeb and TeleSat can provide 11.3Gbps, 10.7Gbps and 6.1Gbps maximum throughput respectively. As the uniform architectural design of Starlink enables better flexibility to accommodate traffic on alternative low-latency paths, on average Starlink achieves the highest area-to-area throughput as compared to other constellations, if ISLs are enable.

Results of resilience. Finally, we explore the resilience under different constellation designs. Figure 8 plots the cumulative distribution function (CDF) of the betweenness which quantify the resilience of the constellation. Interestingly, since satellites in Starlink are distributed evenly, all nodes have similar betweenness in Starlink, indicating a good resilience that Starlink can provide and maintain data forwarding in the face of node or link failure. TeleSat obtains the highest betweenness among the three constellations, showing that some nodes in TeleSat have much higher centrality than others. Constellation operator should develop and deploy error resilience techniques for those nodes with high centrality to avoid service suspend.

B. Insights obtained.

Summarily, above benchmark results indicate several insights for optimizing the performance of modern satellite networks, as listed below.

- (i) Emerging mega-constellations indeed offer low-latency opportunities for long-distance communications if ISLs are deployed, especially for communications between different continents. The attainable network performance can be significantly affected by the concrete constellation design. Satellites working on lower orbits may provide lower latency due to the shortened route length. However, lower orbits are also faster with a higher orbital velocity, which is more likely to cause intermittent network connectivity and higher jitter. Thus, the constellation design and network policies should be jointly optimized to support various upper applications.
- (ii) The orbital decision and the scale of satellites can significantly affect the resilience of the constellation. An even constellation design (*e.g.,* Starlink) has more nodes with

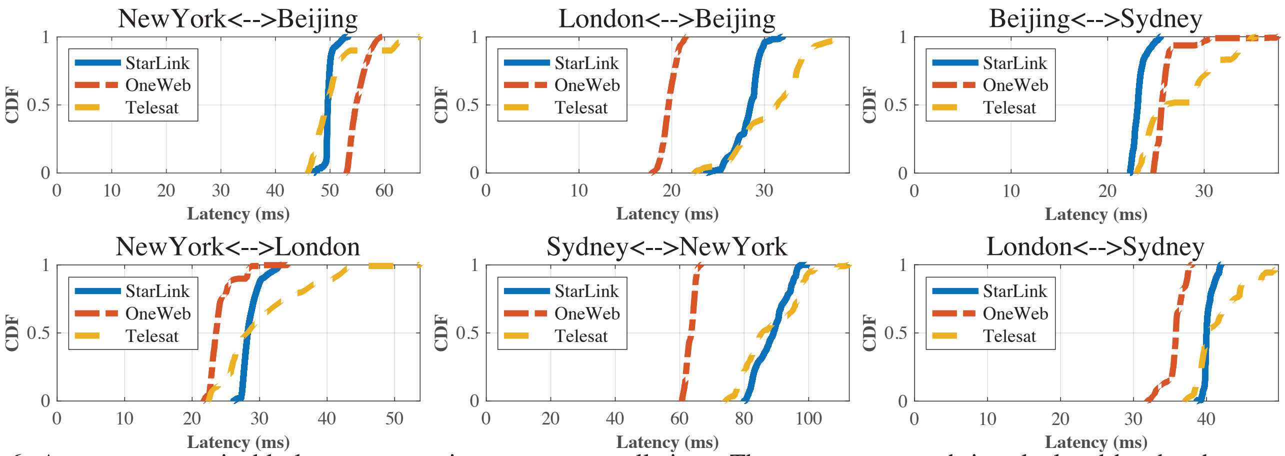

Fig. 6: Area-to-area attainable latency on various mega-constellations. The area-to-area path is calculated by the shortest path identification algorithm, using the number of hops as the routing metric.

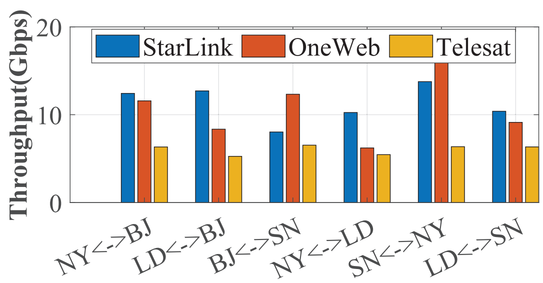

Fig. 7: Throughput obtained under different constellations.

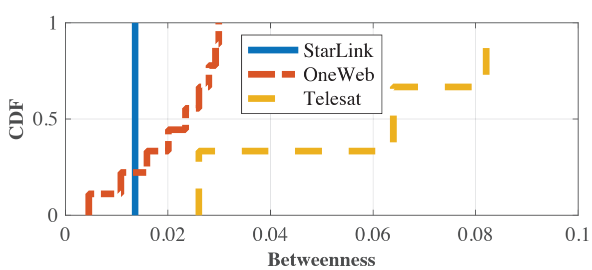

Fig. 8: Resilience of various constellation patterns.

lower betweenness in the constructed network, indicating that failures occur on these nodes may have smaller impact on SN traffic. To guarantee good network resilience and keep stable connections, it is recommended to keep a balanced constellation architecture with an evenly coverage.

V. Use case: low-latency Relay Selection in space

Above benchmark has evaluated the usefulness of StarPerf on characterizing and understanding mega-constellations. In this section, a use case study is conducted to further show how content providers can use StarPerf to improve their services.

A. *Relay selection problem in real-time communication.*

Low-latency requirement in real-time communication. Over the last several years, we have seen a dramatic rise in Internet-based Real-Time Communication (RTC), especially for long-distance internal video-conferencing. The key difference between RTC and on-demand video streaming is the *interactivity*, which requires ultra-low latency and jitter.

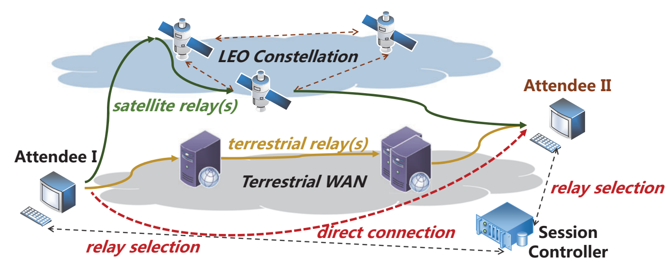

Fig. 9: The relay selection problem in typical real-time communication systems. StarPerf profiles the benefit of leveraging LEO satellites to build communication paths, which can be used for optimizing the relay selection process.

A classic solution to reduce communication latency (especial for long-distance cross ASes communication) is *relay selection* [34], [47] which uses an intermediate server to relay RTC traffic. Choosing a relay server for a RTC session (*e.g.*, video-conferencing) typically contains two key stages: (1) find a *relay* server which is "good" enough for all attendees (*i.e.*, the average attendee-to-relay latency is minimum); (2) each attendee communicates to each other via the relay server.

In particular, the relay server is typically built upon cloud infrastructures such as Amazon AWS and Azure. However, as we have analyzed in section IV, the terrestrial routing path may suffer additional delay due to the physical constrains, especially in inter-ASes scenarios. Considering the potential low-latency property enabled by LEO satellites, we leverage StarPerf to design an intelligent star relay selection mechanism to improve the RTC communication quality.

Problem formulation for relay selection in RTC applications. The goal of the relay selection problem is to allocate each session with a set of attendees to a particular relay option. As shown in Figure 9, a session can: (1) use direct connection in WAN, without relaying on a server; (2) use a selected server or servers as relay nodes located in cloud infrastructures. Let $Sess$ denote the RTC session set for optimization, and we denote $Relay$ as the set of all possible relay options. Let

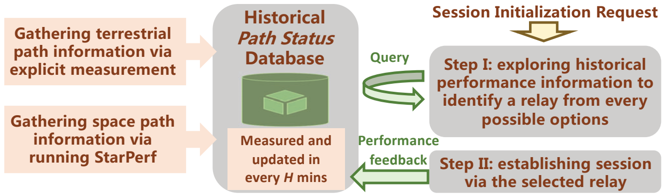

Fig. 10: Our relay selection approach in the integrated network.

$s \in Sess$ and $r \in Relay$ denote a specific RTC session and relay selection respectively. Further, we denote $D(s, r)$ as the estimated interactive latency for session s relaying on relay option r. In addition, we assume that all decisions on relay server selection are independent to each other, and thus the latency of a certain session is not affected by relay selections calculated for other RTC sessions.

Accordingly, the goal of the relay selection problem is to find the optimal relay option for every session $s \in Sess$. We denote $allocate$: $Sess \rightarrow Relay$ as the allocation decision and $r = allocate(s)$ indicates to allocate relay r to session s. Therefore, our goal is to calculate the allocation that minimizes the average latency among all sessions:

$$arg\,\min\left(\frac{\sum_{s \in Sess} D(s, allocate(s))}{|Sess|}\right) \tag{6}$$

B. Our approach in the satellite-cloud integrated architecture.

The key intuition behind our approach is the insight we identified in previous section that leveraging satellites running on low earth orbit can potentially build a low-latency path for long-distance communication. This insight extends the possible set of relay options and offers new opportunity in improving real-time communications, as shown in Figure 9.

Accordingly, we propose a Low-latency **S**atellite-**C**loud **R**elay **S**election (SCRS) algorithm that explores in optimal relay option in both terrestrial cloud computing platforms and mega-constellations in space. Essentially, SCRS is an measurement-based exploration approach that exploits historical performance information to predict and select the low-latency relay. Figure 10 depicts the key operating process of SCRS. In a nutshell the logical stages in SCRS include:

- Periodically, each attendee explicitly probes the latency to every relay options. The performance information for satellite relays are profiled by StarPerf. Historical path performance information are then gathered and saved in the database on the session controller.
- When initializing a RTC session for a set of attendees, the session controller explores historical performance information to calculate the optimal relay option.
- Establishing the RTC session for all attendees based on the relay server(s) selected. Performance feedback of the RTC session is sent to the session control server.

C. Numeric results.

To show the effectiveness of improving RTC quality by comprehensively utilizing relays in the satellite-cloud integrated infrastructure, we perform data-driven simulations based on network traces measured from real cloud platforms and StarPerf.

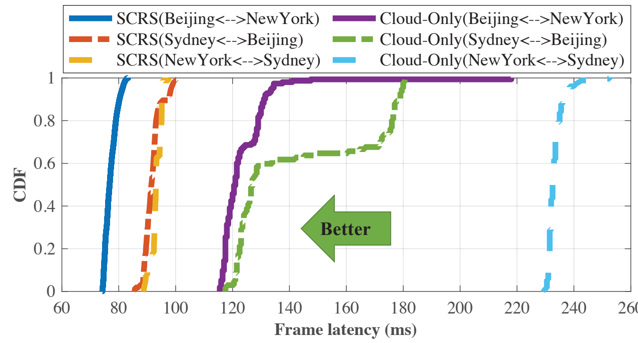

Fig. 11: Interactive latency improvement by StarPerf.

Methodology. To simulate an interactive RTC session, we extend WebRTC [15], which is an open-source framework that enables peer-to-peer real-time video and audio communication, to support communication via a relay server. Then we run the WebRTC application on two laptops, and both of them are connected to a controlled relay server. We use `tc` [6] to tune the link quality between the relay server and the laptop, and simulate the link performance (*e.g.,* RTT and bandwidth) according to the network trace. We simulate the communication between three populated areas, NewYork, Sydney and Beijing. For relay options in existing cloud platforms, we use the Amazon EC2 instances located in Oregon, Paris, Ireland, Singapore and Hong Kong. For relay options in space, we use the constellation of Starlink Phase I, and assume each satellite is equipped with ISLs for packet switch.

Reductions of interactive latency. Figure 11 plots the interactive latency of communication sessions for different city pairs. The interactive latency calculated form the time when a video frame is encoded and sent to the transport layer on the sender, to the time when the same frame is assembled on the receiver. By exploring the relay options hidden in the satellite-cloud infrastructure, SCRS effectively reduces the end-to-end interactive latency by up to 62% for the long distance communication. The interactive latency is slightly higher than the one-way packet delay via SNs as we profiled in section IV since it includes the packetization and de-packetization delay in real-world RTC systems.

VI. Limitations and Future Work

Characterizing network performance of future hybrid SNs. Unlike previous SN simulators that simulate communications over GEO satellites (*e.g.,* SNS3 [9]), the current implementation of our StarPerf platform mainly focuses on characterizing the network performance of emerging LEO mega-constellations. However, constructing a hybrid constellation that integrates satellites working in various kinds of orbit (*e.g.,* LEO, GEO and MEO) to collaboratively provide global network access, is another blooming picture in the evolution of SNs. We will extend StarPerf to model and profile such kind of hybrid SNs in the future.

Improving the fidelity of StarPerf. Like other recent works that study on the network performance of emerging constellations [19], [27], [31], [32], our performance results are obtained from the model-based estimation, in which satellite and orbital configurations are based on public data released by satellite operators or the astronomy community [10]. At the time of this submission (August, 2020), Starlink is still under heavy deployment and we have no public access to run Internet traffic over real Starlink constellation. Hence it is very difficult to compare the network performance obtained by StarPerf with the corresponding value measured from real Starlink. However, we will track the evolution of Starlink and other similar mega-constellations. We will keep upgrading StarPerf to follow the latest updates in Starlink and other constellations, combine StarPerf with more fine-grained physical layer models and improve the fidelity by calibrating the performance results, if Starlink offers available public access in the future.

VII. Related Works

We briefly discuss related works in this section.

Modeling and analyzing satellite networks. A body of previous literatures have studied on the modeling and analysis on satellite networks [20]–[22], [27], [29], [39], [40], [46]. Del Portilo *et al.* have studied on the architectural design [20], [22] and conducted technical comparison [21] for large LEO satellite constellations. Sanchez *et al.* conducted a stakeholder analysis to identify the main stakeholders of NASAs Space Communication and Navigation (SCaN) program systems, and explored the architectural trade-space of the system [43]. These existing works mainly focus on modeling and analyzing the physical layer performance under different physical payloads, while StarPerf characterizes the achievable network performance, such as area-to-area latency and throughput, under various constellation options and routing schemes. Brian *et al.* proposed to leverage SDN applications to optimally and autonomously handle aerospace network operations, including steerable beam control and network routing updates [17]. Moreover, authors in [27] studied cost-performance tradeoffs in the design space for Internet routing, and proposed a CDN-inspired routing mechanism. The cost analysis in [27] complements our study, and in addition to the design option for routing, StarPerf also explores the impact of various constellation options on the final network performance. In addition, the community also has many simulators for SNs. The European Space Agency (ESA) provided a list of open source software resources for developing space downstream applications [3]. Most of these open source projects are designed for positioning and navigation, or earth observation, while StarPerf focuses on characterizing the network performance of emerging constellations. SNS3 [9] is a high-fidelity ns3-based simulator for satellite communications. However SNS3 is built on a static system configuration, with only one geostationary satellite and does not support LEO constellations in its current version.

Routing protocols in satellite networks. Existing studies working on routing in satellite networks typically fall into two key categories: (1) inter-domain satellite routing [24], [33], [37], [48], and (2) intra-domain satellite routing [18], [19], [23], [25]–[28], [31], [32], [41], [42]. Authors in [33], [48] have studied and analyzed the inter-domain routing instability that is caused by the high-speed movement of satellite. In addition, routing inside a satellite constellation is also a well studied problem [23], [25], [26], [28], [41]. More recently, as the topic of using large commercial constellations of LEO satellites has re-gained popularity, several works have revisited the topology design and routing in emerging mega-constellations [18], [19], [27], [31], [32]. Giuliari *et al.* [27] studied the cost-performance tradeoffs in the design of routing over satellite networks. These recently works are mainly built on a certain constellation pattern (*e.g.,* Starlink). StarPerf complements above researches as it provides an open platform to explore the performance benefit of various routing designs and topological decisions.

Relay selection for delay-sensitive applications. Optimizing the server selection to attain low-latency communication is a much studied topics in the terrestrial Internet [34], [44], [47]. While existing works focus on using cloud infrastructures to construct low-latency path, our work in this paper further explores the benefits of integrating on-satellite node as the relay options to reduce end-to-end latency.

Satellite mobility management. Satellite networks represent a new category of wide-area network where thousands of satellites move in high speed but connect to each other. The mobility of satellites is also a well studied problem [16], [45]. Tsunoda *et al.* proposed a handover-independent mobility management scheme specifically designed for IP/LEO satellite networks. The basic idea of the proposed approach is to make IP addresses independent of logical locations and associated to only geographical location information.

VIII. Conclusion

This paper presents StarPerf, a simulation platform that enables constellation manufacturers and content providers to estimate the achievable network performance under a variety of constellation options. StarPerf makes three contributions: (1) proposing a novel approach that can profile the time-varying network performance under different constellation options; (2) leveraging StarPerf, we evaluate and compare the performance of three state-of-the-art LEO constellations to obtain insights on network optimization for mega-constellations; (3) based on these insights obtained, we further propose an adaptive relay selection algorithm that intelligently chooses on-satellite traffic relay to reduce end-to-end communication latency. Data-driven simulation shows that by properly selecting a LEO satellite as the network relay, end-to-end communication latency can be reduced by up to 62%.

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