Integrating Space Edge Computing with Terrestrial Networks for Futuristic 6G Pervasive On-Demand Services

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***Abstract*—Futuristic 6G technologies will integrate emerging low earth orbit (LEO) mega-constellations into terrestrial networks, promising to provide ubiquitous, low-latency and high-throughput network services on-demand. However, several unique characteristics of satellites (*e.g.,* high dynamics and error-prone operational environments) make it very challenging to unleash the potential of mega-constellations and accomplish these promises above.**

In this article, we study a new computation paradigm, called *“Space Edge Computing (SEC)”*, which wisely combines the advanced computation, network, and storage resources on emerging satellites to achieve pervasive and performant on-demand services for futuristic 6G communications. Specifically, we investigate SEC in three steps. First, we explore the technical feasibility of SEC, and envision a novel integrated satellite-cloud architecture that collaboratively exploits “space edges” and “terrestrial clouds” to provide on-demand services *anytime*, *anywhere*. Second, through a series of quantitative experiments, we showcase SEC’s potential on enhancing the network availability and performance for several quintessential applications. Finally, we conclude the practical challenges facing the SEC, and accordingly outline a list of corresponding new directions for future research.

***Index Terms*—Future 6G Networks, Mega-Constellations, Pervasive On-Demand Services, Space Edge Computing.**

I. INTRODUCTION

Emerging mega-constellation consisting of thousands of low-earth-orbit (LEO) satellites is one of the key building blocks for futuristic 6G networks. Recently, we have witnessed a renaissance in the space industry, which significantly reduces the cost of launching spacecrafts to space, and stimulates an exponential increase in constructing Internet mega-constellations. As compared to their predecessor, recent LEO satellites can be equipped with high-resolution sensors, space-grade multi-core processors, high-speed communication links and multi-functional space software. Satellites in free-space accomplish wide-area network coverage and improve the network availability for terrestrial users, especially for those users in remote or rural regions. While there are several existing technologies like Citizens Broadband Radio Service (CBRS) that can provide communication services in a flexible and low-cost manner without having to acquire spectrum licenses, these terrestrial communication techniques offer limited coverage and data rate as compared to upcoming broadband satellites.

To unlock the power of emerging broadband satellites, the concrete approach for inter-networking LEO mega-constellations and terrestrial networks plays a critical role in the service quality of the entire integrated network. Fig. 1 plots several existing approaches proposed for space-ground integration. First, current operational mega-constellations like SpaceX’s Starlink follow a “bent-pipe” architecture to integrate LEO satellites into ground facilities. Data from the ground are first transmitted to the satellites, which then send the data right back down again like a bent pipe. Second, another inter-networking approach has been proposed in [5], in which ground stations work as access points or gateways for satellite networks (**GSAS**). LEO satellites leverage inter-satellite links (ISLs) to build space routes for long-haul communications. Data packets from users are first forwarded to an access ground station via terrestrial networks, and then forwarded to the satellite backbone in space. Finally, recent studies [7] have proposed a paradigm where users leverage satellite terminals to directly access the ISL-enabled satellite networks (**SDAT**). Satellites work not only as routers, but also as access points or gateways for ground users.

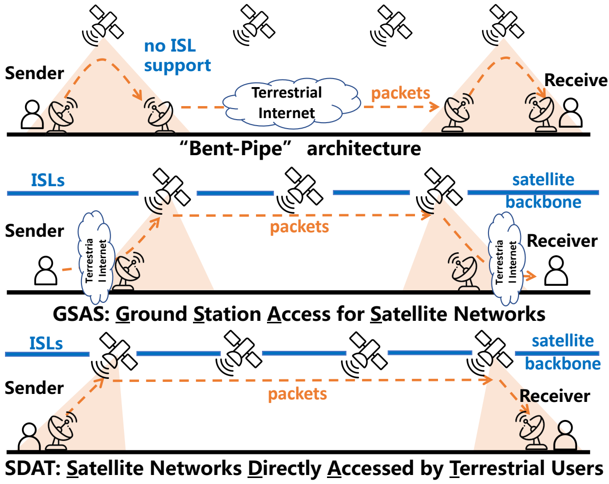

Fig. 1: Existing design-space of space-ground integration.

However, due to a series of unique characteristics of emerging mega-constellations, it is still difficult for existing space-ground architectures to *simultaneously* accomplish pervasive, reliable and low-latency network services. First, the bent-pipe architecture only uses satellites as relays to exchange data between users and ground stations, and its network accessibility is limited as it can only serve users close to certain ground stations. Second, GSAS is also accessibility-limited, as it

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requires well-deployed terrestrial networks between users and ground stations, and can not offer services for users in regions where terrestrial facilities are constrained. Finally, although SDAT can achieve pervasive network accessibility since it does not require a large number of geo-distributed ground stations, the user-satellite connectivity suffers from frequent changes due to LEO dynamics. Users' IP addresses have to be frequently updated, making it difficult to guarantee stable and reliable routes and end-to-end transport connections.

In this article, we study a new computation paradigm, called *"Space Edge Computing (SEC)"*, and explore the potential of integrating SEC with terrestrial networks to accomplish pervasive, reliable and low-latency service for futuristic 6G networks. The key idea behind SEC is to wisely combine and schedule advanced resources (*e.g.,* computation, storage and network resources) in emerging LEO satellites to satisfy various application requirements on-demand.

We carry out our quest in three steps. First, we conduct an in-depth analysis on the feasibility of realizing SEC in emerging satellite systems, and propose a new satellite-cloud integrated architecture in futuristic 6G paradigm which *collaboratively* exploits the heterogeneous computation, storage and network resources in space edges and terrestrial cloud data centers to enable on-demand service anytime, anywhere (§II).

Second, through a series of quantitative experiments driven by public details of real constellation design and orbital information, we quantitatively show the potential opportunities enabled by SEC, and demonstrate how quintessential applications can benefit from the collaborative architecture, regarding network accessibility, reliability and performance (§III).

Finally, we highlight a collection of practical challenges facing the deployment and application of SEC, which are jointly involved by the high dynamics of LEO satellites and the failure-prone, resource-constrained space environment. We also conclude a list of corresponding future research problems (§IV). Future efforts are expected to cope with these challenges and improve the robustness and efficiency of SEC.

II. ON-DEMAND PERVASIVE SERVICE ABOVE THE ATMOSPHERE: SPACE EDGE COMPUTING (SEC)

A. Feasibility Analysis for Futuristic SEC

We first analyze several critical aspects about the feasibility of building edge-like service platforms in space.

Inter-satellite and ground-satellite communications. The total capacity of satellite communication systems has increased significantly over the past decade. For example, during the beta test of Starlink, end users can achieve data speeds varying from 50Mbps to 150Mbps and latency from 20ms to 40ms in most available locations. Many constellations under construction also suggest the use of laser inter-satellite links (ISLs), which can potentially support up to tens or even hundreds of Gbps data transmission rate for inter-satellite communication [8]. Moreover, leading cloud providers such as Amazon and Microsoft are actively deploying their Ground-Stations-as-a-Service platforms [4], allowing satellite operators to use ground services on a flexible "pay-as-you-go" basis with affordable costs, and without the need to deploy their own ground infrastructures. For instance, the reserved wideband services provided by Amazon's ground station services, which enable satellite operators to download their satellite data or build backup downlinks, are billed at a rate of $15 maintenance cost per minute [1].

On-board computation systems. Recently BAE Systems and Boeing are developing their next-generation high-performance multi-core processor for space-computing platforms [6], promising to support complex computational workloads. Researchers also start to explore the feasibility of using commercial off-the-shelf (COTS) devices in space environments. In 2021, Hewlett Packard Enterprise (HPE) announced the COTS Spaceborne Computer-2 [3] which costs less than $20,000, to introduce edge computing and AI capabilities to international space stations (ISS), focusing on astronaut healthcare and image processing, *etc.* Similarly, European Space Agent (ESA) has launched two COTS Astro Pi units to ISS for education-focused experiments in space. Each unit is based on a Raspberry Pi computer, which costs less than $100. The latest progress above demonstrates the feasibility of bringing performant, affordable and compact computation systems to the outer space.

Storage, weight and volume. In addition to the evolved computation and communication capabilities, future satellites may also provide data storage services in space. The storage capacity of spaceborne Solid State Recorder (SSR) has raised from 2Gbit in 2000 to the present 20Tbit per spacecraft. Taking Starlink as an example, the weight of a typical SSR is about 6-20kg, which is about 2.3-7.6% of the weight of the latest launched Starlink satellite. The volume of SSR is about 250mm*250mm*250mm, less than 3% of a Starlink satellite.

Launch capability. SpaceX has already been able to position sixty 260kg satellites into orbit in one launch. The current Falcon-9 first-stage booster is said to be capable of at least 10 flights, which further decreases the cost. The enhanced launch capability and reduced cost thus make it probably feasible to deploy mega-constellations with thousands of satellites in orbit within a few years and accomplish pervasive satellite coverage.

B. Integrating SEC with Terrestrial Networks

Thus, we envision a new integrated architecture for future wireless communication: integrating Space Edge Computing (SEC) with terrestrial networks for future 6G pervasive on-demand services. As shown in Fig. 2, collectively the integrated architecture consists of three primary segments.

- **Satellite edge network.** This segment includes a number of ISL-enabled LEO satellite edges which inter-connect with each other and construct a network. We use space edge and satellite edge interchangeably. In each satellite, at least one server is embedded to provide computation and storage capabilities. Therefore, beyond working as a router, each edge-like satellite can also provide computation and storage services for specific requirements on demand.
- **Distributed ground network.** In this segment, a collection of geographically distributed ground stations and cloud data centers are deployed. Ground stations inter-connect LEO

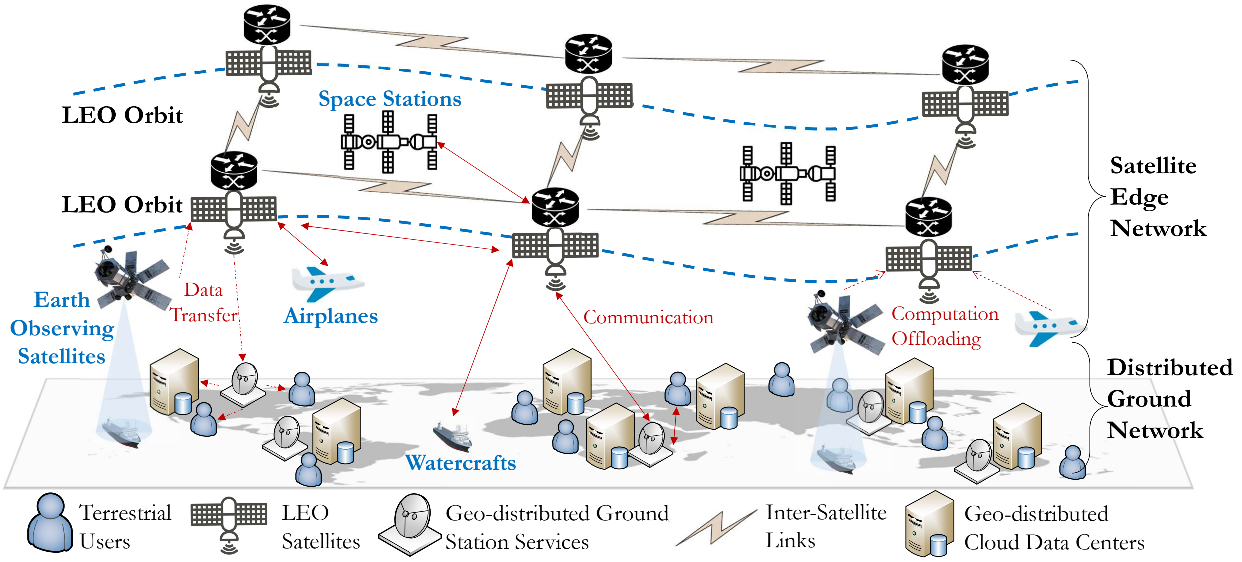


Fig. 2: Integration of SEC and terrestrial networks for pervasive on-demand services at a global scale.

	Shell	# Orbits	# Sats/Orbit	Height (km)	Inc.
Starlink	S1	72	22	550	53°
	S2	72	22	540	53.2°
	S3	36	20	570	70°
	S4	6	58	560	97.6°
	S5	4	43	560	97.6°

TABLE I: Primary constellation parameters.

satellites and terrestrial cloud data centers which can provide high-performance computation and storage capabilities on the ground. By integrating satellite edges with terrestrial cloud platforms, the entire architecture facilitates pervasive computation, storage and network services globally.

- **Terrestrial users.** The satellite-cloud architecture serves various customers in the integrated satellite and terrestrial network, including but not limited to terrestrial Internet users, maritime watercrafts and remote spacecrafts, *etc.* Note that there might be multiple satellites visible to a ground user, and a user's terminal selects the access satellite based on certain principles configured by the satellite operators, *e.g.,* based on the distance, single strength or traffic workloads.

III. NEW OPPORTUNITIES

A. *Enabling Pervasive Low-latency Network Services*

Global content distribution. Content Distribution Networks (CDN) play an important role in today's terrestrial networks. However, a recent measurement study [13] has revealed that the effectiveness of existing cloud-/edge-based CDNs is limited due to their insufficient infrastructure deployment and the unstable last-mile access. From a global perspective, there are still a large number of users suffering from poor content accessibility or high latency due to the scattered data center deployment.

SEC is promising to extend the availability and network performance of today's terrestrial CDNs. Intuitively, contents can be stored in satellite caches, which are operated in LEO and close to terrestrial users. We conduct an experiment to quantitatively analyze the reachability and access latency from different ground locations to their closest LEO satellite in the first phase of Starlink constellation, which plans to launch about 4400 satellites in total. We quantify the reachability of a ground user by the number of reachable satellites in the current location of the user, and quantify the access latency by the round-trip time (RTT) between a ground user and the satellite it connects to. According to the FCC filings, the angle at which a Starlink satellite is reachable is about 25°. Satellites in each shell inter-connect with each other following a +Grid topology, in which each satellite connects two adjacent neighbors in the same orbit, and other two adjacent neighbors in the left/right orbit. Table I summarizes the primary constellation parameters, including the number of orbits, the number of satellites in each orbit, orbital height and inclination. We calculate the latency by the method proposed in a recent satellite analysis tool [10].

Fig. 3 shows the number of reachable satellites, and Fig. 4 plots the RTT estimations in various locations that differed in latitudes. We observe that in most terrestrial locations, the number of simultaneously reachable satellites varies from 15 to 40. Since most satellites in the constellation are operated in the inclined orbits, the reachability concentrates on latitude range [60°S,60°N]. In addition, since the orbital height is less than 600km, all LEO constellations enable about 3-8ms propagation RTT inside their coverage. Our experiment results indicate that if satellites are properly designed to cache Internet contents, allowing users to fetch data objects directly from the closest reachable satellite instead of fetching data from the remote original server, the content access latency can (potentially) be significantly reduced, especially for those users in remote or rural areas suffering from limited terrestrial networks. Note that it is also very important to protect data privacy and prevent leakage for satellite caches, as satellites are operated in a public, intermittent and resource-constrained environment. We leave the data privacy issue in satellite edges as our future work.

Wide-area real-time communication (RTC). Recent years we have seen a dramatic rise in Real-Time Communication

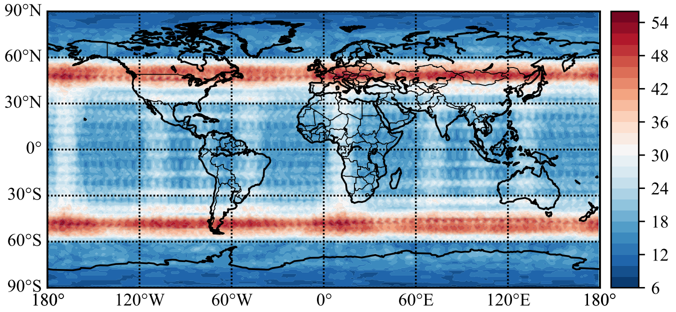


Fig. 3: The number of reachable satellites in different geo-distributed locations.

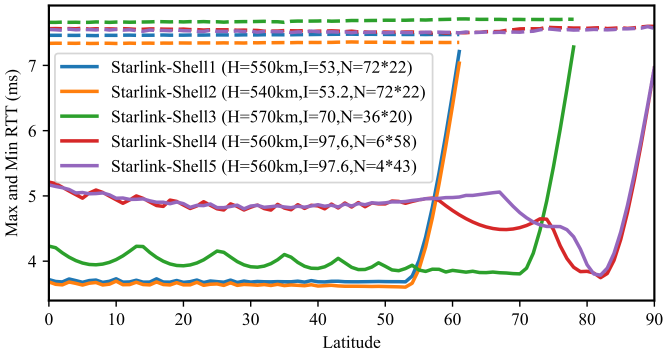


Fig. 4: RTT (ms) estimations between Starlink satellites and ground users in different geo-distributed locations. H: orbit height. I: orbit inclination. N: number of satellites. The dotted/solid line represents the maximum/minimum values.

(RTC) applications, *e.g.,* videoconferencing, interactive immersive applications (*e.g.,* AR/VR), emerging remote surge and autonomous vehicles *etc.*, with significantly stringent latency requirements on underlying networks. As the end-to-end latency is very critical for these applications, a well-known approach to optimize RTC latency is leveraging cloud-based *RTC relays* to forward RTC traffic [9]. This method leverages geographically distributed cloud data centers that are connected by an overlay network to construct highly performant wide-area networks.

SEC extends the optional set of RTC relays: servers in either terrestrial cloud data centers or LEO satellites can be selected as RTC relays to control and forward RTC traffic. The potential benefit of using in-orbit relays is two-folder. First, for long-distance communications (*e.g.,* cross-continent RTC sessions), inter-connected satellites can build obstacle-free, low-latency paths and avoid meandering routes. Second, laser links can communicate at the speed of light, which is about 47% faster as compared to that in existing terrestrial fibers.

To quantitatively demonstrate the potential latency reduction made by SEC for long-distance communication, we conduct an analysis to calculate and compare the achievable latency by terrestrial networks and by the satellite-cloud integrated architecture. Fig. 5 plots the low-latency communication path for wide-area cross-continent sessions enabled by SEC. Specifically, dash arrows indicate the terrestrial Internet paths connecting two populated areas on different continents, while solid arrows refer to the path constructed by networked satellite edges. We identify these paths by the `traceroute` tool between two vantage points in corresponding cities. In practice, the terrestrial path is generated by Internet routing protocols (*e.g.,* BGP), following specific policies in different ASes. Solid arrows indicate the shortest paths built upon a large number of satellite edges. Here satellites are interconnected following the topology of Starlink's first shell. Quantitatively, we find that SEC can achieve significantly reduced latency by avoiding meandering paths. In each case shown in Fig. 5a and 5b respectively, the end-to-end propagation latency is about 106.05/124.8ms over terrestrial paths and 34.6/47.8ms over SEC paths. Since Starlink is still under heavy development today and we have very limited access to them, in this experiment we mainly focus on the propagation latency which is determined by the network topology and the speed of light.

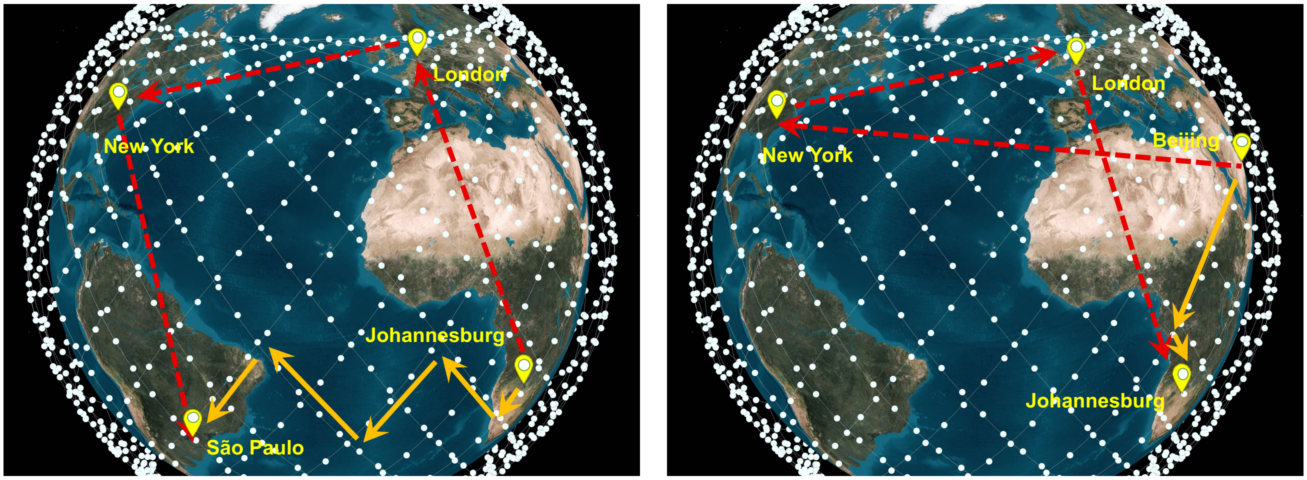
In addition to the pervasive and low-latency capability, recent technologies also enable high-throughput LEO communication for terrestrial users. For example, a recent measurement study [12] demonstrates that the current form of Starlink can provide 100-250Mbps download speed, which is sufficient for high-definition video streaming. Combining the low-latency and high-throughput potential, SEC promises to support various emerging applications with delay- and bandwidth-sensitive requirements, such as self-driving, mixed reality, remote surgery *etc.* in the future. Due to the page limit, we leave the analysis on SEC's application in other scenarios to our future work.

B. *Reliability Enhancement*

Typically, network reliability captures how long the network infrastructure is correctly functional without interruptions. In futuristic 6G networks which integrate LEO satellites into terrestrial networks, sustaining high reliability is still very difficult in the intermittent, error-prone environment.

Reliability strengthening agent. To eliminate frequent user address updates, SEC allows satellite operators to deploy *reliability strengthening agent* in satellites. In particular, for each terrestrial user, the agent works as an *anchor* which allocates and maintains addresses for terrestrial users in the dynamic environment to guarantee stable network connections. Fig. 6 shows an example illustrating the basic idea of SEC-based agent. The network topology changes in each slot due to the LEO dynamics. Two ground users src and dst establish a communication session over the satellite network. One satellite is selected as the reliability strengthening agent, and it allocates unchanged addresses to src and dst. During the session, src forwards packets to the agent first, and then forwards to the dst. Although the ground-satellite connectivity changes from slot 1 to slot 3, the source-to-agent and agent-to-destination connections can be kept stable since terrestrial users do not change their addresses under the fluctuating topology.

Network-driven fast recovery. In conventional networks, loss recovery is typically controlled by the sender. For example, a TCP sender estimates current loss rate based on the received ACK sequence number, and re-sends lost packets to guarantee reliable transmission. However, for long-haul communications in satellite networks where loss could be common and frequent,



(a) Communication path from South Africa to Brazil.

(b) Communication path from China to South Africa.

Fig. 5: Potential low-latency paths enabled by SEC. Dash arrows indicate the default terrestrial path generated by today's Internet routing protocol (*e.g.,* BGP) and solid arrows refer to the low-latency paths built upon networked space edges.

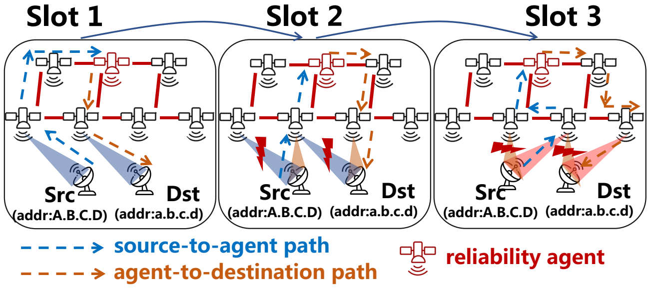


Fig. 6: Reliability strengthening agent based on space edges.

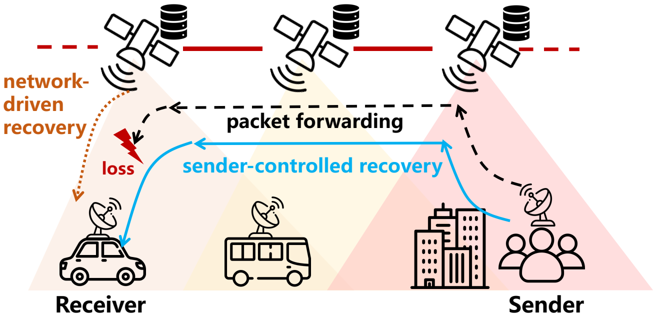


Fig. 7: Network-driven loss recovery based on space edges.

a sender-controlled recovery mechanism can be slow and inefficient. SEC can improve the recovery efficiency by adopting *network-driven fast recovery*. In particular, SEC can cache packets on error-prone paths. As shown in Fig. 7, when a packet loss occurs, the sender-controlled mechanism needs to re-send the packet from the sender, while the network-driven solution achieves fast and efficient packet recovery by re-sending the lost packet from an edge close to the receiver.

C. Improving Transmission Efficiency for Space Missions

SEC can also be used to improve the transmission efficiency for space missions, such as high-quality earth observation (EO) services. In recent years, EO data are growing in size and variety at an exceptionally fast rate. Data collected by sensors in space needs to be downloaded to terrestrial control and operating centers for further data processing. Existing methods for delivering data from space can typically be classified into two categories: (i) leveraging ground stations to download data when a sensing satellite arrives at the transmission range of a certain ground station [15]; or (ii) exploiting geostationary satellites to build a two-hop bent-pipe path for data delivery.

EO services are used in many scenarios, including situations where EO data collected in orbit is expected to be delivered to the ground as soon as possible. Examples include disaster management, emergency response, remote surveillance and security. However, the above methods for EO data download suffer from limited transmission efficiency. In the former method (i), because sensing satellites move at high velocity during their orbit, a certain ground-satellite link can last for only a few minutes (*e.g.,* 3min or less) in one pass. It may take multiple passes (*e.g.,* several hours or even days) to complete the entire EO data delivery. The latter method (ii) exploits geostationary satellites to form a stable delivery path to forward EO data to the ground. While geostationary satellites working at 36,000km altitude can relay and forward data for sensing satellites and facilitate long-duration stable communication, this method still suffers from high transmission completion time due to the limited data rate from the sensing satellite to GEO satellite relays [14]. SEC enables two opportunities to improve the transmission efficiency for EO tasks.

Fast data delivery via networked space edges. We conduct a quantitative experiment based on real constellation information and EO data trace to demonstrate the effectiveness of SEC on reducing the transmission completion time. We build a simulator which simulates sensing satellites based on the public information of the Dove EO constellation, which is currently one of the largest EO constellations, and simulates networked satellite edges based on the Starlink broadband constellation.

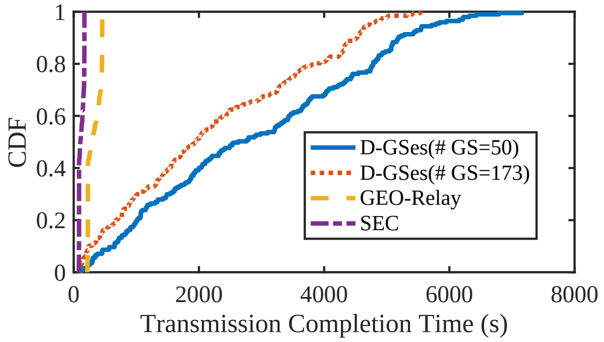


Fig. 8: Transmission completion time (TCT) of 12h EO data of Amazon Forest from Dove EO constellation to terrestrial data centers.

Satellite edges inter-connect with each other following the +Grid topology. The ground station topology is configured based on the information of real ground station infrastructures [2]. In our simulator, once a sensing satellite collects EO data, it connects to a nearby satellite edge, which then exploits the shortest path to forward EO data back to the ground data center.

Fig. 8 plots the CDF of transmission completion time (TCT) of delivering 12-hour EO data collected from Amazon Forest by networked SEC, and by other two existing methods, *i.e.,* download by distributed ground station networks with different numbers of available ground stations (denoted as D-GSes), and download by GEO relays (denoted as GEO-Relay). In particular, TCT is calculated as the duration from the time when an EO satellite starts to download its data, to the time when the collected data is fully delivered to the ground. For ground station networks, we change the number of available ground stations, and the TCT is about 82-7161 seconds (2868.8 on average) under 50 ground stations, and 81-5546 seconds (2205.3 on average) even though 173 distributed ground stations are all used. This is because in the worst case it may take tens of minutes to hours for the sensing satellite to move into the transmission range, and the duration of the visible window of an LEO satellite in one pass is very limited. GEO relays offer stable data transmission but the download latency is about 215-461 seconds (324.3 on average), limited by the insufficient forwarding data rate. SEC achieves 80-172 seconds (121.6 on average) download latency, and reduces up to 94.49% and 62.50% TCT on average as compared to the existing methods.

Reducing bandwidth overhead by on-board intelligence. On-board processing is another promising direction to improve the transmission efficiency of EO data delivery and other distant tasks. Emerging spaceborne computer systems facilitate the run of applications with high computational complexity such as data compression and deep learning [11]. For some remote missions, naively transferring all large-volume space data can impose significant bandwidth overhead on inter-satellite and ground-satellite links and involve high communication power consumption. Exploiting on-board data compression or intelligence technologies to compress raw data, or detect and discard unnecessary information, can significantly reduce the burden on data transmission. For example, a sensing satellite observing the earth can run object detection and classification algorithms to identify and discard unavailable images (*e.g.,* cloudy pictures where targets on the ground are covered by clouds), and accordingly save the bandwidth overhead.

IV. CHALLENGES AHEAD AND FUTURE DIRECTIONS

A. *Dynamics in the Core Network Infrastructure*

Unlike traditional mobile networks where only end users are mobile (*e.g.,* cellular networks) or dynamics are limited to a local area (*e.g.,* vehicular ad-hoc networks), the high velocity of LEO satellites results in *high dynamics in the core network infrastructure at a global scale*. Such dynamics result in issues such as frequent address updates and connectivity disruptions, and accordingly impose significant challenges on sustaining stable and long-duration SEC services. We highlight two future research directions related to taming the dynamics in SEC.

Resilience techniques in failure-prone space environments. The space backbone network of the SEC architecture is exposed in the complex outer space environment, suffering from risks such as debris collisions and radiation hazards. All these factors can result in node or link failures in space. Therefore, future researches are expected to study the resilience techniques for SEC, *e.g.,* resilient network protocols and resource scheduling techniques, to accomplish robust and highly-reliable SEC services in failure-prone environments.

Content distributions upon the satellite-cloud integrated architecture. Since SEC promises pervasive and low-latency content access, it is thus very important to decide how to collaboratively place Internet contents (*e.g.,* web contents, video clips) on satellites and clouds. Essentially, satellite caches and cloud caches complement each other, in terms of their coverage, performance and cost. For example, satellite caches achieve better coverage especially for users in remote and rural regions, but also involve higher delivery cost as compared to cloud platforms. A wise content provision approach is expected to balance the cost and effectiveness for various content distribution tasks under the integrated architecture.

B. *Scarce Resources in Space*

Space resources are still precious and limited as compared to well-provisioned and well-optimized terrestrial infrastructures. Thus, it is very important to properly and efficiently exploit the precious resource in space.

Space-ground collaborative computation. As we have introduced previously, in the SEC architecture, earth-observing satellites can pre-process data acquired in space, *e.g.,* through deep-learning models, to detect and discard unnecessary information. In particular, machine learning models contain a sequence of layers to sequentially process input images and extract features. However, a high-accuracy model for object detection or classification can still involve high computation overhead on power-limited satellite edges. To accelerate the EO data processing, the entire model can be properly divided into two parts collaboratively executed by satellites and terrestrial data centers respectively. Future works are expected to find the optimal division for various on-board processing tasks.

C. Limited Power Budget

Typically, LEO satellites can spend over 30% of their orbital period under the earth's eclipse, during which they have to be powered by rechargeable batteries. Satellite systems typically include a number of subsystems working for various dedicated functions. The communication subsystem may take a large portion of the entire power budget. Although the batteries can be recharged by solar energy, the depth of discharge (DoD) can significantly affect the battery lifetime. Key technologies for SEC, including space routing, transmission control, resource scheduling and data processing are expected to be energy-efficient and battery-friendly to extend the lifetime of satellites.

V. CONCLUSION

Recent evolution in both spaceborne hardware and software envisions a new paradigm of computing service, *i.e., "Space Edge Computing (SEC)"*. This article explores SEC in three aspects. First, we analyze the feasibility of SEC and propose a novel integrated satellite-cloud architecture. Second, through a series of quantitative experiments, we identify several use cases demonstrating that SEC can potentially enhance the network accessibility, reliability and performance for various applications. We finally conclude key technical challenges facing the SEC, and highlight related future directions.

VI. ACKNOWLEDGMENT

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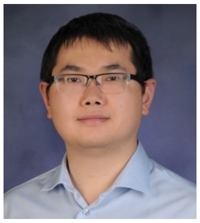

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