Closing the Performance and Management Gaps with Satellite Internet: Challenges, Approaches, and Future Directions

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I. Introduction

Recent advancements in low-Earth orbit (LEO) satellites represented by large constellations and advanced payloads provide great promises for enabling beyond 5G and 6G telecommunications and high-quality and ubiquitous Internet connectivity to everyone anywhere on Earth. LEO satellite networks are envisioned to bridge the urban-rural connectivity gap for the digital divide. However, the digital divide can hardly be closed by only providing connectivity to rural and remote areas. Various unprecedented challenges brought by the emerging satellite Internet still need to be resolved, such as inconsistent end-to-end performance guarantees and a lack of efficient management and operations in these areas, which are referred to as "performance gap" and "management gap", respectively. This position paper will briefly discuss these gaps, approaches to addressing the gaps, and some research directions based on our recent works [1]–[8].

II. Gaps Beyond Connectivity

In this paper, the satellite Internet is considered to be enabled by the emerging LEO satellite constellations, such as SpaceX's Starlink, Amazon Kuiper, Eutelsat OneWeb, and Telesat Lightspeed. If we consider the connectivity gap as the urban-rural connectivity gap, where rural and urban regions do not have access to high-speed Internet with "a download speed of at least 50 Mbps and an upload speed of at least 10 Mbps" [9], such a gap can be closed with the emerging satellited Internet enabled by LEO satellite constellations. However, does it mean we can close the digital divide? The answer is no, as we still need to close the gaps identified as performance and management gaps as described in the following.

A. Performance Gap

To examine the performance gap, let us focus on the fundamental throughput and latency performance with real-world data. Based on the available Ookla's Internet speed test results in Q2 2023, high-speed Internet connectivity can be achieved across the regions, but the high variance of performance metric values across regions exists, in particular for the latency performance. Due to the broad landscape and the communities across rural and remote areas, we can take the latency performance in Canadian provinces as an example. Specifically, latency results in two adjacent geographical tiles in Nunavut are 257 ms and 600 ms on fixed and mobile network connection types as defined in [10], respectively. For satellite Internet, the data shown in the Starlink availability map (https://www.starlink.com/map) on September 5, 2023, indicates that the variance in latency performance exists across Northern and Arctic regions. For example, the latency is 54–67 ms in Saskatchewan, 38–52 ms in British Columbia, and 44–56 ms in Quebec, while in Northwest Territories and Nunavut, it is 60–83 ms and 60–94 ms, respectively. From these results, the satellite Internet can reduce the latency values but not necessarily resolve the latency variance issue. In addition, different LEO satellite network operators may use different schemes for the internetworking between space and ground entities, and the choice of schemes has a large impact on the latency performance [11].

B. Management Gap

With the increasing implementation of terrestrial telecommunications infrastructures such as the fiber point of presence (PoP) in rural and remote areas, many of the traditional satellite-dependent communities [12] are envisioned to have access to space, aerial, and ground entities, which can transform the traditional satellite-dependent community networks (SDCNs) into satellite-integrated CNs (SICNs) [1], featuring an integration of heterogeneous networks and segments to provide broadband, resilient, and agile end-to-end connections. These SICNs will embrace significant autonomy, intelligence, and scalability in network management. However, the users of SICNs may represent a small portion of the population but can be geographically distributed across a country.

However, transforming from SDCNs to SICNs imposes unprecedented challenges. The complex, heterogeneous, and dynamic nature of the space and ground components in an integrated non-terrestrial networks (NTN) infrastructure introduces persistent operations challenges. For example, malfunctioning components, atmospheric events, or anomalous traffic on any network segment can easily degrade or disrupt network services. Furthermore, network management and operations efforts need to ensure low costs with high efficiency, resilience, and scalability. These challenges are collectively perceived as the management gap.

III. Proposed Approaches & Future Directions

Some approaches to addressing the performance and management gaps with their research directions are discussed in the following.

A. Deploying TN entities

There are different ways of resolving the regional performance variance on a satellite Internet. One way is to optimally deploy additional TN entities such as an Internet exchange point (IXP), PoP, and edge data center (EDC) closer to a community. IXPs can make the Internet faster and more affordable [13], and placing PoPs close to communities can enhance affordability, reliability, and equity. An EDC can be deployed to provide consistent low-latency performance. An EDC can be deployed in rural and remote areas similar to AWS Local Zones deployed in large metropolitan areas, where the AWS Local Zones is an infrastructure deployment that places compute, storage, database, and other services closer to end users to achieve single-digit millisecond latency.

The design and deployment of TN entities for a satellite Internet can lead to a rich research direction. Although relevant works such as content delivery networks (CDNs) exist in the literature, the optimal deployment of the TN entities for a satellite Internet still demands new solutions. In addition, how to use these TN entities to guarantee consistent performance for multiple metrics in addition to throughput and latency needs to be investigated.

B. Multi-layer satellite networking

LEO satellites, once launched, are physically settled into different orbital shells. These shells can be viewed as layers [3]. In this context, how to design networking schemes among the satellite nodes in these layers for different tasks becomes a research question. The idea of satellite networking in different layers can be rooted in the work in [14], where multi-layer satellite networking (MLSN) was coined to improve the throughput. Here MLSN is considered a general approach for satellite internetworking that can enable reliable data transmission, disruptive/delay-tolerant networking, and resource management. The adoption of the layers concept can help achieve the abstraction that is needed among the inter-orbital and intra-orbital constellations of satellites operated by one or more providers. The multi-layer networking may occur via multiple shells of a large constellation with LEO satellites, such as Starlink's mega-constellation [15], although the cross-shell networking is considered complex [16]. Layers of satellite networks can help formulate the internetworking schemes between geostationary (GEO), medium-Earth orbit (MEO) and LEO satellites. Additional conceptual layers on top of the physical typologies can also be considered.

Our recent works in [2], [3] have shown the efficiency of applying the MLSN approach to address the timing requirements and resilience assurance for message transmissions in telemetry, tracking, and control (TT&C) missions. MLSN schemes providing consistent performance metrics with access fairness across areas in additional scenarios need to be made. How to apply MLSN to security countermeasures, resilience assurance, and sustainable satellite network operations suggests another research direction.

C. Autonomous maintenance

Equipping a satellite Internet infrastructure with autonomous capabilities such as autonomous maintenance (AM) capability [1] can offer ideal solutions to close the management gap. Such solutions can handle the increasing complexity of a satellite Internet consisting of various NTN/TN elements and mitigate performance degradation. In this case, AM can enhance network performance on an SDCN or SICN in supporting various applications for healthcare, education, businesses, etc. Through a data-driven architecture, generalizable anomaly detection and mitigation schemes based on novel machine learning (ML) models and frameworks can be designed. As uninterrupted use of satellite Internet services is usually not guaranteed, AM can also help enhance resilience aligned with service-level agreements (SLAs).

From another angle, as indicated in the Global Connectivity Report 2022 [17], there are 30% of the global population covered by a broadband network but are not online due to lack of affordability, lack of access to a device, and/or lack of awareness, skills, or purpose. Bringing the AM solutions can help resolve the issues that prevent people from using the broadband networks, including satellite Internet. For example, self-diagnosing the issues and self-managing the network can reduce the operating and capital expenditures.

One research direction is to enable resilience and responsive actions to consequences caused by anomalous events on the satellite Internet. This research includes the ML-based root cause analysis (RCA) based on the multivariate time-series (MTS) data from LEO satellite networks [7], [8]. The MTS data based on onboard states, network measurements, diagnostic signals, and protocol traces can be used to devise efficient ML-based solutions. These data types may also be used for threat detection caused by malicious attacks on NTN and TN segments of a satellite Internet. This research needs to consider standards-based NTN architectures to derive generalizable fault identification and localization schemes through transfer learning and federated learning with novel ML models and frameworks. The generation of high-quality open datasets on different entities of a satellite Internet to facilitate the design and benchmarking of ML-based RCA solutions is another important research.

From the perspective of artificial intelligence (AI) for IT operations (AIOps), developing cross-cutting AI services based on the entire life-cycle of satellites can address performance and management gaps and can enable new application domains [6], such as space circular economy, satellite-integrated networks, green space communication, and digital twinning.

D. NTN-integrated networking

With the consideration of space-air-ground entities on an NTN, there are various topics that need to be explored in NTN-integrated networking (NTN-IN). For example, the optimal trajectory design of aerial network entities, including unmanned aerial vehicles (UAVs) [4], resource allocation and deployment can address the needs for different scenarios. The optimal placement of the ground infrastructures, such as IXPs, POPs, and EDCs, can provide consistent end-to-end performance assurance on a satellite Internet.

In software-defined networking (SDN) enabled LEO satellite network [18], research topics such as joint controller and gateway placement in an SDN-enabled can be explored to maximize the average network reliability. Flow setup time minimization and efficient flow table management are also active research topics due to the frequent handovers and limited flow table size on small satellites. NTN-based open radio access network (O-RAN) [19] can provide potential solutions to closing the management gap while the architecture design, functional split optimization, and radio resource management are open research problems.

NTNs and TNs provide essential connectivity to all users and devices, which enable many new digital services to run on a satellite Internet, such as the Internet of Things (IoT) applications and services for environmental monitoring and smart agriculture/aquaculture. The support for new digital services following the NTN-IN approach needs to be explored in various scenarios in rural, remote, and hard-to-reach places.

IV. Conclusion

Emerging satellite Internet is expected to be pivotal in the next-generation global telecommunications infrastructure and beyond. It can strongly enable ubiquitous Internet connectivity and help accelerate the implementation of the UN's Sustainable Development Goals in many ways, but there is still much room for improvement. The performance and management gaps discussed in the paper demand new approaches and research directions on the way of closing the urban-rural connectivity gap for the digital divide.

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