Titre: Title:	Access Inequality in LEO Satellite Networks: A Case Study of High-Latitude Coverage in Northern Québec
Auteurs: Authors:	Mohammed Almekhlafi, Antoine Lesage-Landry, & Gunes Karabulut Kurt
Date:	2025
Type:	Article de revue / Article
Référence: Citation:	Almekhlafi, M., Lesage-Landry, A., & Karabulut Kurt, G. (2025). Access Inequality in LEO Satellite Networks: A Case Study of High-Latitude Coverage in Northern Québec. IEEE Open Journal of Vehicular Technology, 6, 1613-1630. https://doi.org/10.1109/ojvt.2025.3575546

IEEE Open Journal of
Vehicular Technology

Received 10 May 2025; accepted 23 May 2025. Date of publication 2 June 2025;
date of current version 25 June 2025. The review of this article was coordinated by Editor Lipeng Zhu.

Digital Object Identifier 10.1109/OJVT.2025.3575546

Access Inequality in LEO Satellite Networks: A Case Study of High-Latitude Coverage in Northern Québec

MOHAMMED ALMEKHLAFI [1] (Member, IEEE), ANTOINE LESAGE-LANDRY [2] (Senior Member, IEEE), AND GUNES KARABULUT KURT [1] (Senior Member, IEEE)

(Invited Paper)

[1]Department of Electrical Engineering, Polytechnique Montreal & Poly-Grames, Montreal, QC H3T 1J4, Canada
[2]Department of Electrical Engineering, Polytechnique Montreal, Mila & GERAD, Montreal, QC H3T 1J4, Canada

CORRESPONDING AUTHOR: MOHAMMED ALMEKHLAFI (e-mail: mohammed.al-mekhlafi@polymtl.ca).

This work was supported in part by Fonds de recherche du Québec secteur Nature et technologies (FQRNT) and in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada Alliance under Grant ALLRP 579869-22 ("Artificial Intelligence Enabled Harmonious Wireless Coexistence for 3D Networks (3D-HARMONY)").

ABSTRACT Low Earth orbit (LEO) satellite networks play a crucial role in bridging the digital divide, particularly in remote and high-latitude regions. However, access inequality remains a significant challenge, limiting broadband connectivity for communities in northern areas compared to mid-latitude urban regions. This study reviews recent advancements in non-terrestrial networks (NTNs). We conduct a detailed analysis of coverage disparities in LEO satellite networks considering LEO networks, namely Starlink, Telesat-like, Kuiper-like, and OneWeb, with a specific focus on Québec, Canada versus urban centers in New York City, USA. Our findings highlight a significant disparity in the number of visible satellites resulting in increased transmission delays and reduced network reliability in high-latitude regions. Additionally, we observe that higher elevation angles, more accessible in mid-latitude regions especially for Starlink and Kuiper, contribute to superior signal quality and transmission rates. To mitigate this gap, we propose an inter-constellation/orbit roaming mechanism that enables ground users to be served by different LEO constellations—leveraging OneWeb's and Telesat's strong polar coverage along with the high satellite density of Starlink and Kuiper at mid-latitudes. Jointly, terrestrial network (TN) expansion can enhance signal quality and transmission efficiency, particularly in underserved areas where NTNs act as edge computing and backhaul infrastructures. Additionally, the associated challenges—such as roaming handovers, and radio resource and network slicing management are discussed in detail, where designing a unified management and control entity to ensure seamless interoperability is not a trivial task. Furthermore, we envision wireless power transfer through either relay-based (ground-to-satellite-to-ground) or direct (satellite-to-ground) power beaming as a sustainable approach to energize TN components in remote regions. These strategies collectively support the scalability and resilience of NTNs in bridging the global access inequality.

INDEX TERMS Access inequality, digital divide, low Earth orbit, non-terrestrial networks.

I. INTRODUCTION

Non-terrestrial networks (NTNs) are increasingly recognized as a cornerstone in the evolution of 6 G and beyond communication systems. NTNs are anticipated to support various 6 G and beyond applications including, but not limited to, eHealth, automotive, positioning, and public safety to ensure service continuity, ubiquity, and scalability [1], [2], [3]. According to the 3 rd Generation Partnership Project (3GPP) standard, continuity refers to providing service in situations where terrestrial networks are not feasible. NTN networks will also play a critical role in the scalability of meeting the growing demand for advanced communication services by providing

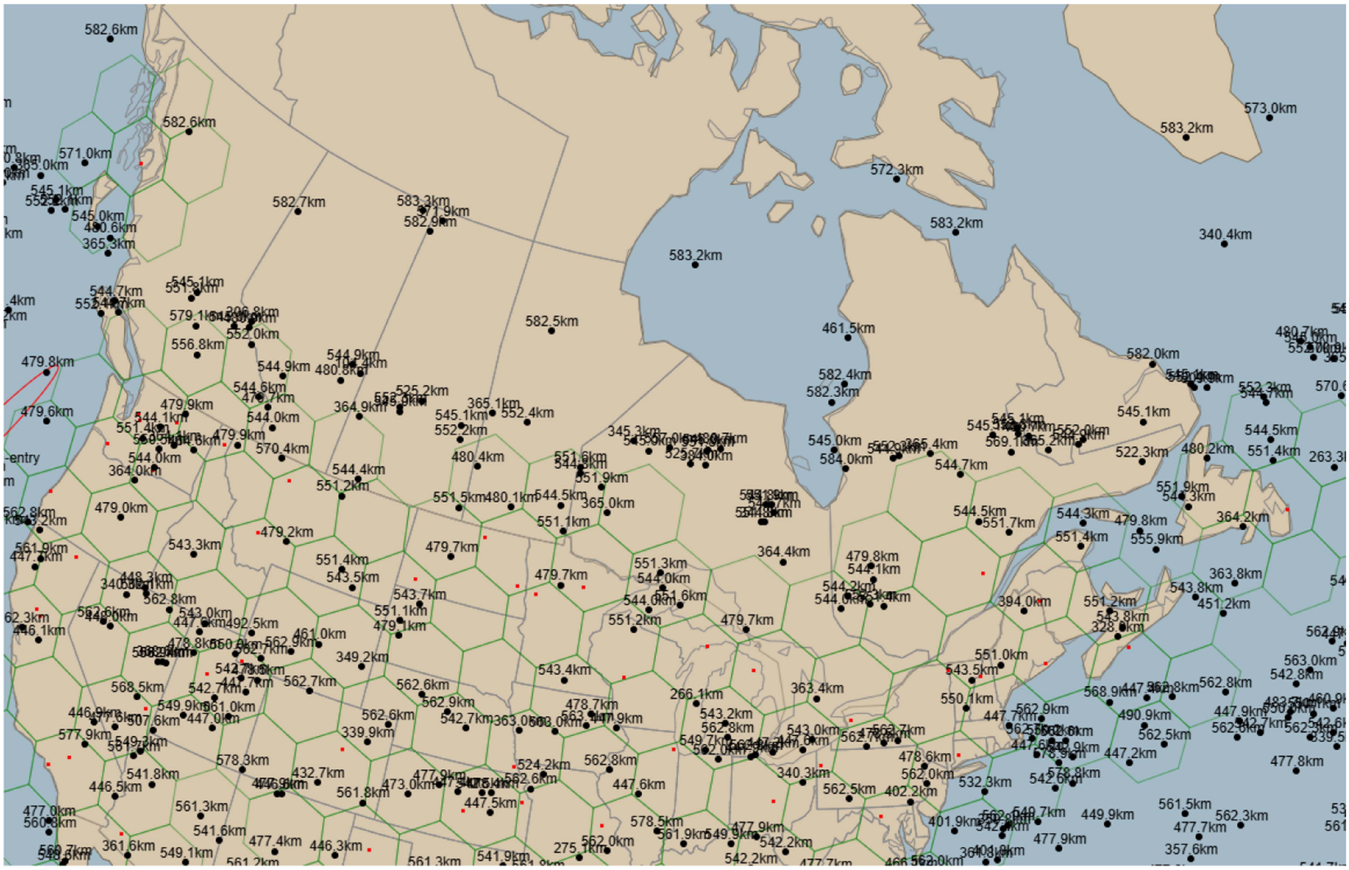


FIGURE 1. **Snapshot of Starlink satellite constellation, created using [5].**

seamless global connectivity, supplementary computational resources, and efficient backhauling alternatives [4]. NTNs are considered cost-effective and efficient solutions for ensuring ubiquitous connectivity in scenarios where network coverage is disrupted due to natural disasters or the destruction of terrestrial infrastructure. These advantages are largely due to the extensive coverage provided by NTNs' satellites, including highly elliptical orbit (HEO), geostationary orbit (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) satellites [3], [4].

A. DIGITAL DIVIDE AND CHALLENGES

Among the various satellite architectures, LEO and MEO satellites are particularly well-suited for emerging applications that demand low latency and high data rates. Their closer proximity to the surface of the Earth enables higher throughput and significantly lower latency compared to traditional GEO satellites [3]. In this context, LEO satellite networks, such as SpaceX's Starlink [6], Amazon's Project Kuiper [7], and Eutelsat's OneWeb [8], are deployed as large-scale constellations consisting of hundreds or even thousands of satellites distributed across multiple orbital planes. In this context, NTNs, such as OneWeb and Telesat Lightspeed, are designed to comply with 3GPP standards and support integration with terrestrial mobile infrastructure to enable wide-area public connectivity. In contrast, private satellite systems like Project Kuiper and the current phase of Starlink operate as proprietary, vertically integrated platforms that prioritize direct-to-user services, typically outside standardized mobile network frameworks. This LEO configuration ensures continuous global coverage and facilitates low-latency, high-speed Internet connectivity. Nonetheless, challenges related to the digital divide and equitable access remain unresolved, particularly in remote regions, necessitating further research and the development of innovative solutions.

LEOs are identified as a viable component of airborne systems for addressing–if not eliminating– the digital divide. By ensuring global communication coverage, NTNs significantly contribute to the goal of universal connectivity. Despite their global coverage potential, LEO constellations exhibit disparities in service equity between regions [9], [10]. For instance, northern Québec, a high-latitude area in Canada, experiences poorer satellite coverage than mid-latitude regions such as the United States. This is especially evident in the Starlink network, see Fig. 1. The issue arises from optimizing satellite networks for densely populated areas within mid-latitudes, where higher ground track densities ensure consistent connectivity. Additionally, Earth's curvature and satellite trajectories result in satellites spending less access (coverage) time in high-latitude areas compared to mid-latitudes, where their ground tracks span longer arcs. As a result, high-latitude regions like northern Québec face several challenges, including less frequent satellite revisits, suboptimal elevation angles, and inadequate ground infrastructure, which collectively degrade the quality of service.

In light of the above discussion, several works have highlighted the digital divide [9], [10], [11], [12], [13], [14]. In [10], the authors studied the digital divide in Canada, which refers to the gap between Canadian users with access to high-speed internet and those without. The paper discusses the significant impacts of the divide on rural communities. Specifically, the study emphasizes the urgent need to bridge this gap, noting that 19% of Canadians live in hard-to-reach areas where the lack of internet access has adversely affected daily activities, such as students submitting assignments during the COVID-19 pandemic. The authors highlight the potential role of LEO satellite constellations as a solution to this issue, either by providing direct internet access or by serving as a backhaul for terrestrial networks. The author of [9] broadened the concept of the digital divide to encompass not only connectivity disparities but also gaps in network performance and management. The performance gap refers to the inconsistent end-to-end performance experienced by satellite Internet users, particularly those in rural and remote areas. For instance, measurements of Starlink-based satellite Internet access reveal significant variability in round-trip time (RTT) results, ranging from 20 ms to 1000 ms [11]. While satellite Internet can achieve low latency values, it does not necessarily address the issue of latency variability. In contrast, the management gap pertains to persistent operational challenges stemming from the complex, heterogeneous, and dynamic nature of integrating NTN airbornes.

The study in [12] identifies key challenges related to the digital divide, categorizing them as follows: 1) Affordability, referring to the high costs of deployment and operation in low-income areas, such as urban regions; 2) Accessibility, which pertains to the absence of infrastructure and challenging geographic or topographic conditions; 3) Spectrum availability, addressing licensing issues and limited bandwidth in remote areas; 4) Energy constraints, caused by the lack of reliable power sources; and 5) Network maintenance difficulties, arising from inaccessible and harsh environments. To tackle these challenges, several solutions were proposed, including the introduction of new service classes tailored to the specific needs of these areas, the use of multi-RAT (radio access technologies) and shared infrastructure to reduce deployment costs, and the adoption of green power technologies such as simultaneous wireless information and power transfer (SWIPT), intelligent reflecting surfaces (IRS), and ambient energy harvesting.

The work done by the Defence Research and Development Canada (DRDC) further explores communication options, including data, video, and voice, for operations in the Canadian Arctic [13]. It considers the challenges posed by adverse conditions such as atmospheric disturbances–both natural and man-made and adversarial attacks on satellites and terrestrial infrastructure. Reference [14] reports on experimental observations from Starlink-enabled wild salmon monitoring sites located in the remote regions of Northern British Columbia, Canada. It underscores several critical challenges, including limitations in energy availability and environmental factors such as extreme temperatures, heavy precipitation, solar storms, and interactions with local wildlife. Additionally, the study highlights the necessity of honouring the cultural and historical values of local communities, which adds another layer of complexity to leveraging the full potential of LEO satellite technology. The authors also suggest some strategies, such as cross-orbit collaboration and the use of coordinated multi-path transmission supported by inter-satellite links (ISL), as promising approaches to achieving seamless and reliable connectivity.

B. CONTRIBUTIONS

This paper seeks to examine the coverage provided by LEO satellites in high-latitude areas, focusing on Northern Québec. The study aims to identify the factors contributing to coverage disparities, i.e., access inequality, and propose strategies to enhance satellite network performance, thereby ensuring equitable access to broadband services across diverse geographic regions. In summary, the contributions of this work are presented as follows:

- We provide an overview of recent activities regarding NTNs' architecture elements, standardization, and LEO constellations. Then, the study presents a comprehensive analysis of access inequality within LEO networks, with a particular focus on the challenges encountered by remote communities in Northern Québec compared to mid-latitude urban regions such as New York City and Québec City. Our findings indicate a significant disparity in the number of visible satellites between these regions, highlighting a fundamental limitation in network accessibility for remote users. This issue particularly affects users of the Starlink and Kuiper networks, where the constrained availability of visible satellites exacerbates connectivity challenges for users in Northern Québec. Such limitations have a direct impact on the reliability, service time, and efficiency of internet services in these remote areas. Moreover, the analysis reveals that higher elevation angles are more readily accessible in mid-latitude regions such as New York City and Québec City, which contributes to improved transmission rates and enhanced link reliability. This advantage is particularly crucial in mitigating signal blockages and minimizing atmospheric interference, factors that are essential for ensuring consistent network performance. Conversely, users in remote, northern regions face persistent challenges in achieving stable and high-quality connectivity, emphasizing the need for targeted improvements in satellite coverage and network infrastructure.
- We propose inter-constellation roaming between LEO satellite networks as a viable solution to mitigate the

impact of access inequality in remote regions. Our approach enables ground users to leverage the advantages of multiple LEO constellations, such as the improved coverage provided by OneWeb and Telesat in polar regions and the high satellite density of the Starlink and Kuiper networks, which facilitates both communication and efficient caching and/or task offloading. We assess this with a comprehensive simulation that validates the benefits of inter-constellation roaming where it shows significant enhancement of reliability and outage probability.
- Challenges such as handover between different constellations, radio resource management, and network slicing are discussed. Future research directions are also presented focusing on developing of a centralized mobility management function (CMMF) as a key solution. In the context of TN expansion, power beaming, either through a relay-based system or direct energy transmission, could provide sustainable power sources for the expansion of TNs.

C. OUTLINES

The remainder of this paper is structured as follows: Section II discusses recent advancements in NTNs. Section III explores the issue of access inequality. Sections IV and V present potential solutions to mitigate access inequality along with associated challenges. Future research directions are discussed in Section VI. Finally, the paper is concluded in Section VII.

II. PRELIMINARIES AND RECENT ACTIVITIES

NTNs have gained significant attention from both academia and industry due to their potential to enhance global connectivity. In this section, we provide an overview of recent advancements in NTN development, with a particular focus on standardization efforts and industrial progress in the deployment of LEO satellite networks.

A. PRELIMINARIES

In this part, we introduce key definitions relevant to NTNs and the essential terminology that will be referenced throughout this paper. These definitions provide a foundational understanding necessary for the discussions and analyses presented in the following sections.

Satellite Orbit *is the trajectory of the satellite as it moves around a celestial body, such as Earth, influenced by gravitational forces*. The orbit's parameters of– such as altitude, inclination, and eccentricity– define the satellite's purpose and the area it covers. Based on this, we can define the satellite revisit time.

Satellite Revisit time (RT) *defined as the time interval between two consecutive observations of the same ground point on Earth's surface by a satellite.* RT is a critical parameter for integrating ground track repeatability with satellite attitude control requirements [15]. RT is frequently utilized as a key performance metric for LEO systems for areas with a lack of continuous coverage and is related to the visibility duration.

Visibility duration *refers to the time interval during which a satellite remains visible within the line of sight of a ground station or observer* [16]. Visibility duration depends on many factors including the satellite's altitude, minimum elevation angle, and satellite orbital speed. To enhance the visibility duration and achieve better coverage, LEO constellations are built in multiple shells.

Elevation angle *is defined as the angle between the surface and the line of sight connecting the ground station (user) to the accessing satellite* [17]. The design of LEO satellite constellations aims to maintain a continuous minimum elevation angle to ensure reliable communication and global coverage [18].

Constellation shell *is a grouping of satellites arranged in orbits sharing similar parameters such as altitude, inclination, and other orbital characteristics* [19]. Each shell is part of the overall constellation design and is used to achieve specific coverage and performance goals.

Following these definitions, satellites are classified based on the satellite orbit into various types, i.e., HEO, GEO, MEO, LEO, and VLEO. Next, we provide a detailed description of these classifications and underscore the importance of each class in addressing global and regional technological needs, with a focus on their role in northern regions. Our discussion is also summarized in Table 1.

- GEO satellites are positioned in the equatorial plane at an altitude of 35,786 km [20], [21]. Due to their considerable distance from the Earth's surface, communication signals between terrestrial users and GEO satellites experience significant propagation delays and attenuation. The typical transmission round-trip time (RTT) for GEO satellites exceeds 250 ms [21], making them unsuitable for latency-sensitive applications. Consequently, the initial focus of GEO-based communications has been on fixed broadband and IoT services, which are less sensitive to delays [20]. Despite this, the stationary nature of GEO satellites—achieved by synchronizing their orbital speed with the Earth's rotation—enables them to cover vast geographical areas effectively, i.e., only three GEO satellites can theoretically provide seamless global coverage, ensuring consistent visibility for terrestrial users.
- HEO satellites operate in elliptical orbits characterized by a significant difference between their closest and farthest point to Earth, known as perigee and apogee, respectively [22], [23]. At their apogee, HEO satellites remain over a specific region for an extended duration, providing quasi-continuous coverage. For HEO, only two satellites are sufficient to provide continuous coverage for each pole of the Earth [23]. Typical configurations of HEOs, such as the Molniya orbit with a 12 hours orbital period and the Tundra orbit with a 24 h period, are optimized for high-inclination angles to ensure stabile coverage on high-latitude regions [23]. This operational flexibility makes HEO satellites indispensable for applications like communication, navigation, and Earth observation in the polar region of Earth re-

TABLE 1. Comparison of Satellite Orbits (VLEO, LEO, MEO, GEO, HEO)

Orbit	Altitude (km)	Revisit Time	Visibility Duration	Constellation Size
VLEO	150 – 450	($<$ 100 min)	Very short (several min)	Small
LEO	500 – 2,000	(minutes to hours)	Short (5 – 50 min)	Large
MEO	2,000 – 35,786	Less frequent (hours)	Long (several hours)	Small
GEO	35,786	Continuous	Permanent visibility	Single-layer shell
HEO	Perigee 500, Apogee $>$ 35,786	Variable	Variable	Single-layer shell

sulting in better access equality in such regions.

- MEO satellites typically operate at altitudes ranging from 2,000 to 35,800 km above the Earth's surface, positioning them between LEO and GEO [2], [24]. This intermediate position offers unique advantages, combining some of the low latency and high coverage benefits of LEO satellites with the extended coverage area and longer RT and visibility duration compared to LEO satellites. MEOs also have a reduced signal propagation delay compared to GEO satellites, improving the quality of time-sensitive applications such as voice and data communications. One of the most prominent uses of MEO satellites is in Global Navigation Satellite Systems (GNSS), such as the United States' Global Positioning System (GPS) [25], [26]. Beyond navigation, MEO satellites are increasingly being leveraged in communication networks, offering expanded connectivity for rural and underserved regions and providing reliable services for maritime and aviation industries. However, deploying and maintaining costs of MEO satellites also presents challenges, i.e., higher costs than of LEO satellites, due to their altitude and the need for advanced propulsion systems.
- LEO satellites usually refer to satellites operating between 500 and 2,000 km above Earth's surface and with orbital plane of inclination angles between 0 and 180 degrees [3]. LEO satellites can achieve latencies as low as 20–50 ms [3], making them indispensable for supporting emerging 6G applications such as IoT deployments in smart cities, autonomous vehicle communication, and extended reality. Companies like SpaceX, OneWeb, and Amazon are spearheading efforts to deploy large LEO constellations, aiming to bridge the digital divide while providing high data rates. However, LEO satellite constellations incur high networking and maintenance costs, with frequent handovers posing challenges for routing and association algorithms [27]. Additionally, the rapid growth in LEO deployments raises concerns about orbital debris, spectrum congestion, and sustainability.
- VLEO[1] satellite constellations, operating at orbital altitudes below 500 km, have become a central focus in advancing NTN architectures [28]. These constellations offer significant advantages, including reduced latency and the cost-efficiency of deploying multiple satellites in a single launch, such as micro-launchers and in-orbit transfer vehicles [29]. Furthermore, VLEOs offer higher revisit frequencies, enhanced optical resolution, reduced collision risk with space debris, and lower exposure to cosmic radiations. However, their non-stationary nature and high orbital velocities pose challenges in routing, channel estimation, and synchronization.

[1]Some scholars include them as part of the LEO orbit.

B. OVERVIEW OF ACTIVITIES

Acknowledging the significant potential of NTNs, 3GPP has been making efforts to incorporate satellite elements into the framework of 5 G technologies [30]. Starting from Release 14, 3GPP has focused on key study items (SIs) including NTN architecture, integrating with new radio (NR), use cases and challenges, etc. In the following, we summarize these activities.

1) RELEASE 14

This release evaluates use case provisions and requirements for extending 5 G networks through satellite and other non-terrestrial networks for scenarios where the terrestrial service is unavailable [31]. For instance, the control plane in satellite communication links was defined, in 3GPP TR 38.913, to support RTTs of up to 600 ms for GEO/HEO, 180 ms for MEO, and 50 ms for LEO systems [31].

2) RELEASE 15

This release introduces SIs focusing on the role of NTNs, emphasizing on deployment scenarios and network architecture. In TR 38.811 [32], use cases where NTNs can contribute to 5 G networks were the focus, including 5 G services such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC) [3], [32]. It also focuses on channel modelling specific to NTNs, accounting for satellite communication conditions such as free-space propagation, atmospheric fading, and ionospheric interference.

3) RELEASE 16

In Release 16, 3GPP introduced two SIs to enhance satellite access integration. Under the Technical Specification Group (TSG), 3GPP TR 22.822 [33] studied 12 use cases, analyzing their conditions, impacts, and 5 G interactions. Key capabilities included seamless roaming, satellite-backed broadcast, IoT connectivity, temporary deployments, optimized routing, transborder continuity, global overlays, indirect 5 G links, backhaul, premises connectivity, and remote offshore links. Concurrently, under radio access network (RAN), 3GPP TR 38.821 focused on adapting NR for NTN, addressing service continuity and multi-connectivity in integrated and dual

NTN scenarios [34]. Building on Release 15, RAN3 analyzed satellite access via GEO and LEO networks, treating HAPS as a specialized NTN case. The study examined pedestrian and vehicular users, considering GEO and LEO satellites with steering beams and both transparent and regenerative payloads. RAN3 recommended prioritizing GEO access with transparent payloads and LEO access with either payload type for standardization. These findings provided actionable recommendations for integrating satellite capabilities into 5 G while addressing the technical feasibility and user needs.

4) RELEASE 17

3GPP TR 36.763, in Release 17, focuses on identifying relevant scenarios for NB-IoT/eMTC and a recommending changes for satellite support, including aspects like random access procedures, timing adjustments, hybrid automatic repeat request (HARQ) operations, mobility mechanisms, system information enhancements, and tracking area improvements, while assuming GNSS capability in user equipment. By late 2019, two work items (WIs) for NTNs were initiated: (i) "Solutions for NR to support NTN" under RAN and (ii) "Integration of satellite components in the 5 G architecture" under Service and System Aspects (SA) [3]. The objectives of both WIs are to assess how the physical layer is impacted by satellite integration in 5 G, propose solutions, and evaluate NR performance in GEO and LEO satellite deployment scenarios through system-level and link-level simulations. Additionally, they aim to identify upper-layer requirements, analyze core network and RAN interactions, and propose solutions for terrestrial-satellite roaming and 5 G fixed backhaul. Moreover, 3GPP Release 17 initiated the exploration of network slicing support over NTN systems, enabling differentiated service offerings and efficient resource utilization across shared satellite infrastructure [30].

5) RELEASE 18

3GPP Release 18 introduced substantial advancements in satellite-based 5 G connectivity, with a primary focus on enhancing satellite radio interface technology, backhauling solutions, and charging mechanisms. The Release 18 SI, "Study on Self-Evaluation Towards the IMT-2020 Submission of the 3GPP Satellite Radio Interface Technology," assessed the NR-NTN solutions from Release 17, ensuring improved support for 5 G satellite communications while addressing the remaining Radio Access Network 4 (RAN4) aspects for LTE-based IoT over NTNs [35], [36]. Additionally, the SI "Study on Support of Satellite Backhauling in 5GS" investigated satellite backhauling as a crucial enabler for connectivity in remote and mission-critical regions. This study addressed challenges related to multi-hop ISL connections, satellite edge computing, and local data switching, all of which contribute to reduced latency and optimized backhaul resource utilization [35], [36].

6) RELEASE 19

WG SA1 Release 19 SI "Study on Satellite Access - Phase 3" explores use cases and requirements aimed at enhancing 5 G system capabilities over satellite networks [35]. The study focuses on several key areas. First, it examines store-and-forward (S&F) satellite operations, which enable delay-tolerant communication services without requiring a continuous ground link, particularly benefiting IoT applications over non-geostationary orbit (NGSO) satellites. Second, it investigates user equipment (UE)-Satellite-UE communication, which allows direct communication between UE via satellite, reducing latency, improving data rates, and optimizing backhaul resource utilization. Third, the study addresses GNSS-independent operation, which extends satellite access to UEs that lack GNSS receivers or access to GNSS services, thereby overcoming a limitation of previous 5 G releases. Fourth, it focuses on localization improvements by integrating 3GPP positioning methods for UEs that rely exclusively on satellite access, ensuring accurate location services in satellite-based networks. These advancements are particularly relevant to mitigating access inequality in remote regions, where latency is a critical challenge.

Release 19 SI "Study on Management Aspects of NTN Phase 2" focuses on the management of satellite regenerative payloads in GSO and NGSO constellations. First, it explores the management of S&F operations and UE-Satellite-UE communications. Second, it addresses end-to-end management, including coordination with non-3GPP systems. Third, it enhances NTN-TN and NTN-NTN mobility, improving service continuity across different network architectures. In the context of slicing, the concept of indirect network sharing (INS), initially introduced in Release 19 and further expanded in Release 20 specifications such as TS 22.261, provides a new architectural model where multiple operators can independently access a shared satellite or terrestrial RAN via the hosting operator's core network [37]. INS facilitates enhanced coverage, service consistency, and disaster resilience without the complexity of maintaining direct interfaces between each participating operator and the shared network.

C. LEO MEGA-CONSTELLATIONS

Mega-constellations comprising hundreds or even thousands of LEO satellites promise global connectivity and the capability to serve remote and underserved areas. They have attracted considerable interest from both academia and industry, driving research in their design and deployment. In this part, we focus on the state-of-art research on mega-constellation designs.

1) TELESAT

is developing its next-generation LEO satellite constellation aimed at delivering high-speed, low-latency broadband connectivity worldwide, with a focus on the Canadian North [38]. Telesat initially proposed a two-phase deployment comprising 1,671 satellites [39]; however, as of August 2023, the plan was revised to confirm the deployment of 198 satellites [38], with the potential for future expansion. These satellites are operating at altitudes between 1,015 and 1,325 km, with an inclination optimized for broad polar and global coverage [2], [38], [39], [40]. Telesat's architecture emphasizes low-latency performance, targeting latency levels below 50 milliseconds, suitable for latency-sensitive applications such as cloud computing, video streaming, and industrial IoT, and is well tailored for enterprise, government, and maritime markets. With its reliable satellite design, Telesat aims to be a competitive force in the LEO satellite broadband market, contributing to solving digital divides in northern regions.

2) STARLINK

a SpaceX-operated mega-constellation, provides high-speed, low-latency internet for military, commercial, and scientific applications. Initial operational deployment began in 2019, with the first phase including 4,425 LEO satellites across four orbital shells (540–570 km altitude, 53°–97.6° inclination), enabling near-global coverage, including partial access in remote and polar regions [6], [41]. As of early 2024, over 5,500 active satellites deliver connectivity worldwide, including the maritime and aviation sectors. The first-generation system operates in the X/Ku and Ka bands, while future phases plan to expand significantly, potentially reaching over 40,000 V-band satellites in LEO and VLEO [41]. In February 2023, the second-generation deployment began, with approval for 7,500 satellites at $\approx$ 500 km altitude. By December 2023, 1,602 V2 Mini satellites were active, featuring advanced phased arrays, improved solar panels, and optimized frequency allocations for enhanced performance. However, while Starlink remains the primary licensed constellation in Canada, its coverage in polar regions remains a challenge, as we illustrate in the sequel.

3) ONEWEB

a satellite communications company, is actively deploying an LEO satellite constellation to deliver global broadband internet coverage. In its initial deployment phase, the company plans to launch a total of 648 satellites, positioning itself as a major player in the high-speed global connectivity market. These satellites operate at an approximate altitude of 1,200 km, utilizing the Ku-band for downlink and the Ka-band for uplink communications. This advanced configuration enables for low transmission latency, ranging between 30 and 50ms, hence significantly lower than the 500–600ms typically associated with geostationary satellites [3], [8], [41]. The constellation is designed with a polar orbit inclination of 87.9°, ensuring comprehensive global coverage, particularly benefiting high-latitude regions that often face connectivity challenges [3], [41]. OneWeb's network architecture is fully compatible with 5G backhaul solutions, making it a viable enabler for emerging technologies such as IoT, autonomous systems, and rural broadband expansion. By integrating these capabilities, OneWeb is an important player in bridging the digital divide and access inequality, particularly for polar regions.

4) PROJECT KUIPER

is a large LEO satellite mission that will provide low-cost, high-speed broadband internet to remote and underserved communities across the globe. The constellation will consist of up to 3,236 satellites launched into multiple orbital shells between altitudes of approximately 590 km and 630 km, with inclinations of 33°, 42°, and 51.9° to provide competitive mid-latitude and equatorial coverage [41]. Amazon attempts to compete with other LEO systems through Kuiper with a proposal to cross the digital divide and cement its place in the satellite communications space.

III. ACCESS INEQUALITY WITHIN NTN NETWORKS

This section examines access inequality arising from the design of LEO satellite constellations. As previously discussed, access inequality refers to the gap resulting from disparities in service quality, i.e., in coverage, latency, and continuity, across different regions due to the structural characteristics of the satellite constellation. To illustrate this concept, we consider a simplified NTN architecture, as depicted in Fig. 2. Based on this framework, this architecture highlights the key components required to support users in remote regions.

A. SIMULATION SETUP

The analysis is based on a scenario of ground users in distinct geographical regions considered in this work. The first region corresponds to mid-latitude areas, specifically New York City and Québec City, while the other two represent high-latitude locations in Northern Québec, Canada. To evaluate satellite network performance, we consider four LEO constellations, namely Starlink, OneWeb, Kuiper, and Telesat. Although networks used throughout simulations differ significantly in their architectural frameworks and service objectives, we include all systems in our coverage comparison to evaluate their potential roles in future inter-constellation roaming scenarios, presented in the next section. This comparative analysis helps highlight the feasibility of enabling roaming across heterogeneous satellite networks, bridging standardized NTNs and proprietary systems. The simulation is conducted over a 12-hour time horizon with 1 s time slot duration and performed using *Skyfield* [43], a Python-based simulator package designed for precise astronomical and orbital calculations. This tool is utilized to model the deployment of LEO constellations by incorporating the latest two-line element (TLE) data [44], enabling accurate estimation of the positions and velocities of satellites. Because the full constellations of Telesat and Kuiper are not yet deployed, i.e., TLE data are not available in [44]. We developed them for simulation purposes using the parameters in Table 2. The study primarily focuses on key performance metrics, including the number of visible satellites and the discontinuity duration. As the elevation angle and coverage discontinuity duration correlate with the distance between the ground user and the satellite, as well as with the signal strength, they provide crucial insights into access inequality, highlighting disparities in satellite availability across different regions. Next, the simulations are extended

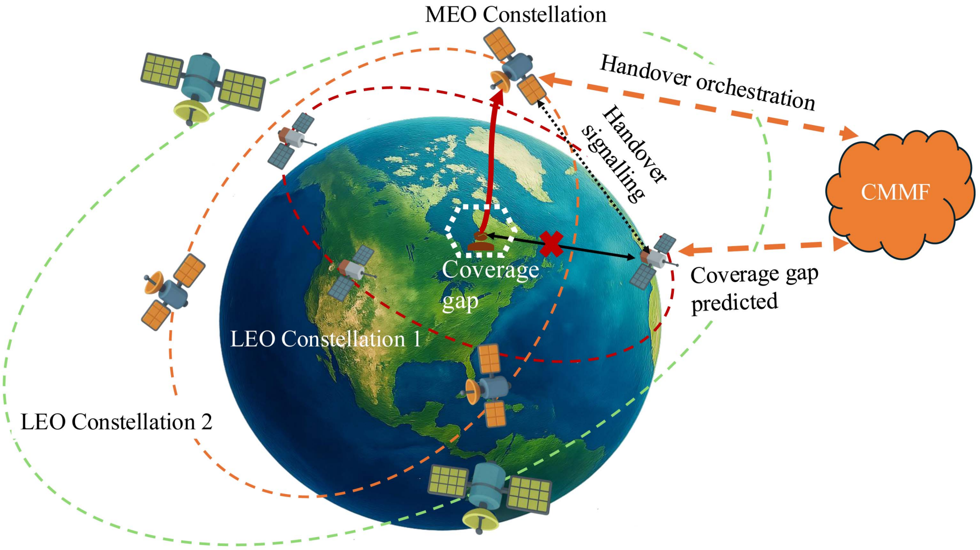


FIGURE 2. NTN architecture enabling inter-constellation and inter-orbit roaming to enhance connectivity for users in remote areas. It outlines various roaming scenarios, allowing users to transition between constellations through direct links or terrestrial network extensions, ensuring seamless communication across multiple network layers.

TABLE 2. Design Parameters for Telesat-Like and Kuiper-Like Constellations [42]

Parameter	Telesat-like	Kuiper-like
Shells Type	Polar and inclined	3 inclined shells
Altitude (km)	1015, 1325	590, 610, 630
Inclination	98.98°, 50.8°	33°, 42°, 51.9°
Orbital Planes	27, 40	36, 36, 28
Satellites/ Plane	13, 33	36, 36, 23
Total Satellites	1,671	3,236

to elaborate the advantages of inter-constellation roaming. To achieve this, we consider four distinct geographical regions for analysis:

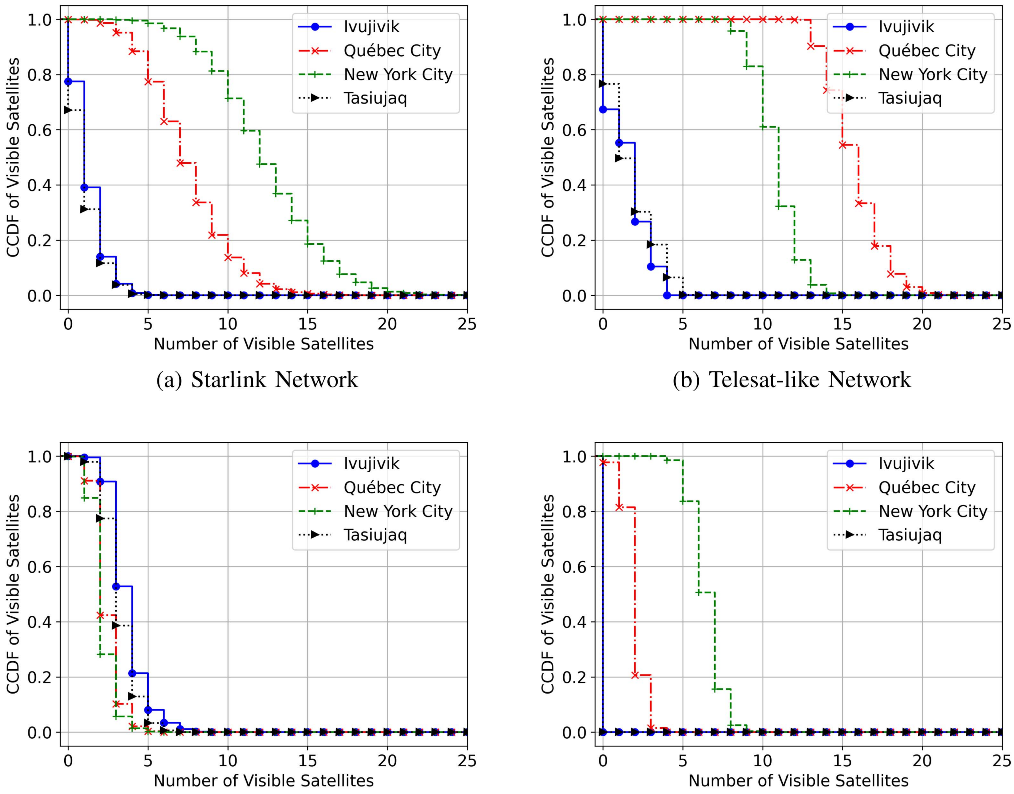
- *Remote areas in Northern Québec (QC), Canada:* The selected remote regions include Ivujivik and Tasiujaq, are defined by latitudes and longitude values (62.42°N, −77.90°W) and (58.1°N, −68.4°W), respectively. These areas are characterized by their sparse population, limited terrestrial infrastructure, and challenging environmental conditions, making them ideal studies for evaluating access inequality.
- *New York (NY) City, USA:* This region is defined by latitude and longitude values (40.7128°N,–74.0060°W). As a densely populated urban centre well covered by LEO satellites, it serves as an ideal case for comparison.
- *Québec City, (QC), Canada:* Québec City, located at coordinates (46.8139°N, −71.2082°W), is a major mid-latitude urban center with excellent LEO satellite coverage, making it an appropriate reference point for comparative analyses.

These simulation parameters will be used consistently throughout the paper unless stated otherwise. Any deviations or modifications to these parameters will be explicitly mentioned in the relevant sections to ensure transparency and reproducibility of the results.

B. NUMBER OF VISIBLE SATELLITES

To investigate access inequality within NTN, we analyze the number of visible satellites as a function of the elevation angle threshold, as complementary cumulative distribution function (CCDF) depicted in Fig. 3. At an elevation angle threshold of 50°, it is evident that ground users in mid-latitude regions, i.e., New York City and Québec City, have access to a significantly larger number of Starlink and Kuiper satellites than users in Northern Québec, i.e., Ivujivik and Tasiujaq. For example, for Northern Québec, ground users experience no access to any Starlink satellites that meet the minimum elevation angle approximately 25% and 30% of the time for both Ivujivik and Tasiujaq, respectively. In contrast, ground users in New York City consistently have access to at least three Starlink satellites. Similarly, Telesat-like's coverage is stronger in mid-latitude regions compared to northern regions. An interesting observation is that the gap between the two regions has narrowed, with Québec City exhibiting better visibility than New York City. This result illustrates that, despite operating with a lower number of satellites, Telesat can achieve competitive coverage in Northern Canada when compared to Starlink. Moreover, with a probability of 18%, users in Northern Québec are visible to two Starlink satellites or more, whereas there are always 2 or more satellites are visible in New York City. This implies a higher degree of freedom for user-satellite associations in New York City while maintaining QoS requirements.

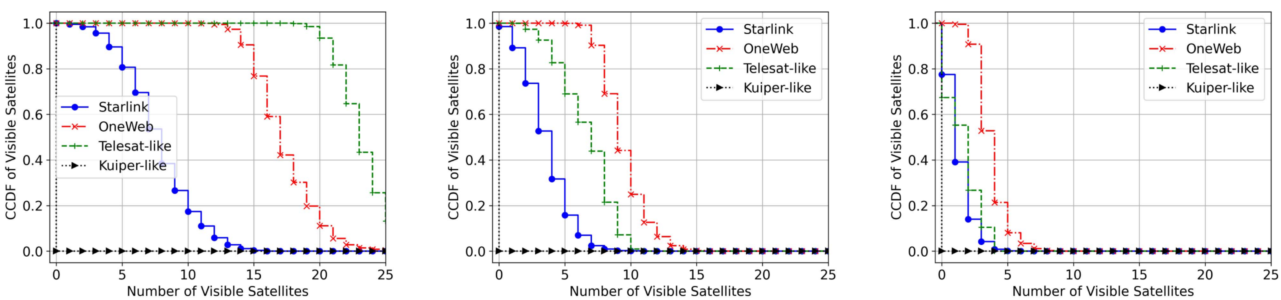
OneWeb demonstrates better coverage in Northern Québec compared to Starlink, though it provides relatively worse coverage in New York City, where approximately 15% of the time, the elevation angle between users and satellites falls below the threshold. This disparity is somewhat anticipated, as the OneWeb network is specifically designed to improve connectivity near the Earth's poles. Nevertheless, with a probability of 80%, the number of visible OneWeb satellites



(a) Starlink Network (b) Telesat-like Network

(c) Oneweb Network (d) Kuiper-like Network

FIGURE 3. **CCDF of visible satellites at minimum elevation angle 50° in four cities: (a) Starlink Network; (b) Telesat-like Network; (c) OneWeb Network; (b) Kuiper-like Network.**

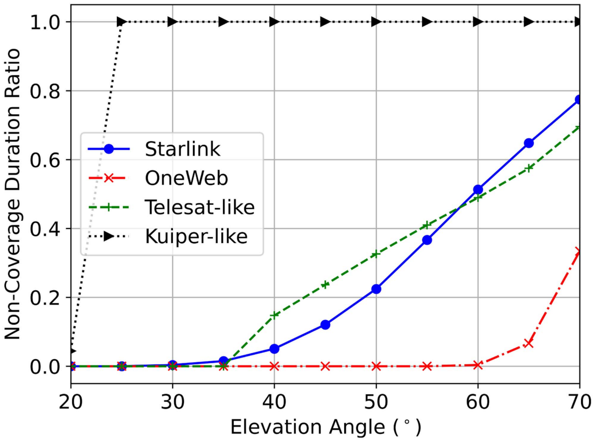


(a) Minimum elevation angle 25°. (b) Minimum elevation angle 35°. (c) Minimum elevation angle 50°.

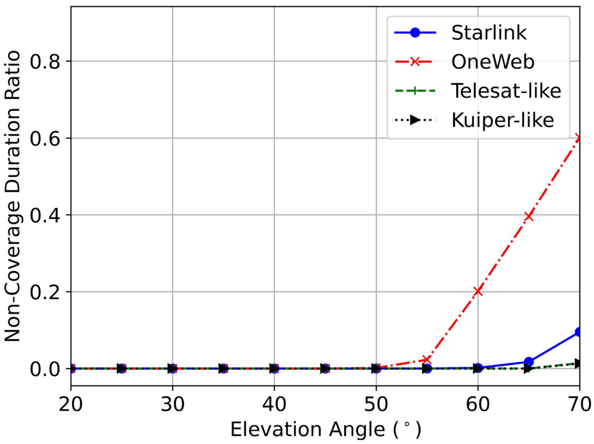
FIGURE 4. **CCDF of visible satellites in Ivujivik for Starlink, OneWeb, Telesat-like, and Kuiper-like networks under minimum elevation angles of (a) 25°; (b) 35°; (c) 50°.**

remains limited to four for Northern Québec and New York City, which is insufficient to ensure consistent service accessibility. Finally, Kuiper has no northern region coverage for such a minimum elevation angle. This analysis underscores the essential need to address service accessibility challenges, particularly in remote areas such as Northern Québec.

Fig. 4 depicts the CCDF of the number of visible satellites in Ivujivik for the considered LEO networks, evaluated under minimum elevation angle thresholds of 25°, 35°, and 50°. At 25°, Fig. 4(a), the Telesat-like network outperforms other networks due to its higher satellite altitude, which enables broader low-angle coverage, thanks to its combination of polar and inclined orbital designs of satellites to provide seamless connectivity at high-latitude regions. However, as the minimum elevation angle increases, OneWeb surpasses Telesat-like, benefiting from its large constellation polar-based planes, hence a denser network at the polar regions. Starlink, despite its large constellation size, provides fewer visible satellites because of its mid-latitude-optimized design. The Kuiper-like network exhibits almost no visibility across all cases, reflecting its low orbital inclinations focusing only on mid-latitude coverage, which results in



(a) Ivujivik.



(b) New York City.

FIGURE 5. Duration ratio of non-visibility: no satellite satisfies the minimum elevation angle. (a) Ivujivik; (b) New York City.

the exclusion of northern regions such as Ivujivik. These results emphasize the need for novel approaches to mitigate the impact of access inequality in LEO constellation networks.

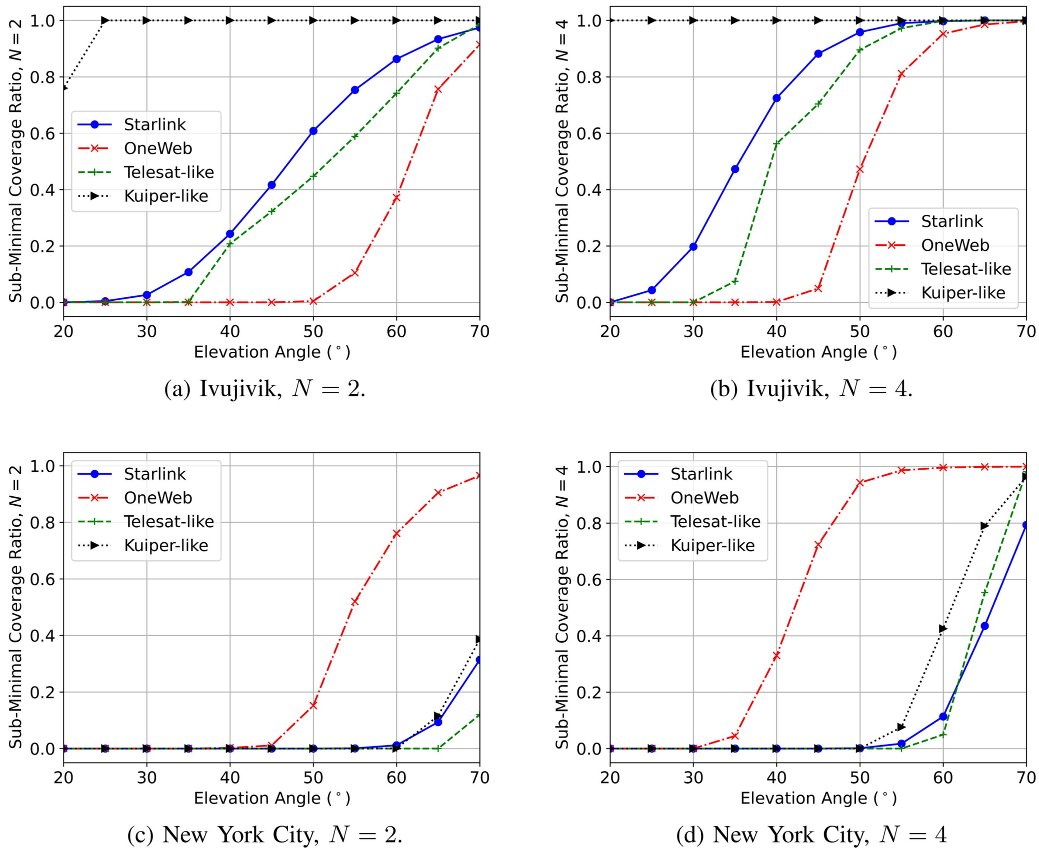
C. SERVICE DISCONTINUITY

Fig. 5 depicts *service discontinuity*, defined as the ratio of the period during which no satellite satisfies the coverage condition, i.e., the minimum elevation angle. The figure shows that, for the Starlink and Telesat-like networks, the elevation angle between users and satellites is generally lower in Northern Québec (Ivujivik) compared to New York City. This trend becomes evident at elevation angle thresholds of 30° and 35° for Starlink and Telesat-like, respectively, in Ivujivik, whereas it begins at 60° and 65° for the same networks in New York City. This implies that users in Northern Québec experience higher latency and poorer channel conditions than those in New York City, leading to reduced bandwidth efficiency and decreased user satisfaction. The figure also shows that the Telesat-like constellation provides competitive coverage despite its limited number of satellites, owing its high orbital altitude. Additionally, users in both Ivujivik and New York City demonstrate nearly similar performance with the OneWeb constellation, with a slightly better service continuity observed in Northern Québec (Ivujivik). This improvement aligns with OneWeb's design objective to enhance coverage in polar regions. However, the enhancement is limited by the small number of visible satellites, as shown in Fig. 3(c), which affects service accessibility. Finally, Kuiper-like targets mid-latitude regions, as it provides almost no coverage in Northern Québec while offering optimal coverage in New York City. This observation further highlights the access inequality inherent in current LEO constellations.

To further illustrate access inequality, we introduce the concept of limited coverage (sub-minimal), a metric that can be critical for user association (and coordinated multi-point transmission) in cases of high load or adverse environmental conditions, which can be defined as the scenario where only a limited number of satellites satisfy the coverage condition, leading to shorter coverage durations [45]. Fig. 6 depicts the ratio of limited coverage to the total time. Fig. 6 reveals that when considering a small number of satellites, such as $N = 2$ or $N = 4$, as a threshold to guarantee link reliability (via coordinate-multi-point) between users and satellites. In Northern Québec, unlike New York City, it is clear that Starlink coverage is significantly impacted by increasing N. This limited accessibility translates to the adoption of lower elevation angles for user-satellite communication, which in turn implies reduced channel quality, resulting in higher transmission delays, and lower spectrum efficiency. Furthermore, the coverage of OneWeb and Telesat-like is only slightly affected, highlighting the resilience of their constellation designs in high-latitude regions. Additionally, all networks exhibit reliable performance in mid-latitude regions, with OneWeb showing slightly reduced coverage compared to the others.

D. SERVICE TIME

In this section, we examine the access inequality in terms of service time, defined as the duration of a single satellite that can provide service to a user while satisfying the minimum elevation angle constraint, i.e., the satellite visibility duration. Fig. 7 presents the average service time for the best satellite (i.e., the satellite that offers the longest continuous visibility) across the considered LEO networks in New York City (mid-latitude) and Ivujivik (high-latitude). The figure shows that OneWeb and Starlink offer comparable service times in both regions; however, Starlink's average service time is approximately half that of OneWeb. This difference is attributed to OneWeb's higher orbital altitude, nearly double that of Starlink (550 km and 1200 km), resulting in longer visibility durations per satellite pass. As a result, more frequent handovers are required in the Starlink network to maintain continuous service. Telesat-like network exhibits a behaviour similar to OneWeb's, with slightly higher or lower service durations depending on the region. This variation stems from



(a) Ivujivik, $N = 2$. (b) Ivujivik, $N = 4$. (c) New York City, $N = 2$. (d) New York City, $N = 4$

FIGURE 6. Coverage under a limited number of visible satellites requirements. (a) Ivujivik, $N = 2$; (b) Ivujivik, $N = 4$; (c) New York City, $N = 2$; (d) New York City, $N = 4$.

the combination of polar and inclined orbital planes in the Telesat-like design, as well as differences in orbital altitude, i.e., 1015 km and 1325 km. Additionally, Kuiper-like constellation has almost the same performance in New York City and this is due to both networks having almost the same altitude of $550 - 630$ km. Finally, Fig. 7 shows that users in different regions may experience different average service durations even within the same satellite network. In particular, users in Ivujivik benefit from longer average service times than those in New York City, especially at lower elevation angles. This is clear for networks like Telesat-like, where satellites are visible for a longer time in New York City due to the orbital design and higher altitudes. For example, Telesat-like provides over 700 seconds of service at an angle of 20° in New York City, compared to about 500 seconds in Ivujivik. This means that Telesat-like users in Ivujivik experience more frequent handovers. However, these results are based on the longest service time and may vary based on the association algorithm and channel conditions, they show that satellite service access is uneven—some users experience better continuity and lower handovers and it comes to the expense of large fading losses.

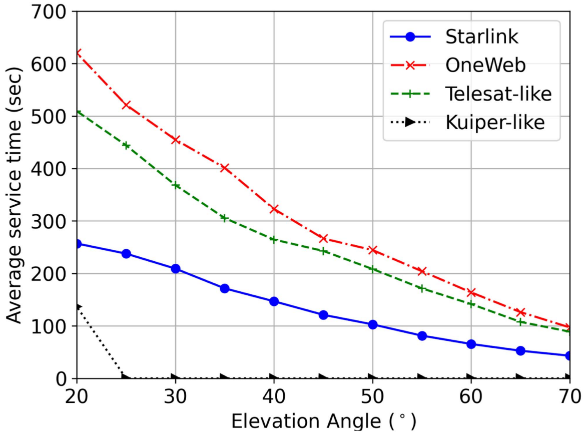
IV. POTENTIAL APPROACHES

As discussed, remote regions of Québec or more broadly of Northern Canada, face significant coverage challenges with LEO satellites, highlighting the issue of access inequality. To address this problem, several approaches can be considered. In this work, we discuss two potential solutions; 1) enabling roaming between constellations in the same or/and different orbital plane; 2) and developing a distributed terrestrial network expansion. These solutions are mainly targeting regions little to no access to TN infrastructure. In this context, these communities (users) can be classified into two categories: users with limited access to TNs, who possess sufficient resources to connect to the network via either TN or NTN elements, and users with no access to terrestrial networks, who may instead rely on NTN connectivity through LEO, MEO, or higher-orbit satellites, the latter of which is our focus.

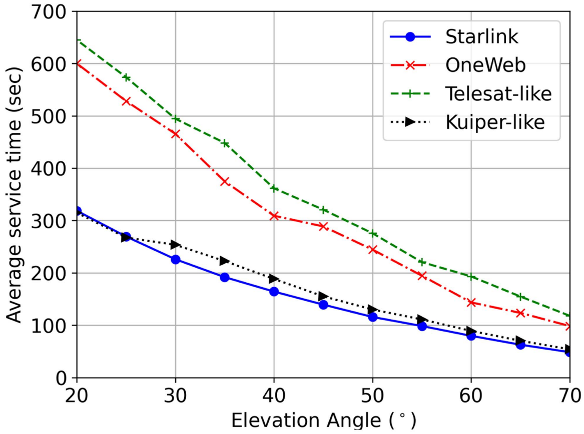
A. INTER-CONSTELLATIONS ROAMING

Through our analysis in Section III, we have highlighted the impacts of the LEO constellation design and satellite orbits on the coverage. For instance, polar orbits provide enhanced coverage for northern regions, e.g. the OneWeb network, while inclined orbits provide better connectivity for mid-latitude regions. So, to benefit from both orbital designs, it is recommended to adopt different constellations (networks) to provide internet services.

Given that LEO orbits are becoming increasingly congested due to the deployment of large satellite constellations in addition to the ambitious next-phase expansion plans of existing



(a) Ivujivik.



(b) New York City.

FIGURE 7. Average service time against the minimum elevation angle. (a) Ivujivik; (b) New York City.

networks, that the standardization of roaming between already deployed LEO networks could serve as a promising and sustainable solution for mitigating the access inequality problem. Such a strategy has the potential to significantly improve service continuity, optimize resource utilization, and ensure global coverage, particularly for underserved and remote regions near the northern pole, where connectivity is often limited or non-existent. In this approach, ground users would have the flexibility to be served through different LEO constellations (networks), based on their specific QoS requirements, real-time connectivity conditions, and environmental factors such as weather or geographical obstacles. Roaming, a well-established and widely implemented concept in TNs, could be effectively expanded to NTNs.

1) PERFORMANCE BASED ON ELEVATION ANGLE CONSTRAINTS

Fig. 8 depicts the advantages of LEO inter-constellation roaming in mitigating access inequality, i.e., satellites' visibility. We compare the inter-constellation roaming performance

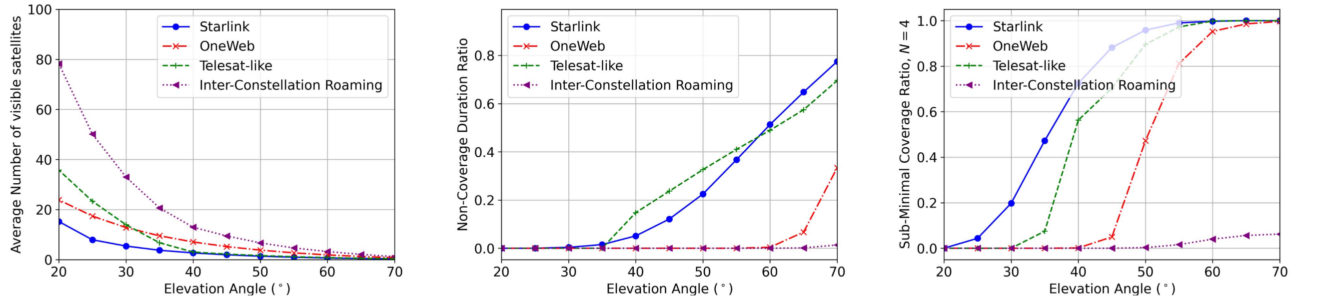
TABLE 3. Simulation Parameters

Parameter	Starlink	OneWeb	Telesat-like
Bandwidth	13.5	13.5	18.5
Frequency	250	250	250
EIRP (dBw)	36.7	34.6	38
Reuse Factor	4	2	5

with only Starlink, Telesat-like and OneWeb constellations, because Kuiper-like network has very low performance in Northern Québec. Fig. 8(a) illustrates that at lower elevation angles constraint, roaming improves the average number of visible satellites, meaning a higher chance of achieving a better data rate and lower latency due to the greater degree of freedom in being served by different satellites. In other words, ground users in remote regions of Québec (e.g., Ivujivik) can benefit from improved connectivity by leveraging the better visibility of OneWeb and Telesat-like satellites and the higher degree of association freedom offered by using all networks. Additionally, the results indicate the improvement of inter-constellation roaming in terms of coverage based on elevation increases for higher elevation angles. This improvement reaches 100% for the outage probability at an elevation angle of 70° for all constellations. This observation becomes very clear for the sub-minimal case where the benefits of inter-constellation roaming benefits start from low elevation angles, i.e., 25°, 35°, and 45° for Starlink, Telesat, and OneWeb users, respectively. Moreover, users requiring higher elevation angles because of physical obstructions or environmental factors can be assigned to any LEO network, whereas users with a lower elevation angle constraint can be associated with satellites with lower elevation angles; thereby optimizing network resource allocation and guaranteeing service continuity. This can be explained through Fig. 8(c), which shows that the duration of which users have access to a minimum number of satellites that satisfy the visibility condition. Furthermore, the figure demonstrates that roaming between all networks increases accessibility to more LEO satellites, further helping to meet QoS requirements for ground users by providing greater alternatives for resource allocation from various satellites.

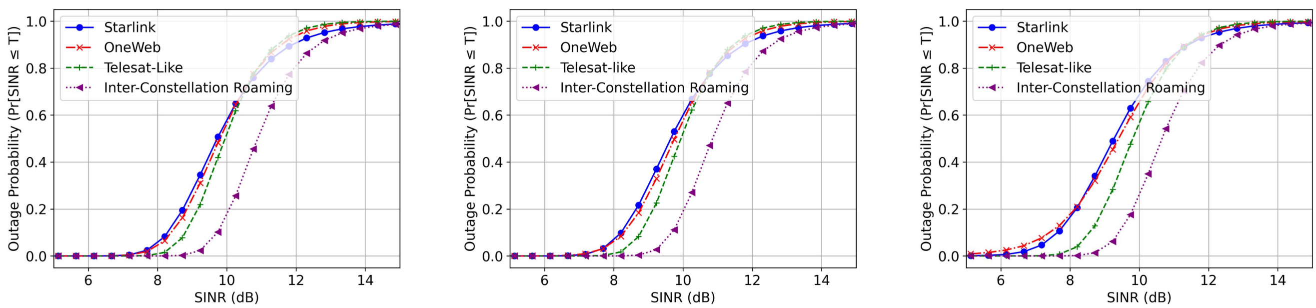
2) PERFORMANCE BASED ON SIGNAL STRENGTH

This section evaluates the advantages of inter-constellation roaming for outage probability and link reliability, which is defined as the probability that the SINR satisfies a minimum threshold, T, and a minimum elevation angle. The simulation assumes a Rician fading channel with a factor of $K = 10$. To guarantee fairness between constellations we set receiver gain, atmospheric loss, and cross polarization discrimination at, 38, 2, and 17 dB, respectively. All parameters specific to each constellation are detailed in Table 3 [46]. This analysis aims to illustrate the potential benefits of inter-constellation roaming; however, actual networks may operate under different configurations depending on their design objectives. Future work should also consider the integration of realistic



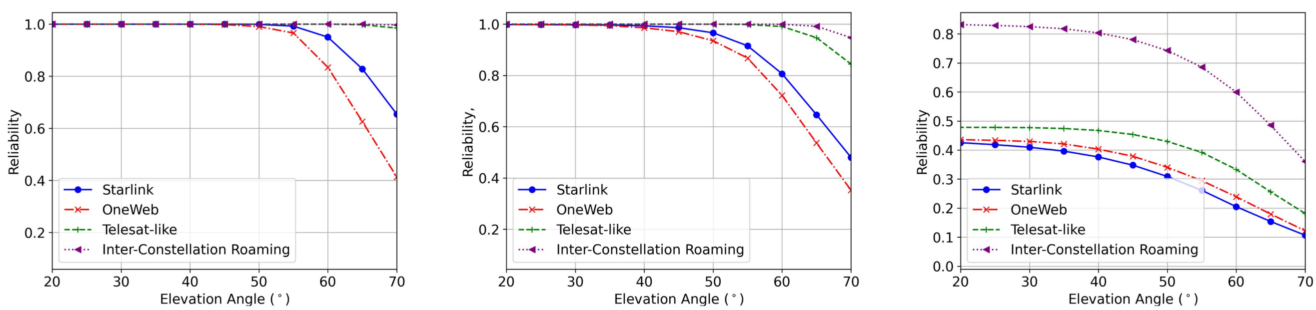
(a) Number of visible satellites (b) Duration ratio of non-visibility (c) Duration ratio of limited-visibility

FIGURE 8. Visibility performance of inter-constellation roaming in Northern Québec. Roaming assumes ground users can associate with any satellites of Starlink, OneWeb, or Telesat-like networks: (a) Number of visible satellites; (b) Non-visibility duration ratio; (c) Limited-visibility duration ratio.



(a) Outage at elevation angle 25°. (b) Outage at elevation angle 35°. (c) Outage at elevation angle 50°.

FIGURE 9. Outage performance of inter-constellation roaming at different elevation angles in Ivujivik: (a) 25°; (b) 35°; (c) 50°.



(a) SINR threshold 5 dB. (b) SINR threshold 7 dB. (c) SINR threshold 10 dB.

FIGURE 10. Reliability of inter-constellation roaming at different SINR thresholds in Ivujivik: (a) 5 dB; (b) 7 dB; (c) 10 dB.

receiver models to account for radio frequency characteristics. The results in Fig. 9 demonstrate that inter-constellation roaming significantly reduces the outage probability by offering receivers increased degrees of freedom, enabling dynamic association with multiple LEO constellations and thereby enhancing service continuity. Furthermore, the observed improvement correlates with the minimum elevation angle. This gain reaches about 1 dB and 2 dB to both Starlink and OneWeb and, Telesat-like networks, respectively. This is intuitively because ground users benefit from the complementary visibility of constellations with distinct orbital architectures as a higher angle means more restrictions on the number of visible satellites. This diversity in design—such as varying inclination angles and altitudes—contributes to improved link availability and reduced service interruptions across different geographical regions.

Fig. 10 illustrates the reliability performance of inter-constellation roaming compared to individual Starlink, OneWeb, and Telesat-like networks. The results show that inter-constellation roaming yields substantial reliability gains, particularly at higher minimum elevation angles. This improvement is attributed to the reduced number of visible satellites at higher elevations, which increases the likelihood of service interruption unless seamless switching between LEO networks is enabled. Specifically, the gain in reliability reaches up to 100% and 70% compared to Starlink and OneWeb, and the Telesat-like network, respectively. A similar trend is observed as the SINR threshold increases, further highlighting the benefit of roaming under stricter QoS requirements. As expected, the reliability of all networks symmetrically converges toward zero at high SINR thresholds. It is also worth noting that the Telesat-like network demonstrates comparatively better standalone reliability, which aligns with its architectural emphasis on high availability and service continuity[2].

B. INTER-ORBIT ROAMING

Although VLEO and LEO networks offer lower latency and higher data rates compared to MEO and GEO satellites, MEO satellites can serve as a viable alternative for regions where there is a discontinuity in LEO coverage and connectivity. Consequently, inter-layer NTN communication, particularly involving MEO satellites, presents a promising solution to bridge the coverage gaps within LEO constellations. This approach becomes increasingly attractive due to MEO satellites' capability to provide high throughput while maintaining relatively low latency compared to traditional GEO satellites [47]. Additionally, MEO satellites possess a significantly larger footprint, enabling them to serve users for extended durations– often exceeding an hour– whereas LEO satellites typically provide coverage for only a few minutes before moving out of range. These inherent advantages make MEO satellites a suitable solution for mitigating coverage gaps, which may arise due to the limited availability of LEO or VLEO satellites within a constellation.

C. DISTRIBUTED TN EXPANSION

Expanding TNs for NTNs is a promising approach to improve connectivity in remote communities where traditional TN deployment is impractical or too costly. By integrating passive TN base stations with NTN elements, particularly LEO and MEO satellite networks, a hybrid communication infrastructure can be developed to maximize coverage, power efficiency, and spectrum utilization. These base stations can serve as relay nodes and improve signal strength and transmission rate while minimizing the energy burden on end-user devices, such as low-power IoT sensors. Advanced technologies, including directional antennas and high-powered relay stations, further enhance link reliability and communication quality by optimizing data flow between terrestrial users and satellite-based infrastructure. For example, companies like CERAGON are actively researching and developing innovative, low-cost, and low-latency communication solutions designed to address the specific connectivity challenges of rural and remote populations [48], which can be expanded for our case in supporting TN expansion.

[2]Telesat Lightspeed aims to deliver high-reliability, low-latency connectivity for enterprise, government, and remote regions, as outlined in official documentation and public filings [2], [38], [40].

V. CHALLENGES

We have discussed several potential solutions to address the issue of access inequality, including inter-constellation roaming and TN expansion. However, these approaches present several challenges, which we will outline in this section.

A. HANDOVER MECHANISMS IN ROAMING SCENARIOS

Handover in satellite networks is a fundamental challenge, particularly in LEO constellations, where satellites have limited visibility windows due to their high orbital velocity. While intra-constellation handover, i.e., handover within the same satellite system, is generally well understood and managed by a single operator using consistent protocols and centralized control, inter-constellation handover presents greater complexity. The key challenges include:

- *Lack of protocol uniformity:* Each satellite constellation, whether 3GPP-compliant or privately deployed, typically uses different physical-layer technologies (e.g., frequency bands, modulation schemes), network architectures, and control-plane signalling. Intra-constellation handovers benefit from architectural consistency, but inter-constellation handovers must bridge protocol mismatches and system incompatibilities.
- *Increased latency and interruption risk:* Although roaming handovers aim to reduce service discontinuity, they often require complete re-authentication, session re-establishment, and routing reconfiguration. These steps introduce latency and potential service gaps if not tightly coordinated. However, any solution must meet strict security requirements, possibly through federated identity frameworks or third-party trust anchors.

B. RADIO RESOURCE MANAGEMENT

The high orbital velocity of LEO satellites results in a rapidly changing link availability for ground users. Regarding resource management, this leads to a continuous need for real-time beam reassignment, load redistribution, and capacity adaptation. While single-operator networks can optimize these transitions using historical data, roaming scenarios raise an additional layer of uncertainty. Particularly, roaming users may be external to the serving operator's resources and arrive dynamically based on communication conditions and the user's QoS, and/or traffic profiles. As a result, the system cannot proactively reserve beam capacity or adjust power allocations for them ahead of time. This increases the likelihood of suboptimal spectrum use, or underutilized capacity if users hand off without coordination. Moreover, because these users may be subject to different QoS requirements or prioritization policies, dynamically balancing their needs against those of local users becomes a nontrivial task.

C. NETWORK SLICING IN ROAMING SCENARIOS

Network slicing enables operators to allocate dedicated virtual resources for different services or users, ensuring service isolation and customized performance levels. While this concept is well established in terrestrial 5 G networks, applying it in NTNs—particularly in roaming scenarios—introduces additional challenges for resource management. When users roam across satellite constellations, maintaining slices' continuity of different operators becomes challenging. The roaming operator must either extend the existing slice or instantiate a compatible one locally. This process requires dynamic allocation of spectrum, compute, and backhaul resources to meet the original slice's performance requirements (e.g., low latency, data rate, reliability). However, unlike in the home network, the serving operator may lack visibility into the user's full-service context, making it hard to provision the right level of slices' resources. Moreover, the dynamic nature of satellite connectivity—caused by fast-moving LEO satellites and varying link conditions—means that slices must be elastic and capable of adapting to frequent handovers, fluctuating traffic loads, and non-uniform coverage. Without a shared slice orchestration framework or cross-operator resource guarantees, there is a high risk of resource under-provisioning, QoS violations, or slice collapse during roaming.

D. STANDARDIZATION FOR INTER-CONSTELLATION/ORBIT ROAMING

As discussed earlier, LEO inter-constellation roaming could play an important role in facilitating global connectivity and in mitigating the access inequality problem. However, multiple technical, regulatory, security, and economic challenges still remain to be addressed. Technically, the diversity of satellite networks—defined by differences in communication protocols, frequency bands, and network architectures—poses challenges to their seamless integration. There is therefore a need to establish common rules or guidelines by international standardization organizations such as the 3GPP, which governs spectrum allocation, orbital slot management, and operations. From a regulatory perspective, inconsistencies in national licensing frameworks, spectrum coordination procedures, and data governance policies further complicate the implementation of cross-constellation handovers. Each network may operate under different regulatory authorities (e.g., 3GPP or the international telecommunication union (ITU)), making unified roaming policies difficult to enforce. Operationally, the absence of standardized inter-operator agreements, secure authentication protocols, and data exchange mechanisms hinders the realization of seamless roaming across systems. Connecting multiple constellations (users) renders satellite networks more vulnerable to cyber threats, requiring standardized security measures to protect data and prevent unauthorized access. Additionally, economic competition among satellite operators may slow down the standardization of roaming protocols for several reasons.

E. PLANNING FOR TN EXPANSION

Although expanding TNs to support NTNs in remote and underserved areas is critical for reducing connectivity gaps, achieving this goal presents several planning and sustainability obstacles besides the inherited challenges that also be considered in roaming scenarios where resources of these extensions should also be optimized to support different class requirements and muli-constellation coordination. However, the major challenge lies in the deployment and long-term maintenance of ground infrastructure in harsh environments, such as high-latitude or disaster-prone regions. These locations often face extreme weather conditions, logistical barriers, and limited local workforce availability, which make even basic operations—such as inspection, fault diagnosis, and component replacement—highly complex and costly [12]. Additionally, the difficulty in maintaining physical sites, due to extreme temperature variations, wind gusts, or heavy snow loads, increases operational expenditure and raises concerns over network reliability and service continuity.

From a sustainability perspective, the lack of stable power infrastructure in such areas necessitates alternative solutions, such as renewable energy sources (e.g., solar or wind) paired with energy storage systems [12]. Moreover, maintenance strategies should be adapted to minimize physical interventions—for instance, by incorporating modular hardware, remote diagnostics, and AI-driven predictive maintenance tools. Uncrewed aerial vehicles (UAVs) and robotic inspection systems can also be used to perform routine site checks or even minor repairs without requiring on-site personnel.

VI. RESEARCH DIRECTIONS

Reaching a seamless inter-constellation roaming in non-terrestrial networks (NTNs) necessitates comprehensive research across architecture design, protocol development, and resource coordination frameworks. As satellite systems evolve into more heterogeneous and multi-operator environments, the following areas emerge as critical research directions.

A. MOBILITY MANAGEMENT AND INTER-OPERATOR HANDOVER

Future NTN deployments must support seamless handover across satellite constellations operated by different providers. Extending existing 5 G inter-PLMN mobility procedures to NTN scenarios is a foundational step. However, given the unique mobility patterns and link dynamics in LEO systems, more advanced predictive handover strategies and make-before-break mechanisms are needed. A key direction is the development of a CMMF— a logical entity that can coordinate handover signalling, identity federation, and mobility context transfer across networks. This function would reduce signalling overhead, ensure service continuity, and operate as a trusted broker for cross-domain mobility.

Remark: Algorithm 1 outlines an inter-constellation roaming handover procedure, which is adapted to align with established 3GPP handover principles (See Fig. 2).

Algorithm 1: Inter-Constellation Roaming Handover Procedure.

Input: Current serving satellite network (SN-1), candidate satellite network (SN-2), ground user (GU), CMMF.

Step 1: Coverage Prediction (SN-1)
- SN-1 predicts upcoming coverage loss (e.g., satellite moving out of range).

Step 2: Target Selection (SN-1 ↔ CMMF ↔ SN-2)
- SN-1 notifies CMMF of the coverage loss.
- CMMF coordinates verification of roaming agreements with SN-2.
- CMMF confirms GU eligibility and policy compliance.
- CMMF coordinates selection of SN-2 satellite for handover.

Step 3: Handover Initiation (SN-1 ↔ SN-2)
- SN-1 sends handover request to SN-2.

Step 4: User Command (SN-1 ↔ GU)
- SN-1 issues handover command to GU.

Step 5: Connection Establishment (GU ↔ SN-2)
- GU completes registration and context transfer.

B. DYNAMIC RESOURCE COORDINATION IN MULTI-OPERATOR ENVIRONMENTS

Future NTNs will require intelligent resource management systems capable of real-time response to rapid topological changes. A promising direction is to extend the INS model, introduced in 3GPP Release 17, to support flexible, policy-based resource sharing for roaming users. Research should also explore the design of cross-operator orchestration interfaces, where operators can exchange resource availability, load status, and admission control policies securely and dynamically. Integrating software-defined networking (SDN) and network function virtualization (VNF) based control frameworks with satellite-ground edge intelligence will be essential for load balancing, congestion avoidance, and efficient beam selection in roaming contexts.

C. RESILIENT NETWORK SLICING

Ensuring service continuity for roaming users will require slicing mechanisms that are robust to mobility and capable of operating across administrative domains. Future work should focus on the development of standardized slice templates and inter-operator slice age management protocols. The integrated mobility management entity (IMME) could play a key role in negotiating and instantiating compatible slices during roaming events and monitoring cross-domain QoS. In parallel, frameworks for slice-level trust, billing, and dispute resolution must be investigated to ensure secure and fair sharing.

D. POWER-BEAMING ARCHITECTURE FOR TN EXPANSIONS

Power-beaming technology offers a promising alternative by transmitting energy from airborne elements to ground stations [49], [50]. Two power-beaming scenarios can be envisioned: a relay-based system or direct energy transmission. The relay-based method, i.e., ground-to-satellite-to-ground, involves sending power from a terrestrial station to an orbiting satellite, which then redirects it to a ground receiver. This approach can be useful for delivering power to remote or disaster-affected areas where traditional energy infrastructure is unavailable. The satellite captures energy using efficient microwave or laser reception systems and beams it to the base station. However, further research is needed to overcome challenges such as energy loss due to multiple conversions and the need for highly accurate beam-tracking systems. The second approach is based on space-based solar power (SBSP) [51], [52], where satellites in HEO, GEO, or even potentially LEO collect solar energy using onboard photovoltaic panels. This energy is then converted into microwave or laser beams and transmitted directly to ground-based receivers [53]. Unlike the relay-based system, SBSP eliminates the need for intermediary ground stations, making it a reliable power source for remote areas, space missions, and military operations. However, large-scale deployment requires further research to improve beam alignment, energy conversion efficiency, and regulatory compliance. In this context, it is expected that the use of advanced beam tracking and antennas could enhance the feasibility and effectiveness of this technology.

Additionally, several future directions for improving inter-constellation standardization in LEO satellite networks can be performed. Advanced routing algorithms, such as semantic addressing and routing [54], present potential solutions for efficiently managing data transmission across different satellite constellations. Finally, different satellite systems may adopt unique handover processes, creating challenges in minimizing service interruptions. Hence, developing efficient handover solutions remains a key area of research, with a focus on enhancing network interoperability, reducing latency, and improving communication reliability in LEO satellite networks.

VII. CONCLUSION AND FUTURE WORKS

In this paper, we examined the issue of access inequality in NTNs, specifically focusing on LEO constellations in remote areas. As a case study, we selected Ivujivik in Northern Québec, Canada, to highlight this challenge. First, we provided a comprehensive overview of NTNs, including their key components, definitions, LEO constellations, and the digital divide. We then conducted a detailed analysis of access inequality within LEO networks, with a particular emphasis on coverage discontinuity and elevation angles. To offer a clearer perspective, we compared the locations in Québec with New York City, USA, demonstrating the disparities in terms of the minimum observed elevation angle, the number of visible satellites, and service continuity. To address these challenges, we proposed inter-constellation/orbit roaming as a viable solution to mitigate access inequality. Furthermore, we suggested that the cost-effective relay-based expansion of TNs could further bridge connectivity gaps in underserved regions.

Additionally, we outlined our vision on key research gaps related to access inequality in NTN networks. Major challenges for inter-constellation roaming are the handover management besides frequency and slicing resource management. Lastly, advancements in power-beaming technologies are expected to address power sustainability issues, facilitating the expansion of TN in remote regions, where infrastructures are scarce. Future efforts must also focus on designing self-sustaining, low-maintenance TN deployments that can integrate with satellite systems, support dynamic traffic loads, and withstand prolonged periods without human intervention.

As part of our future work, we plan to extend the access inequality analysis across the four geographic regions studied in this paper. We will collect real-world measurement data from Starlink satellites, focusing on multiple performance metrics including end-to-end latency, throughput, received signal strength, and satellite visibility angles. The objective is to investigate the interplay among these metrics and their joint impact on user access inequality in LEO networks.

REFERENCES

[1] P. He et al., "Non-terrestrial network technologies: Applications and future prospects," *IEEE Internet Things J.*, vol. 12, no. 6, pp. 6275–6299, Mar. 2025.

[2] M. Y. Abdelsadek et al., "Future space networks: Toward the next giant leap for humankind," *IEEE Trans. Commun.*, vol. 71, no. 2, pp. 949–1007, Feb. 2023.

[3] T. Darwish, G. K. Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, "LEO satellites in 5 G and beyond networks: A review from a standardization perspective," *IEEE Access*, vol. 10, pp. 35040–35060, 2022.

[4] M. A. Jamshed et al., "A tutorial on non-terrestrial networks: Towards global and ubiquitous 6 G connectivity," *Found. Trends Netw.*, vol. 14, no. 3, pp. 160–253, Feb. 2025.

[5] S. Map, "Satellite map of starlink and oneweb," 2024. [Online]. Available: https://satellitemap.space/

[6] SpaceX, "Starlink," (n.d.). [Online]. Available: https://www.starlink.com

[7] Amazon, "Project kuiper," (n.d.), Jun. 2025. [Online]. Available: https://www.aboutamazon.com/news/project-kuiper

[8] OneWeb, "Internet connectivity for everyone, everywhere," (n.d.). [Online]. Available: https://www.oneweb.world

[9] P. Hu, "Closing the performance and management gaps with satellite internet: Challenges, approaches, and future directions," 2024, *arXiv:2401.07842*.

[10] T. Ahmmed, A. Alidadi, Z. Zhang, A. U. Chaudhry, and H. Yanikomeroglu, "The digital divide in Canada and the role of LEO satellites in bridging the gap," *IEEE Commun. Mag.*, vol. 60, no. 6, pp. 24–30, Jun. 2022.

[11] J. Pan, J. Zhao, and L. Cai, "Measuring a low-earth-orbit satellite network," in *Proc. IEEE Annu. Int. Symp. Pers., Indoor Mobile Radio Commun.*, Toronto, ON, Canada, Oct. 2023, pp. 1–6.

[12] A. Chaoub et al., "6 G for bridging the digital divide: Wireless connectivity to remote areas," *IEEE Wireless Commun.*, vol. 29, no. 1, pp. 160–168, Feb. 2022.

[13] P. Labbé, "LEO satellite constellations: An opportunity to improve terrestrial communications in the Canadian Arctic," in *Proc. Int. Conf. Adv. Satellite Space Commun.*, Lisbon, Portugal, Feb. 2020, pp. 19–24.

[14] S. Ma et al., "LEO satellite network access in the wild: Potentials, experiences, and challenges," *IEEE Netw.*, vol. 38, no. 6, pp. 396–403, Nov. 2024.

[15] A. A. Avram, C. Bettanini, S. Chiodini, A. Aboudan, G. Colombatti, and M. Giuliani, "Maximization of LEO nanosatellite's transmission capacity to multiple ground stations: Orbit selection and requirements on attitude control," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 37, no. 8, pp. 4–19, Aug. 2022.

[16] M. Mahyoub, H. Yanikomeroglu, G. K. Kurt, and S. Martel, "Visibility-aware user association and resource allocation in multi-slice LEO satellite networks," *TechRxiv.*, Sep. 2024, doi: 10.36227/techrxiv.172651039.98758697/v1.

[17] H.-W. Chu, T.-Y. Kim, and J.-H. Kim, "Analysis of LEO satellite network performace according to phasing factor: Polar region boundary, minimun elevation angle," in *Proc. 15th IEEE Int. Conf. Ubiquitous Future Netw.*, Budapest, Hungary, Jul. 2024, pp. 451–453.

[18] T. W. Beech, S. Cornara, M. B. Mora, and G. Lecohier, "A study of three satellite constellation design algorithms," in *Proc. 14th Int. Symp. Space Flight Dyn.*, 1999, pp. 1–11.

[19] E. S. Lohan and K. Çelikbilek, "On the impact of the number of the constellation shells on standalone LEO-PNT positioning metrics," in *Proc. 36th Conf. Open Innovations Assoc.*, Oct. 2024, pp. 353–360.

[20] M. Giordani and M. Zorzi, "Non-terrestrial networks in the 6 G era: Challenges and opportunities," *IEEE Netw.*, vol. 35, no. 2, pp. 244–251, Mar./Apr. 2021.

[21] M. M. Azari et al., "Evolution of non-terrestrial networks from 5 G to 6 G: A survey," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 2633–2672, Fourthquarter 2022.

[22] A. M. Voicu, A. Bhattacharya, and M. Petrova, "Handover strategies for emerging LEO, MEO, and HEO satellite networks," *IEEE Access*, vol. 12, pp. 31523–31537, 2024.

[23] A. P. Trishchenko, L. Garand, L. D. Trichtchenko, and L. V. Nikitina, "Multiple-apogee highly elliptical orbits for continuous meteorological imaging of polar regions: Challenging the classical 12-h Molniya orbit concept," *Bull. Amer. Meteorological Soc.*, vol. 97, no. 1, pp. 19–24, Jan. 2016.

[24] F. S. Prol et al., "Position, navigation, and timing (PNT) through low earth orbit (LEO) satellites: A survey on current status, challenges, and opportunities," *IEEE Access*, vol. 10, pp. 83971–84002, 2022.

[25] M. Hosseinian, J. P. Choi, S.-H. Chang, and J. Lee, "Review of 5 G NTN standards development and technical challenges for satellite integration with the 5 G network," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 36, no. 8, pp. 22–31, Aug. 2021.

[26] P. Kumar, P. K. Srivastava, P. Tiwari, and R. Mall, "Application of GPS and GNSS Technology in Geosciences," in *GPS GNSS Technol. Geosciences*. Amsterdam, Netherlands: Elsevier, 2021, pp. 415–427.

[27] G. Chen, S. Wu, Y. Deng, J. Jiao, and Q. Zhang, "VLEO satellite constellation design for regional aviation and marine coverage," *IEEE Trans. Netw. Sci. Eng.*, vol. 11, no. 1, pp. 1188–1201, Jan./Feb. 2024.

[28] Z. Niu et al., "Reliable low-latency routing for VLEO satellite optical network: A multi-agent reinforcement learning approach," *IEEE Internet Things J.*, vol. 12, no. 3, pp. 2309–2321, Feb. 2025.

[29] EOI Space, "Stingray VLEO constellation," (n.d.), Feb. 2023. [Online]. Available: https://www.eoportal.org/

[30] M. M. Saad, M. A. Tariq, M. T. R. Khan, and D. Kim, "Non-terrestrial networks: An overview of 3GPP release 17 & 18," *IEEE Internet Things Mag.*, vol. 7, no. 1, pp. 20–26, Jan. 2024.

[31] 3rd Generation Partnership Project (3GPP), "Study on scenarios and requirements for next generation access technologies," 3GPP, Sophia Antipolis, France, Tech. Rep. TR 38.913, May 2017.

[32] 3rd Generation Partnership Project (3GPP), "Study on New Radio (NR) to Support Non-Terrestrial Networks (NTN)," 3GPP, Sophia Antipolis, France, Tech. Rep. TR 38.811, 2020.

[33] 3rd Generation Partnership Project (3GPP), "Study on using satellite access in 5G, stage 1," 3GPP, Sophia Antipolis, France, Tech. Rep. TR 22.822, 2018.

[34] 3rd Generation Partnership Project (3GPP), "Solutions for NR to support NTN," 3GPP, Sophia Antipolis, France, Tech. Rep. TR 38.821, 2023.

[35] 3rd Generation Partnership Project (3GPP), "Study on extended reality (XR) for NR and NG-RAN," 3GPP, Sophia Antipolis, France, Tech. Rep. TR 22.865, Dec. 2022. [Online]. Available: https://www.3gpp.org/DynaReport/22865.htm

[36] M. A. Jamshed et al., "Non-terrestrial networks for 6 G: Integrated, intelligent and ubiquitous connectivity," *IEEE Commun. Standards Mag.*, May 2025.

[37] 3rd Generation Partnership Project (3GPP), "TS 22.261: Service requirements for the 5G system (5GS)," 3GPP, Sophia Antipolis, France, Tech. Rep. TS 22.261 V18.2.0, Mar. 2024. [Online]. Available: https://www.3gpp.org/ftp/Specs/archive/22_series/22.261/

[38] Telesat, "Telesat - global satellite operator," 2025. [Online]. Available: https://www.telesat.com/

[39] Federal Communications Commission, "Space station applications accepted for filing," FCC, Washington, DC, USA, Rep. SAT-01632, May 2022. [Online]. Available: https://www.fcc.gov/

[40] O. B. Yahia et al., "Evolution of high-throughput satellite systems: A vision of programmable regenerative payload," *IEEE Commun. Surveys Tuts.*, early access, Aug. 26, 2024, doi: 10.1109/COMST.2024.3450292.

[41] N. Pachler, I. del Portillo, E. F. Crawley, and B. G. Cameron, "An updated comparison of four low earth orbit satellite constellation systems to provide global broadband," in *Proc. IEEE Int. Conf. Commun. Workshops*, Montreal, QC, Canada, Jun. 2021, pp. 1–7.

[42] S. Kassing, D. Bhattacherjee, A. B. Águas, J. E. Saethre, and A. Singla, "Exploring the 'internet from space' with hypatia," in *Proc. ACM Internet Meas. Conf.*, Oct. 2020, pp. 214–229.

[43] B. Rhodes, "Skyfield: High precision research-grade positions for planets and earth satellites generator," *Astrophysics Source Code Library*, Jul. 2019, Art. no. ascl-1907.

[44] T. Kelso, "Celestrak," 2024. [Online]. Available: https://celestrak.com/

[45] Z. Zhang, Y. Wu, Z. Ma, X. Lei, L. Lei, and Z. Wei, "Coordinated multi-satellite transmission for OTFS-Based 6G LEO satellite communication systems," *IEEE J. Sel. Areas Commun.*, vol. 43, no. 1, pp. 156–170, Jan. 2025.

[46] I. Del Portillo, B. G. Cameron, and E. F. Crawley, "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband," *Acta Astronautica*, vol. 159, pp. 123–135, Jun. 2019.

[47] SES, "The power of medium earth orbit (MEO) satellites," (n.d.), Dec. 2023. [Online]. Available: https://www.ses.com/power-medium-earth-orbit-meo-satellites

[48] Ceragon Networks, "Ceragon networks - Wireless backhaul solutions," 2025. [Online]. Available: https://www.ceragon.com

[49] C. T. Rodenbeck et al., "Microwave and millimeter wave power beaming," *IEEE J. Microw.*, vol. 1, no. 1, pp. 229–259, Jan. 2021.

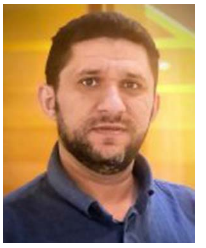
[50] M.-A. Lahmeri, M. A. Kishk, and M.-S. Alouini, "Charging techniques for UAV-Assisted data collection: Is laser power beaming the answer?," *IEEE Commun. Mag.*, vol. 60, no. 5, pp. 50–56, May 2022.

[51] E. Rodgers et al., "Space based solar power," 2024, Art. no. 4944. [Online]. Available: https://ntrs.nasa.gov/citations/20230018600

[52] B. E. Y. Belmekki and M.-S. Alouini, "NOMA as the next-generation multiple access in nonterrestrial networks," *Proc. IEEE*, vol. 112, no. 9, pp. 1303–1345, Sep. 2024.

[53] American Foreign Policy Council, "The promise of space-based solar power," Sep. 2022. [Online]. Available: https://www.afpc.org/publications/policy-papers/the-promise-of-space-based-solar-power

[54] L. Han, A. Retana, C. Westphal, R. Li, T. Jiang, and M. Chen, "New IP based semantic addressing and routing for LEO satellite networks," in *Proc. IEEE 30th Int. Conf. Netw. Protocols*, Lexington, KY, USA, Nov. 2022, pp. 1–6.



MOHAMMED ALMEKHLAFI received the Ph.D. degree from the Concordia Institute for Information Systems Engineering, Concordia University, Montreal, QC, Canada, in 2023. He is currently a Postdoctoral Researcher with Polytechnique Montréal, Montreal, QC. His research interests include wireless communications, artificial intelligence, and non-terrestrial networks. He was awarded the prestigious FRQNT Doctoral Scholarship during his Ph.D. studies and subsequently received the FRQNT Postdoctoral Fellowship. In addition to his research activities, he contributes to the academic community by serving on the Technical Program Committees of leading IEEE conferences and reviewing various peer-reviewed journals and conferences.

ANTOINE LESAGE-LANDRY received the B.Eng. degree in engineering physics from Polytechnique Montréal, Montreal, QC, Canada, in 2015, and the Ph.D. degree in electrical engineering from the University of Toronto, Toronto, ON, Canada, in 2019. From 2019 to 2020, he was a Postdoctoral Scholar with the Energy & Resources Group, University of California, Berkeley, CA, USA. He is currently an Associate Professor with the Department of Electrical Engineering, Polytechnique Montréal. His research interests include optimization, machine learning, and their application to renewable power systems and wireless communication networks.

GUNES KARABULUT-KURT received the B.S. (Hons.) degree in electronics and electrical engineering from Bogazici University, Istanbul, Türkiye, in 2000, and the M.A.Sc. and Ph.D. degrees in electrical engineering from the University of Ottawa, Ottawa, ON, Canada, in 2002 and 2006, respectively. She was with different technology companies in Canada and Türkiye between 2005 and 2010. From 2010 to 2021, she was a Professor with Istanbul Technical University, Istanbul. She is currently a Canada Research Chair (Tier 1) of new frontiers in space communications and a Professor with Polytechnique Montréal, Montréal, QC, Canada, Director of the Poly-Grames Research Center, Co-Founder and the Director of education and training of ASTROLITH, Transdisciplinary Research Unit of Space Resource and Infrastructure Engineering, Polytechnique Montréal. She is also an Adjunct Research Professor with Carleton University, Ottawa, ON. Gunes is a Marie Curie Fellow. She was the recipient of the Turkish Academy of Sciences Outstanding Young Scientist (TÜBA-GEBIP) Award in 2019.