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SURVEY

# A Survey of Mobility Management in Non-Terrestrial 5G Networks: Power Constraints and Signaling Cost

**ALAA A. R. ALSAEEDY** [1,2] **AND EDWIN K. P. CHONG** [2], **(Fellow, IEEE)**
[1] Department of Electronics and Communication Engineering, College of Engineering, University of Al-Qadisiyah, Diwaniyah 58001, Iraq
[2] Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523, USA

Corresponding author: Alaa A. R. Alsaeedy (alaa.alsaeedy@colostate.edu; alaa.refeis@qu.edu.iq)

**ABSTRACT** Mobility management is a critical and challenging requirement for 5G networks and their successors, as numerous highly mobile user equipment (UE), including massive Internet-of-Things (IoT) devices, generate extreme traffic volumes. In the integration of non-terrestrial networks (NTNs) with 5G, mobility management is of utmost importance to track these highly mobile UE/IoT throughout the network coverage area for the purpose of data-packet delivery. In this context, we thoroughly discuss the integration of satellite-based NTNs with 5G technology, which has become increasingly active in recent years, and studies are still ongoing to develop innovative frameworks to provide seamless connections to the extremely increasing density of high-mobility UE/IoT. The goal of this integration is to extend coverage and improve reliability beyond current 5G networks, enabling ubiquitous connectivity in remote areas and delivering high-speed data to UE/IoT. However, this integration poses numerous challenges in terms of mobility management, especially concerning the power constraints and signaling overhead of UE/IoT, as these devices are limited in battery power and processing capabilities. Handling these challenges is crucial to ensure successful integration and provide seamless connectivity to UE/IoT. In this paper, we highlight recent research efforts and potential solutions in these areas, contributing to the ongoing development of non-terrestrial 5G networks and improving global connectivity. To the best of our knowledge, this paper is the first study to emphasize and critically assess different mobility management solutions for satellite-based 5G NTNs, evaluating their impact on UE/IoT battery power consumption and signaling overhead, with implications extending to 6G networks.

**INDEX TERMS** 5G, 6G, handover, LEO, mobility management, NTN, power saving, vLEO.

## I. INTRODUCTION

The integration of 5G technology with satellite-based communication has become vital for extending the wireless coverage and capacity of 5G networks. This integration is driven by the urgent requirement to support not only a variety of essential applications but also to guarantee seamless connectivity anywhere, at all times. This ensures consistent access, ubiquitous coverage, and scalable services. However, global wireless coverage remains lacking, with only about 5% of ocean coverage and about 20% of land coverage [1]. This integration is also required for mobile network operators (MNOs) to provide wireless coverage in extreme situations when terrestrial networks (TNs) are partially or completely destroyed by natural hazards or even attacks, supporting mission-critical and public safety communication and improving emergency response and disaster recovery efforts.

The ever-increasing number of user subscriptions will impose another challenge on current 5G and future successor networks. According to forecasts, there will be over 5 billion user subscriptions and around 300 million fixed wireless

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access[1] (FWA) by 2028 [2]. Across North America, 5G mobile connections are expected to reach 280 million connections by 2025 [3]. Furthermore, the emergence of massive Internet-of-Things (mIoT) devices has dramatically increased the need for broadband connections, enabling these devices to exchange data packets at higher rate and facilitating the digital transformation of industry for companies, customers, and investors. For example, in 2021, Walmart planned to use and manage about 1.5 billion messages from their IoT devices daily for maintaining food in refrigerators and coolers and planning beforehand in-store maintenance needs [4]. In this context, mIoT is a new paradigm of network connectivity that enables devices/things to connect on an extremely massive scale, and 5G technology has become a critical platform for mIoT deployment [5]. This is crucial for supporting various use cases, such as smart homes/cities, smart agriculture, connected vehicles, and wearable devices. It is expected that the number of these devices will reach around 75 billion by 2025 [6].

To accommodate the continually increasing demands for data-intensive applications and services, 5G networks need to integrate new technologies to meet current and future demands. However, 5G alone might not be able to cope with the future demands of the massive number of user equipment (UE), including mIoT devices. According to forecasts, 5G is expected to reach its potential limit by 2030 [7].

To address these challenges and to bridge the gap in wireless connections, aiming to provide connectivity across the entire Earth, the 3rd Generation Partnership Project (3GPP) has started adopting satellite-based non-terrestrial networks (NTNs) into 5G technology. This is to meet the unprecedented demands for a massive number of connections, which have never been seen before, and to provide ubiquitous wireless access [8], [9]. While still in the development stage, 5G NTNs are expected to provide crucial services to the ever-growing density of high-mobility UE, massive machine-type communication (mMTC), and ultra-reliable low-latency communications (URLLC)[2] [9], [10].

As more UE, including mIoT devices, connect to TNs and/or NTNs, the signaling load associated with mobility management (MM) procedures becomes increasingly crucial. Two essential procedures, called handover (HO) and cell (re)selection (CS), detailed later in the paper, involve a set of algorithms/schemes dedicated to tracking the movement of all connected UE/IoT devices across the network coverage area to ensure seamless wireless mobile connectivity and service continuity, whether these devices move or stand still, for the purpose of delivering data packets. To this end, the implementation of highly efficient MM schemes is essential to accommodate the growing density of these devices. Moreover, managing the mobility of these UE/IoT devices incurs costs in terms of power consumption and signaling overhead, which is important to consider because these devices are mostly battery-powered. Thus, it is critical to optimize UE/IoT power consumption and minimize associated signaling overhead, avoiding excessive battery drain. This optimization aligns with the 5G requirement to prolong the battery life of these devices by 10 times. These challenges will be discussed in detail in the paper.

The motivation and importance of this paper arise from the critical need to address the unique challenges posed by MM in satellite-based 5G NTNs. Traditional MM procedures designed for TNs are insufficient for the high mobility and dynamic environments of NTNs. Also, this work aims to enhance the performance and efficiency of 5G NTNs and pave the way not only for 5G use cases but also for future 6G networks. By enabling ubiquitous connectivity, satellite-based NTNs can bridge the digital divide, offering seamless worldwide connectivity.

In this context, we list the main contributions of the paper as follows:

1) Necessity of 5G NTNs: We justify the need for 5G NTNs over traditional cellular networks by discussing their advantages in providing ubiquitous connectivity. We highlight the importance of satellite-based NTNs in achieving seamless worldwide connectivity and connecting the unconnected.
2) Critical analysis of MM in 5G NTNs: We provide an in-depth analysis of the challenges and current solutions for MM in 5G NTNs, highlighting the limitations of existing methods in mitigating signaling overhead and power consumption imposed by satellite-based systems.
3) Impact on UE/IoT devices: We explore how frequent HO/CS events affect UE/IoT, particularly given their limited battery power and processing capabilities. We also highlight the significant power consumption and signaling costs associated with MM in highly dynamic satellite-based 5G NTNs.
4) Evaluate conventional MM procedures: We assess the effectiveness of MM procedures, including HO/CS, in 5G TNs for their applicability in 5G/6G NTNs. Our findings highlight the need for more innovative MM strategies to address the unique challenges of future 5G and 6G NTNs.
5) Future research directions: We propose several future research directions, including the development of intelligent algorithms for mobility prediction, utilizing artificial intelligence (AI) and machine learning (ML) for dynamic MM optimization. Additionally, we recommend exploring context-aware HO/CS mechanisms. We also address the challenges in managing the coexistence of TNs and NTNs, laying the foundation for supporting advanced technologies, multi-connectivity, and ultra-heterogeneity. This vision aligns with the imminent integration of 4G, 5G, and 6G networks with their TN and NTN counterparts.

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[1] Type of 5G/4G wireless technology that offers broadband access to homes and business instead of cables.

[2] Critical applications such as remote surgery and autonomous vehicles that require ultra-low latency and extremely high reliability.

It is worth mentioning that throughout our paper, we utilize the term ''NTNs'' specifically to refer to satellite-based platforms, particularly LEO and vLEO, because of their significance as detailed above. Other types of NTNs, including unmanned aerial vehicles, low-altitude platforms, and drones, are outside the scope of this particular paper; for discussions on other types of 5G NTNs, see [11].

### A. SCOPE OF THE PAPER

From the preceding discussion and before proceeding, this paper focuses on addressing the following questions:

1) What does MM look like in 5G NTNs?
2) Considering that most UE/IoT devices have limited battery power and processing capabilities, how do these devices experience MM in 5G NTNs? Additionally, how do these limitations impact the overall network performance?
3) Will conventional 5G MM procedures, including HO and CS, work for 5G NTN use cases and be suitable for utilization in 6G NTNs?
4) Why do we need the 5G NTNs over and above traditional cellular mobile networks?

In this paper, we address the above questions with a focus on the UE experience. Our discussion aims to highlight and address the unique benefits and importance of 5G NTNs while drawing attention to their limitations compared to 5G TNs and the need to meet the demands of future connectivity, including 6G NTN systems.

### B. PAPER OUTLINE

The paper is organized as follows. Section II introduces different types of satellite constellations, such as low Earth orbit (LEO) and very-low Earth orbit (vLEO) platforms, and their roles in supporting 5G NTN applications and use cases. In Section III, we cover a variety of 5G NTN architectures and associated terminologies. This section details the configuration of 5G base stations, outlining how NG-RAN services are facilitated through satellite platforms. Following this, Section IV discusses 5G NG-RAN NTN elements, including the two 3GPP NTN architectures: transparent and regenerative payloads. We introduce Section V to explain how 5G NTNs can be accessed, outlining the multi-radio dual connectivity communication technique and its applications in different scenarios. Section VI illustrates how the NTN NG-RAN can offer radio coverage to UE/IoT devices on the ground, discussing the benefits and drawbacks of different radio coverage scenarios. Section VII offers detailed insights into the HO/CS mobility procedures, which are vital to ensuring wireless service continuity. We elaborate on various HO/CS scenarios specifically intended to function within the context of NTNs. Section VIII highlights challenges associated with MM procedures, specifically highlighting HO and CS procedures, including the implications arising from the coexistence of TNs and NTNs. In Section IX, we explore and discuss the mobility improvements introduced for NTNs by the 3GPP specifications and relevant solutions in the literature. In Section X, we summarize and emphasize the key challenges involved in implementing space-based 5G technology. Also, we provide concluding remarks and outline potential future research directions in Section X. For clarity, Table 1 lists the contents of the paper.

**TABLE 1.** Paper contents.

| Section | Title |
|---|---|
| I | Introduction:<br>I-A Scope of the Paper<br>I-B Paper Outline |
| II | 5G NTN Applications and Scenarios:<br>II-A Preliminaries<br>II-B LEO and vLEO constellations<br>II-C 5G NTN use cases and scenarios |
| III | 5G NTN Architecture:<br>III-A 5G gNB design and functional units<br>III-B 5G NTN satellite payload-based access |
| IV | 5G NG-RAN NTN Elements |
| V | 5G NTN Multimode-based Access:<br>V-A Benefits of applying MR-DC in 5G NTN<br>V-B Scenarios involving MR-DC in 5G NTN |
| VI | NTN NG-RAN Radio Coverage:<br>VI-A Fixed-beam coverage<br>VI-B Moving-beam coverage<br>VI-C Security aspects of FbC and MbC |
| VII | NTN NG-RAN MM and Service Continuity:<br>VII-A HO and CS for MM in NTN<br>VII-B HO types in NTN |
| VIII | MM Challenges and Implications in 5G NTNs:<br>VIII-A Challenges of frequent HO/CS<br>VIII-B Implications of TN-NTN coexistence<br>VIII-C RSRP measurement report validity<br>VIII-D Cell/beam capacity limitation |
| IX | Mobility HO Enhancement for NTN:<br>IX-A 3GPP-based mobility solutions for NTNs<br>IX-B Literature-based mobility solutions for NTNs |
| X | Final Remarks and Conclusion |

## II. 5G NTN APPLICATIONS AND SCENARIOS

### A. PRELIMINARIES

Satellite-based communication is increasingly being used for a variety of use cases. They serve to provide wireless communication for remote (or harsh) areas where traditional TNs are unavailable or for regions where cellular mobile coverage is lacking. More importantly, they also play a crucial role in securing wireless connectivity during critical situations, such as natural disasters. For example, in September 2019, when Hurricane Dorian hit the Bahamas, satellite-based communications were utilized in the aftermath to swiftly restore cellular mobile networks and provide internet connectivity [12]. This was crucial to provide essential wireless communication for first responders and the impacted population. In this context, satellite-based communication

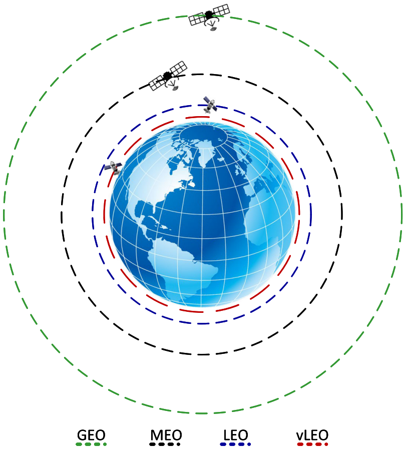


**FIGURE 1.** **Satellite orbits (the altitude scales are for illustration purposes and do not represent accurate values).**

utilizes a range of satellite systems including geostationary Earth orbit (GEO), medium Earth orbit (MEO), and LEO satellite systems, which serve as the primary spaceborne platforms (see Fig. 1)—these are positioned at altitudes ranging from about 35, 786 km down to 400 km [10]. Moreover, recently, vLEO satellites have been developed to offer even more advantages and benefits compared to LEO/MEO satellites [13], discussed in the following subsection. Fig. 2 shows the various satellite constellations.

As detailed earlier, satellite-based communication has been considered an essential part of 5G technology, forming the basis for 5G NTN systems. These systems leverage the benefits of satellite platforms to extend 5G coverage globally, aiming for universal connectivity not only on the ground but also in space. Because of their significance and promising features in serving 5G technology and its successors, we detail the most recent and common satellite constellations, namely LEO and vLEO, in the following subsection.

### *B. LEO AND VLEO CONSTELLATIONS*

LEO satellite constellations have shown promise as platforms to provide global connectivity because of their proximity to Earth, offering relatively low latency and propagation loss compared to MEO/GEO constellations and enabling cost-effective deployment. Notably, satellite operators such as Starlink-SpaceX, OneWeb, and Kuiper-Amazon have leveraged the advantages of LEO constellations. Starlink-SpaceX has successfully launched over 2000 satellites, with plans to deploy approximately 30000 satellites within the LEO constellation. Moreover, OneWeb envisions deploying more than 6372 satellites in the coming years, and Kuiper, in 2019, announced plans to deploy around 3236 satellites in LEO [14]. These three constellations will comprise a total of 40000 satellites in LEO (see Table 2), enabling global NTN systems for broadband services and supporting LEO-based NTN for 5G technology. For information about other satellite constellations, see [15].

To extend the advantages of using LEO-based NTN systems, aiming to further reduce latency and minimize the propagation loss while supporting near-real-time applications, vLEO satellites have been introduced. These are positioned at altitudes ranging from 100 to 350 km, which is much closer to Earth compared to LEO, as shown in Fig. 1 by a red dashed circle. They are specifically designed to accommodate time-sensitive applications and enable almost zero latency, supporting the crucial features of 5G technology and beyond. Moreover, this close proximity offers highly appealing features that further contribute to reducing transmission latency, minimizing propagation delays, and providing a high area capacity [13]. These features are beneficial in areas such as earth observation, real-time remote sensing, high-precision navigation, and quick disaster response. Furthermore, they also play an essential role in paving the way for more advanced wireless mobile technologies like 6G, which falls beyond the scope of this paper; see [1] for more details. In addition to their benefits and advantages, vLEO satellites are prone to disadvantages that are listed in Table 3, which are based on the information in [16].

Our next discussion will focus on the utilization of vLEO/LEO-based 5G NTN and the use cases that these vLEO/LEO satellites can offer for the 5G NTNs. Throughout the paper, we use "vLEO/LEO" or "v/LEO" interchangeably to refer to vLEO or LEO, as required by the context.

### *C. 5G NTN USE CASES AND SCENARIOS*

In the following, we elaborate on the primary use cases of integrating NTNs with TNs to improve the utilization of 5G [9].

1) Service Continuity: This is intended to deliver uninterrupted 5G services in challenging mobility environments. Typically, MNOs deploy cellular services in areas with dense populations, prioritizing regions of high network demand. However, this approach can leave certain areas with inadequate coverage or completely unserved. Such gaps can significantly impact users on the move, whether they are pedestrians, vehicle occupants, airline passengers, or maritime travellers. In these situations, the seamless provision of 5G services may be compromised, creating uncertainty in connectivity and limiting access to TN services. To address this issue, the concept of service continuity comes into play. The primary aim is to address the issue of maintaining uninterrupted 5G connectivity across diverse mobility scenarios. This involves ensuring consistent access to 5G services as users move between TNs and NTNs.

2) Service Ubiquity: This is to address extreme situations where TNs might not be accessible because of economic constraints, natural disasters (e.g., earthquakes

**TABLE 2.** Deployment of LEO satellite constellations.

| Satellite Constellation | Current Authorization | Total Satellites (planned) |
|---|---|---|
| Starlink-SpaceX | 4,408 LEO satellites | ≈ 30,000 |
| OneWeb | 716 LEO satellites (completed in 2022) | Second phase with 6,372 |
| Kuiper-Amazon | 3,236 LEO satellites | — |
| Total (combined) | | Over 40,000 satellites envisioned |

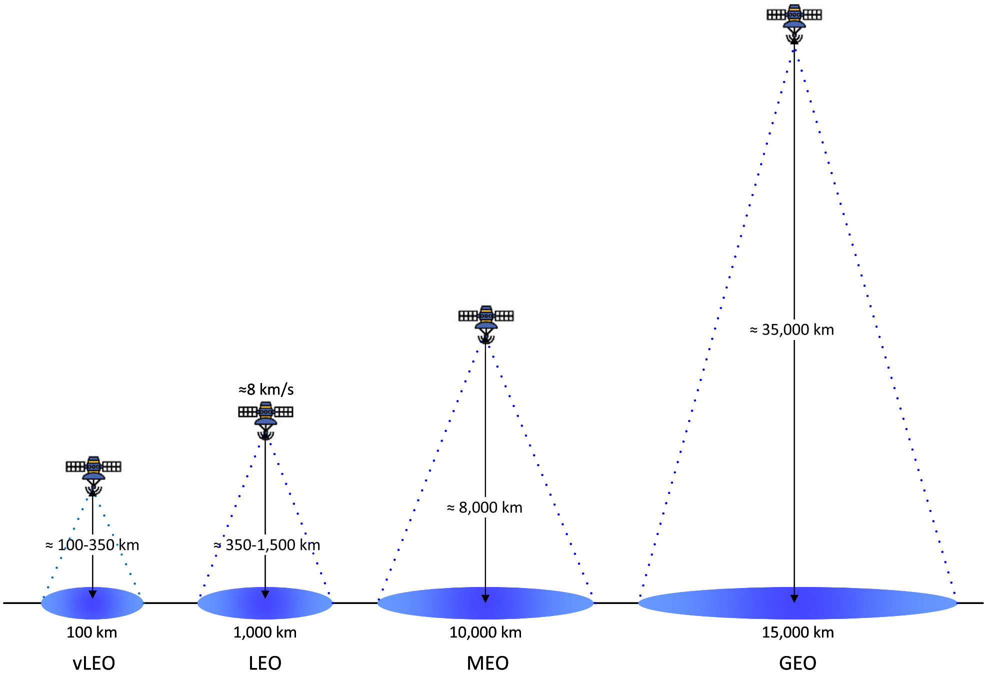


**FIGURE 2.** Satellite systems, showing different altitudes constellations.

or hurricanes), or even attacks, resulting in temporary outages or even complete destruction of TN infrastructures. These cases urge the need for alternative connectivity solutions.

Such crucial cases need to provide access to 5G services in areas that are either underserved or entirely unserved by TNs. This becomes vital for users who require uninterrupted connectivity despite geographical constraints posed by TN limitations. There are also several use cases highlight the significance of NTNs:

- *IoT applications for specialized industries:* These include connecting a vast number of IoT devices (i.e., mMTC) for applications like smart agriculture, critical infrastructure monitoring/control (e.g., oil/gas pipelines), waste management, environmental monitoring, as well as asset tracking and tracing.
- *Enhanced mission-critical communication:* Maintaining continuous 5G connectivity during emergencies is vital for public safety. Satellite networks can bridge communication gaps in times of crisis.
- *Home connectivity in remote/isolated areas:* Satellite-based access networks can provide much-needed home internet services in regions where TNs are unreliable or non-existent.

3) Service Scalability: NTNs, in particular, offer a wide coverage area that can span tens of thousands of cells found in TNs. This coverage advantage enables efficient content multicast or broadcast across large regions, potentially delivering data packets directly to UEs. Moreover, NTNs play an essential role in offloading TNs during peak periods. By broadcasting non-time-sensitive data during non-peak hours, they effectively reduce the network's burden. In this context, we will further detail this point later in the paper.

In sum, integration of satellite-based communication, particularly v/LEO-based 5G NTNs, plays a vital role in supporting the scenarios detailed above. From ensuring service continuity in challenging environments to achieving ubiquity where terrestrial networks are lacking, and enabling scalable broadcasting for a vast array of content, these scenarios showcase the potential of NTNs to reshape the landscape of wireless communication. This integration paves the way for a new era of connectivity that goes beyond the TN limitations.

**TABLE 3.** Advantages and challenges of vLEO satellites.

| Aspect | Advantages of vLEO | Challenges of vLEO |
|---|---|---|
| ✓Altitude | ≈ 100 – 450 km above Earth's surface | High atmospheric drag |
| ✓Power Requirements | Reduced power draw due to proximity to Earth | Regular propulsion needed to maintain orbital altitude |
| ✓Resolution | Higher resolution imagery due to closer proximity | Damage and erosion from higher atomic oxygen density |
| ✓Latency | Lower latency in communication | Smaller coverage footprint by sensors |
| ✓Deorbiting | Natural deorbiting of objects within weeks | Restricted elevation angle |
| ✓Cost Effectiveness | Cost-effective deployment compared to higher orbits | Reduced communication windows with ground stations |

## III. 5G NTN ARCHITECTURE

In 5G, the radio access network that connects to the 5G Core (5GC) is referred to as the Next Generation Radio Access Network (NG-RAN). It uses New Radio (NR), which is a new 5G radio access technology (RAT), and it can also incorporate the Evolved Universal Terrestrial Radio Access (E-UTRA), a RAT associated with Long-Term Evolution (LTE) systems [17]). In this paper and according to [18], using the term NG-RAN implies accessibility to the 5GC via NR, represented by gNBs (the term for base stations in 5G), or via E-UTRA, represented by eNBs (the term for base stations in LTE). This design allows not only 5G-enabled UEs but also their predecessors to establish connections with the 5GC through either 5G or LTE systems as needed.

The NG-RAN is vital in providing wireless connections between UE/IoT devices and the 5GC network. This architecture comprises several elements, including radio access network nodes (i.e., gNBs), and network functions [19]. As these gNBs are the main components responsible for direct interactions with the UE and facilitating their access to the network, we examine the architecture of 5G gNBs in the following subsection, as shown in Fig. 3.

### A. 5G GNB DESIGN AND FUNCTIONAL UNITS

According to the 3GPP technical report [20], and to enable network function virtualization (NFV), software-defined networking (SDN), load management, and performance optimization, the gNBs are split into two functional units: central unit (CU) and distribution unit (DU). Additionally, the CU is further subdivided into two associated logical nodes: control plane (CP) and user plane (UP). These logical nodes are illustrated in Fig. 3, and we provide brief definitions of these units (see [21] for more information), as follows:

- *gNB-CU (gNB Central Unit):* This is a logical node responsible for hosting specific communication protocols, including Radio Resource Control (RRC), Service Data Adaptation Protocol (SDAP), and Packet Data Convergence Protocol (PDCP). It serves as the control point for one or multiple gNB-DUs. Also, the gNB-CU handles the termination of the F1 interface, which connects it to the gNB-DU.

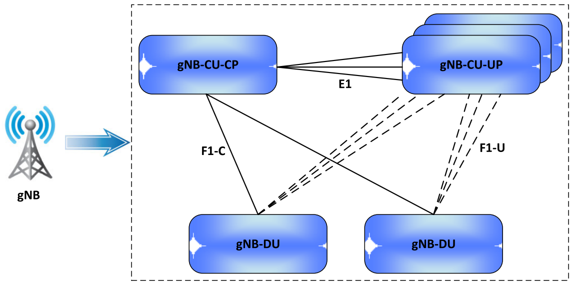


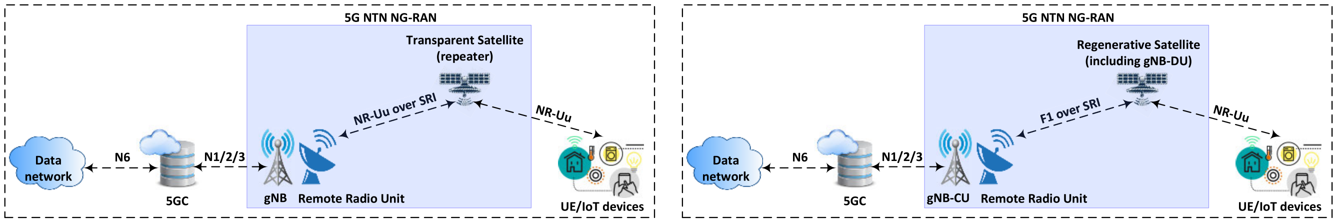
**FIGURE 3.** gNB architecture in 5G NG-RAN (adapted from [21]).

- *gNB-DU (gNB Distributed Unit):* This node hosts the Radio Link Control (RLC), Medium Access Control (MAC), and Physical (PHY) layers. Its operation is partially controlled by gNB-CU. A single gNB-DU can support one or multiple cells, with each cell exclusively served by one gNB-DU. The gNB-DU also serves as the termination point for the F1 interface connected to the gNB-CU.
- *gNB-CU-CP (gNB-CU-Control Plane):* This node hosts the RRC and CP part of the PDCP protocol of the gNB-CU that serves the gNB. The gNB-CU-CP serves as the termination point for the E1 interface connected to the gNB-CU-UP and the F1-C interface connected to the gNB-DU.
- *gNB-CU-UP (gNB-CU-User Plane):* This is to handle the UP portion of the PDCP and SDAP protocols within the gNB-CU, which serves the gNB. Its function includes terminating the E1 interface linked with the gNB-CU-CP and the F1-U interface connected to the gNB-DU.

It is worth noting here that the preceding logical nodes are also applied to a special version of a base station known as en-gNBs (see [22] for more information), which can connect with LTE networks and their eNBs, to provide 5G services over LTE. en-gNBs provide NR C/UP protocol terminations towards UEs.

### B. 5G NTN SATELLITE PAYLOAD-BASED ACCESS

To ensure that 5G NTNs accommodate various scenarios and use cases (detailed in Section II-C), numerous working



(a) (b)

**FIGURE 4.** **5G NTN with NG-RAN network access based on satellite payloads (adapted from [8], [9]).**

groups and studies have developed different designs for 5G NTNs, aimed at providing global wireless access. Among these design approaches in this context are those led by the 3GPP. These are categorized based on the type of network access they provide, as shown in Fig. 4.

In Fig. 4a illustrates the 5G NTN provide NG-RAN services via a satellite platform, where the satellite acts as a repeater with a transparent payload, as detailed previously. In this configuration, the NR-Uu radio protocol is utilized between UE/IoT devices and the satellite. The same protocol is also used between the satellite and the satellite GW, avoiding the need for a new communication protocol.

The scenario with a regenerative payload is illustrated in Fig. 4b, where the satellite takes on the role of a 5G gNB, functioning as a gNB-DU. Meanwhile, the gNB-CU is located on the ground and communicates with the satellite via a satellite GW, using the F1 protocol, which is an essential interface linking the gNB-DU and gNB-CU (see Section III-A) for connectivity.

The above satellite payload scenarios can be utilized to offer wireless access to UE/IoT devices in conjunction with TN 5G-RAN. This can be achieved through various network design approaches, including both TN and NTN 5G NG-RANs, which we elaborate on in Section V.

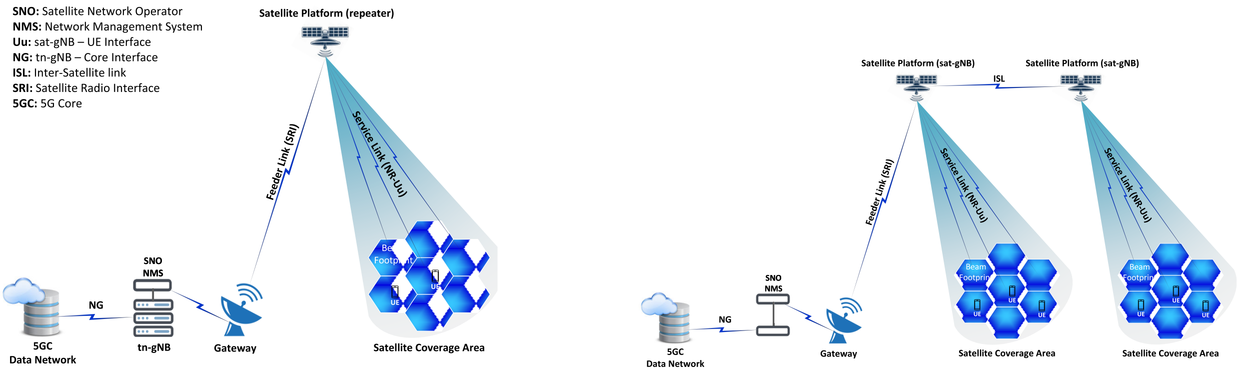
## IV. 5G NG-RAN NTN ELEMENTS

Basically, NTNs have emerged as a complement to existing TN (i.e., 5G networks), expending the utilization of a variety of use cases. Unlike terrestrial/ground gNBs (referred to as tn-gNBs), NTNs incorporate satellite constellations, v/LEO, along with airborne gNBs (we refer to as sat-gNBs); satellites serve as flying gNBs. These sat-gNBs provide significantly larger wireless coverage compared to their ground counterparts. As a result, these v/LEO constellations play an essential role in hosting radio equipment like gNBs. Furthermore, within the NTN architecture, v/LEO satellites can also function as repeaters (i.e., relay node), reflecting signals from ground gateways (GWs) to extend coverage to specific areas as needed.

In this context, the 3GPP has introduced two architectures for NTNs: transparent and regenerative payloads [10], which are depicted in Figs. 5a and 5b, respectively.

A typical NTN is composed of the following essential network elements, as detailed below:

- **Satellite GWs:** These are vital components that establish the connection between NTNs and public data networks, including the 5G core (5GC) network. Satellite GWs serve as the link through which data packets are transmitted between the TN infrastructure and the satellites of the NTN system.
- **Feeder Links:** These are connections that bridge the gap between satellite GWs on the ground and satellite platforms in orbit. They ensure the seamless exchange of data packets between the ground-based (i.e., satellite GWs) infrastructure and the satellites. Feeder links are also referred to as satellite radio interfaces (SRI), which are responsible for carrying various communication protocols and interfaces.
- **Service Links:** These are to interface UE/IoT devices with the gNB. Satellites can provide wireless bidirectional communication between UE/IoT devices and the serving gNB. In the context of 5G NTN, this interface is also referred to as the New Radio Uplink Unicast (NR-Uu).
- **UE/IoT:** These are devices used by end-users, such as smartphones, tablets, or other communication devices (e.g., IoT devices, including very small aperture terminal (VSAT) systems) capable of transmitting/receiving data packets with the satellite platforms. These devices are served by the satellite coverage area through what is called the service link (marked as NR-Uu in Fig. 5), providing them with connectivity and access to the network.
- **Satellite Payloads:** Satellites can be equipped with different types of payloads, which can be either transparent or regenerative. Transparent payloads facilitate the direct passage of signals without onboard processing. In contrast, regenerative payloads have onboard processing capabilities, enhancing their ability to manage and process signals before re-transmission.
- **Beam Generation:** Satellites generate multiple beams that cover designated service areas, as shown in Fig. 5. These beams together cover a larger geographic region. The extent of the service area covered by these beams is determined by the satellite's field of view, which depends on factors such as the satellite's altitude, onboard antenna design, and minimum elevation angles.



(a) Transparent (b) Regenerative

**FIGURE 5.** NTN typical scenarios based on: transparent/regenerative payloads (adapted from [10], [23]).

- **Inter-Satellite Links (ISL):** In some cases, constellations of satellites may include inter-satellite links (ISL). These links allow satellites within the constellation to communicate with each other. This can facilitate more efficient data packet routing and communication across the satellite network. ISL may operate using either radio frequency or optical bands.

Fig. 5a shows the transparent architecture, where a tn-gNB is positioned between the GW and the 5GC. The satellite serves as a repeater, limited to radio frequency processing tasks like frequency conversion, filtering, amplification, and beam management, unlike the regenerative architecture. In the latter, as depicted Fig. 5b, the satellite functions as a flying gNB (sat-gNB), carrying a full gNB or part of it (e.g., gNB-DU: gNB distributed unit [9], as explained later in the paper) onboard, enabling it to decode/encode and process data packets similar to conventional gNBs.

## V. 5G NTN MULTIMODE-BASED ACCESS

This concept is based on a communication technique known as multi-radio dual connectivity (MR-DC), which is already in use within 5G NG-RAN and has been utilized in its predecessor, LTE networks [22], [24]. MR-DC enables UE/IoT devices to establish simultaneous connections with multiple independent base stations (i.e., gNBs) for signaling messages and data packets exchange. These base stations can be of the same or different RATs, e.g., eNBs, or even a combination of gNBs and eNBs. Specifically, within MR-DC, a UE with multiple transmission/receiving capabilities can connect to one gNB, serving as the main node (MN), while the other (gNB or eNB) acts as the secondary node (SN) for the same UE.

### A. BENEFITS OF APPLYING MR-DC IN 5G NTN

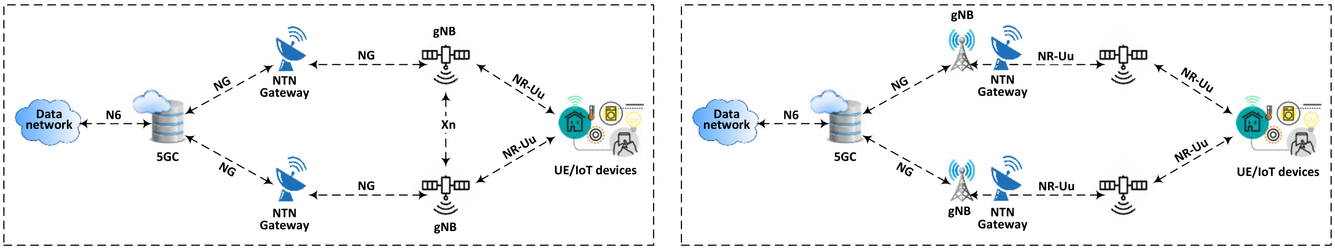
MR-DC is a highly promising feature for 5G and beyond, especially in supporting applications that demand high reliability, low latency, and high throughput, such as mMTC and URLLC. Importantly, MR-DC can also significantly reduce HO interruptions and minimize HO frequency [22]. These factors are critical in 5G NTNs because of their highly mobile nature. These networks experience significantly higher HO rates compared to 5G TNs. This is a result of both the mobile users and the swift movement of the satellite-based gNBs (sat-gNBs), an issue that we will elaborate on later in the paper. In this context, it is worth noting here that MR-DC's multimode connectivity can be applied in 5G NTN NG-RAN, involving not only scenarios with transparent and regenerative payloads but also in conjunction with conventional 5G TN deployments.

It is important to note that the above concept can be effectively leveraged to offload 5G TNs during peak-hour traffic and in extreme situations where the traffic volume exceeds the network capacity. In situations with high-traffic volume, especially during emergencies/crises, where the serving TNs may struggle to accommodate sudden traffic spikes, MR-DC offers a solution. Instead of routing all the traffic through tn-gNBs/eNBs, the TNs and NTNs can collaborate to share their resources and split the traffic. That is, data traffic associated with UE/IoT devices (also known as UP traffic; see Section III-A) is handled by the serving tn-gNB, while the corresponding signaling messages (also known as CP traffic) are routed to the sat-gNB (or gNB-DU) of the corresponding NTN.

This is just one scenario highlighting how TNs and NTNs can work together, particularly in emergency situations (e.g., earthquakes). During such crises, the surviving tn-gNBs may experience overwhelmingly high demand and limited capacity to serve all the surging traffic driven by the urgent need for mobile communication services. This scenario can address the concern we raised in Section I, item 4.

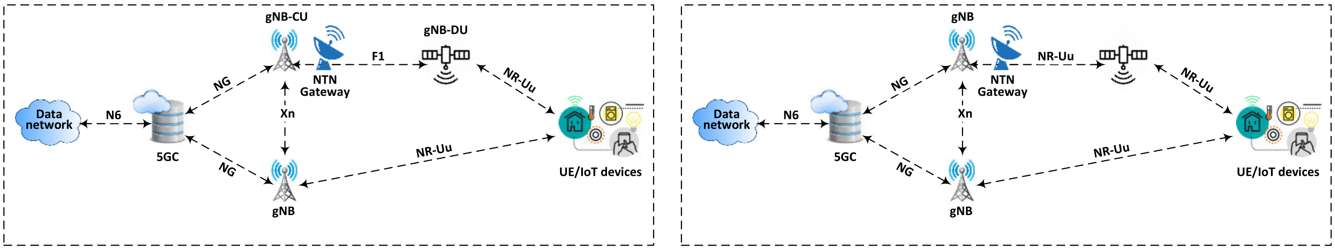
Furthermore, the following scenarios provide further insights into this concern:

- *Underserved Areas:* In rural/remote areas, conventional TNs often offer access to the network but with limited bandwidth, especially at the cell edges of the available radio coverage. In such cases, integration NTNs based



(a) MR-DC Regenerative NTN NG-RAN

(b) MR-DC Transparent NTN NG-RAN



(c) MR-DC Regenerative TN-NTN NG-RAN

(d) MR-DC Transparent TN-NTN NG-RAN

**FIGURE 6.** **MR-DC for TN-NTN NG-RAN in combination with satellite payloads (adapted from [10]).**

on NG-RAN becomes essential to achieve the desired data rates and the network performance.

- *High-Speed Mobility:* Ensuring consistent network coverage in high-speed trains can be challenging because of varying signal strengths along the railway. Here, the deployment of MR-DC involving 5G NTN NG-RAN becomes crucial to ensure the targeted levels of reliability and seamless connectivity for UE/IoT devices in these highly dynamic varying environments. This technology is also essential to support users in flight or for aviation and space operations.

Based on the preceding discussion, 5G NTNs can provide wireless services to UE/IoT devices by utilizing the MR-DC technique. That is, these devices can be served by two different simultaneous connections, which we refer to as hybrid NTN connectivity (HNC) and dual NTN connectivity (DNC). Thus, UE/IoT devices can access the network through at least one of the following. In HNC, devices connect via NTN NG-RAN in conjunction with the conventional TN NG-RAN. In contrast, in DNC, the wireless communication involves two separate NTN NG-RAN connections, each established by two different gNBs to enable MR-DC.

### B. SCENARIOS INVOLVING MR-DC IN 5G NTN

Following the 3GPP guidelines outlined in [10], we elaborate in detail on scenarios where the MR-DC technique can be used to provide wireless connectivity. This will be achieved in accordance with the HNC and/or DNC techniques, including the use of transparent and regenerative payloads, as below:

1) In Fig. 6a, dual sat-gNBs serve as onboard units on satellite platforms and function as full gNBs in regenerative payload access (NTN-based NG-RAN). In this setup, one sat-gNB serves as the MN, while the other functions as the SN, providing dual connectivity to UE/IoT devices. These two sat-gNBs are interconnected by a special interface protocol called Xn (which also links traditional tn-gNBs for signaling messages exchange) transported on the ISL interface; for more detail about the Xn interface, see Section X in [21]. This scenario is designed to address situations where UE/IoT devices are located in areas with limited or no wireless coverage, providing services to these devices not only on the ground or at sea but also in near-space environments, including cases where users are flying onboard. The use of v/LEO-based 5G NTN can offer relatively low latency, typically one-way propagation delay in the range of 2 to 7 msec. for the orbit altitude of 600 km [25], making it suitable for supporting delay-sensitive applications.
2) Unlike the setup in Fig. 6a, Fig. 6b illustrates the MR-DC's multimode connectivity using a transparent NTN NG-RAN payload. In this configuration, the serving gNBs (i.e., tn-gNBs) are located on the ground, and UE-specific signaling messages and data packets are forwarded to the corresponding NTN GW. Then, they pass all the way to the satellite platforms, where they are reflected to the designated area as needed. In the MR-DC mode, one tn-gNB and its associated satellite platform serve as the MN, while the others (i.e., a similar combination of their counterparts) serve as the SN, providing dual connectivity. As previously detailed, and more specifically, in the case of transparent satellite, the NTN GW supports all the necessary functions to relay the NR-Uu interface signals. Hence, the satellite replicates the NR-Uu radio interface, transmitting it from the feeder link (between the NTN

GW and the satellite) to the service link (between the satellite and the UE/IoT devices) and vice versa.

3) A different setup within the context of the MR-DC mode is depicted in Fig. 6c. In this regenerative architecture, the dual-mode connectivity is provided through collaboration between TN and NTN NG-RANs. As illustrated in the figure, a satellite platform is equipped with gNB-DU onboard, which provides one service link to UE/IoT devices. Simultaneously, this gNB-DU connects to its counterpart on the ground, gNB-CU, via the F1 interface over the SRI link through the NTN GW. The second service link to UE/IoT devices is provided via a tn-gNB situated on the ground. This design is particularly useful for providing services to devices located in remote or underserved ground areas. In contrast to the scenarios shown in Figs. 6a and 6b, this design provides wireless coverage to the UE/IoT devices but not in the near-space environments (e.g., user flying onboard).

4) The approach in Fig. 6d demonstrates a multimode connectivity achieved through collaboration between TN and NTN NG-RANs, utilizing a transparent payload setup. Similar to the above scenario in item 3, the satellite platform provides a service link but acts as a repeater, forwarding signaling between UE/IoT devices and their associated tn-gNB through the serving NTN GW, which acts as a MN, for example. The SN is provided via a tn-gNB to provide the second service link to UE/IoT devices. This design offers wireless coverage similar to the setup described in item 3.

From the preceding discussion, we can see that various network configurations have been employed to enable multimode connectivity using both transparent and regenerative satellite payloads, extending 5G access from space. In the following, we will describe how these NTNs provide radio coverage to the users on the ground.

## VI. NTN NG-RAN RADIO COVERAGE

As we have seen from the above, 5G NTN-based NG-RAN represents a cutting-edge wireless technology that is currently under development and holds great promise. However, numerous partnerships have already started to pave the way towards the implementation of this technology, laying the foundation for future developments. For example, on January 5, 2023, Qualcomm unveiled an agreement with Iridium[3] to incorporate satellite connectivity into "next-generation premium Android smartphones." This aims to provide global services, including two-way emergency messaging, and other messaging applications, utilizing Iridium's fully operational LEO constellation consisting of 66 satellites [27]. Likewise, in North America, in August 2022, T-Mobile and SpaceX announced plans to provide satellite-based direct-to-cellphone services. Following this, in January 2024, SpaceX launched its first group of Starlink satellite platforms aimed at providing direct smartphone connectivity. Initially, this enables text messaging from space within the US for most LTE-enabled UE/IoT devices, with voice and data connectivity scheduled to be enabled by 2025 [28].

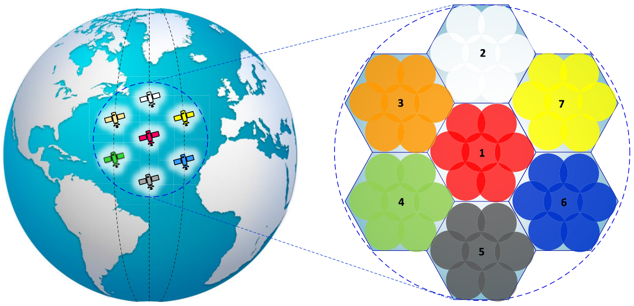


**FIGURE 7.** Illustrative example of satellite constellation.

Despite the various network configurations described before, UE/IoT devices on the ground will have a similar experience of radio coverage. They may also experience radio coverage from other sat-gNBs in a way similar to TNs, where tn-gNBs and other tn-gNBs in close proximity serve as neighbors, together serving a group of UE/IoT devices within the same vicinity simultaneously. Likewise, these devices may receive radio coverage through multi-radio beams[4] from the same serving sat-gNB; see Fig. 5. One radio beam serves as the primary connection, while the others function as neighboring beams. This is an attempt by NTNs to mimic ground radio coverage achieved by TNs. However, there are exceptions related to satellite mobility (among other factors in terms of varying path loss and latency, though these are beyond the scope of this paper). In TNs, gNBs (or eNBs) typically remain stationary, whereas in NTNs, they are constantly in motion. We will provide further details on this below.

For illustration, we use an example to show what satellite radio coverage looks like for UE/IoT devices on the ground. In the example shown in Fig. 7, seven satellite constellations are arranged to cover a specific area. These satellites are marked by different colors, illustrating their corresponding radio coverage on the ground, as depicted on the right side of the figure. Each satellite can serve its designated area through multiple beams, covering a given service area bounded by the satellite's field of view. For instance, each satellite's central beam is labeled as 1, 2, 3, etc., as shown in the figure, accompanied by neighboring beams subdividing the satellite's field of view. The footprints of the beams are shown by circles enclosing the entire radio coverage area. However, the footprints of the coverage area are not perfect circles and depend on various factors such as the satellite's altitude,

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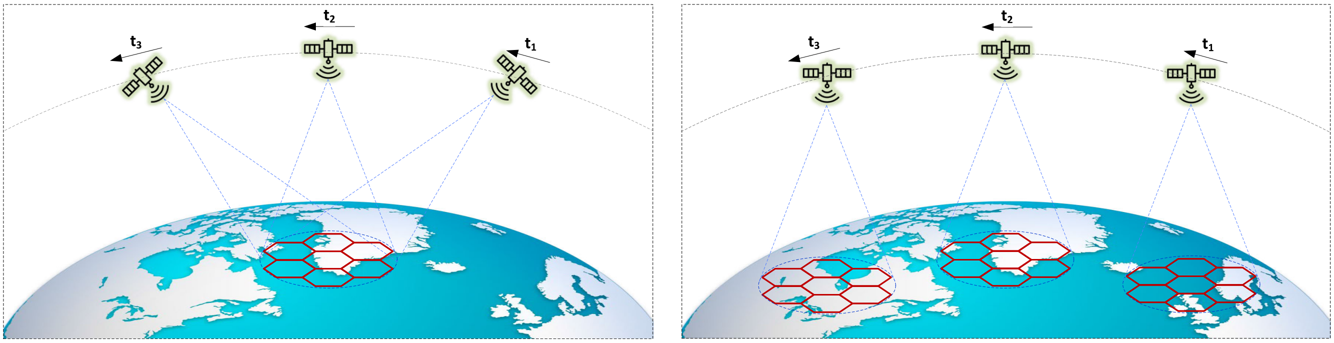
[3] A network of low Earth orbit communication satellites operated by Iridium Communications Inc., providing global voice, data, and tracking services [26].

[4] A fundamental 5G NR technology often associated with massive multi-input multi-output (mMIMO) antenna design, providing significant benefits over LTE, see [29].



(a) FbC (b) MbC

**FIGURE 8.** **Illustration of ground-based radio coverage in FbC vs MbC technique.**

antenna design, and the minimum elevation angle [30]. This cell layout simplifies and facilitates the simulation of 5G NTNs, allowing researchers to simulate scenarios already in place such as frequency reuse, an important feature of mobile cellular networks. Also, these satellite constellations can be interconnected via ISL links to provide the onboard sat-gNBs with the necessary Xn signaling. This signaling, transported on the ISL link, is used for resource sharing and exchanging information about mobility procedures, such as HOs. Within the v/LEO constellation's movement, it can provide radio coverage to ground-based users in two different ways: fixed-beam coverage (FbC) and moving-beam coverage (MbC), depending on how these multi-beams are utilized, as detailed below.

### A. FIXED-BEAM COVERAGE

In FbC technique, satellites are equipped with beam-steering antennas (i.e., steerable radio beams). As the satellite orbits the Earth, it adjusts its beams to continually cover a certain geographical area. Thus, as long as the satellite is above the horizon relative to a specific geographical area, it can adjust its beams to cover that area. Hence, UE/IoT devices can remain within the coverage area of the same satellite for a maximum duration. This duration is determined by the time the satellite remains above the horizon relative to the UE's location, lasting about 7 to 10 minutes, depending to the speed of the v/LEO satellites, moving approximately at a speed of around 8 km/sec. [23]. Fig. 8a depicts that while moving through times $t_1$ to $t_3$, the satellite radio-beams coverage remain stationary over a specific geographical region during the time it's above the horizon.

The FbC technique offers relatively low computational complexity because the required beamforming (and steering) calculations for FbC only need to be performed during the initial network setup or UE/IoT association [29]. This reduces the repeated computational burden on the serving network compared to MbC. Moreover, since locations of ground-based UE/IoT devices are relatively static within FbC, radio resource allocation and scheduling become less computationally intensive.

### B. MOVING-BEAM COVERAGE

In MbC technique, unlike the FbC, the satellite uses antennas with non-steerable beams (i.e., fixed beams). In this case, the radio coverage area shifts as the satellite moves relative to fixed points on the ground. For ground-based UE/IoT devices, the satellite beams rapidly pass over their locations at very high speeds. Typically, these devices will only receive radio coverage for a very short period of time, lasting about several seconds. This case is shown in Fig. 8b, where the satellite's radio beams move as the satellite orbits the Earth, producing very-fast moving radio coverage areas on the ground, which we refer to as "moving coverage" throughout this paper.

In contrast to FbC, MbC introduces higher computational complexity. The continuous calculations required to maintain alignment between cells/beams for ground-based UE/IoT devices can place a burden on the processing capabilities of NTN elements, especially in scenarios with high user density. Moreover, frequent changes in cells/beams necessitate dynamic radio resource allocation and scheduling algorithms, which can be computationally expensive for both the serving NTNs and the corresponding UE/IoT compared to the FbC technique.

The above techniques offer different tradeoffs in terms of coverage duration, mobility support, and signaling overhead, making them suitable for various use cases based on the specific requirements of the applications or UE/IoT devices involved. FbC is suitable for ground-based devices that require relatively longer periods (within the range of 7 to 10 mins) of radio coverage (i.e., wireless connections), enabling them to transmit/receive (Tx/Rx) data packets continuously during this period. In contrast, MbC is ideal for IoT/FWA, including their industrial versions known as industrial IoT (IIoT) devices [31]. These devices do not necessitate continuous and uninterrupted wireless connections. Instead, they typically Tx/Rx data packets sporadically or at specific intervals, rather than needing to Tx/Rx data packets continuously over time. In terms of signaling overhead, the FbC technique exhibits lower signaling overhead and fewer HO/CS events as compared to

**TABLE 4.** Comparison of FbC vs MbC.

| Aspect | FbC | MbC |
|---|---|---|
| Beam features | Steerable beams that continuously cover a fixed area. | Fixed beams, coverage shifts with movement. |
| Coverage period | Longer coverage duration: $7-10$ mins. | Very short coverage duration: $\sim 15$ sec. |
| Mobility support | Ideal for devices requiring continuous connectivity. | Ideal for IoT Tx/Rx data intermittently. |
| Signaling cost | Relatively lower signaling overhead and fewer HO events. | Generates higher signaling overhead due to frequent HOs. |
| Suitable use cases | Ground-based devices with persistent wireless connections. | IoT, IIoT, and FWA with intermittent Tx/Rx. |
| Security issues | May lead to prolonged security risks (e.g., jamming) because of predictable beam patterns. | Complicates security protocols but shortens threat exposure; however, frequent HO/CS may create vulnerabilities. |
| Computation cost | Lower computational complexity, reduced signaling cost, less battery consumption for UEs, fewer HO/CS events. | Higher computational complexity, increased signaling cost, higher battery consumption for UEs, more frequent HO/CS events. |

MbC. The latter results in frequent HO/CS, which is also costly in terms of the battery power of UE/IoT (detailed later in Section VIII-A).

### C. SECURITY ASPECTS OF FBC AND MBC

While FbC and MbC techniques offer different use cases and provide benefits, these might come at a risk of security concerns associate with them, which we elaborate as follows.

In FbC, the fixed nature of the cell/beam can potentially expose the coverage area to a higher risk of prolonged eavesdropping, spoofing, jamming, or denial of service attacks [32], as malicious entities have a predictable window of opportunity (7 to 10 mins.) to target the communication links. In such cases, implementing suitable security measures is critical to protect the communication link between GWs and their corresponding sat-gNBs to avoid such attacks [33]. Moreover, this relatively fixed radio coverage allows satellite GWs to establish and maintain secure communication channels with the ground-based devices, providing enough time to establish robust encryption and security protocols.

In MbC, the fast-moving nature of the cell/beam makes it more challenging for malicious entities to carry out threats (e.g., jamming attacks) because of the short exposure window (a few seconds). However, this rapid ''moving coverage'' results in frequent HO/CS transitions between cells/beams (detailed in Section VIII-A), complicating the implementation of continuous and stable security protocols. This could potentially create vulnerabilities during HO/CS events. Ensuring robust, quick-authentication methods and efficient encryption management is essential to secure the confidentiality of the corresponding communication links.

For a clearer overview, we summarize the main features of the above techniques in Table 4.

## VII. NTN NG-RAN MM AND SERVICE CONTINUITY

As we have seen, UE/IoT devices may receive radio coverage from different satellites, including multi-beam coverage from the same satellite. All of these coverage scenarios involve satellite movement, creating what we call ''moving coverage.'' In this context, we will elaborate on scenarios involving multiple beams/satellites radio coverage and their impact on service continuity, which is essential to ensure uninterrupted mobile services for UE/IoT devices. This is achieved through MM procedures such as HO and CS, which correspond to the mobility states of these devices: idle and connected states (or modes), respectively—we provide detailed information about UE/IoT's mobility states in [19].

### A. HO AND CS FOR MM IN NTN

The two MM procedures CS and HO play a vital role in ensuring wireless service continuity, not only in traditional TNs but also in the development of 5G NTN NG-RAN. To highlight their significance, it is important to clarify when UE/IoT devices need to trigger the HO or CS procedures. In conventional TNs, mobile UE/IoT devices initiate requests to start HO when they are in connected mode or CS when they are in idle mode. The purpose of these procedures is to ensure seamless wireless connectivity and service continuity.

In both HO and CS procedures, UE/IoT devices are provided with a list of candidate neighboring cells transmitted via the system information downlink channel, and the serving network continuously updates this list based on the devices' locations [34]. In HO, devices in the connected mode send requests to their serving cell to search for another serving cell with a better signal strength—this procedure involves the serving cell, a candidate cell, and the correspond UE/IoT device. In CS, however, devices in idle mode, if receiving a signal level below a certain threshold, the device selects the best serving cell from the list of candidate cells—this procedure involves only the UE/IoT device, which independently (re)selects a suitable new serving cell. Whether HO or CS is initiated, the purpose is to keep UE/IoT devices connected as they move or search for a suitable serving cell.

In the case of NTNs, the same principle applies, as there is also a concept of ''moving coverage,'' as detailed earlier. The corresponding devices will trigger HO or CS procedures every time they experience a change in the serving radio coverage or when they come into range of a new serving cell or experience a degradation in the signal strength of the current serving cell.

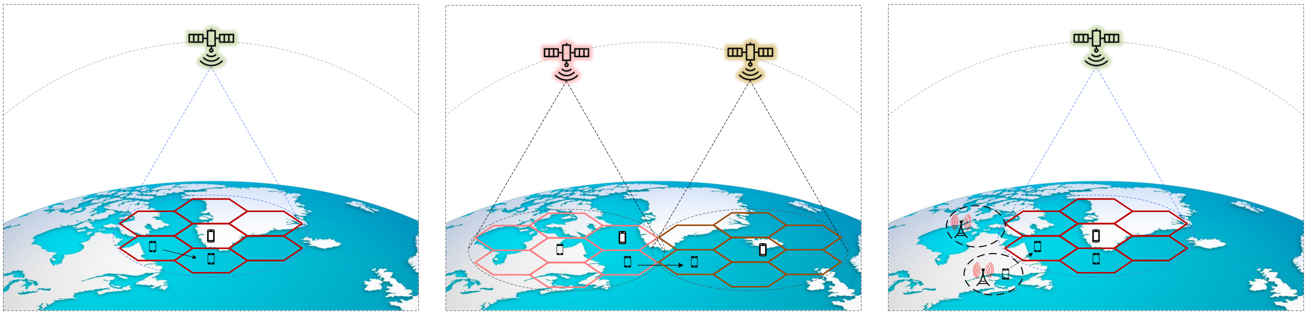

(a) Intra-satellite HO (b) Inter-satellite HO (c) Inter-access HO

**FIGURE 9.** Overview of different NTN HO scenarios.

### B. HO TYPES IN NTN

As the HO procedure requires an exchange of information between all the involved parties, including the current serving cell, the corresponding UE/IoT device (in connected mode), and the candidate neighboring cell, this can be achieved through three HO scenarios [10]:

1) Intra-satellite HO: This involves transferring a UE/IoT device connection from its current serving cell to a neighboring cell in close proximity within the same coverage area served by the same satellite. Likewise, in cases where the satellite has multi-beam coverage, this involves transferring the connection from the serving beam to another; see Fig. 9a.
2) Inter-satellite HO: This involves HO between cells (or beams) served by different satellites, typically in close proximity. It occurs when a UE/IoT device moves from the coverage area of one satellite to another; see Fig. 9b. As stated before, this procedure requires that both involved satellites should be interconnected with an Xn interface via ISL (see Fig. 6a).
3) Inter-access HO: This involves transferring a device's connection from a serving cell in TN to a neighboring cell in NTN, and vise versa; see Fig. 9c. This type of HO is referred to as vertical HO, enabling the corresponding devices to seamlessly switch between different RATs. For example, this HO can occur between cells in LTE and cells in 5G NTN.

The above HO scenarios can be applied to satellite platforms, whether they function as a transparent or regenerative payload architecture; see Figs. 5 and 4. It is important to note that for a successful HO procedure in tn-gNB, a necessary link Xn must exist. Likewise, HOs between two neighboring sat-gNBs should be interconnected via Xn across the corresponding ISL. HOs between cells in TNs and cells in NTNs are only possible when Xn connectivity exists between them. However, this can pose a significant challenge because of satellite platform mobility [10]. Furthermore, this introduces another HO issue related to Xn mobility HO because of the mobility of the interconnected satellites. This results in a specific HO procedure that does not exists in TNs, where the Xn connection remains stationary.

## VIII. MM CHALLENGES AND IMPLICATIONS IN 5G NTNS

As v/LEO platforms have become an essential component of the envisioned future of 5G and beyond, providing wireless mobile coverage via spaceborne gNBs in various payload scenarios discussed earlier (see Sections III-B and V), they offer the potential to provide global mobile connections at all times. However, this new integration of NTNs into 5G technology presents a range of challenges that impact not only MNOs but also end-user experience. In this section, we specifically address challenges related to MM procedures, with a particular focus on HO and CS procedures, as they play a significant role in ensuring wireless mobile connectivity and seamless services, as highlighted below.

### A. CHALLENGES OF FREQUENT HO/CS

Unlike traditional TNs, where radio coverage remains fixed because the tn-gNBs are stationary, and the only moving parts are the mobile UE/IoT devices (although there are also stationary devices), NTNs always provide dynamic "moving coverage" for these devices, as v/LEO platforms move swiftly at very high speeds. For example, v/LEO satellites, at altitudes of around 400 km, move at speeds of about 8 km/s, orbiting the Earth approximately every 90 minutes [23]. Consequently, ground-based devices experience an extremely dynamic wireless coverage environment, which contrasts to the nature of non-"moving coverage" provided by tn-gNBs to end-user devices on the ground. The dynamic nature of this "moving coverage" prompts UE/IoT devices, whether they are mobile or stationary, to initiate HO/CS procedures more repeatedly. This results in several negative impacts, including an increase in the associated signaling overhead and power consumption in UE/IoT. Moreover, it can also impact other MM procedures, such as the paging procedure [19], which, in turn, affects what are called the key performance indicators (KPIs)—a set of indicator values used by the MNOs to measure the network performance over time [17]. One crucial KPI impacted is the *handover success rate*, which may decrease because of rapid fluctuations in signaling strength, interruptions caused by latency, or conflicts arising from concurrent MM procedures, leading to conflicts with UE's internal processing. That is, these devices may struggle to adapt to these fast-changing behaviors related to HO/CS events.

To better understand of how the HO/CS rate changes, we calculate the time in which a UE/IoT device remains connected to the same serving cell/beam before initiating the HO/CS procedure. It is important to note that we neglect the signaling overhead associated with the CS procedure since it involves the device only, as mentioned earlier, resulting in significantly lower overhead compared to HO. We denote this time as $\mathrm{Trig\_time}_{\mathrm{HO}}$ sec., reflecting the frequency of HO events. We also refer to a ground-based UE/IoT device velocity as $\mathrm{Vel}_{\mathrm{UE}}$ km/h, moving within a serving cell/beam with a diameter of $\mathrm{Dia}_{\mathrm{cell}}$ km. Also, we refer to the velocity of the v/LEO platform as $\mathrm{Vel}_{\mathrm{sat}}$ km/s. For simplicity, we assume that the ground-based device moves at a constant speed and direction, while it travels from one cell/beam edge to another, crossing the diameter of its serving cell/beam. In TNs, a mobile UE moving at $\mathrm{Vel}_{\mathrm{UE}}$ can stay connected with its serving cell for a duration equal to the cell/beam's diameter divided by $\mathrm{Vel}_{\mathrm{UE}}$. In NTNs, the device's velocity is either added to or subtracted from the satellite's velocity, $\mathrm{Vel}_{\mathrm{sat}}$, depending on whether the device moves in the opposite direction as the serving satellite or in the same direction, respectively. Thus, we approximate the term $\mathrm{Trig\_time}_{\mathrm{HO}}$ in the "moving coverage" environment of the NTN, as follows:

$$\mathrm{Trig\_time}_{\mathrm{HO}} \approx \frac{3600 \cdot \mathrm{Dia}_{\mathrm{cell}}}{|3600 \cdot \mathrm{Vel}_{\mathrm{sat}} \pm \mathrm{Vel}_{\mathrm{UE}}|} \text{ sec.} \tag{1}$$

This formula can also be used for TNs by setting $\mathrm{Vel}_{\mathrm{sat}}$ to 0, as the serving gNB (or eNB) is stationary. In this case, as long as the device stands still, it would not trigger a HO procedure; hence, the value of $\mathrm{Trig\_time}_{\mathrm{HO}}$ would be extremely high, indicating that the device is not moving. However, the serving network may enforce HOs for certain devices to achieve load balancing, for example. Based on the assumptions we have made, the formula in (1) represents the maximum duration in which a device remains connected in the scenario mentioned above. In practical cases, this duration may be shorter, showing that frequency of HO/CS events could be higher than what (1) shows. Moreover, considering factors such as the effects of propagation loss, environmental conditions, fast fading, and overlapping radio coverage (i.e., multiple beams), the HO/CS frequency is expected to be even higher than in the previous case. However, apart from simplicity, including other factors can add more computation complexity (for more detail, see [34]), resulting in an even higher HO/CS frequency.

For illustrative purposes, we consider a v/LEO platform with cell/beam diameters ranging from 50 to 1000 km [10], taking into account the MbC coverage scenario (see Section VI-B). We use these cell/beam diameter values to calculate both worst and best cases for the values of $\mathrm{Trig\_time}_{\mathrm{HO}}$, respectively. Furthermore, we examine different velocities of UE/IoT devices: 500 and 1200 km/h, representing users traveling in high-speed trains and onboard airplanes [8], respectively, for example. We consider these two velocities in both directions, with and against the movement of the serving v/LEO, which can orbit at a velocity of about 8 km/sec. [23]. By substituting these values in (1), we generate Table 5 to illustrate the varying durations during which a UE/IoT device remains connected before the need to trigger the HO/CS events.

**TABLE 5.** Comparison of HO triggering time.

| $\mathrm{Vel}_{\mathrm{UE}}(\mathrm{km/h})$ | $\mathrm{Trig\_time}_{\mathrm{HO}}(\mathrm{s})$, $\mathrm{Vel}_{\mathrm{sat}} \approx 8$ km/s<br>$\mathrm{Dia}_{\mathrm{cell}} = 50$ km | <br>$\mathrm{Dia}_{\mathrm{cell}} = 1000$ km |
|---|---|---|
| +500 | 6.14 | 122.86 |
| −500 | 6.36 | 127.20 |
| +1200 | 6.00 | 120.00 |
| −1200 | 6.52 | 130.43 |
| Stationary | 6.25 | 125.00 |

As shown in Table 5, in this highly dynamic "moving coverage," each UE/IoT device can trigger the HO/CS procedure, on average, every 6 or 125 sec. for cell/beam diameters of 50 or 1000 km, respectively, regardless of the end-user device's movement. This example highlights the significant signaling overhead associated with HO/CS procedures in 5G NTN NG-RAN. To further illustrate this point, we now consider the following situation:

One of the primary use cases of 5G systems is to support ultra-dense UE/IoT device connections at a density of $10^6$ UE/km$^2$. If we consider a cell/beam diameter of 50 km, resulting in an area of 1963.5 km$^2$, the expected device density within this area would be approximately $2 \times 10^9$ devices (i.e., over 2 billion). Now, when these devices are exposed to the "moving coverage" scenario, and we refer to the corresponding results in Table 5, about $2 \times 10^9$ HO/CS procedures will be triggered almost simultaneously every 6 seconds. This substantial signaling load becomes even higher with a cell/beam size of 1000 km.

These challenges pose unprecedented situations for 5G technology and beyond. Looking ahead to 6G technology, where device densities are envisioned to reach $10^8$ UE/km$^2$ [1], the discussed issues become exceptionally critical and require further attention. The huge signaling overhead weighs not only on the serving network but also on the associated UE/IoT devices. Additionally, these challenges are also accompanied by an unavoidable increase in battery power consumption in these devices, thereby impacting the overall KPIs of the serving network.

Unlike the HO/CS procedure in the MbC scenario, the signaling overhead in the FbC scenario (see Section VI-A) associated with the HO/CS procedure would be lower. Specifically, in FbC, the associated UE/IoT devices remain connected to the same serving cell/beam for a longer period compared to the MbC scenario before initiating the required

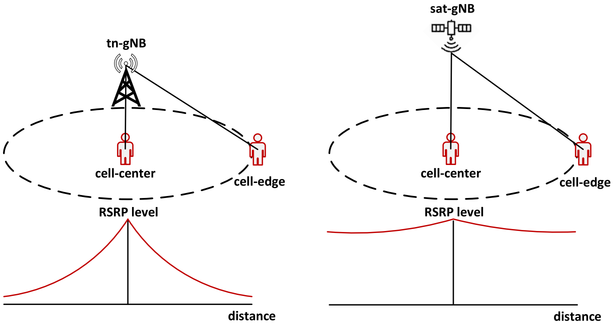


**FIGURE 10.** Depicts RSRP levels in TN (left) and NTN (right).

HO/CS procedure. In other words, the value of $\text{Trig\_time}_{\text{HO}}$ is greater than what is calculated in Table 5. In the case of FbC, the associated devices receive non-"moving coverage" for a time duration ranging from 7 to 10 minutes [33]. This time duration corresponds to the time when the serving sat-gNB remains above the horizon relative to the UE/IoT's location. To this end, MNOs face challenges in minimizing frequent HO rates, as these rates are critical factors in optimizing the overall network performance and improving their KPIs because of the drawbacks discussed above.

### B. IMPLICATIONS OF TN-NTN COEXISTENCE

Despite the numerous benefits of integrating NTNs with 5G technology, this development poses challenges when TNs and NTNs work in conjunction. In such cases, UE/IoT devices on the ground are exposed to different types of wireless mobile coverage. These include stationary radio coverage from tn-gNBs and the "moving coverage" from sat-gNBs, which can be either FbC-based or MbC-based coverage. This dynamic situation results in frequent switching between several serving cells/beams over time, adding more conflicting HO/CS scenarios (including inter-access HO/CS, detailed in item 3, Section VII-B) than the case detailed above.

The implication here is that the corresponding devices have a rapidly changing neighboring cell set (which are sent by the serving network via the information system channel as mentioned before). The list of candidate neighboring cells can change within seconds as the v/LEO platform moves (see Table 5). The duration of this change can be even shorter when these devices are in motion. This places a higher processing load on the UE/IoT devices to identify/select the best valid candidate cell within a very short time. This depends on how long the list of candidate neighboring cells remains valid—the more frequently the candidate cell list changes, the higher the processing load on the UE/IoT. Consequently, the corresponding UE/IoT devices may undergo HO/CS very rapidly, switching back and forth between multiple neighboring cells, entering what is referred to as "ping-pong" or "toggling" effect [19], particularly when cells are overlapped or co-located, as is the case with TN-NTN coexistence.

Another issue that arises here is the difficulty of differentiating between the best cells/beams in terms of the received signal strength to select the best serving cell/beam to camp on. This selection process is a key factor in the decision-making of HO/CS procedures in TNs. In such network deployments, UE/IoT devices can choose the best serving cell/beam from a list of neighboring cells based on a metric known as the reference signal received power (RSRP) level, often compared to a predefined threshold. By using RSRP measurements, a UE/IoT device can clearly determine whether is receiving signals from the cell center (or close to it) or from the cell edge because of the clear difference in the corresponding received RSRP levels, as illustrated in the left side of Fig. 10.

In NTN deployments, however, the RSRP measurements might not assist UE/IoT devices in clearly selecting the best candidate serving cell. This is because RSRP levels tends to be relatively uniform throughout the sat-gNB's coverage area (i.e., v/LEO's serving area) [10]. In this "moving coverage" environment, the UE/IoT devices receive minimal variation in RSRP levels, regardless of their location—whether near the cell center or cell edge—resulting in nearly consistent RSRP levels for most UE/IoT devices within the sat-gNB's serving area, as illustrated in the right side of Fig. 10. Hence, the traditional scheme used for HO/CS procedures in TN deployments, which depends primarily on RSRP levels for decision-making, becomes less effective in selecting the optimal serving cell within NTN deployments. This highlights the concern we raised earlier back in item 3, Section I-A. However, in this context, many studies have proposed solutions to assist UE/IoT devices in selecting the best candidate cell/beam for HO/CS procedures, as discussed later in the paper.

Among the above discussion about how RSRP will be impacted in the case of sat-gNBs, as height of the sat-gNB significantly influences the HO/CS events and the corresponding RSRP levels as below:

1) Radio coverage: As altitude increases, the corresponding sat-gNB coverage area of each cell/beam expands. This can lead to a larger number of overlapping cells/beams, making it more challenging for UE/IoT devices to distinguish the best serving cell/beam using RSRP levels. The received signal strength might not vary as distinctly between adjacent cells/beams, complicating the HO/CS events.
2) Signal strength: Higher altitudes result in increased path loss, which can reduce the overall received signal strength. This reduction in signal strength must be considered when comparing RSRP levels to predefined thresholds. Devices closer to the cell center will still receive stronger signals compared to those at the edge, but the differences may be less pronounced with increasing height.
3) Dynamic HO/CS: At higher altitudes, the sat-gNB will have a broader view of the UE/IoT devices. This broader view requires more frequent handover and cell

selection procedures as the devices move, especially in scenarios with high mobility. The model must account for the increased frequency of these procedures, driven by the larger footprint and varying signal strengths.

### C. RSRP MEASUREMENT REPORT VALIDITY

In addition to the preceding drawback of using RSRP-based HO/CS, RSRP measurements might not accurately reflect real-time conditions. Typically, the UE/IoT devices send the RSRP report back to the serving cell/beam (or serving sat-gNB) as initial step of requesting HO from their current serving cell/beam. Because of the high-speed nature of the "moving coverage," this can result in triggering HO/CS procedures either too late or too early. These factors contribute to wireless service interruptions, HO failures, and undesirable KPI metrics such as the *handover failure rate*. These issues can occur because RSRP measurements may expire before, during, or shortly after the initiation of the HO/CS procedure.

This situation also arises because of the delay between receiving the RSRP report and the transmission time by the relevant UE/IoT device. This delay or latency typically depends on the sat-gNB's elevation angle. For example, with a v/LEO at an altitude of 800 km, when the sat-gNB is at a 10° elevation angle, the corresponding propagation delay (satellite to UE/IoT) is about 7.9 ms. However, at an elevation angle of 90° the corresponding propagation delay is about 2.7 ms relative to UE/IoT's location [9].

### D. CELL/BEAM CAPACITY LIMITATION

During the initial connection setup, a serving cell (gNB or eNB) assigns to each device a temporary unique identifier called the Cell Radio Network Temporary Identifier (C-RNTI) to identify UE/IoT devices within a specific cell in wireless mobile networks, and it is necessary in maintaining the radio link between each individual device and its serving cell [35]. At the time of writing this paper and in accordance with the 3GPP specification in [35], the maximum value of C-RNTI is 65522, which is the highest value that a serving cell can assign to devices within its transmission range. For typical TNs, where cell sizes are relatively small, this maximum C-RNTI value is sufficient to accommodate devices within the serving coverage area, each serving cell supporting up to 65522 devices at the same time. To illustrate, consider the example of a typical microcell with a radius of around 2 km [19]. In this scenario, the existing capacity of C-RNTI is relatively more than sufficient to serve all UE/IoT devices connected to the microcell coverage area.

However, NTNs present a different scenario, where the cell/beam coverage area can be significantly larger. As mentioned previously, this coverage area can extend to a minimum cell diameter of 50 km and may reach up to 1000 km. This poses a challenge. Considering the current maximum limit of the C-RNTI value (which is 65522, representing the maximum number of devices that can be supported simultaneously), 5G NTNs might face challenges accommodating more than 65522 devices within a 50 km diameter cell unless MNOs introduce a novel design for C-RNTI to address the envisioned device capacity in 5G NTNs—this capacity is envisioned to support ultra-dense UE/IoT devices, with an expected density of about $2 \times 10^9$ within a cell with a diameter of 50 km (as detailed in an earlier example; see Section VIII-A).

Without such innovation, a substantial number of UE/IoT devices could be left unserved. To solve this issue, the capacity of C-RNTI to simultaneously support the envisioned UE/IoT density in 5G NTNs within a cell of 50 km diameter should be increased to at least $2 \times 10^9$, a value not yet reached by the current C-RNTI. This current limitation of C-RNTI is a bottleneck in NTN deployments, contradicting the vision of 5G NTNs to support ultra-dense UE/IoT connections ($10^6$ UE/km$^2$). This constraint would also be problematic in future 6G technology, where the envisioned device density is $10^8$ UE/km$^2$.

## IX. MOBILITY HO ENHANCEMENT FOR NTN

In this section, we will discuss solutions introduced by 3GPP specifications and existing work in the literature. The 3GPP's mobility enhancements for NTN scenarios involve reusing the existing conditional handover (CHO) scenarios, which are already in place for LTE and 5G systems [36], as detailed in the following subsections.

### A. 3GPP-BASED MOBILITY SOLUTIONS FOR NTNS

These CHO scenarios are event-triggered based on signal measurements reported by the UE/IoT devices, which are then transmitted back to their serving cell to request a HO because of the received signal degradation. If specific conditions are met, the serving cell initiates the HO procedure for the corresponding UE/IoT devices, allowing them to reselect another suitable serving cell from a list of candidate cells. These particular conditions (or events), named A3, A4, A5, and A6, serve as essential triggers for the necessary HO, as detailed in Table 6.

It's worth noting that there are other event-triggered HO, but they are beyond the scope of this paper; see [36] for more detail. Here, we are excluding other HO scenarios that involve mandatory HO, where serving cells enforce HO for certain UE/IoT devices. These mandatory HO scenarios are typically related to load balancing, congestion avoidance, or emergency situations. The event-triggered HO listed in Table 6 are mainly based on RSRP signal measurements and are well-suited for TNs, but are not as effective in the case of NTNs for the reasons explained in Section VIII-B.

In this context, the 3GPP specification has introduced another CHO event to work in NTN use cases [10]. These triggering conditions are designed to enhance HO in NTN environments, considering factors like measurements quality, locations, time, timing advance values, and elevation angles to improve overall network performance, as detailed below:

**TABLE 6.** CHO events.

| HO Event | Purpose |
|---|---|
| A3 Event | Triggered when the measured signal quality of the current serving cell falls below a certain threshold, which may indicate that the signal from a neighboring cell is stronger or of better quality. |
| A4 Event | Triggered when the signal strength from a neighboring cell exceeds a certain threshold, which suggests that the signal from the neighboring cell is stronger or better, prompting the initiation of a HO to that cell. |
| A5 Event | Based on the relative signal strength between the serving cell and neighboring cells. When the relative signal strength of a neighboring cell becomes stronger than the serving cell by a predefined margin, the A5 event is triggered, leading to a HO. |
| A6 Event | Similar to A5 but focuses on the relative signal strength between neighboring cells, triggered when a neighboring cell is significantly stronger than another neighboring cell, indicating a potential HO to the stronger neighboring cell. |

1) Measurement-based triggering:
    - Triggering based on network measurements.
    - Adjust thresholds and measurement events for NTNs, considering the unique NTN characteristics.
2) Location-based triggering:
    - Triggering based on the location of UE and satellites.
    - Factors like distance between UE and satellite can initiate HOs.
    - Especially useful in v/LEO scenarios with predictable satellite movements.
3) Time-based triggering:
    - Triggering based on time.
    - Can use UTC time or timers to trigger HOs.
    - Consider satellite movements in v/LEO scenarios.
4) Timing advance (TA)[5] value-based triggering:
    - Triggering based on the timing advance value to the target cell.
    - Can be used in conjunction with other triggers.
5) Elevation angles of source and target cells-based triggering:
    - Triggering based on the elevation angles of source and target cells.
    - Useful in NTNs and can work in combination with other triggers.

The above-mentioned mobility enhancements for NTNs exhibit some pros and cons, which are outlined in Table 7. Additionally, these event-triggering HOs show different levels of computational complexity depending on the specific method used. These comparisons are detailed in Table 8.

### B. LITERATURE-BASED MOBILITY SOLUTIONS FOR NTNS

Many working groups and researchers have introduced frameworks to improve the MM of NTNs. Some efforts have focused on refining the conventional CHOs used in TN-based 5G, while others have proposed new methods designed for NTN scenarios. The authors of [37] conducted a performance analysis to assess the applicability of conventional 5G HO algorithms within LEO-based NTN scenarios. They used various parameters for HO margin and time-to-trigger values to evaluate the performance of the HO procedure in NTN use cases, comparing the results with two TN deployments: an urban area covered by macro cells and a highly mobile train scenario. According to the simulation results, the HO and radio link failures was 10 times more frequently in NTNs while the duration of service interruption was 5 times longer. These results align with the challenges discussed earlier, particularly related to the concept of "moving coverage." In this context, another study explored the potential usability of the conventional CHO for NTN use cases. In [38], the authors evaluated the use of the conventional CHO for the NTN MbC scenario. According to this study, simulation results show that CHO eliminates radio link failures and HO failures but increases unnecessary HOs by over 60%, resulting in undesirable higher signaling and measurement reporting.

To mitigate the frequent HO, the authors of [39] developed user-centric HO framework for NTN in ultra-dense environment. The main concept here is to utilize the storage capacity of the serving sat-gNB aimed to improve user communication quality. This is done by buffering the downlink data and distributing the data among multiple sat-gNBs, enabling seamless HO and consistent access to the satellite with the best link quality. The simulation results in [39] show that the user-centric HO outperforms traditional TN-based HO methods in terms of throughput, HO delay, and end-to-end latency.

To address the issues presented in [38] regarding the use of conventional CHO, the author of [40] proposed an enhanced CHO scheme to improve the MM in NTNs. According to the author, the proposed CHO outperforms the baseline HO and conventional CHO in terms of reducing the "ping-pong" effect and HO failure rate. Despite these improvements, the solution in [40] assumes that UE/IoT devices have built-in GNSS capabilities, requiring these devices to continuously update their location, thereby adding more burden on the UEs. Furthermore, the simulations in [40] were conducted with a small number of UEs (only 10 devises), which is insufficient to simulate real-world ultra-dense area expectations in 5G NTNs. This leaves uncertainty about its scalability under high UE densities (e.g., $10^6$ UE/km$^2$).

As both 5G TNs and NTNs will work together, UE/IoT devices will encounter various HO scenarios: from TNs

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[5] TA is a parameter used in mobile networks to adjust the timing of transmissions between UE and its serving cell, compensating for varying distances between UE and the cell to maintain synchronization [8].

**TABLE 7. Comparison of event-triggering HO methods in 5G NTNs.**

| Triggering Method | Pros | Cons |
|---|---|---|
| Measurement-based | • Similar to TNs in terms of specification impact.<br>• Relies on UE estimates and established channel estimation techniques.<br>• Utilizes measurements of receiving power and cell quality for operation. | • Challenges in maintaining neighboring cell lists because of the highly dynamic nature of "moving coverage" in v/LEO platforms.<br>• Unreliable triggering due to small RSRP variation in cell overlap regions (i.e., A3 event) and propagation delay.<br>• Complexity in ensuring UEs perform HOs to specific countries. |
| Location-based | • Suitable when cell boundaries are not clearly defined (i.e., dispersed).<br>• Enables mandatory HO decisions based on UE/IoT's location.<br>• Provides a precise trigger since the UE/IoT's location can be accurately known.<br>• Effective to mitigate the issue of small RSRP variation in areas of cell overlap.<br>• Allows prediction configuration of triggering conditions using satellite ephemeris and deterministic satellite movement.<br>• Reduces the number of measurements that UE/IoT need to perform for HOs.<br>• Configuring the distance between the UE/IoT and the serving sat-gNB as a triggering condition can reduce both calculations and battery-power consumption in UE/IoT when calculating the timing advance. | • UE/IoT might trigger HO to a wrong/unavailable cell. This can happen when the NTN cell is inconsistent or under varying channel conditions. It can also occur if the network incorrectly sets the triggering conditions.<br>• Some UE/IoT devices may not have the necessary positioning capability to support location-based triggering.<br>• UE/IoT must continually monitor to track the satellite's trajectory, and the network requires up-to-date (i.e., real-time) UE/IoT's location information, which can result in increased power consumption for UE/IoT and higher overall signaling overhead. |
| Time(r)-based | • Useful for maintaining service continuity when UE/IoT lose terrestrial coverage.<br>• Enables mandatory HO based on timing.<br>• Network can adjust timing lengths to reduce random access channel (RACH) congestion.<br>• Utilizes satellite ephemeris data to leverage the predictable movement of satellites.<br>• Potentially reduces the number of measurements needed for HOs. | • May trigger HO to a wrong cell (as in the above item of location-based).<br>• Ephemeris data accuracy and UE mobility can affect trigger accuracy, possibly leading to early or late HOs.<br>• Using multiple timers for each UE may result in significant overhead. |
| Timing Advance-based | • Suitable for situations where UEs must adjust the timing of RACH preamble transmissions to ensure that the target cell receives the preamble correctly.<br>• Offers enhanced accuracy for determining the triggering point, especially in scenarios with minimal differences in RSRP values between overlapping cells. | • Requires Global Navigation Satellite System (GNSS)-capable UEs (GNSS refers to satellite constellations providing positioning, navigation, and timing services either globally or within specific regions). |
| Elevation Angles-based | • Useful for irregular-shaped HO regions. | • UE/IoT require to calculate the elevation angle based on its location and satellite ephemeris data. |

to NTNs or vice versa. The author of [41] examined this coexistence and its influence on HO procedures. The author showed that using GNSS data during HO events significantly increases the associated HO delay time. However, simulation results indicate that adjusting A3 measurement parameters (see Table 6) can significantly reduce "ping-pong" events between NTNs and TNs, including unnecessary HO to NTNs, thereby improving overall network performance. The impact on UE battery power during transitions between TNs and NTNs was not addressed in this scenario.

To address the issue detailed in Fig. 10, the authors of [42] proposed a HO method that utilizes angle-based (i.e., elevation angle) measurements, instead of relying on the RSRP-based measurement (see Section VIII-C). The elevation angle is calculated based on the distance between the serving sat-gNB and its cell center and between the sat-gNB and the UE. According to the authors, results show

**TABLE 8.** **Computational complexity of event-triggering HO methods in 5G NTNs.**

| Triggering Method | Computational Complexity Description |
|---|---|
| Measurement-based | High. Requires continuous monitoring and analysis of multiple network parameters (e.g., receiving power, cell quality). The complexity increases with the number of monitored parameters and the dynamic nature of the environment. |
| Location-based | Moderate. Dependent on periodic location checks and updates. Real-time tracking can introduce moderate computational demands, but efficiency is higher when updates are less frequent. |
| Time(r)-based | Low to Moderate. Involves simple timer checks with minimal computational load per check. Managing multiple timers across many UEs can lead to significant overhead. |
| Timing Advance-based | Low. Light computational demands per check of timing advance values. Suitable for precise timing adjustments with minimal computational load. |
| Elevation Angles-based | Low. Requires calculation of elevation angles based on location and satellite ephemeris data. The complexity is low per calculation but dependent on the accuracy of the data. |

that the angle-based method outperforms the RSRP-based one in terms of HO failure rate, ''ping-pong'' rate, short time-of-stay, and radio link failure rate. However, the proposed method does not take into account the impact on UEs in terms of battery power and associated signaling overhead. Also, it is unclear how this method would work in an environment with multiple sat-gNBs (i.e., MR-DC; see Section V).

Given that the movement of serving sat-gNBs (i.e., satellite platforms) can be predicted using ephemeris information,[6] the authors of [44] leveraged this data to propose a solution utilizing the distance between the location of UE/IoT devices and the center of the ''moving coverage'' on the ground. This study is based on two vital conditions: the UE/IoT devices should have GNSS (or be able to determine their location information), and the serving sat-gNBs should broadcast their location information continuously. These information items are utilized by both entities to estimate when to trigger CHO based on the difference between the center of serving cell and the corresponding location of UE/IoT. According to [44], their proposal eliminates HO failures, unnecessary HOs, and ''ping-pong'' effects. The results demonstrate an extension of the mean time that a UE/IoT stays served by the same serving cell before triggering the HO procedure, from values below 2 seconds to 4.8 seconds, with the optimal mean duration time determined to be 4.9 seconds. Despite this improvement, the duration remains relatively short, imposing significant challenges for both the serving network and UE/IoT devices, as discussed in Section VIII-A.

Although [44] shows enhancement in the performance of the CHO procedure, their study does not take into account the propagation delay between the serving sat-gNB and the associated UE/IoT devices, which is a crucial factor impacting the *handover failure rate* KPI, as detailed in Section VIII-C. To address this issue, the authors of [45] proposed a machine learning (ML)-based model to assist in determining the optimal timing for triggering HO procedures. This model predicts the distance and elevation angle between the UE/IoT and the serving sat-gNB's cell center, considering the propagation delay. According to [45], the proposed solution relies on several assumptions, including GNSS-enabled UE/IoT devices, broadcasting of cell location information by sat-gNBs, a non-time-varying channel, and line-of-sight (LOS) conditions. While their proposed model shows improvements over existing schemes that neglect propagation factors, the assumed conditions might not always align with reality. In practical scenarios, LOS conditions might not persist continuously, leading to additional unpredictable variabilities. Factors such as obstacles between communication terminals, unexpected orbit deviations, and changes in channel quality over time could be likely occurrences. This solution shows improvements in HO triggering performance in v/LEO-based NTN but imposes additional processing burdens on UE/IoT devices, which is particularly challenging as most of these devices are battery limited. This aspect contradicts the vision of 5G and its successor, 6G, aiming to extend battery lifetimes to approximately 10 to 20 times the capacity of current standards [1].

Likewise, the authors of [46] introduced ML-based solutions for HO decisions in NTNs. They proposed using a K-means algorithm to group users based on similar features (e.g., distances from their serving cell center). Then, ML classification models determine whether UEs are ready to trigger HO based on features such as distance. This method depends on group HO to decide which group of UEs is ready to initiate HO. The authors' assumption of built-in ML on UEs adds more burden on them. Although this study is helpful in using ML classifiers to mitigate the signaling overhead associated with HO events, the authors overlook how their solution behaves in FbC and MbC scenarios. Additionally, they do not address improvements in UE performance concerning processing capabilities and battery power.

Another study, as proposed in [47], leverages the capabilities of neural networks for HO optimization within NTN systems. In this study, the authors utilized convolutional neural networks (CNN) to improve the HO performance in v/LEO-based NTNs. This method involves analyzing

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[6] Ephemeris information provides precise data on celestial object positions in space at a given time [43].

**TABLE 9.** Comparison of studies on MM in 5G NTNs.

| Ref./Year | Key points/Problem addressed | Drawbacks |
|---|---|---|
| [37]/2020 | • Assesses applicability of conventional 5G HO algorithms in NTNs.<br>• HO failures were 10 times more frequent.<br>• Service interruption was 5 times longer compared to TNs. | • High frequency of HO and radio link failures.<br>• prolonged service interruption. |
| [38]/2022 | • Evaluates the use of conventional CHO in NTNs.<br>• CHO eliminates HO failures but increases unnecessary HOs by over 60%. | • Increases unnecessary HOs.<br>• Higher signaling and measurement reporting. |
| [39]/2020 | • Develops a user-centric HO framework utilizing storage capacity of sat-gNBs to improve communication quality.<br>• Buffering and distributing data among multiple sat-gNBs. | • Implementation complexity.<br>• Relies on sat-gNBs' storage capabilities. |
| [40]/2020 | • Develops enhanced CHO over conventional HO.<br>• Mitigates the "ping-pong" effect.<br>• Reduces HO failure rate compared to baseline HOs and conventional CHOs. | • Assumes UE/IoT have built-in GNSS capabilities.<br>• Requires continuous location updates.<br>• Adds more burden on the UEs.<br>• Insufficient to simulate real-world ultra-dense area expectations in 5G NTNs.<br>• concerns about the scalability of the solution under high UE densities (e.g., $10^6$ UE/km$^2$). |
| [41]/2022 | • Investigates how TNs and NTNs coexist and affect HO procedures.<br>• Adjusting A3 measurement parameters (refer to Table 6) can reduce "ping-pong" events between NTNs and TNs and unnecessary HO to NTNs. | • Assumes UE/IoT have built-in GNSS capabilities.<br>• Utilizing GNSS data during HO events increases the associated HO delay.<br>• Adds more burden on the UEs.<br>• Did not address the impact on UE battery power during transitions between TNs and NTNs. |
| [42]/2023 | • Proposes a HO method using elevation angle-based measurements instead of RSRP-based measurements.<br>• Elevation angle is calculated based on the distance between the serving sat-gNB and its cell center and the distance between the sat-gNB and the UE.<br>• Outperforms the RSRP-based method in terms of HO failure rate, "ping-pong" rate, short time-of-stay, and radio link failure rate. | • Does not consider impacts on UEs in terms of battery power and associated signaling cost.<br>• Unclear how the method would work in an environment with multiple sat-gNBs (i.e., MR-DC). |
| [44]/2022 | • Proposes HO solution based on the distance between UE/IoT devices and the center of the moving coverage.<br>• Extends mean time served by the same cell to 4.8 seconds. | • Duration of service remains short.<br>• Imposing significant challenges.<br>• Does not consider propagation delay. |
| [45]/2023 | • Proposes a machine learning-based model to predict the optimal timing for HO by considering propagation delay and the distance/elevation angle between UE/IoT and sat-gNB. | • Assumes GNSS-enabled devices, LOS conditions, and non-time-varying channels.<br>• Additional processing burden on battery-limited devices. |
| [46]/2023 | • Introduces ML-based solutions for HO decisions.<br>• Proposes using a K-means algorithm to group users based on similar features (e.g., distance, cell radius).<br>• Uses ML classification models to determine whether UEs are ready to trigger HO.<br>• Relies on group HO to decide which group of UEs is ready to initiate HO. | • Assumes UEs have built-in ML capabilities.<br>• Adds more burden on UEs.<br>• Does not consider how the solution behaves in FbC/MbC scenario.<br>• Does not address improvements in UE performance, processing capabilities, and battery power. |
| [47]/2022 | • Utilizes CNN to predict HO occurrences based on historical RSRP data, aiding in HO decision-making. | • Adds burden on UE/IoT devices to store and analyze RSRP history.<br>• Frequency of HOs only reduced by 3%. |
| [48]/2022 | • Designs a reward function to predict optimal HO sequence.<br>• enhancing service continuity by adjusting monitoring conditions for satellite candidates. | • Implementation complexity.<br>• Signaling overhead.<br>• Challenges in adapting to real-time network dynamics. |
| [49]/2022 | • Discusses NGMA schemes like OTFS and NOMA to support high-mobility scenarios in 5G NTNs. | • Potential complexity in implementation.<br>• Needs for further validation in real-world scenarios. |

historical RSRP, enabling UE/IoT devices to predict the next HO occurrence, assuming knowledge of their future RSRP. This predictive approach aids in making HO decisions. According to [47], the frequency of HOs can be reduced by only 3%. While this result is crucial in lowering HO rates, this approach adds more burden on UE/IoT devices. They need to store and analyze the history of received RSRP over time, impacting their processing capabilities and storage space.

Similar to the scheme in [47], the authors of [48] proposed a CHO mechanism intended to predict an optimal HO sequence supporting stable and high-quality data services. They designed a reward function, considering link service time and service capability, to adjust the monitoring conditions for target satellite candidates. In this scheme, the authors developed an algorithm to maximize the reward function for each CHO. Also, they constructed a service continuity performance graph model to predict various potential CHO combinations and their impact on service duration. Based of the simulation results in [48], although the proposed scheme reduces HO rates across different NTN conditions, it introduces complexities in terms of implementation cost and signaling overhead for both the serving NTNs and UE/IoT devices. Moreover, The predictive nature of the scheme might face challenges in adapting to real-time network dynamics and sudden changes in the mobility patterns of user or in network conditions, potentially impacting the scheme's responsiveness.

It is worth mentioning that as 5G NTNs support high-speed mobility scenarios (see Section V-A), new multiple access schemes should be developed to handle the nature of this highly dynamic radio coverage (i.e., "moving coverage"). In this context, the authors of [49] provide extensive detail and discussion about next-generation multiple access (NGMA) schemes. They also include detail about orthogonal time frequency space (OTFS) modulation to support high-mobility UE/IoT devices. Moreover, [49] discusses how non-orthogonal multiple access (NOMA) can support such a high-mobility environment. These schemes have the potential to support mobility in 5G NTNs effectively, ensuring efficient and reliable communication for both high and low-mobility users.

In summary, Table 9 provides a detailed comparison of proposed solutions proposed for MM scenarios in v/LEO-based 5G systems, highlighting key points, addressed problems, and their impacts on UEs and/or serving networks.

## X. FINAL REMARKS AND CONCLUSION

From the previous discussions, various solution schemes have been proposed to mitigate signaling overhead and to reduce power consumption associated with mobility management in v/LEO-based NTN networks, not only for existing 5G networks but also for 6G and beyond. However, as of the time of writing this paper, the proposed solutions remain relatively simplistic and have not significantly reduced the associated signaling cost related to MM. It is clear that the challenges imposed by high HO/CS rates are unavoidable in NTN systems, particularly because of the predominant "moving coverage" nature of the primary wireless services. Furthermore, v/LEO-based NTN systems are prone to frequent radio link and HO failures. This occurs because of the extremely high mobility of sat-gNBs. In practice, the associated UE/IoT devices can remain in the same radio coverage for an average of 15 seconds in the MbC scenario, and even less for high-mobility UE/IoT, around 6 seconds (see Table 5), generating an extensive number of signaling messages and consumes battery power in UE/IoT devices.

Referring back to the data listed in Table 2, it is anticipated that an extensive number of satellite platforms, exceeding 40000, will be deployed for v/LEO-based NTN systems. With this massive scale, it is expected that UE/IoT devices will be simultaneously served by varying numbers of sat-gNBs, ranging from 10 to 60 [50]. This "mega-constellation" will generate an unprecedented flow of HO/CS events, continuously occurring over time and at levels never seen before. Furthermore, the challenge escalates further when managing the coexistence of NTNs with TNs (see Section VIII-B).

Our paper highlights several key contributions: it justifies the necessity of 5G NTNs for ubiquitous connectivity; offers a critical analysis of MM challenges and solutions, raising concerns on signaling overhead and power consumption; examines the impact of frequent HO/CS procedures on the serving network and UE/IoT devices; and assesses the effectiveness of conventional MM procedures in v/LEO-based 5G NTNs and evaluates them with a view toward 6G NTNs.

Future research requires intelligent mobility prediction algorithms to mitigate signaling overhead, optimize UE/IoT power consumption, and reduce HO/CS events in fast-moving sat-gNB scenarios. This is particularly crucial given the expected large-scale deployment of satellite platforms, serving ground-based users ranging from 10 to 60, forming a "mega-constellation." Novel MM strategies are needed to manage cell/beam HOs and mitigate interference, especially in ultra-dense areas, using new antenna designs for massive multi-input-multi-output (mMIMO) techniques and narrow-beam beamforming for 5G and future 6G systems.

Additionally, AI and ML algorithms should be used to dynamically optimize MM decisions and resource allocation by learning from network traffic patterns and user mobility behaviors. Context-aware HO/CS mechanisms are vital for optimizing resource allocation, considering user traffic, device capabilities, and network congestion. Looking ahead, these algorithms should support multi-connectivity, and handle ultra-heterogeneity, aligning with the 2030 vision [51].

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**ALAA A. R. ALSAEEDY** received the B.Sc. degree in electronics and communication engineering, the Graduate degree in computer science, and the M.Sc. degree in electronics engineering from the University of Technology, Baghdad, Iraq, in 2000, 2002, and 2012, respectively, and the Ph.D. degree from Colorado State University, Fort Collins, CO, USA, in 2020.

His research interests include wireless mobile networks, mobility management, LTE systems, 5G and 6G technologies, beamforming and tracking, non-terrestrial networks, D2D, and mission-critical communications. He received the Best Research and Development Paper Award for his contribution to the Proceedings of Resilience Week, in 2019, San Antonio, TX, USA.

**EDWIN K. P. CHONG** (Fellow, IEEE) received the B.E. degree (Hons.) from The University of Adelaide, SA, USA, in 1987, and the M.A. and Ph.D. degrees from Princeton University, in 1989 and 1991, respectively.

He held an IBM Fellowship with Princeton University. He joined the School of Electrical and Computer Engineering, Purdue University, in 1991, where he was named as an University Faculty Scholar, in 1999. Since August 2001, he has been a Professor (and currently the Head) of Electrical and Computer Engineering and a Professor in mathematics with Colorado State University. He has co-authored the best-selling book *An Introduction to Optimization* (5th Edition, Wiley, 2023). He received the NSF CAREER Award, in 1995, and the ASEE Frederick Emmons Terman Award, in 1998. He was a co-recipient of the 2004 Best Paper Award for a paper in the *Computer Networks* journal. In 2010, he received the IEEE Control Systems Society Distinguished Member Award. He was the Founding Chairperson of the IEEE Control Systems Society Technical Committee on Discrete Event Systems and served as an IEEE Control Systems Society Distinguished Lecturer. He was a Senior Editor of IEEE TRANSACTIONS ON AUTOMATIC CONTROL. He was the General Chair of the 2011 Joint 50th IEEE Conference on Decision and Control and European Control Conference. He has served as a member for the IEEE Control Systems Society Board of Governors and as the Vice President for Financial Activities, until 2014. He served as the President, in 2017.

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