Handover challenges in disaggregated open RAN for LEO Satellites: tradeoff between handover delay and onboard processing

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Given the advancements in next-generation low Earth orbit (LEO) satellites, there is an expected shift from transparent architectures (acting as radio repeaters) to regenerative architectures (hosting a part or all of the gNodeB (gNB) onboard). Such regenerative architectures enable disaggregation and distribution of radio access network (RAN) functions between the ground and space. Open RAN is a promising approach for non-terrestrial networks and offers flexible function placement through open interfaces. The present study examines three open RAN-based regenerative architectures, namely, Split 7.2x (low-layer physical functions onboard), Split 2 (Layers 1 and 2 onboard), and a gNB onboard the satellite. Handover (HO) management becomes increasingly complex in this disaggregated RAN, particularly for LEO satellites, where the part of the gNB is constantly in motion. The choice of regenerative architecture and its dynamic topology influence the additional HO control signals required between the satellite and ground stations. Using a realistic dynamic LEO constellation model, we analyze the interplay among conditional handover (CHO) delay, computational complexity, and control signaling overhead under different network architectures. Our findings reveal that transitioning from a transparent architecture to Split 7.2x does not reduce CHO delay despite the introduction of additional onboard processing. The gNB onboard the satellite minimizes cumulative CHO delay but demands 55%−70% more computational resources than the Split 7.2x architecture. Conversely, although Split 7.2x is computationally more efficient, it increases the cumulative CHO delay by 25%−30%. Additionally, we observed that under limited onboard processing conditions, only the transparent and Split 7.2x architectures supported delay-sensitive services up to 100 ms. In contrast, under ample processing conditions, gNB was suitable for stringent 50 ms requirements, while Split 2 best supported delay-tolerant services with 200 ms requirements.

KEYWORDS

open radio access network, non-terrestrial network, functional split, conditional handover, low Earth orbit satellite, regenerative architecture

1 Introduction

The advent of next-generation low Earth orbit (LEO) satellites with regenerative architectures has enabled onboard baseband processing by offering flexible distribution of radio access network (RAN) functions between the ground stations (GSs) and satellites. Regenerative architectures enable autonomous signal processing and formation of inter-satellite links (ISLs), thereby enhancing the network flexibility and reducing dependency on terrestrial infrastructure. In contrast, transparent architectures act as mere signal repeaters, and the gNodeB (gNB) is situated entirely in the GS. Given the limited processing power and energy constraints of satellites, a disaggregated RAN is a cost-efficient solution for LEO-based non-terrestrial networks (NTNs). The open RAN architecture is a suitable candidate for NTNs to accommodate such flexibility in functional split (FS) with open interfaces (O-RAN Alliance, 2021). These satellites are particularly advantageous owing to their lower communication latencies, support for higher data rates, and reduced transmission power requirements compared to traditional geostationary Earth orbit (GEO) satellites (Voicu et al., 2024; Yue et al., 2023). However, the dynamic nature of LEOs introduces significant challenges in handover (HO) management within a disaggregated RAN framework. To enable efficient regenerative architectures, it is imperative to evaluate the FSs that balance the onboard processing capabilities with network performance. In our previous work (Seeram et al., 2024), we analyzed various FSs in NTNs to provide insights into their feasibility and performance tradeoffs.

Unlike terrestrial networks (TNs), where the network infrastructure remains static and movement of only the user equipment (UE) triggers HOs, LEO satellites continuously traverse their orbits and lead to HOs in a dynamic topology. These satellites often experience frequent GS HOs that can result in management problems. Simultaneously, UE experiences frequent HOs as they switch between satellites, where the complexity of the HO procedure depends on whether the serving and target satellites are connected to the same or different GSs as well as the placement of core network (CN) functions. Based on the satellite network architecture and topology, the different HO procedures (3GPP, 2024b) with additional control signaling requirements across multiple interfaces include UE to satellite [service link (SL)], satellite to GS [feeder link (FL)], ISL, and inter-GS links (IGSLs). The resulting increases in signaling overheads not only add to the HO delays but also complicate the maintenance of seamless connectivity. Hence, end-to-end mobility management considering GS connectivity and disaggregated RAN is crucial for ensuring uninterrupted and high-quality communication services. For instance, enhanced mobile broadband (eMBB) delay-sensitive applications, such as online gaming, require delays below 50 and 100 ms, whereas delay-tolerant services like video streaming and web browsing can accommodate higher delays up to 500 ms based on the application (Masoudi et al., 2022; Dazhi et al., 2024; Houle et al., 2007). To support diverse service requirements, a thorough evaluation of the HO procedures, onboard processing capabilities, and network design strategies tailored to dynamic NTN environments are essential.

The conditional handover (CHO) scheme was introduced in the third-generation partnership project (3GPP) Rel-16 to enhance the robustness of mobility and reduce connectivity failures in dynamic environments. Unlike conventional HO, which is network-controlled (where the gNB sends a HO command), CHO allows the network to preconfigure multiple target cells but the HO is triggered by the UE. The UE continuously monitors the prepared target cells and initiates HO when the conditions are met (Wang et al., 2022). In general, measurement-based HO techniques rely on received signal strength metrics such as reference signal received power (RSRP), reference signal received quality (RSRQ), or received signal strength indicator (RSSI) to trigger a HO. Among the various triggering events, we limit our focus to the widely popular event A3 (where a neighboring cell becomes offset-better than the serving cell). Beyond measurement-based triggers, 3GPP has also introduced NTN-specific HO trigger mechanisms to account for satellite mobility and predictable trajectories. The distance-based HO trigger associates the UE with the nearest satellite by assuming precise knowledge of both the UE and satellite positions. A hysteresis margin is applied to prevent unnecessary HOs owing to small positional variations. Similarly, the elevation-angle-based approach selects the satellite with the highest elevation angle. The timer-based HO trigger leverages the satellite trajectory and speed to estimate the instance at which a satellite will exit the UE coverage area, thereby initiating a HO in advance based on a preconfigured time window (Demir et al., 2022). Although these geometry-aware methods are predictable, they do not inherently account for the radio link quality; this can lead to suboptimal HO decisions, such as switching to a satellite with poor link conditions. To address this, we consider two CHO schemes, namely the service-capacity-based (SCB) and SL-rate-based (SLRB) methods (Wang et al., 2022). The SCB scheme considers both link quality and remaining service duration in the HO decision to optimize connection stability and reduce unnecessary HOs. In contrast, the SLRB scheme relies solely on the instantaneous link rate, potentially leading to more frequent HOs while guaranteeing high data rates.

Several satellite HO approaches have been proposed in literature using diverse decision criteria, such as elevation angle (Dai et al., 2019), maximum service time (Hu et al., 2018; Leng et al., 2021; Seeram et al., 2025), satellite availability (Papapetrou et al., 2004; Li et al., 2020a), delay (Duan et al., 2018; Yang et al., 2016), HO failure reduction (Li et al., 2020b), and network load balancing (He et al., 2020; Eydian et al., 2025). The existing studies primarily focus on minimizing the number of HOs by improving the CHO schemes (Wang et al., 2022) or reducing HO delays by eliminating specific control signaling steps (Lee et al., 2024). For instance, Rehman et al. (2017) employed the maximum service time as a criterion for satellite selection, while Juan et al. (2022) introduced a trajectory-aware HO procedure to minimize unnecessary HOs and failures. Other works have proposed velocity-aware HO prediction (Hu et al., 2018) and caching-aware intelligent HO (Leng et al., 2021) strategies based on deep reinforcement learning (DRL). Additionally, Liu et al. (2021) presented a load-balanced HO strategy by optimizing the HO frequency and system capacity, while Wang et al. (2021) proposed a DRL-based HO scheme wherein each UE determines its HO decisions independently.

Despite recent advances in satellite HO management, a unified framework that captures the complex interplay among dynamic LEO satellite topologies, CHO delays, satellite architectures, and processing constraints is lacking. The extant solutions tend to optimize isolated aspects, such as HO frequency, signaling, or

link quality, without accounting for the manner in which the choice of satellite architecture, CHO scheme, and dynamic topologies influence the CHO delays and applicability of each architecture, especially when various service requirements remain underexplored. Unlike prior studies, the present work adopts a novel and holistic approach to address the HO challenge in NTNs by integrating multiple layers of analysis. Thus, we first examine the control signaling overheads across various dynamic HO topologies by considering end-to-end (UE-satellite-GS) connectivity, which enables us to model the corresponding CHO delays under different configurations. Next, we extend the analysis using a dynamic satellite network simulator to quantify the occurrence probability of each HO topology and evaluate the CHO scheme performance, including the HO metrics and CHO delay distributions across different architectures. Finally, we integrate these findings to assess the practical applicability of each architecture for delay-sensitive and delay-tolerant use cases under the conditions of both limited and ample onboard processing capabilities. This layered analysis provides a novel and cohesive understanding of HO challenges and their implications to NTN RAN design.

In the present work, we evaluate three regenerative architectures by employing different open RAN FSs, namely Split 7.2×, Split 2, and gNB onboard the satellite, before comparing them with a transparent architecture as the benchmark. In Split 7.2×, only Layer 1 (L1) functions like beamforming, precoding, inverse fast Fourier transform (IFFT), and radio frequency (RF) processing are implemented onboard the satellite, while all higher-layer functions remain at the GS. In contrast, the Split 2 configuration places both L1 and Layer 2 (L2) functions on the satellite, while Layer 3 (L3) functions are executed at the GS. The key contributions of this work can be summarized as follows:

- Investigation of the network architecture and end-to-end dynamic topology with GS connectivity that influence additional control signaling overheads across various links.
- Modeling and characterization of CHO delays with different FSs in regenerative architectures and their mobility under dynamic topologies.
- Accurate estimation and modeling of the connection time between the UE and multibeam satellites to enhance the precision of mobility predictions.
- Performance assessments of CHO schemes in terms of HO frequencies and CHO delays across different FSs in regenerative architectures.
- Development of a realistic dynamic LEO satellite constellation model with multibeam configuration and GS connectivity that enables monitoring of the characteristics of end-to-end HO process, including (1) intra-satellite HO, (2) inter-satellite HO between satellites connected to the same GS, and (3) inter-satellite HO between satellites connected to different GSs, considering the placement of CN functions in one of the GSs.
- Comprehensive evaluation of the practical applications of RAN architectures in NTNs through joint consideration of CHO delay performance and onboard processing constraints across both delay-sensitive and delay-tolerant service requirements.

The remainder of this manuscript is structured as follows: Section 2 presents an overview of the RAN architectures in TNs and NTNs. Section 3 entails evaluations of FSs in NTNs. Section 4 presents various NTN HO scenarios under different dynamic topologies, CHO procedures, and CHO delay models. Section 5 describes the dynamic LEO constellation model and CHO algorithms. Section 6 elaborates on the results and analyses of different system setups. Finally, Section 7 presents the conclusions of this work along with the key findings and future research directions.
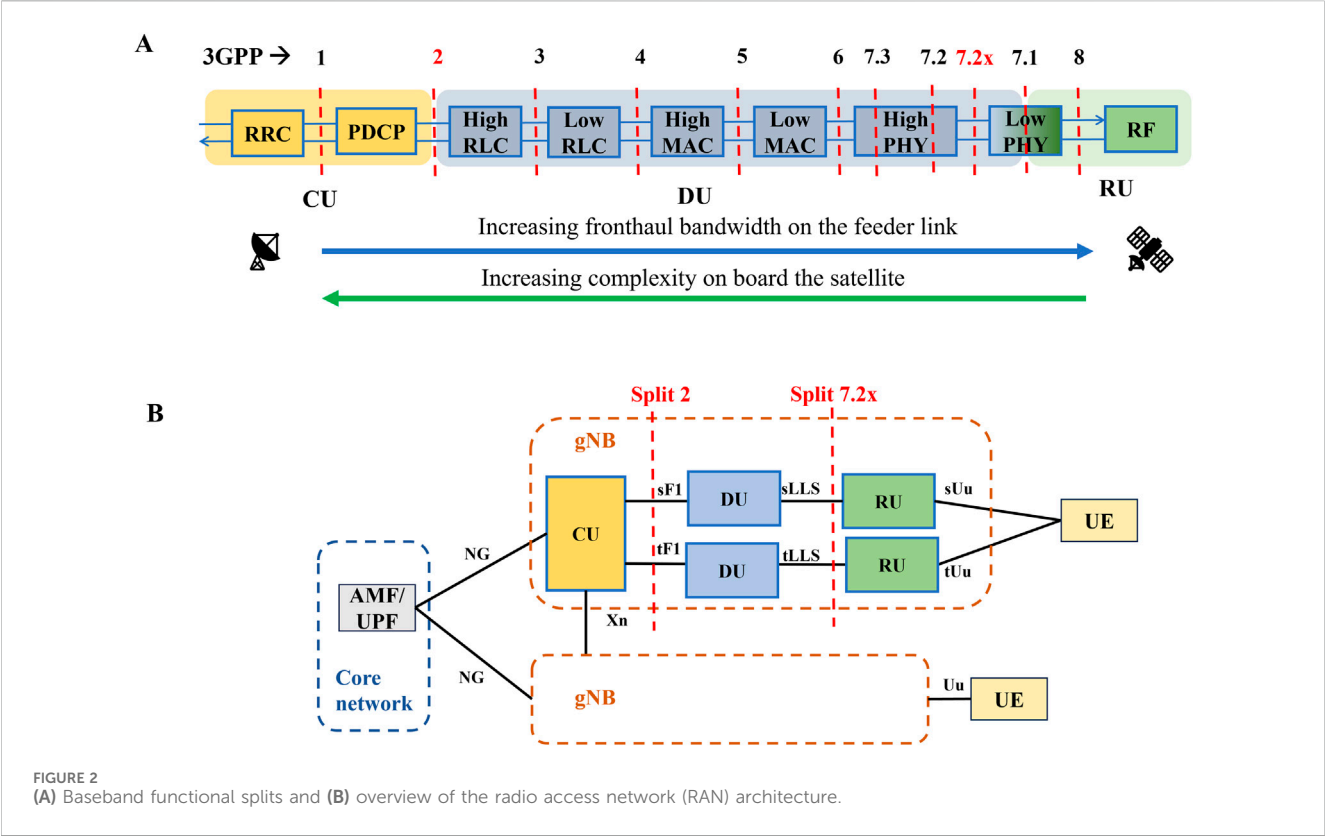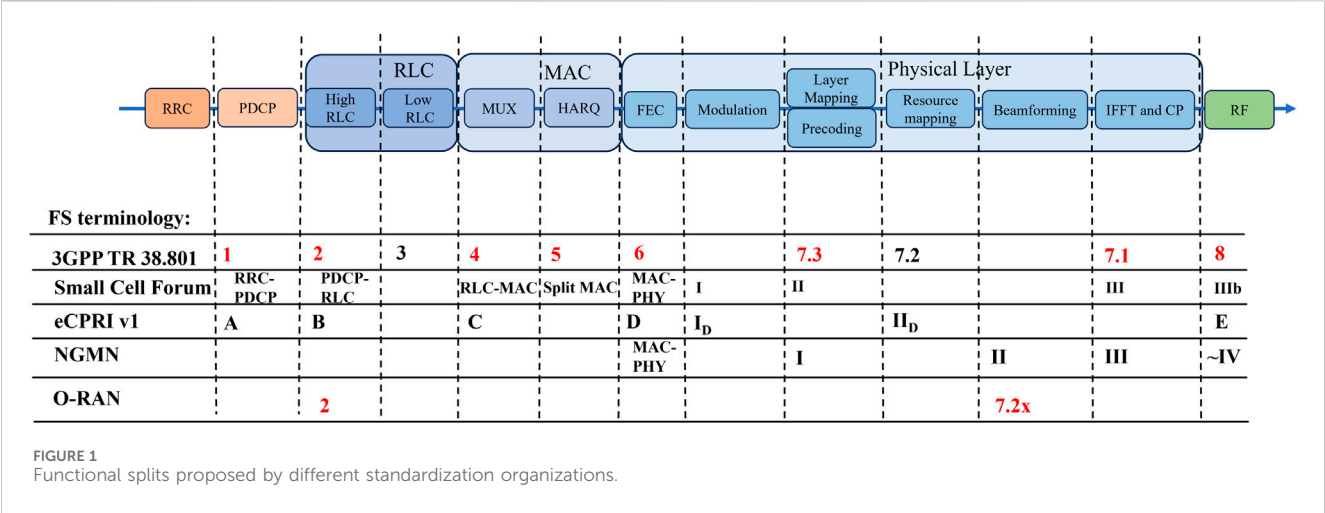
2 Background

2.1 RAN architectures in TNs

In a TN, the conventional base station (BS) typically consists of two primary components, namely the baseband unit (BBU) and remote radio head (RRH) or radio unit (RU). In traditional distributed RAN (D-RAN) architectures, these components are colocated at the same cell site, where each BS is connected to the CN through a backhaul link. This setup minimizes latency but lacks scalability; as the number of cell sites increases, the power consumption and capital expenditure associated with the D-RAN increase proportionally (Wang et al., 2017b; Masoudi et al., 2020; China Mobile, 2011). To address these limitations, the centralized RAN (C-RAN) architecture was developed, in which the BBU processing functions are separated from those of the RU and moved to a centralized resource pool. This configuration improves energy efficiency through centralized cooling (Wang et al., 2017a; Alabbasi et al., 2018). However, each RU still requires a dedicated baseband processing unit, leading to underutilization of processing resources during peak hours when the traffic is unbalanced between the cells. To improve resource utilization, BBUs were subsequently virtualized and implemented on general purpose processors (GPPs), allowing multiple RUs to share the baseband resources. This approach resulted in cloud RAN (CRAN) or virtualized CRAN (V-CRAN) architectures, in which the processing resources are dynamically allocated based on cell load, thereby enhancing the network efficiency while reducing both energy consumption and BS payloads (Larsen et al., 2018; Demir et al., 2024). Recent industry efforts have aimed to further open and standardize RAN architectures and interfaces, resulting in the development of open RAN initiatives (O-RAN Alliance, 2021). Despite advancements in FSs and virtualization, many interfaces between the RAN components remain proprietary, leading to vendor lock-in, except for the open F1 interface. The open RAN standards developed by the O-RAN Alliance represent a major effort at creating interoperable interfaces between network elements from different vendors, thus enabling a more flexible and vendor-neutral RAN ecosystem. The introduction of a RAN intelligent controller (RIC) within the open RAN framework further enhances network operations by enabling automated and optimized RAN functions, advancing the field toward intelligent V-CRAN (Pérez-Romero et al., 2023).

2.2 Disaggregated RAN and FSs

The centralization of all baseband processing functions in C-RAN presents significant challenges owing to the stringent latency and high bandwidth demands placed on the fronthaul

FIGURE 1
Functional splits proposed by different standardization organizations.

FIGURE 2
(A) Baseband functional splits and **(B)** overview of the radio access network (RAN) architecture.

transport network. To mitigate these constraints, FSs were introduced to disaggregate the RAN functions and distribute processing across different network nodes. Various standardization bodies, including the 3GPP (3GPP, 2017), Small Cell Forum (SCF) (Small Cell Forum, 2016), Next-Generation Mobile Networks (NGMN) Alliance (Alliance, 2015), Common Public Radio Interface (CPRI) (Common Public Radio Interface CPRI, 2018), and O-RAN Alliance (O-RAN Alliance, 2021), have proposed FSs at different points within the RAN, as illustrated in Figure 1. In this work, we interchangeably use the FS terminologies from the 3GPP, SCF, and O-RAN Alliance standardizations.

Regardless of the RAN architecture, each data packet or request must traverse a stack of protocol layers, namely, the radio resource control (RRC), packet data convergence protocol (PDCP), radio link control (RLC), medium access control (MAC), and physical (PHY) layers, which is collectively referred to as the baseband functions. The PHY layer encompasses several key operations, including forward error correction (FEC), quadrature amplitude modulation (QAM), layer mapping, precoding, resource mapping, beamforming, IFFT, and cyclic prefix addition. The 3GPP standard introduced the next-generation RAN (NG-RAN) architecture, which defines the FSs for the gNB by partitioning the

baseband functions such that the higher protocol layers are managed by the central unit (CU), while the lower protocol layers are handled by the distributed unit (DU). Additionally, the RU is responsible for RF operations and signal processing. In the proposed architecture, all entities below a selected FS are deployed on a remote node (e.g., a satellite), while the remaining functions reside on a central node (e.g., a GS), as depicted in Figure 2A. In open RAN, these functional entities are prefixed with "O-" to indicate open interfaces, resulting in open CU (O-CU), open DU (O-DU), and open RU (O-RU). Moreover, these components are 3GPP-based functionalities adapted to the open RAN architecture (O-RAN Alliance, 2021; Wani et al., 2024).

2.3 RAN architectures in NTNs

NTNs are wireless communication systems designed to extend connectivity beyond the TNs by utilizing space-borne and airborne platforms (Giordani and Zorzi, 2021). The space-borne platforms include satellites classified into GEO, medium Earth orbit (MEO), and LEO based on their orbital altitudes, whereas the airborne platforms consist of high-altitude platforms (HAPs) and unmanned aerial vehicles (UAVs). The present study primarily focuses on LEO satellites, which play crucial roles in NTNs owing to their lower altitudes that enable lower delays and higher throughput than GEO and MEO satellites. The NTN architecture comprises multiple components, including NTN payloads hosting RAN functions onboard satellites, UE, and GSs. The UE establish connectivity with satellites via SLs, whereas the GSs maintain connectivity with satellites through FLs. NTN coverage is facilitated using either fixed or moving cells (Campana et al., 2023). Fixed cells provide consistent coverage over designated ground areas using steerable antennas, whereas moving cells dynamically shift the coverage areas by following the satellite orbital trajectory. Additionally, satellites may employ single-beam or multibeam systems, where the latter improves coverage and capacity by segmenting the service area into more focused regions. The satellite architecture significantly influences the operational efficiency and performance of an NTN, and these architectures are broadly classified into transparent and regenerative categories (Rihan et al., 2023).

2.3.1 Transparent architecture
In the transparent satellite architecture, the gNB is situated in the GS, such that the satellite functions primarily as a signal repeater. The onboard processing capabilities are limited to RF operations, such as frequency conversion, amplification, and beam management. Consequently, the satellite retransmits the received waveforms without modifications, maintaining direct links between the UE and TN infrastructure.

2.3.2 Regenerative architecture
In contrast, the regenerative architecture integrates baseband processing capabilities onboard the satellite to enable autonomous operations and inter-satellite connectivity. This architecture reduces reliance on terrestrial infrastructure while allowing dynamic implementation of ISLs for enhanced network flexibility. By supporting multihop topologies, regenerative satellites extend

coverage to remote and underserved areas to complement TNs. Additionally, this architecture improves network resilience as the traffic routing and HOs can be managed directly between satellites with minimal dependency on the CN located on the ground. The three fundamental baseband components are interconnected through standardized interfaces, as illustrated in Figure 2B. The F1 interface establishes communication between the CU and its associated DUs, ensuring efficient coordination of the higher-layer and lower-layer functionalities. The DU is connected to the RU through the low layer split interface. Furthermore, the gNB connects to the UE through the Uu interface that provides service to the end user. The next-generation interface provides connectivity between the entire gNB or specifically its CU and the CN through the access and mobility function (AMF) and user plane function (UPF). The AMF plays crucial roles in authentication, authorization, and mobility management of the UE to ensure secure and seamless network access. Conversely, the UPF is responsible for managing data traffic by facilitating interconnections between the data network and overall network architecture. Finally, the Xn interface enables inter-gNB communication within the RAN, thus supporting HOs and coordination between the different gNBs to enhance mobility and network efficiency (3GPP, 2024a).

3 Functional splits in NTNs

As discussed in the previous section, different FSs offer varying levels of flexibility and efficiency, particularly in terms of latency, processing capability, and resource management. In the traditional TN, the fronthaul and backhaul links are fixed installations that do not change once deployed. However, when examining RAN over NTNs, such as LEO satellites, several unique challenges emerge owing to the dynamic movements of the satellites. These challenges cause frequent disruptions in the fronthaul links owing to satellite movements, increased propagation delays, intermittent connectivity, and the inherent mobility of satellites. Despite these challenges, NTNs present significant opportunities for expanding coverage, especially in remote areas where terrestrial infrastructure deployment may be impractical or cost-prohibitive. By leveraging satellite technology, NTNs can deliver ubiquitous coverage, allowing service providers to reach underserved or unserved populations, thereby bridging the digital divide. We study the applicability of various FS options for NTNs, which have traditionally been used in terrestrial RAN models. We assess the constraints and requirements posed by the unique characteristics of NTN environments by focusing on latency, bandwidth, processing power, and separation distance challenges as well as exploring potential solutions.

3.1 FS requirements for NTNs

Here, we consider a typical NTN setup in which the satellite serves a ground UE via a SL fed by a GS through an FL. The separation distances are determined by the elevation angles between the satellite and both the UE and GS, which are denoted as θ and β, respectively. The separation distance d between the ground entity and satellite at a specified elevation angle θ or β is calculated using Equation 1:

TABLE 1 Functional splits, fronthaul parameters, and processing requirements (Seeram et al., 2024).

f'	Functional split (3GPP/SCF)	$\delta_{f'}$[a] [ms]	$d_{f'}$ [km]	Required fronthaul bandwidth [Mbps]				Processing requirements [GOPS]	
				$N_{ant} = 2$		$N_{ant} = 64$		GS	Satellite
				DL	UL	DL	UL		
1	1/RRC-PDCP	30	9,000	149.9	48.6	149.9	48.6	<8	>36.5
2	2/PDCP-RLC	30	9,000	150	48.7	150	48.7	<8	>36.5
3	4/RLC-MAC	30	9,000	150.6	48.9	150.6	48.9	<8	>36.5
4	5/Split MAC	6	1,800	151.3	49.4	151.3	49.4	<8	>36.5
5	6/MAC-PHY	6	1,800	152.3	49.9	152.3	49.9	<8	>36.5
6	–/PHY I	2	600	173.1	451.6	173.1	451.6	8	36.5
7	7.3/PHY II	2 0.25	600 75	932.6	903.2	29,843	28,901	15.9	28.6
8	7.1/PHY III	2 0.25	600 75	1,075.2	921.6	34,406	29,491	18.5	26
9	8/PHY IIIb	2 0.25	600 75	1,966.1	1,966.1	62,915	62,915	19.8	24.7
10	–/PHY IV	0.25	75	2,457.6	2,457.6	78,643	78,643	23.8	20.7

[a]Non-ideal fronthaul latency: 30 ms; sub-ideal fronthaul latency: 6 ms; near-ideal fronthaul latency: 2 ms; ideal fronthaul latency: 0.25 ms.

$$d(\beta) = \sqrt{R_e^2 \sin(\beta)^2 + h^2 + 2R_e h - R_e \sin(\beta)}, \quad (1)$$

where R_e is the radius of the Earth in km, h is the satellite altitude in km, and β is the elevation angle of the GS. The maximum fronthaul distance for a given fronthaul latency requirement for the FS f', $\delta_{f'}$, is calculated using Equation 2:

$$d_{f'} = c\delta_{f'}, \quad (2)$$

where c is the speed of light, and $f' \in \{1, 2, \ldots, 10\}$ corresponds to the FS in Table 1.

Our objective is to evaluate different FS configurations between the GS and satellite, as illustrated in Figure 2A. In this analysis, we assume various FS options (Table 1), where each FS is characterized by distinct fronthaul latency ($\delta_{f'}$), maximum fronthaul distance ($d_{f'}$), and fronthaul bandwidth requirements as well as processing demands at both the GS and satellite. The fronthaul latency and bandwidth requirements are categorized into four types based on SCF specifications (Small Cell Forum, 2016). The non-ideal fronthaul supports up to 30 ms of latency with variable bandwidth, which is suitable for RRC-PDCP and PDCP-RLC splits. The sub-ideal fronthaul allows up to 6 ms of latency with unconstrained bandwidth, supporting MAC splits. The near-ideal fronthaul supports up to 2 ms of latency with unlimited bandwidth, while the ideal fronthaul offers up to 0.25 ms of latency and unlimited bandwidth. Processing requirements are generally measured in terms of giga operations (GOPS) (Alabbasi and Cavdar, 2017) to account for both user processing functions (e.g., PDCP, RLC, MAC, FEC, and modulation functions) and cell processing functions (e.g., resource mapping, IFFT, and cyclic prefix functions) at the GS and satellite based on the FS.

3.2 FS evaluation

We evaluate each FS option for the NTN by examining three main factors: separation distance and latency, bandwidth requirements, and processing demands.

3.2.1 Distance and latency constraints

The feasibility of FS options in an NTN depends heavily on the achievable maximum fronthaul distance ($d_{f'}$) constrained by the latency of the interface deployed over the FL. An FS option is deemed feasible if the separation distance $d(\beta)$ is less than or equal to $d_{f'}$. For a LEO satellite orbiting at an altitude of 600 km with FL elevation angles (β) of 10° and 90°, the corresponding $d(\beta)$ values are 1,935 km and 600 km, respectively. Table 1 shows that as the FS moves toward the lower layers (closer to the physical layer), the fronthaul latency ($\delta_{f'}$) requirements become increasingly stringent, thus reducing $d_{f'}$. Based on these constraints,

- for $\beta = 10°$, the 3GPP FS options 1–4 are feasible;
- at $\beta = 90°$, the 3GPP FS options 1–7.1 are feasible assuming near-ideal conditions for the physical layer splits.

The gNB onboard the satellite includes the next-generation interface in the FL, for which the backhaul latency and bandwidth requirements are generally less stringent than those for the fronthaul case. However, there are some latency and capacity considerations that must be managed effectively.

3.2.2 Bandwidth requirements

The fronthaul bandwidth requirements of both the uplink and downlink increase as the FS moves toward the lower layers. Table 1

indicates that for the minimal antenna setup (N_{ant} = 2), the fronthaul bandwidths in the downlink and uplink nearly triple when the FS is changed from split PHY I to PHY II (7.3) (Small Cell Forum, 2016). However, for a larger antenna configuration (N_{ant} = 64), the bandwidth requirements multiply drastically by over 170 times in the downlink and 64 times in the uplink. At the lowest split layer, each beam of the satellite requires a fronthaul link rate of approximately 2.4 Gbps for N_{ant} = 2 and up to 78.6 Gbps for N_{ant} = 64 even for a single-user scenario. These high demands may challenge the fronthaul capacity of the NTN, especially for satellites serving multiple beams. Thus, FS options with lower layer splits are more likely to have bandwidth feasibility issues in NTNs.

3.2.3 Processing requirements

The processing resource requirement is influenced by the FS and is divided between the GS and satellite as shown in Table 1. The processing load on the satellite decreases as the FS shifts to the lower layers, offloading the complexity to the GS, as seen in Table 1. For multiuser scenarios, the processing requirements for user-processing functions increase as the number of users increase, while the complexity of the cell processing functions remains relatively constant (Small Cell Forum, 2016). Moreover, the onboard gNB is suitable for NTNs, in which the satellite has sufficient processing power to manage gNB functions, including the user and cell processing functions.

3.2.4 Challenges and potential solutions

Given the distinct challenges posed by NTNs, especially with respect to the lower-layer FSs, certain adjustments and optimizations are proposed by 3GPP. The latency requirements shown in Table 1 are based on long-term evolution (LTE) with TN features. For NTNs, these requirements can be relaxed by leveraging new radio (NR) NTN specifications that allow asynchronous hybrid automatic repeat request (HARQ) instead of LTE synchronous HARQ, thereby relaxing the fronthaul latency. In NTN Rel-17 (3GPP, 2023), complete disabling of the HARQ feedback is permitted owing to the significantly longer round-trip delays in the NTN. Furthermore, disabling features such as channel state information (CSI) reporting, which impose high latency requirements, could enable feasibility. CSI is typically used to enhance throughput under good terrestrial coverage conditions and may not be essential in NTNs with high-latency links.

4 Network topology and architecture-aware CHO delay analysis

To accurately model CHO delay, it is crucial to identify the topology involved in HO and the satellite architecture. This enables selection of the appropriate CHO procedure to determine the signaling loads across various links, thereby allowing estimation of the CHO delay. Hence, we analyze different topologies and CHO procedures to facilitate comprehensive CHO delay modeling. Given the dynamic nature of NTN environments, where satellites are in constant motion and the UE can be mobile, it is essential to evaluate how the selected FS options perform in terms of delay when performing a HO. This delay analysis help us understand the implications of mobility on the network performance by focusing

on aspects such as HO delays, processing times at the GS and satellite, and impacts of varying separation distances during user mobility. By assessing these delays, we can identify the most suitable FS configurations that meet the latency requirements while enhancing the overall system efficiency in mobile NTN scenarios. This understanding will be critical for optimizing network performance and ensuring seamless connectivity for the end users, especially in applications that demand low latencies.

4.1 Handover scenarios under dynamic topologies in NTNs

4.1.1 Disaggregated RAN between the ground and space

To comprehensively evaluate the impacts of delay, we consider three distinct dynamic topologies during CHO, namely A, B, and C, where each case represents a distinct network topology involving different configurations of the satellite, UE, and GS. In each scenario, we consider a mobility context with two cells: a source cell (denoted in blue in Figure 3) in which the user resides initially and a target cell (denoted in yellow) that the user moves into during CHO. The key components include at least one satellite with a network architecture, one GS connected to the CN, and several types of links, such as the SL between the satellite and UE, FL between the satellite and GS, ISL connecting multiple satellites, and IGSL connecting different GSs. The traffic flows are labeled with prefixes "s" and "t" to denote "source" and "target" links, respectively, to indicate the direction of traffic flow before and after CHO.

4.1.1.1 Topology A: Single satellite with multiple cells/beams

Topology A shown in Figure 3A involves a single satellite connected to a GS serving as both the source and target cells. This scenario is also known as intra-satellite HO, and each beam simply represents a cell. Given a large constellation of satellites, this is the most likely topology encountered by the UE since each satellite handles a large number of cells. As the CHO occurs within the same satellite, the impact on CHO delay varies with the satellite architecture used.

4.1.1.2 Topology B: Two satellites connected to the same GS

Topology B (Figure 3A) involves two satellites to manage the source and target cells separately but connected to the same GS. This scenario is typical at the boundaries of coverage areas managed by different satellites and reflects the HOs between adjacent satellites (also known as inter-satellite HOs). The shared GS simplifies CHO coordination but requires ISLs to form subtopologies B1, B2, and B3, as depicted in Figure 3.

4.1.1.3 Topology C: Two satellites connected to different GSs

Topology C (Figure 3A) involves two GSs that are each associated with a different satellite. However, a single AMF/UPF is colocated with one of the GSs to produce subscenarios C1 and C2. This topology is also a part of inter-satellite HO and is less common
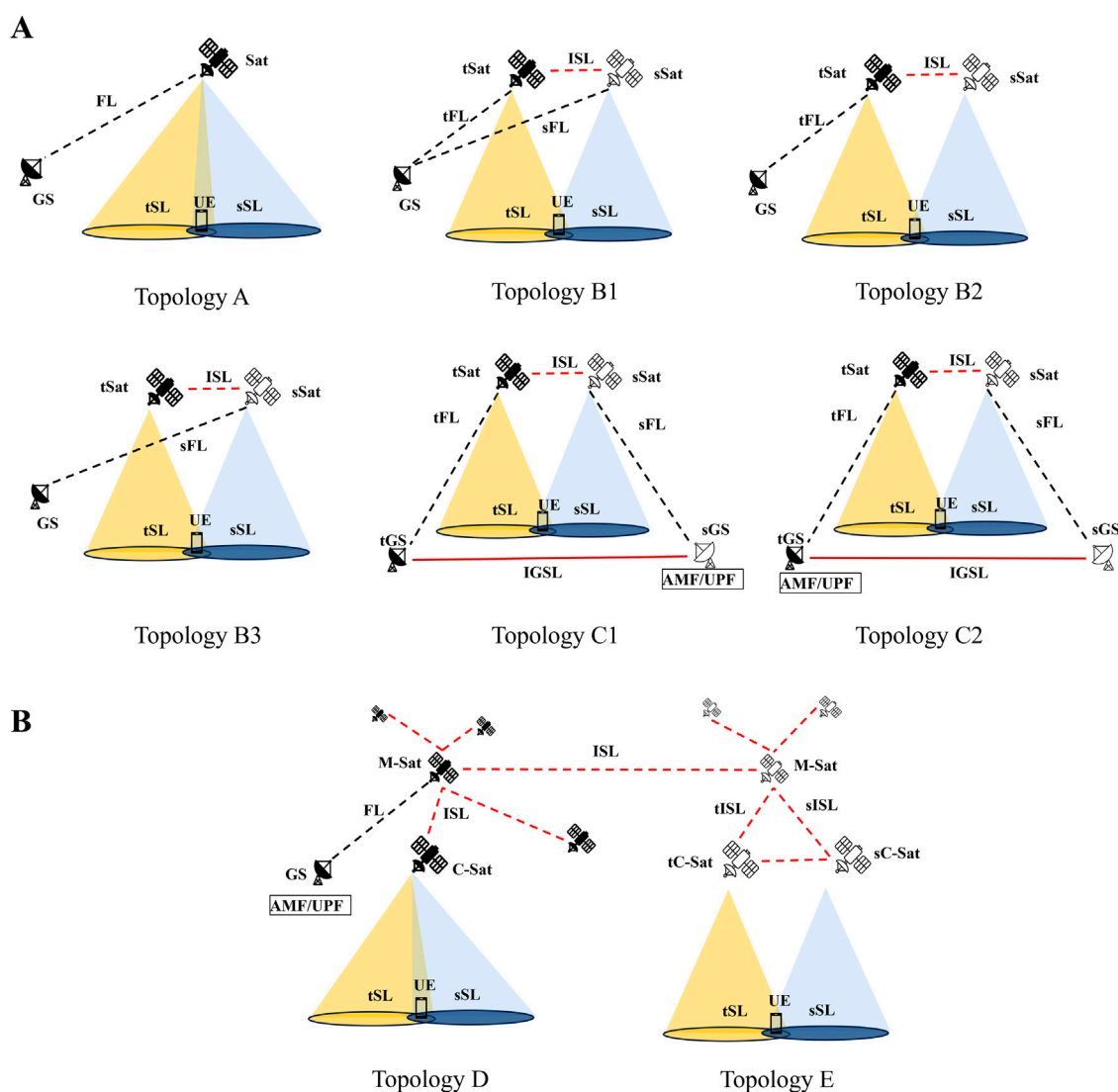
FIGURE 3
(A) Disaggregated RAN between the ground and space. A: one satellite connected to one ground station (GS); B: two satellites connected to the same GS; C: two satellites and two different GSs. **(B)** Disaggregated RAN in space. D: one child satellite connected to a master satellite; E: two child satellites connected to the same master satellite.

but may arise at regional boundaries, such as borders between countries. In the CHO scenario C, two complete gNB chains are involved between the GS and satellite, unlike scenarios A and B that have some common function processing at the GS. It is important to note that in realistic cross-border deployments, the presence of two AMFs, each in a different country, is also plausible. This would involve inter-gNB and inter-AMF CHO procedures. However, such cases are not analyzed in this study.

4.1.2 Disaggregated RAN in space

Disaggregated RAN in space enables realization of satellite swarms that can form clusters of smaller satellites operating in coordination. In this topology, all of the RAN functions are performed in space and are split among the satellites. Each cluster comprises one cluster head, which is designated as the mother satellite or master satellite (M-SAT) (Ibrahim et al.,

2024), while the remaining satellites are designated as children satellites (C-SATs). However, this topology is vulnerable to a single point of failure: if the M-SAT in a cluster fails, all satellites in the cluster are affected. Figure 3B depicts the satellite swarm network consisting of M-SATs and C-SATs, wherein the RAN functions are pooled in an M-SAT instead of the GS. However, the AMF and UPF remain at the GS and are connected to the M-SAT by an FL. This design enables efficient resource sharing and centralized processing within the satellite network and managed by the M-SAT while still relying on the GS for CN functions, such as user authentication and mobility management.

4.1.2.1 Topology D: C-SATs with multiple cells connected to the M-SAT

Topology D illustrated in Figure 3B shows the scenario where the serving satellite operates under the control of an M-SAT. Here,
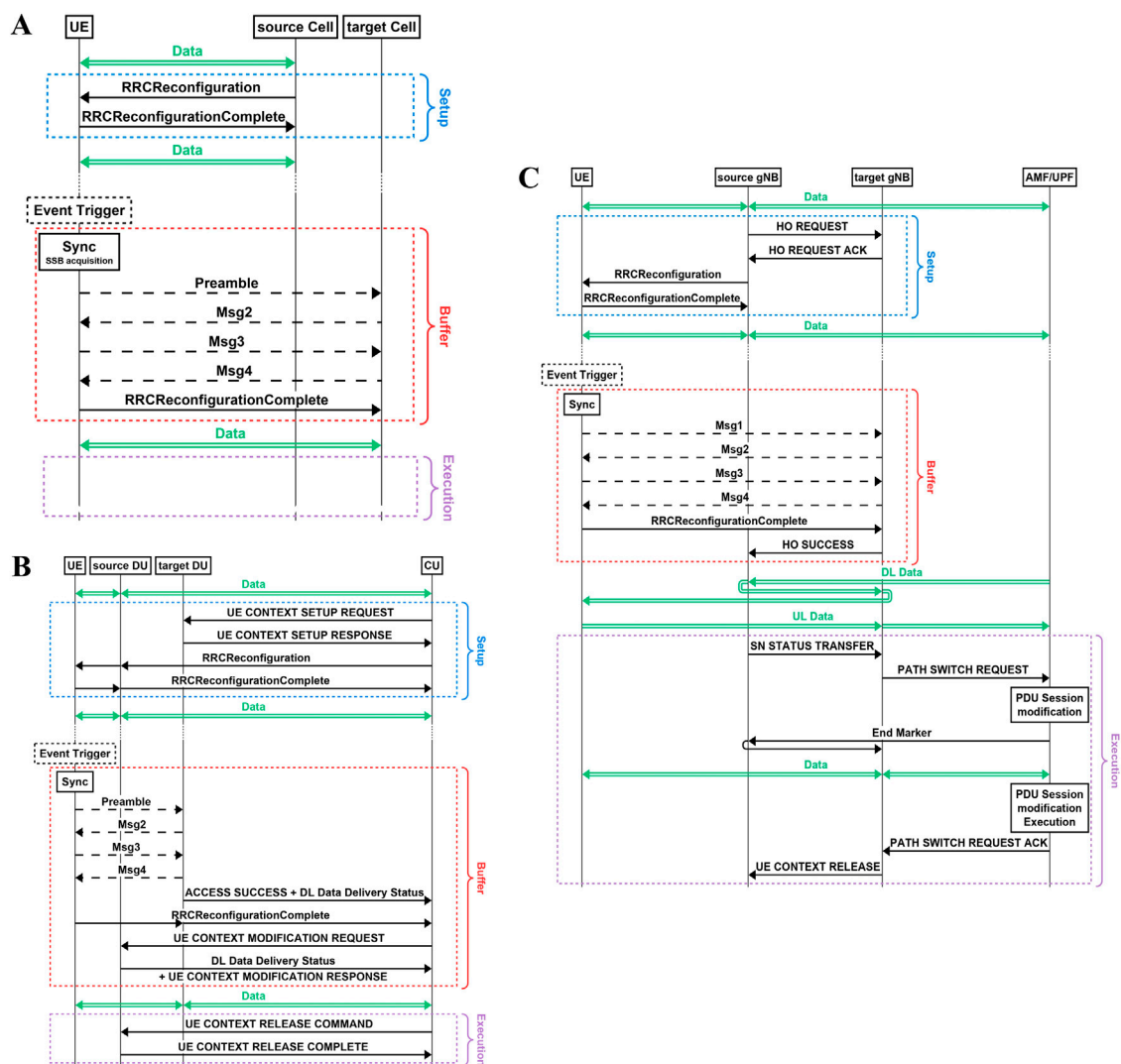
FIGURE 4
(A) Intra-distributed-unit (DU) conditional handover (CHO) procedure. **(B)** Inter-DU CHO procedure. **(C)** Inter-gNB intra-AMF CHO procedure.

the UE transition from the source SL to the target SL as they move across cells similar to HO scenario A.

4.1.2.2 Topology E: C-SATs with a shared M-SAT

Topology E depicted in Figure 3B involves a UE moving from the source SL of one satellite to the target SL of another satellite, where both satellites are connected to the same M-SAT node similar to HO scenario B1. Although this scenario resembles B1, there is a key difference in that the resource pooling and higher-layer RAN functions are always executed in space and are split in different ways between the satellites.

4.2 Control and signaling procedures in CHO

To analyze CHO procedures in an NTN architecture, we consider a network setup comprising two chains of gNB

functions, one for the source cell and another for the target cell, with the AMF and UPF serving in the CN, as illustrated in Figure 2B. Depending on the satellite network architecture and topology, the RAN functions in the source and target chains are either shared or separated. This setup defines different CHO procedures based on the split option and architecture, which are categorized as intra-DU CHO, inter-DU CHO, and inter-gNB intra-AMF CHO. Each CHO procedure follows a standardized sequence, with signaling over the Uu interface involving the RRC connection (3GPP, 2024b). The procedure can be divided into three phases as setup, buffer, and execution phases, as detailed below.

4.2.1 Intra-DU CHO procedure

In scenarios where the source and target cells share a common DU or RU (e.g., when both RU and DU are deployed on the same satellite), the UE can perform intra-DU CHO. Here, the HO is managed within the same gNB DU, simplifying the process as shown in Figure 4A.

4.2.1.1 Setup phase

The source cell (i.e., source beam) of the satellite configures the UE with a trigger condition based on specific metrics (e.g., time, distance, or signal strength between the target and source cells). The UE then starts monitoring the configured metric to prepare for HO.

4.2.1.2 Buffer phase

When the trigger condition is met, the UE synchronizes with the target cell of the satellite by acquiring its synchronization signal block (SSB) to complete the random access channel (RACH) procedure. This process consists of four messages: *Msg1* that involves transmission of the random access (RA) preamble; *Msg2* or the RA response from the network; *Msg3* that may carry RRC signaling messages; and *Msg4* that primarily contains an RRC reply to establish a connection other than the contention resolution message. The contention resolution message includes the identity of the UE to confirm that the gNB has successfully identified the UE and resolved any contention. During this phase, data transmission is temporarily paused until the connection is fully reestablished upon receiving the *RRC reconfiguration complete* message from the UE.

4.2.1.3 Execution phase

The UE resumes data transfer in this phase, and no additional signaling is required, making this CHO efficient in terms of latency and resource utilization.

4.2.2 Inter-DU CHO procedure

When the source and target chains share a CU but have distinct DUs, an inter-DU CHO procedure is performed as shown in Figure 4B. The CU coordinates HO between the two DUs.

4.2.2.1 Setup phase

The CU initiates the setup by querying potential target DUs through the F1 interface to reserve the CHO resources for accommodating the UE. Once the responses are received, the CU configures the UE through the source DU, thus setting the conditions for HO.

4.2.2.2 Buffer phase

When the condition is triggered, data delivery is paused, and the UE starts the synchronization and RACH procedures with the target DU. Once the target DU confirms the *Access Success* message to the CU, the CU acquires the data delivery status, effectively switching the data connection to the target DU chain and thereby resuming data delivery to the UE.

4.2.2.3 Execution phase

The CU informs the source DU to release the UE context upon completing HO. Furthermore, the CU informs the other target DUs to release the CHO resources that are reserved for the UE.

4.2.3 Inter-gNB intra-AMF CHO procedure

For mobility scenarios involving two complete gNBs and a single AMF (i.e., when the source and target chains are hosted by separate gNBs across different satellites), the inter-gNB intra-AMF CHO procedure is executed as shown in Figure 4C. This process involves more complex signaling over the Xn or next-generation interface. For simplicity, we assume here that signaling will be performed over the Xn interface.

4.2.3.1 Setup phase

The source gNB (sgNB) queries potential target gNBs (tgNBs) over the Xn interface to check for CHO resources and reserve them for the UE. Once the acknowledgments are received, the sgNB configures the UE, thus setting the trigger conditions.

4.2.3.2 Buffer phase

Once the UE meets the trigger condition and completes the synchronization RACH procedure with the tgNB, the tgNB notifies the sgNB of the successful connection. Although the UE can resume data transfer, the CN's UPF is still unaware of the HO. Therefore, the DL traffic is initially routed through the sgNB, which then forwards it to the tgNB after adding a temporary delay. However, the UL traffic is unaffected as the tgNB directly routes it to the UPF.

4.2.3.3 Execution phase

To finalize HO, the tgNB initiates a path switch request to update the CN functions and UPF. Once the path switch is acknowledged, the tgNB informs the sgNB, which then releases the UE context. This phase fully shifts the DL traffic to the tgNB, thus optimizing data flow by eliminating the forwarding delay through the sgNB.

4.2.4 RACH procedures and impacts on CHO delay

The contention-based RACH is the default procedure used for initial access or when the network does not have prior context about the UE. It involves the exchange of four messages (*Msg1–4*), during which the network resolves the identity and timing advance (TA). Owing to potential collisions, this method may introduce additional delays, especially under heavy loads or in long-propagation NTN links. In contrast, the contention-free RACH is used when the network already has context about the UE, such as during HO or beam switching. The network assigns a dedicated preamble to the UE, thereby preventing collisions, but still uses the same four-message procedure as the contention-based method. The main benefit here lies in avoiding retransmissions caused by collisions rather than reducing the message count (Saarnisaari et al., 2019; Saarnisaari and de Lima, 2019).

The two-step RACH procedure is designed to reduce access delays by merging *Msg1* and *Msg3* into a single transmission (MsgA) as well as *Msg2* and *Msg4* into MsgB. This reduces the number of sequential exchanges and speeds up the access process. However, this approach is only feasible under good coverage conditions as it sacrifices some efficiency for timing alignment. Finally, RACH-less access is an emerging approach applicable when the TA can be assumed to be the same as that of the previous cell. In such cases, the UE may directly transmit *Msg3* since the purpose of *Msg1* and *Msg2* is to determine the TA (Dao et al., 2024). In this work, we focus on contention-based RACH to evaluate its impact on CHO delays in NTNs. However, future studies may explore the two-step RACH and RACH-less methods as suitable, especially for improving support to delay-sensitive applications.

4.3 CHO delay model

To analyze the CHO delay, we define $f \in \{0, 1, 2, 3\}$ corresponding to the set of network architectures {Transparent,

Split 7.2×, Split 2, gNB}. Furthermore, $q \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ represents the HO scenarios under the set of dynamic topologies {A, B1, B2, B3, C1, C2, D, E}. The total delay in the CHO procedure can be expressed as the sum of several components, including synchronization delay, core network API delay, processing delay, and propagation delay. The total delay can be calculated for any scenario and FS using Equation 3:

$$\tau_{f,q}^{\text{CHO}}(t) = \tau^{\text{sync}} + \mathbf{I}\{f = 3\} \cdot \mathbf{I}\{q \neq 1\} \cdot \tau^{\text{core}} + \tau_{f,q}^{\text{proc}} + \tau_{f,q}^{\text{prop}}(t), \quad (3)$$

where τ^{sync} is the synchronization delay, τ^{core} is the CN delay, $\tau_{f,q}^{\text{proc}}$ is the processing delay, $\tau_{f,q}^{\text{prop}}(t)$ is the propagation delay, and $\mathbf{I}\{\cdot\}$ is an indicator function whose value is equal to 1 if the condition within the parentheses holds and 0 otherwise. The processing delay $\tau_{f,q}^{\text{proc}}$ can be modeled using Equation 4:

$$\tau_{f,q}^{\text{proc}} = \left(N_{f,q}^{\text{FL}} + N_{f,q}^{\text{SL}} + N_{f,q}^{\text{ISL}} + N_{f,q}^{\text{IGSL}}\right) \cdot \tau^{\text{ppm}}, \quad (4)$$

where $N_{f,q}^{(\cdot)}$ represents the number of message exchanges across various links, including FL, SL, ISL, and IGSL for the FS f and HO scenario q; τ^{ppm} denotes the processing delay per message. The propagation delay $\tau_{f,q}^{\text{prop}}$ is given by Equation 5:

$$\tau_{f,q}^{\text{prop}}(t) = N_{f,q}^{\text{FL}} \cdot \tau^{\text{FL}} + N_{f,q}^{\text{SL}} \cdot \tau^{\text{SL}}(t) + N_{f,q}^{\text{ISL}} \cdot \tau^{\text{ISL}}(t) + N_{f,q}^{\text{IGSL}} \cdot \tau^{\text{IGSL}}(t), \quad (5)$$

where $\tau^{(\cdot)}(t)$ represents the propagation delays in different links in the time slot t.

5 Handover management in dynamic LEO satellite constellation

Here, we investigate the management of HO within a dynamic LEO satellite constellation. First, we introduce a GS-satellite association method by employing the maximum elevation angle as a criterion to associate LEO satellites with GSs and allocate FLs based on their availability at the GS. Next, we explore CHO schemes for optimizing the HO process using service-specific criteria. Specifically, we implement SCB and SLRB CHO schemes to facilitate HO decisions across various NTN scenarios. These schemes are further analyzed to assess their impacts on CHO delays under different satellite network architectures in the dynamic LEO constellation setup.

5.1 LEO satellite constellation model

As shown in Figure 5, we consider a ground-based UE served by LEO satellites with network architecture. Each satellite is equipped with highly directional circular aperture antennas (3GPP, 2019) that serve the ground UEs using Earth-moving cells (non-steerable beams). The visibility conditions of the UE and GS to the satellite are determined by their respective elevation angles. The elevation angle is defined as the angle between the horizontal plane at the UE (or GS) and line connecting it to the satellite. A specific UE is considered visible to the satellite if its elevation angle exceeds a predefined minimum threshold θ_{min}, ensuring unobstructed line-of-sight (LOS), as shown in Figure 5. Similarly, the GS visibility is constrained by a minimum GS elevation angle β_{min}. Within this

overlapping visibility region, we analyze the CHO performances for satellites as they move in and out over time. Here, the LEO satellite index is denoted as $s \in \{1, 2, \ldots, S\}$, beam index is denoted as $i \in \{1, 2, \ldots, I\}$, and GS index is denoted as $j \in \{1, 2, \ldots, J\}$. The time slots within the service period are indicated by $t \in \{1, 2, \ldots, T\}$, and the time slot duration is denoted as Δt. The service time of the UE is represented by $T\Delta t$. The GS association with satellite s through the FL at time t is indicated by $g_s(t)$, which can take values from the set $\{0, 1, 2, \ldots, J\}$. Here, the value 0 indicates no association between the satellite s and any GS. Additionally, at time t, the elevation angles between the UE and satellite s as well as between the GS j and satellite s are denoted by $\theta_s(t)$ and $\beta_{s,j}(t)$, respectively. The remaining time slots before satellite s exits the visibility of the UE are denoted as $TR_s(t)$. The index of the satellite serving the UE at time t is represented as $o(t)$. An inter-satellite HO occurs when $o(t) \neq o(t-1)$, indicating a switch in the serving satellite. The satellite beam index serving the UE at time t is represented as $p(t)$. An intra-satellite HO occurs when $p(t) \neq p(t-1)$, indicating a switch in the serving beam within the same satellite. Furthermore, during each time slot, the UE has access to a set of potential target satellites that meet specific visibility conditions. This set of potential target satellites $S(t)$ at time t is given by Equation 6:

$$\mathcal{S}(t) = \left\{s: \theta_s(t) \geq \theta_{min}, \beta_{s,j}(t) \geq \beta_{min}, \forall s, \forall j\right\}. \quad (6)$$

5.1.1 Path loss model

The overall path loss (in decibels) is defined by Equation 7 (Guidotti et al., 2020; Liu et al., 2022):

$$PL = PL_g + PL_b + PL_s + PL_e, \quad (7)$$

where PL_g is the attenuation due to atmospheric gases, PL_b is the basic path loss, PL_s is the path loss due to ionospheric scintillation, and PL_e represents the building penetration loss. In this work, we assume that the UE is located in an outdoor setting, which allows us to neglect PL_e. The basic path loss PL_b is given by Equation 8:

$$PL_b = FSPL + SF + CL, \quad (8)$$

where $FSPL$ represents the free space path loss, SF denotes the shadow fading loss, and CL is the clutter loss. Since the UE is assumed to be outdoors under the LOS condition, $CL = 0$. Furthermore, as the environment is considered free of significant obstructions, SF may be neglected. Hence, the basic path loss is mainly attributable to the $FSPL$ component given by Equation 9:
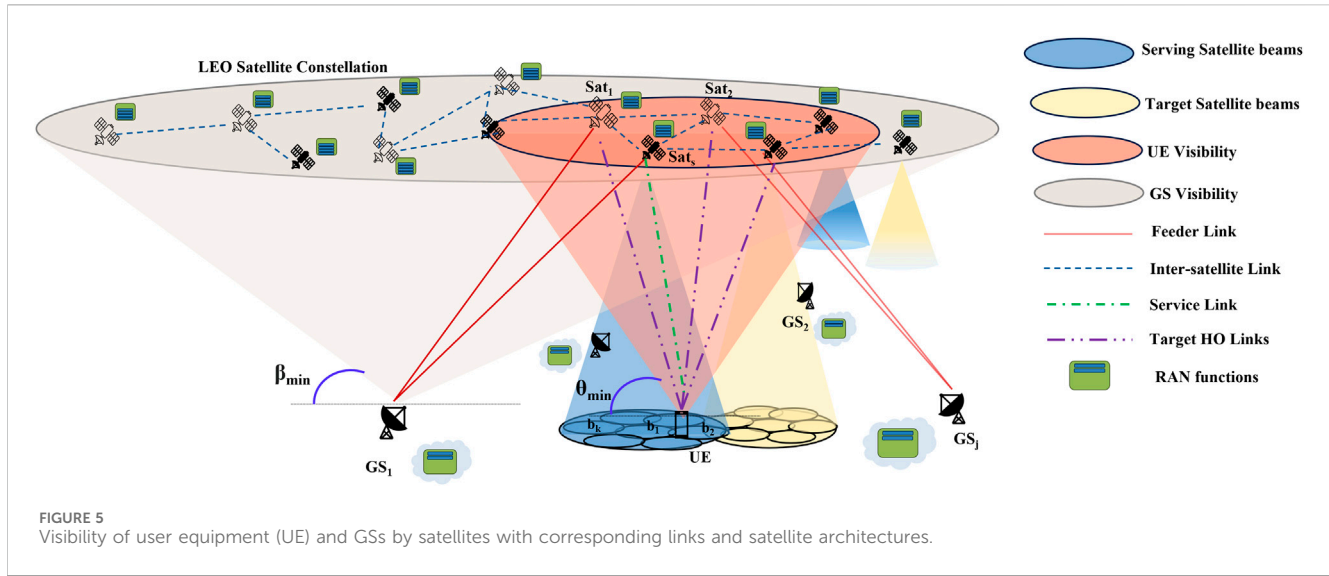
$$FSPL(d(\theta_s(t))) = 32.45 + 20\log_{10}f_c + 20\log_{10}d(\theta_s(t)), \quad (9)$$

where f_c represents the carrier frequency in gigahertz, and $d(\theta_s(t))$ is the distance between the UE and satellite s at time slot t in meters. For simplicity, we assume clear sky conditions and neglect all other losses. Additionally, atmospheric losses are considered to be negligible and are therefore excluded from the analysis.

5.1.2 Downlink rate calculation

The downlink carrier-to-noise ratio (CNR) for satellite s and beam i at the UE is as given by Equation 10 below (3GPP, 2023):

$$CNR_{s,i}(t) = EIRP(\alpha_{s,i}(t)) + \left(\frac{G}{T}\right)_r - k - PL - 10\log_{10}B, \quad (10)$$

FIGURE 5
Visibility of user equipment (UE) and GSs by satellites with corresponding links and satellite architectures.

where $EIRP(\alpha_{s,i}(t))$ is the effective isotropic radiated power (EIRP) of satellite s and beam i at time t in units of dBW, $\alpha_{s,i}(t)$ is the antenna boresight angle between the ith beam center of satellite s and the UE at time slot t, $(G/T)_r$ is the gain-to-noise temperature of the receiver antenna in units of dB/K, k is the Boltzmann constant in units of dBW/K/Hz, and B is the channel bandwidth in hertz. The EIRP can be computed using Equation 11:

$$EIRP(\alpha_{s,i}(t)) = P_s + G_T(\alpha_{s,i}(t)), \tag{11}$$

where P_s is the transmission power of satellite s in units of dBW; $G_T(\alpha_{s,i}(t))$ is the transmission antenna gain in units of dBi and is given by Equation 12:

$$G_T(\alpha_{s,i}(t)) = \begin{cases} G_t, & \text{if } \alpha_{s,i}(t) = 0, \\ G_t + 10\log_{10}\left(4\left|\frac{J_1(\kappa a \sin(\alpha_{s,i}(t)))}{\kappa a \sin(\alpha_{s,i}(t))}\right|^2\right), & \\ & \text{otherwise,} \end{cases} \tag{12}$$

where G_t is the maximum antenna gain, $J_1(\cdot)$ is the first-order Bessel function, $\kappa = \frac{2\pi f_c}{c}$ is the wave number based on c as the speed of light, and a is the radius of the equivalent satellite antenna aperture.

The antenna gain-to-noise temperature ratio of the receiver is determined by Equation 13:

$$\left(\frac{G}{T}\right)_r = G_r - N_f - 10\log_{10}\left(T_0 + (T_a - T_0) \cdot 10^{-0.1N_f}\right) \tag{13}$$

where G_r is the gain of the receiver antenna in units of dBi, N_f is the noise figure in decibels, T_0 is the ambient temperature in kelvin, and T_a is the antenna temperature in kelvin. Hence, the SL capacity of satellite s and beam i at time t can be calculated using the Shannon capacity formula:

$$C_{s,i}(t) = B\log_2(1 + CNR_{s,i}(t)). \tag{14}$$

In this study, we assumed an interference-free environment, which effectively represents the best-case scenario for SL capacity estimation in Equation 14. However, real-world NTNs experience co-channel interference from adjacent beams and inter-satellite interference, which could significantly degrade the link

performances. The assumption of an interference-free model leads to an upper-bound capacity estimate, meaning that the actual capacity would be lower depending on the interference level.

5.2 Multibeam satellite model

To implement a multibeam satellite architecture, it is essential to understand the projection of the satellite beams onto a defined plane. As proposed by the 3GPP (Guidotti et al., 2020), the UV plane is introduced to map the beam boresight projections of the satellite beams. The beam geometry can be analyzed effectively using the UV plane and requires knowledge of the 3dB beamwidth to determine the beam diameter and its layout.

5.2.1 Satellite beam layout

To define and project a multibeam layout from the satellite onto the Earth's surface, the system geometry depicted in Figure 6A is considered. For a given 3dB beamwidth and number of beams, the projections are first mapped onto the satellite's UV plane using Equation 15 (Guidotti et al., 2020):

$$\begin{aligned} u_{sat} &= \sin(\vartheta)\cos(\varphi), \\ v_{sat} &= \sin(\vartheta)\sin(\varphi), \end{aligned} \tag{15}$$
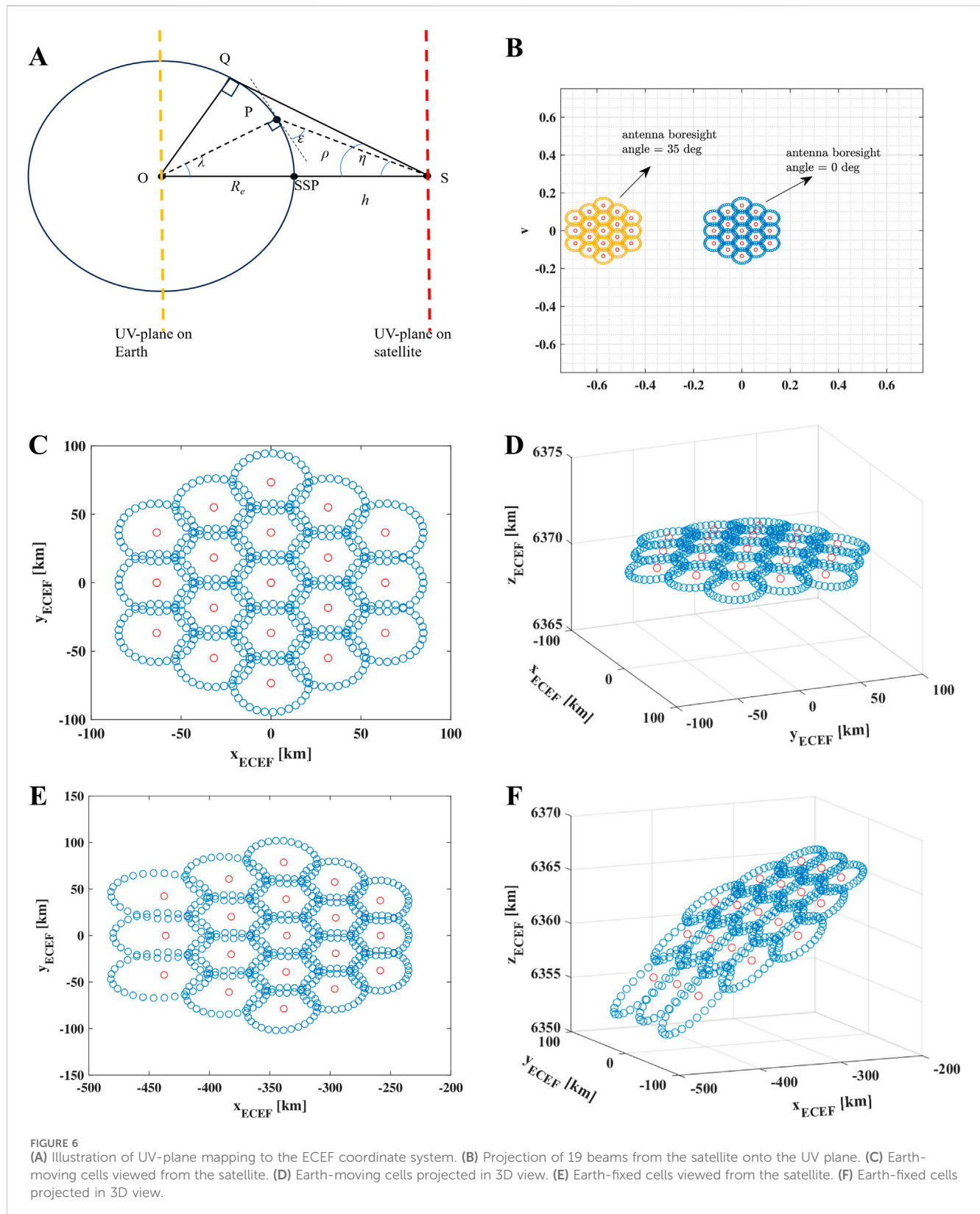
where ϑ and φ represent the azimuthal and elevation angles, respectively. The beam radius in the UV plane is then calculated using Equation 16:

$$d_{3dB} = \sqrt{u_{sat}^2 + v_{sat}^2} = \sin\vartheta_{3dB}, \tag{16}$$

while ensuring that $u_{sat}^2 + v_{sat}^2 \le 1$. The separation between adjacent beams in the UV plane, known as the adjacent beam spacing (ABS), is given by Equation 17:

$$d_{ABS} = 2\left(d_{3dB}\frac{\sqrt{3}}{2}\right) = \sqrt{3}d_{3dB}. \tag{17}$$

For instance, a 3dB beamwidth angle $(2 \cdot \vartheta_{3dB})$ of 4.4127° (3GPP, 2023) corresponds to an ABS (d_{ABS}) of 0.0667. The UV plane on the Earth is mapped using Equation 18 (Liu et al., 2022):

FIGURE 6
(A) Illustration of UV-plane mapping to the ECEF coordinate system. (B) Projection of 19 beams from the satellite onto the UV plane. (C) Earth-moving cells viewed from the satellite. (D) Earth-moving cells projected in 3D view. (E) Earth-fixed cells viewed from the satellite. (F) Earth-fixed cells projected in 3D view.

$$u_{earth} = \frac{u_{sat} \sin(\lambda)}{\sin(\eta)},$$

$$v_{earth} = \frac{v_{sat} \sin(\lambda)}{\sin(\eta)}, \quad (18)$$

where u_{earth} and v_{earth} denote the beam projections on the Earth's UV plane. The angles η and λ in Figure 6A are determined using Equations 19, 20:

$$\eta = \arcsin\left(u_{sat}^2 + v_{sat}^2\right), \quad (19)$$

$$\lambda = \frac{\pi}{2} - \eta - \varepsilon, \quad (20)$$

where ε is calculated by Equation 21:

$$\varepsilon = \arccos\left(\frac{\sin(\eta)}{\sin(\rho)}\right) \quad (21)$$

and ρ is given by Equation 22:

$$\rho = \arcsin\left(\frac{R_e}{R_e + h}\right) \quad (22)$$

In Technical Report 38.811 (3GPP, 2019), the Earth-centered Earth-fixed (ECEF) coordinate system is used to represent the three-dimensional position of any point on the Earth. In this system, the Earth is modeled as a perfect sphere with a radius of 6,371 km, and the origin O of the coordinate system is located at the Earth's center. The x–y plane corresponds to the equatorial plane, where the x-axis is aligned with 0° longitude, y-axis points toward 90° longitude, and z-axis extends from the origin O toward the geographic north pole. The transformation from the UV-plane on Earth to the ECEF coordinate system is given by Equation 23:

$$\begin{aligned} x_{ECEF} &= u_{earth} \cdot R_e, \\ y_{ECEF} &= v_{earth} \cdot R_e, \\ z_{ECEF} &= \left(\sqrt{1 - u_{earth}^2 - v_{earth}^2}\right) \cdot R_e \end{aligned} \quad (23)$$

5.2.2 Earth-moving vs. Earth-fixed cells

Using the above transformations, we can derive the projections of the satellite beams onto the Earth based on the 3dB beamwidth angle and satellite altitude. Satellite beams can be categorized as either Earth-moving or Earth-fixed cells depending on the type of antenna used on the satellite. Figure 6B illustrates the 19-beam projections on the satellite's UV plane for the Earth-moving (blue cluster) and Earth-fixed (yellow cluster) cells for a LEO satellite operating in the Ka-band with a 3dB beamwidth of 4.4127°. For the Earth-fixed cells, the antenna boresight angle is continuously adjusted to ensure that the beam remains fixed relative to a specific point on the Earth's surface. In contrast, for the Earth-moving cells, the boresight angle remains fixed at zero. Figure 6C shows the ECEF coordinates of the Earth-moving 19-beam projection as viewed on the ground from the satellite at an altitude of 550 km. Additionally, Figure 6D highlights the effect of the Earth's curvature on the beam footprint, demonstrating that the size of each beam footprint remains relatively uniform. Figure 6E depicts the ECEF coordinates of the Earth-fixed 19-beam projection as seen on the ground from the satellite at an altitude of 550 km. In Figure 6F, the impact of the Earth's curvature is more pronounced on the Earth-fixed cells, resulting in significant variations in beam footprint size. Understanding the modeling and usage of Earth-moving and Earth-fixed cells is crucial for satellite system design as it concerns aspects like power allocation, beam coverage, and antenna steering mechanisms.

5.2.3 Connection time modeling

The high relative speeds of LEO satellites result in frequent and unavoidable HOs in both intra-satellite and inter-satellite scenarios. The maximum duration that a UE remains connected to a beam depends on the satellite altitude (which influences its speed), beam size, and UE velocity. This connection time is given by Equation 24 (3GPP, 2023):

$$T_s = \frac{D}{v_{UE} + v_s}, \quad (24)$$

where D is the footprint diameter (in km), v_{UE} is the speed of the UE (in km/s), and v_s is the speed of the satellite (in km/s).

It is important to note that this expression assumes non-overlapping beam footprints and hence represents a conservative estimate of the connection duration. In practical systems, satellite beams often overlap to support seamless mobility, allowing the UE to remain connected beyond the nominal footprint boundary. Moreover, this expression assumes that the UE traverses the full beam diameter along a path aligned with the satellite's movement, which results in the longest possible connection time. In practice, the UE may cross the beam at an oblique angle or closer to the edge, covering a shorter distance than the full diameter. Moreover, the relative motion between the satellite and UE is not always purely additive as the direction of movement can vary significantly, leading to a lower effective speed.

Although the maximum connection time can be estimated using the footprint diameter, a more precise approach entails replacing the satellite speed with the beam speed, which represents the velocity at which the beam footprint moves across the Earth's surface. Since the satellite and its footprint share the same orbital period but cover different distances, using the beam speed instead of the satellite speed improves the accuracy of connection time estimation. The beam speed is given by Equation 25:

$$v_b = \frac{2\pi R_e}{T_p} = \frac{R_e v_s}{R_e + h}, \quad (25)$$

where T_p is the orbital period of the satellite. Therefore, accurate estimation of the connection time using beam speed is obtained with Equation 26:

$$T_b = \frac{D}{v_{UE} + v_b}. \quad (26)$$

Table 2 provides a comparison of the connection times for single-beam and multibeam scenarios by considering varying 3dB beamwidths for the Ka-band and S-band configurations. This comparison assumes a stationary UE ($v_{UE} = 0$) and satellite altitude (h) of 600 km (3GPP, 2023). The results indicate that the connection time of a UE is longer when calculated using the beam speed v_b than the satellite speed v_s. This demonstrates that refining the connection time estimation between the UE and a multibeam satellite enhances the precision of mobility prediction, which can be leveraged to develop more advanced HO algorithms for improved network performance.

5.3 GS–satellite association

To model dynamic topologies, we consider a network of GSs and LEO satellites that dynamically enter and exit the UE visibility region (Figure 5). The GS-satellite association is determined based on the maximum elevation angle criterion, ensuring that a satellite connects to the GS with the highest elevation when entering the visibility region. Each GS can support a limited number of FLs between 8 and 16 typically (Del Portillo et al., 2019). A predefined threshold (FL_T) is used to determine the maximum number of FLs available per GS for satellite connections. Once an FL is assigned, the satellite remains

connected to the same GS until it leaves the visibility region. This approach minimizes frequent FL switches and prevents unnecessary switching due to lower elevation angles.

```
1:  Input: Ephemeris data including S, J, T, FL_T, Δt,
    β_{s,j}(t),    TR_s(t),    and    S(t)    ∀t ∈ {1,2,…,T},
    ∀s ∈ {1,2,…,S}, and ∀j ∈ {1,2,…,J}
2:  Output: g_s(t) ∀t ∈ {1,2,…,T}
3:  Initialize g_s(t) ← 0 ∀t ∈ {1,2,…,T} and ∀s ∈ {1,2,…,S}
4:  Initialize l_j(t) ← 0 ∀t ∈ {1,2,…,T} and ∀j ∈ {1,2,…,J}
    ▷ FL status/availability indicator
5:  for each t ∈ {1,…,T} do
6:     for each s ∈ S(t) − S(t−1) do ▷ New satellites
           entering the UE visibility region
7:         Update e(j) ← β_{s,j}(t) ∀j ∈ {1,…,J} ▷ Computing
           elevation angles
8:         Update j' ← argmax_j e(j)  ∀j ∈ {1,…,J}  ▷
           Selecting a GS with the highest
           elevation angle
9:         if l_{j'}(t) == FL_T then ▷ Checking if GS j' has
           reached FL limit
10:            Update e(j') ← 0    ▷    Exclude    j'
               from selection
11:            Update j' ← argmax_j e(j) ∀j ∈ {1,…,J} ▷
               Select the GS with next highest
               elevation angle
12:            Go back to line 9
13:        else ▷ GS j' has available FLs
14:            Update g_s(t') ← j'  ∀t' ∈ {t, t+1,…, t +
               TR_s(t)} ▷ Assigning FL to satellite s
               for remaining time of visibility
15:            Update l_{j'}(t') ← l_{j'}(t') + 1  ∀t' ∈ {t, t +
               1,…, t + TR_s(t)} ▷ Update FL status of GS j'
16:        end if
17:    end for
18: end for
19: return g_s(t) ∀t ∈ {1,2,…,T}. ▷ Return GS-satellite
    association
```

Algorithm 1. GS-satellite association using the maximum elevation angle criterion.

Algorithm 1 establishes a GS–satellite association based on the highest elevation angle $\beta_{s,j}(t)$. The process entails computing the elevation angles between the satellite and each GS before selecting the GS with the highest elevation. If the preferred GS has reached its FL limit, it is excluded, and the next best GS is chosen. This FL limit constraint mitigates GS overload by ensuring that no GS is assigned more satellites than it can support at any given time.

5.4 CHO schemes

We described CHO procedures and signaling involved between the UE, satellites, and GSs in Section 4.2. In this context, we assume that the UE has knowledge of its own location and can access satellite-specific information, such as the satellite ID and ephemeris data. Using this information, the UE continuously monitors the

radio link quality of the candidate satellites and executes HO to the target satellite when the necessary conditions are triggered. We evaluate two CHO schemes (Wang et al., 2022) under dynamic LEO constellation scenarios and provide insights into their impacts on system performance. We analyze the system performance based on simple algorithms and note that sophisticated algorithms tailored to the needs must be built.

```
1:  Input: Ephemeris data S, J, T, Δt, g_s(t), f, and
    S(t) ∀t ∈ {1,2,…,T}
2:  Output: o(t), p(t), and τ_{f,q}^{CHO}(t) ∀t ∈ {1,2,…,T}
3:  for each t ∈ {1,2,…,T} do
4:     ▷ Choose m_{s,i}(t) based on CHO scheme
5:         Update                    o(t) ← argmax_{s'} m_{s',i'}(t)
           ∀s' ∈ S(t), ∀i' ∈ {1,…,I}    ▷    Selecting    best
           satellite s' satisfying condition m_{s',i'}(t)
6:         Update                    p(t) ← argmax_{i'} m_{s',i'}(t)
           ∀s' ∈ S(t), ∀i' ∈ {1,…,I}    ▷    Selecting    best
           satellite beam i' satisfying condition m_{s',i'}(t)
7:         if (o(t) == o(t−1)∥p(t) == p(t−1) then ▷ No inter-
           satellite or intra-satellite HO triggered
8:             Update τ_{f,q}^{CHO}(t) ← 0
9:         else ▷ Handover triggered
10:            Update τ_{f,q}^{CHO}(t) according to Eq. (3) ▷
               Calculating the associated CHO delay
11:        end if
12: end for
13: return o(t),  p(t),  and  τ_{f,q}^{CHO}(t),  ∀t ∈ {1,2,…,T} ▷
    Satellite HO decisions and CHO delays over time
```

Algorithm 2. General CHO scheme.

Algorithm 2 outlines the general CHO scheme based on the triggering condition $m_{s,i}(t)$. The corresponding CHO delay can be computed when the condition is triggered. For the SCB CHO mechanism, the condition metric is $m_{s,i}(t) = C_{s,i}(t) \cdot TR_s(t)$, which is the service capability. Here, the UE is handed over to the satellite with the best service capability, as outlined in Algorithm 2. This CHO scheme ensures that the satellite with the highest service capability is selected, thereby minimizing frequent HOs. For the SLRB CHO mechanism, the condition metric is simply $m_{s,i}(t) = C_{s,i}(t)$, which is the link rate capacity. Here, the UE is transferred to a satellite with the highest link rate capacity beam among all available satellites ($S(t)$), as outlined in Algorithm 2. This CHO scheme ensures that the satellite with the highest link rate is selected. However, owing to frequent changes in link quality, this scheme may result in more frequent HOs.

6 Results and analysis

In this section, we analyze the results of two distinct system setups:

- The first setup involves calculating the CHO delay by considering various end-to-end network topologies and different satellite network architectures. The delay is calculated by considering different HO scenarios corresponding to the different network topologies in Figure 3.

TABLE 2 Comparison of connection times for varying beam sizes.

Parameter	Ka-Band	S-Band
3dB beamwidth	4.41°	8.83°
Single beam diameter (D)	50 km	90 km
Maximum connection time (T_s)	6.61 s	11.9 s
Maximum connection time (T_b)	7.24 s	13.02 s
Three-tier beam (19-beams) diameter (D)	250 km	450 km
Maximum connection time (T_s)	33.07 s	59.52 s
Maximum connection time (T_b)	36.18 s	65.12 s

- The second setup is a realistic dynamic LEO satellite constellation including GSs that provides a comprehensive framework for monitoring the occurrence of different HO scenarios based on dynamic network topology changes over time, as illustrated in Figure 5. The delay model from the first setup is used in this dynamic simulation environment to calculate the overall system performance.

6.1 CHO scenarios under dynamic topologies

CHO delays are calculated under different CHO scenarios associated with the various network topologies detailed in Section 4 by considering different network architectures with various FSs. The signaling load is calculated for each topology on different links by considering the CHO procedures presented in Figure 4. A satellite altitude of 600 km is selected here, with the elevation angle to the UE considered as 30°. The elevation angle to the FL varies between 10° and 90°. Moreover, we assume 20 satellites per orbital plane, which results in an inter-satellite distance of 2,184 km. Assuming a specific altitude and elevation angle, the propagation delays for both the SL and FL can be estimated using trigonometric principles. The two GSs are positioned at the edges of the satellite footprints, which are defined by the FL elevation angles. On average, these GSs are separated by the same angle relative to the Earth's center as the two satellites to facilitate computation of the geodesic distance. For this system setup, the GSs are assumed to be separated by approximately 2,000 km (Satellite Map, 2024). To account for factors such as non-vacuum propagation and indirect routing, this distance is augmented by 20% before being divided by the speed of light to determine the propagation delay (Seeram et al., 2024). The delay parameters used in this setup are listed in Table 3.

6.1.1 CHO signaling load

Figure 7A presents the signaling load distribution across various links for different HO scenarios under the transparent architecture. In this architecture, HO scenarios are not feasible under dynamic topologies like B2, B3, D, and E owing to the absence of ISLs. Consequently, all HO signaling messages must traverse both the SL and FL to reach the gNB at the GS. In scenarios A and B1, the gNBs are located at the same GS (Figure 3A), resulting in zero IGSL messages. Conversely, in scenarios C1 and C2, where the gNBs are

TABLE 3 Simulation parameters for the LEO satellite constellation modeling.
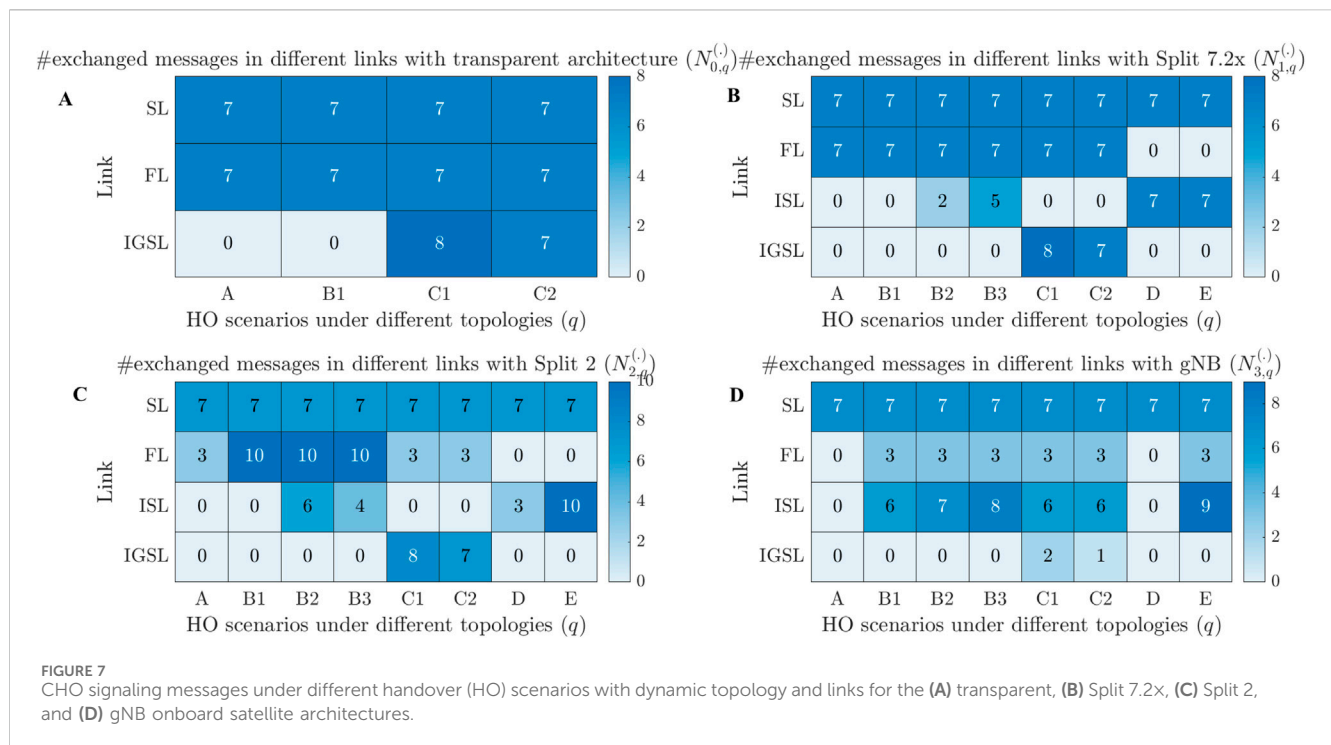
Parameter	Symbol	Value	Units
Delay Parameters[a]			
Synchronization delay	τ^{sync}	20	ms
Core network delay	τ^{core}	50	ms
Processing per message delay	τ^{ppm}	1	ms
Constellation and GS Parameters[b]			
LEO satellite orbital altitude	h	550	km
Orbit inclination	-	53°	deg
Number of satellites	S	1,584	-
Number of GSs	J	4	-
Minimum GS elevation angle	β_{min}	10°	deg
Minimum UE elevation angle	θ_{min}	40°	deg
#FLs available in each GS	FL_T	2	-
Time slot duration	Δt	1	s
Total number of time slots	T	1,200	-
Antenna and Beam Parameters[b]			
Radius of antenna aperture	a	0.1	m
Satellite beam diameter	-	50	km
Satellite Tx power	P_T	23	dBW
Satellite maximum Tx gain	G_t	30.5	dBi
Channel Parameters[b]			
DL carrier frequency	f_c	20	GHz
System bandwidth	B	50	MHz
UE Rx antenna gain	G_r	39.7	dBi
Noise figure	N_f	1.2	dB
Antenna temperature	T_a	150	K
Ambient temperature	T_0	290	K
Boltzmann constant	k	−228.6	dBW/K/Hz

[a]Parameters used in both system setups.
[b]Parameters used in the dynamic LEO satellite constellation setup.

positioned at different GSs (Figure 3A), IGSL signaling is required during HO.

Figure 7B depicts the signaling load distribution for different HO scenarios when implementing Split 7.2×. This FS enables the satellite to decode and route packets, thereby allowing the establishment of ISLs and supporting additional HO scenarios under dynamic topologies such as B2, B3, D, and E. As shown in Figure 4, even RACH-related messages must be processed at the GS (or at the M-SAT for scenarios D and E) owing to the absence of the MAC layer functions at the serving satellite. Consequently, Figure 7B shows that the signaling load across different links remains similar to that of the transparent case, except for the newly introduced scenarios (B2, B3, D, and E). The key

FIGURE 7
CHO signaling messages under different handover (HO) scenarios with dynamic topology and links for the **(A)** transparent, **(B)** Split 7.2×, **(C)** Split 2, and **(D)** gNB onboard satellite architectures.

advantage of Split 7.2× is that it extends GS coverage to satellites through ISLs (scenarios B2 and B3), which results in control signaling exchange within the ISL for these scenarios. In scenarios C1 and C2, IGSL signaling load is observed owing to the geographic separation of the GSs. Additionally, for satellite swarm HO scenarios (D and E), the signaling load patterns resemble those of scenarios A and B1, with the distinction that the load is exchanged through ISL instead of FL owing to complete relocation of the gNB functions across satellites.

Figure 7C illustrates the signaling load distribution when implementing Split 2. Here, the RACH-related messages can be processed at the serving satellite, but the RRC-related messages are forwarded to the GS over the F1 interface (or to the M-SAT for scenarios D and E). The increased onboard processing capabilities of the satellites help reduce FL signaling in scenarios A and C compared to Split 7.2×. However, for scenario B, both FL and ISL signaling increase despite the enhanced onboard processing capabilities. This suggests that Split 7.2× is the most suitable for scenario B. However, this choice comes at the cost of significantly higher fronthaul bandwidth requirements, as shown in Table 1, which range from 1 to 34 Gbps depending on the antenna size while the current FL bandwidth is approximately 20 Gbps (Del Portillo et al., 2018). In the satellite swarm HO scenario D, the Split 2 architecture reduces ISL signaling compared to that in Split 7.2×, whereas ISL signaling increases for scenario E.

Figure 7D shows the signaling load distribution when a fully onboard gNB is deployed. Moving the entire gNB to the satellite significantly reduces the FL message exchanges compared to Split 2 with topologies A and B. However, this increases ISL signaling (for all scenarios except A and D) and decreases IGSL signaling (only for scenario C). Overall, deploying the gNB onboard the satellite reduces control signaling to seven message exchanges over the SL

in HO scenarios A and D, where only intra-satellite HO occurs. For other scenarios, control signaling in the FL and IGSL decrease, albeit with a slight increase in ISL signaling. However, this approach incurs a computational cost as onboard gNB implementation requires 55%–70% higher computational cost (and hence higher power consumption) than Split 7.2×, as detailed in Table 1.

The reduction of control signaling overhead is significant in an NTN where mobility events predominantly occur for changes in the serving satellites for specific cells or cell movements in the case of Earth-moving cells. These events typically occur every few minutes (or every few seconds in case of intra-satellite HO), prompting all users within the cell to simultaneously execute mobility procedures. Although strategies like aggregating the control signaling load or distributing the HOs over time can help mitigate this issue, a significant amount of signaling load is still expected.

6.1.2 CHO delay

Herein, we analyze the CHO delay considering varying FL elevation angles while maintaining a minimum SL elevation angle of 30°. We capture HO trigger instances across different satellite network architectures in various HO scenarios associated with different topologies to investigate the CHO delay dynamics by analyzing how changing topology impacts CHO delay. Note that we focus on scenarios supported by the transparent architecture (A, B1, C1, and C2) for comparative analysis with other regenerative architectures. However, the transparent architecture results are omitted from further plots as they overlap with the Split 7.2× results, meaning that all observations for Split 7.2× also apply to the transparent architecture.

From Figure 8, it is evident that scenario A (intra-satellite HO) has lower CHO delays for any network architecture as the gNB onboard the satellite offers the minimum CHO delay; however, in scenario B1 (inter-satellite HO with common GS), both transparent
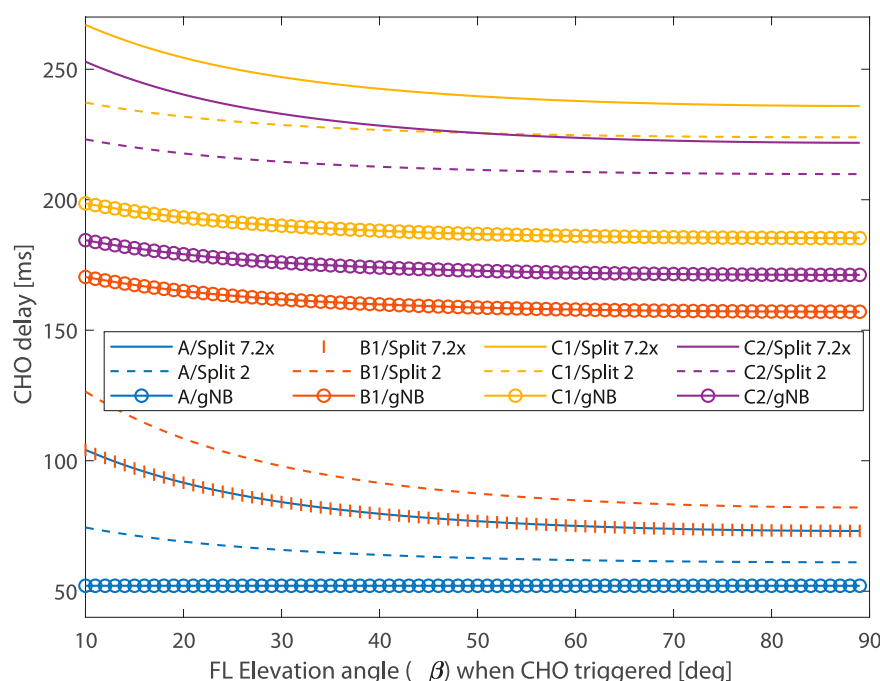
FIGURE 8
CHO delays under different HO scenarios and satellite architectures for varying feeder link (FL) elevation angles. A: CHO within the same satellite; B1: CHO between satellites connected to the same GS; C1: CHO between satellites connected to different GSs with AMF/UPF at the source GS; C2: CHO between satellites connected to different GSs with AMF/UPF at the target GS.

architecture and Split 7.2× offer minimum CHO delays. For scenarios C1 and C2 (inter-satellite HO with different GSs), the gNBs onboard the satellites minimize CHO delays effectively. For HO scenarios involving topologies A, C1, and C2, gNB offers the lowest CHO delay followed by the Split 2 and Split 7.2× architectures; however, for B1, Split 7.2× offers the lowest CHO delay followed by Split 2 and gNB. It is notable that the characteristics of the CHO delays for Split 7.2× with topology A overlap with those of topology B1; this indicates that for inter-satellite HO scenarios, it is better for the HO to occur to a target satellite connected to the same GS as the serving satellite. This is because of the unique benefit of having lower CHO delays when switching from intra-satellite to inter-satellite HO, which is critical for delay-sensitive services. However, the CHO delays are very high in the C1 and C2 scenarios, making them suitable for delay-tolerant services. Similarly, for the Split 2 architecture, topology B1 has the least CHO delays among inter-satellite HO scenarios, which would be the best option for delay-sensitive services. For gNB onboard, inter-satellite HO scenarios typically have higher CHO delays and are not suitable for delay-sensitive services. However, if the service time of the UE can be met before triggering an inter-satellite HO, then gNB onboard is the best architecture that offers minimum CHO delays. A critical consideration here is the frequency at which each scenario occurs, which influences the overall evaluation of the best architecture. For instance, a HO scenario with a higher CHO delay may occur less frequently, potentially altering the assessment of the best configuration. This aspect is further explored in the following section, where we analyze the dynamic LEO constellation setup for different CHO schemes.

6.2 Conditional handover in dynamic LEO constellation

The system-level simulation setup illustrated in Figure 5 is implemented based on recommendations (3GPP, 2023, 2024a, 2019). The main parameters for this simulation setup are outlined in Table 3. For constellation dynamics, the Starlink LEO configuration is used, which comprises 1,584 satellites in 72 orbital planes, with 22 satellites per plane at an altitude of 550 km and inclination of 53° (FCC, 2018). Each satellite is equipped with highly directional circular aperture antennas to serve the UE using Earth-moving cells to enable 19 NR cells through 19 satellite beams, which are distributed on the ground in three concentric tiers, as shown in Figure 6C. The satellite specifications are set based on the assumptions in 3GPP (2023). Starlink GS locations are incorporated (Satellite Map, 2024) with the number of GSs set to four. The GS positions are [38.33458°N, 0.4909°E; 50.9871°N, 2.1255°E; 45.3207°N, 9.1886°E; 50.3353°N, 8.5320°E]. The UE is positioned with coordinates [45.78°N, 1.75°E] to encompass the selected GSs. The LEO constellation dynamics (ephemeris data) are sampled at 1-s intervals over a total duration of 20 min, supplying data for the CHO delay performance analysis across different CHO algorithms and satellite architectures. The occurrence of HO scenarios under different topologies is analyzed for the dynamically changing network topology. In this study, GS1 and GS4 are selected for the AMF/UPF based on the IGSL distance. Both SCB and SLRB CHO algorithms are implemented and tested across this dynamic LEO constellation setup with different satellite network architectures.
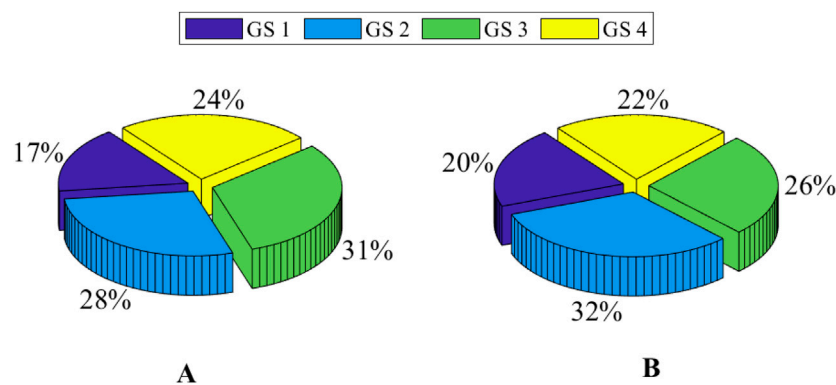
FIGURE 9
Percentage of time that the UE is served by a particular GS through the satellite when using the **(A)** service-capacity-based (SCB) and **(B)** service-link-rate-based (SLRB) schemes.

TABLE 4 Comparison of CHO schemes in terms of HO and occurrence metrics.

Metric	SCB	SLRB
Handovers over 20-min simulation duration		
#Intra-satellite HOs [#/UE]	362	380
Intra-satellite HO rate [#/min/UE]	18.1	19
Inter-satellite #HOs [#/UE]	57	74
Inter-satellite HO rate [#/min/UE]	2.85	3.7
Scenario occurrences over 20-min simulation duration		
#Scenario occurrences (A/B1/C1/C2) [#/UE]	362/3/23/31	380/13/29/32
Occurrence probability (A/B1/C1/C2) [%]	86.4/0.7/5.5/7.4	83.7/2.9/6.4/7

6.2.1 GS–satellite association

Algorithm 1 is implemented to dynamically associate the GSs with satellites entering the visibility of the UE, with each GS limited to a maximum of two dedicated FLs. The UE is served by a satellite that is in turn connected to one of the four GSs through an FL. Analyzing the percentage of time that each GS serves the UE through a satellite provides valuable insights into the dynamic nature of GS selection. This association varies based on the CHO scheme used to trigger HO events. Figure 9 presents the percentage of time that each GS is involved in serving the UE through a satellite and demonstrates that the GS–satellite association algorithm effectively assigns FLs to satellites as they enter visibility. Specifically, Figure 9A shows that GS3 predominantly serves the UE under the SCB scheme, while the other GSs also contribute significantly. Similarly, Figure 9B illustrates that GS2 plays the most prominent role in serving the UE under the SLRB scheme. This analysis is instrumental in identifying the optimal GS for content caching and guiding the development of efficient content placement algorithms.

6.2.2 Performance comparison of the CHO schemes

The SCB and SLRB CHO schemes were implemented to allow the UE to make HO decisions under dynamic system-level simulations. The rate of HOs per minute is a valuable metric for evaluating the performances of the different CHO schemes. Table 4 summarizes the number of intra-satellite and inter-satellite HOs occurring with each scheme over a 20-min duration along with the corresponding HO rates. It is noted that intra-satellite HOs occur due to HOs between beams of the same satellite, which typically corresponds to topology A; however, inter-satellite HOs encompass a combination of topologies B1, C1, and C2. The intra-satellite HO rates are 18.1 and 19 HOs/min/UE for the SCB and SLRB CHO schemes, respectively, implying that the UE performs a HO approximately once every 3 s. For inter-satellite HOs, the rates are 2.85 and 3.7 HOs/min/UE for SCB and SLRB, respectively, corresponding to one HO every 15–20 s. Notably, the SCB scheme outperforms SLRB by reducing unnecessary HOs as it selects the target satellite based on its remaining service time, thereby improving HO efficiency.

Table 4 also provides a quantitative summary of the number and occurrence probability of HO scenarios with topologies A, B1, C1, and C2 over 20 min for each CHO scheme. From the table, it is evident that scenario A has high occurrence probabilities of 86.4% and 83.7% for the SCB and SLRB schemes, respectively. Conversely, scenario B1 has the least occurrence probabilities of 0.7% and 2.9% for SCB and SLRB, respectively. Similar trends are noted for scenarios C1 and C2 in alignment with our initial observations. Given these occurrence probabilities of different scenarios, we can assess whether the performances of the HO scenarios identified in Figure 8 remain the same under the dynamic setup. Accordingly, the hierarchy of CHO delay performance shows that scenario C1 is the least efficient followed by scenarios C2 and B1, with scenario A being the most efficient. We observed that scenarios C1 and C2 occurred with probabilities of 6% and 7%, respectively, while scenario B1 occurred with a probability of 1%–3%. However, scenario A occurred approximately 84%–86% of the time, making it the most frequent contributor to CHO delays despite its efficiency. This high frequency of scenario A is primarily attributed to the intra-satellite HOs, which are generally unavoidable given the system design.

To reduce the overall CHO delay, it may be beneficial to focus on avoiding less-efficient scenarios, particularly scenarios C1 and C2, which contribute more to the total CHO delay than scenario B1.
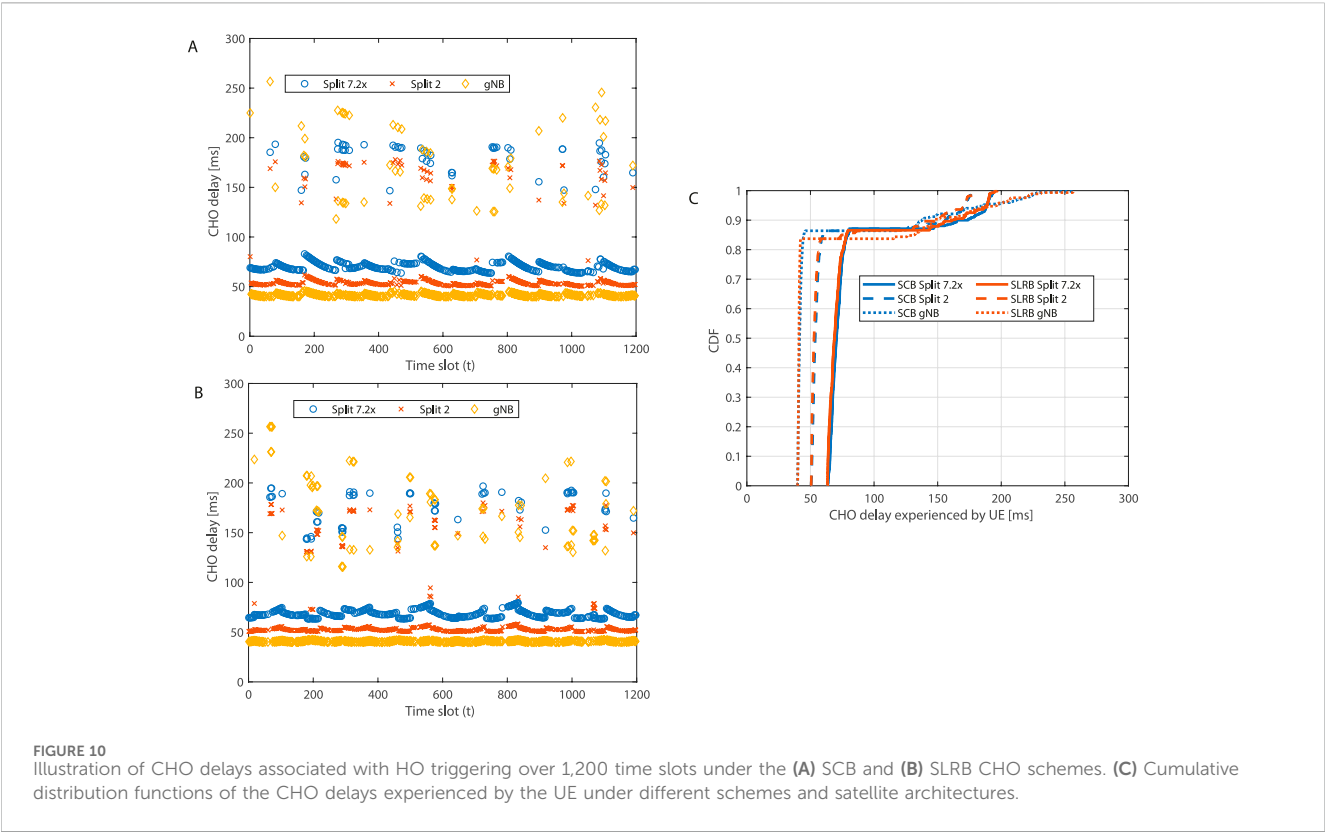
FIGURE 10
Illustration of CHO delays associated with HO triggering over 1,200 time slots under the **(A)** SCB and **(B)** SLRB CHO schemes. **(C)** Cumulative distribution functions of the CHO delays experienced by the UE under different schemes and satellite architectures.

TABLE 5 Cumulative CHO delay and applicability of each architecture.

Cumulative CHO delay [s]				
CHO scheme	Transparent	Split 7.2×	Split 2	gNB
SCB	35.3	35.3	28.5	24.9
SLRB	37.6	37.6	30.8	28.3
		Applicability of each architecture		
Onboard processing	Use case requirement [ms]	Transparent	Split 7.2×	Split 2	gNB
Limited	≤50	✗(83 ms)	✗ (83 ms)	✗ (62 ms)	✗ (45 ms)
	≤100	✓ (83 ms)	✓ (83 ms)	✗ (62 ms)	✗ (45 ms)
	≤200	✗ (197 ms)	✗ (197 ms)	✗ (180 ms)	✗ (257 ms)
Ample	≤50	✗ (83 ms)	✗ (83 ms)	✗ (62 ms)	✓ (45 ms)
	≤100	✓ (83 ms)	✓ (83 ms)	✓ (62 ms)	✓ (45 ms)
	≤200	✗ (197 ms)	✗ (197 ms)	✓ (180 ms)	✗ (257 ms)

Therefore, there is potential to design network-architecture-aware and topology-aware HO algorithms that prioritize avoidance of scenarios C1 and C2 where feasible as this could lead to lower CHO delays overall. However, given that scenarios C1 and C2 only occur with low probabilities, the overall impact of such optimizations on CHO delay may be limited. Further evaluations are therefore needed to determine whether reducing less-frequent scenarios could significantly decrease the total CHO delay in practice.

6.2.3 CHO delay

Figure 10A illustrates the CHO delays incurred during a HO in time slot t across different network architectures when the SCB scheme is used within a dynamic LEO satellite environment. The bottom region wherein the CHO delay is less than 100 ms represents the intra-satellite HO delays. We can see that the gNB has the lowest intra-satellite CHO delay since all RAN functions are processed onboard the satellite, followed by the Split 2 architecture; the highest CHO delay is observed in Split 7.2×.

In Figure 10A, the region where the CHO delay exceeds 100 ms represents the inter-satellite HOs, and we can also see some inter-satellite HOs for Split 7.2× and Split 2 in the region less than 100 ms owing to the characteristics observed in Figure 8. We observe that gNB sometimes exhibits higher CHO delays than Split 2 and Split 7.2× according to Figure 10A. However, from Figure 8, we observe that gNB always has lower CHO delays compared to other architectures, except for the B1 HO scenario. However, in Figure 10A, there are instances where the CHO delay in gNB is higher owing to the dynamicity consideration in the inter-satellite distances and service link distances. Similarly, Figure 10B can be analyzed for the SLRB CHO scheme. However, Figure 10 does not clearly show the contributions of each CHO scheme and architecture to the overall CHO delay. Hence, Table 5 presents the cumulative CHO delay for each satellite architecture and CHO scheme over the 1,200 time slots whenever a HO is triggered. This table reveals that the SCB CHO scheme results in a lower cumulative CHO delay than the SLRB scheme for any satellite architecture. However, despite the instances of higher CHO delays for gNB in inter-satellite HOs, the cumulative CHO delay is lowest for gNB, with values of 24.9 s for the SCB and 28.3 s for the SLRB schemes. The SCB scheme achieves the lowest CHO delay owing to the lower frequencies of both intra-satellite and inter-satellite HOs, as shown in Table 4, where gNB performs the best. Thus, in the long term, gNB is advantageous for minimizing the cumulative CHO delay. However, the gNB onboard decreases the CHO delay by 25%–30% compared to Split 7.2×. There is no gain in terms of the CHO delay between the transparent architecture and Split 7.2×.

Figure10C shows the cumulative distribution functions (CDFs) of the CHO delays for different satellite architectures and CHO schemes. The region below 100 ms mostly represents intra-satellite HO distribution, whereas the region beyond 100 ms represents inter-satellite HO distribution. It is observed that the average CHO delays during intra-satellite HO, irrespective of the CHO scheme, are 70 ms, 53 ms, and 41 ms for Split 7.2×, Split 2, and gNB, respectively. Similarly, the maximum intra-satellite CHO delays are 83 ms, 62 ms, and 45 ms for Split 7.2×, Split 2, and gNB, respectively. However, there are inter-satellite HO delays less than 100 ms for Split 7.2× and Split 2 when the HO scenario is B1. Consequently, the average CHO delays for inter-satellite HOs span a broader range, with averages of 164 ms, 151 ms, and 173 ms for Split 7.2×, Split 2, and gNB, respectively. According to Figure 10C, the maximum inter-satellite CHO delays are 197 ms, 180 ms, and 257 ms for Split 7.2×, Split 2, and gNB, respectively.

Table 5 summarizes the applicability of various satellite architectures (transparent, Split 7.2×, Split 2, and gNB) in NTN scenarios across different use cases (delay-sensitive: 50 ms and 100 ms; delay-tolerant: 200 ms) and onboard processing capabilities (limited vs. ample). For delay-sensitive requirements (50 ms and 100 ms), the maximum intra-satellite CHO delays are considered, while the maximum inter-satellite CHO delays are used for delay-tolerant applications (200 ms), as indicated in the parentheses in Table 5. In scenarios with limited onboard processing, the satellite cannot support computationally intensive RAN functions. Thus, architectures requiring minimal processing on the satellite, namely transparent and Split 7.2×, are more applicable. Under the 100 ms delay requirement, both transparent and Split 7.2× architectures remain viable owing to

their maximum intra-satellite CHO delays of 83 ms, leaving sufficient budget for transmission and propagation. However, these architectures do not meet the more stringent 50 ms requirement or the delay-tolerant 200 ms case, where inter-satellite CHO delays exceed the limit for most options.

When ample onboard processing is available, all architectures are feasible in terms of the computational requirements. In this case, the determining factor is the residual delay budget after accounting for maximum CHO delays. Under the stringent requirement of 50 ms, only the gNB onboard architecture is applicable with its maximum CHO delay of 45 ms, which leaves a narrow 5 ms budget for packet transmission and propagation. For the 100 ms case, all architectures meet the requirement owing to their intra-satellite CHO delays that range from 45 ms to 83 ms. For the 200 ms delay-tolerant case, only Split 2 is considered truly applicable despite all architectures having inter-satellite CHO delays near the limit; here, Split 2 achieves a maximum CHO delay of 180 ms, leaving a reasonable 20 ms budget, whereas the transparent and Split 7.2× architectures have CHO delays of 197 ms, leaving only 3 ms for propagation and transmission. Given that the propagation delay alone may consume approximately 2 ms, the remaining 1 ms for transmission imposes very tight constraints, particularly under large packet sizes or low link rates. Therefore, Split 2 offers the most practical margin for reliable operation under this use case.

7 Discussion

This study investigates the interplay among CHO delay, computational complexity, and control signaling overheads under different FSs using a realistic dynamic Starlink LEO constellation model with GS connectivity. Through extensive simulations, we evaluate three open-RAN-based regenerative architectures (gNB onboard, Split 2, and Split 7.2×) and compare them with a transparent architecture to assess the impacts on control signaling overheads and CHO delays. Our findings reveal distinct tradeoffs among the different FSs in NTNs. For any HO scenario except inter-satellite HO for satellites connected to the same GS, the gNB onboard satellite minimizes CHO delay compared to the Split 2 and Split 7.2× satellite architectures (since there is no signaling in the ISLs). Furthermore, transitioning from a transparent architecture to Split 7.2× does not reduce the CHO delay. However, Split 7.2× has greater onboard processing capabilities that facilitate packet decoding and forwarding through ISLs, enabling extended GS coverage through a multihop topology.

In terms of computational cost, the gNB onboard architecture demands approximately 55%–70% more resources than Split 7.2×. Although Split 7.2× is more efficient computationally, it introduces 25%–30% higher cumulative CHO delay. These observations underscore the need to identify the applicability of each architecture based on the service requirements. With limited onboard processing, only the transparent and Split 7.2× architectures support delay-sensitive services up to 100 ms. When ample processing is available, gNB is the only viable option for stringent 50 ms delay requirements, while Split 2 is best suited for delay-tolerant services with 200 ms requirements.

Further performance improvements can be achieved by optimizing the CHO algorithm to reduce inter-satellite HOs,

thereby decreasing the cumulative CHO delay. However, the HO rate itself cannot be significantly improved through CHO optimization owing to the physical limitations imposed by fast Earth-moving cells. Future research efforts could therefore investigate Earth-fixed cell configurations to provide more stable coverage while significantly reducing HO frequency. Some additional research directions would include leveraging RACH-less or two-step RACH procedures wherever applicable to reduce HO control signaling, thereby reducing CHO delays. Additionally, employing CHO schemes tailored to specific service requirements could help optimize HO frequency. Content caching at strategically selected GSs could further reduce delays in content retrieval to enhance user experience. Another promising research direction involves investigating mixed satellite architectures within a constellation instead of uniform satellite architecture distribution. Analyzing NTN performances under such hybrid architectures could offer new optimization opportunities. Network-topology-aware CHO algorithms that proactively avoid HOs to satellites with high CHO delays could further enhance user experience and improve the overall system performance.

Author contributions

SS: conceptualization, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review and editing, data curation, software, and validation. LF: conceptualization, investigation, writing – original draft, and writing – review and editing. MO: formal analysis, supervision, validation, and writing – review and editing. SZ: investigation, supervision, and writing – review and editing. CC: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, writing – original draft, and writing – review and editing.

Conflict of interest

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Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

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