Enhancing Handover Performance in LEO Satellite Networks with Multi-Connectivity and Conditional Handover Approach

Mohammed Al-Ansi*, Jorge Querol*, Madyan Alsenwi*, Eva Lagunas*, Symeon Chatzinotas*
*Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, Luxembourg
Email: {mohammed.al-ansi, jorge.querol, madyan.alsenwi, eva.lagunas, symeon.chatzinotas}@uni.lu

***Abstract*—Low Earth orbit (LEO) satellites have emerged as an essential technology for 5G and beyond, with the capability to provide high-speed Internet connectivity on a global scale. However, the continuous movement of these satellites is a significant challenge. Most existing handover (HO) solutions rely on switching between serving and target satellites, resulting in a single-connectivity (SC) hard HO. In contrast, this study introduces a soft-HO methodology that uses dual connectivity and packet duplication during the multi-coverage period to connect users to both serving and target satellites via a multi-connectivity (MC) architecture. MC-HO considers the conditional HO technique and location-based trigger criterion. Compared to SC-HO, MC-HO exhibits a reduction in the average number of HOs and radio link failures. Thus, the proposed approach promises to improve the performance of handover, resulting in more stable and reliable connectivity.**

***Index Terms*—LEO satellites, soft-handover, conditional handover, multi-connectivity, dual connectivity**

I. Introduction

Non-terrestrial networks (NTNs) are transitioning from supplementary systems for terrestrial networks (TNs) to critical components of the global connectivity ecosystem. Among the various NTN components, low Earth orbit (LEO) satellites have the potential to revolutionize applications that provide global broadband Internet access services. Due to their close proximity to Earth compared to geostationary orbit satellites, these space components have inherent characteristics such as low latency and better radio link budgets. However, the continuous mobility of these satellites requires handover (HO) solutions, which is one of the main challenges facing this promising technology [1].

In the literature, HO is broadly classified [2], [3] into link layer and network layer types. The former is also categorized into spot beam HO, satellite HO, and inter-satellite link (ISL) HO. In addition, HO schemes are classified into hard HO (HHO), soft HO (SHO), and signaling diversity HO (SDHO). HHO refers to switching the connection from the serving satellite (SSAT) to the target satellite (TSAT) (i.e., break before make). Alternatively, SHO is called the make-before-break technique, which ensures that the connection with the TSAT is established before releasing the connection from the SSAT. SDHO is also an SHO scheme, but a diversity scheme is used to allow signaling control data flows from both satellites, while traffic data is from the SSAT. After ensuring that the traffic data is firmly established with the TSAT, an old connection from the SSAT is released.

Investigating existing NTN studies, we can find that most of the proposed HO solutions [3]–[6] use the HHO approach. It uses only one channel at a time which can also be considered a single-connectivity (SC) mechanism. Generally, the HHO approach offers less signaling overhead and computational complexity compared to SHO [7]–[9] but with drawbacks mainly in the case of multi-link availability from multiple satellites. This availability results from the overlap of coverage, which is typically designed between the beams of neighboring satellites from the same or different orbital planes to ensure fewer coverage gaps and a smooth HO process. It yields more frequent HO, particularly when only a measurement-based triggering condition is applied without adding other conditions such as location-based and timing-based criteria. Also, HHO requires buffering the traffic data in the SSAT before establishing a link with the TSAT. This results in a higher load on the satellites as well as a high possibility of interruption time when the data is not transferred to the user during the HO process.

In contrast, SHO [7]–[9] is a promising approach. In [7], the authors show how the diversity with distributed packet combining is applied to achieve SHO. They also studied and suggested an overlap between the beam footprints for better performance. In [9], an uplink SHO is applied where one of the satellites works as a relay and the results show attractive performance compared to HHO. In addition, the dual active protocol stack (DAPS) HO is a form of the SHO scheme proposed in 3GPP for TN [10]. In DAPS, two independent protocol stacks in the user equipment (UE) allow for simultaneous connection with both the serving and target nodes, enhancing seamless connectivity.

Furthermore, multi-connectivity architecture (MC) [11], [12], with dual connectivity as an enabler technology, has also been studied in TN as a form of SHO that improves HO performance [13]–[15]. Enabling MC allows the UE to communicate with multiple nodes simultaneously, one of which serves as a master node (MN), while one or more secondary nodes (SN) provide enhanced coverage, capacity, and reliability. The MN manages key communication and control functions, whereas the SN facilitates additional data traffic, resulting in a more robust and efficient network experience. The use of MC in conjunction with proper packet operations (split or duplication) results in increased data rate and reliability [12]. Recognizing its potential in NTN, 3GPP explored the possibilities of MC and its feasibility [16]. Recent studies on NTN have also underscored the significant potential of MC to improve network performance in various aspects [17] [18] [11].

The third-generation partnership project (3GPP) has introduced some HO enhancement solutions for NTN considering the NTN environment. Solutions include conditional HO (CHO) and various trigger conditions, such as location- and time-based criteria [10], [16]. By preconfiguring the HO procedure, CHO improves reliability and reduces the probability of failure. This prepares the UE to carry out a handover only if certain specified configurations are met.

In the literature, the techniques mentioned above and others have been investigated and developed to improve HO performance. In [4], several HO strategies were studied, such as closest satellite HO, maximum visibility HO, and carrier-to-interference-based HO. The impact of these techniques has been studied for various constellation types in terms of spectral efficiency, and compared to emphasize the importance of minimizing HO failures. Location-based handovers were studied by [5] for intra-satellite HO in moving cells. This location-based HO was studied in [19]. The authors showed that exploiting the deterministic movement of satellites yields a reduction in link failures and a reduction in the number of HOs. Moreover, CHO has been optimized by finding the optimal target satellite to improve service continuity in [20] through a service continuity graph model to predict probable combinations of CHO and optimize the handover sequence for each user.

Taking into account the aforementioned problems and potential solutions, this study presents an SHO approach that integrates location-based CHO and MC technologies. This approach relies primarily on the multi-coverage area served by adjacent satellites in the same orbital plane. We present handover procedures for the proposed SHO approach, which are developed based on combining the existing CHO procedures and 3GPP's conditional SN addition protocols [21].

The remainder of this paper is organized as follows. Section II discusses the LEO satellite system model. Section III describes the proposed HO method. Section IV presents the numerical results and discussion, followed by the conclusion and future work.

II. Low Earth Orbit Satellite System Model

We consider that LEO satellites with circular Earth-moving beams continuously cover a dense urban area. Figure 1 illustrates LEO satellites from the same orbital plane at a specific instant. These beams are designed with overlap to reduce coverage gaps and facilitate HO. The UEs are uniformly distributed throughout the dimensions of a single beam with a diameter of 50 km. We assume that the UEs are stationary, and their speed is negligible compared to the satellites, which

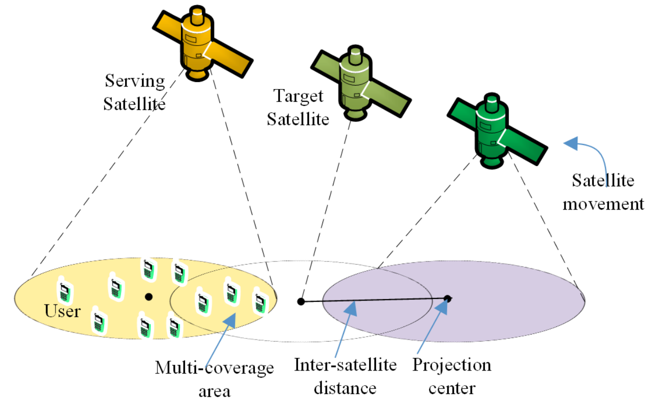

Fig. 1. Illustration of LEO satellites coverage scenario for a region at specific time instant

have a high speed of 7.56km/s. As satellites move through their orbits, some UEs become in the overlap area. As a result, they are in a multi-coverage area, which typically has at least two satellites. We assume that those UEs have the technical and operational capability and omnidirectional antennas to communicate with multiple satellites simultaneously. The satellite constellation comprises three LEO satellites. The inter-satellite distance is designed such that the beams of nearby satellites overlap. In addition, regenerative payloads with ISLs are considered to enable communication and interfaces between the SSAT and TSAT.

CHO is used with a location-based trigger condition. Hence, the HO decision is based on calculating the distances between the UE and the serving and target satellites. We assume that the satellites' mobility is known to the UEs by predicting their orbital trajectory using ephemeris data. UEs have Global Navigation Satellite Systems (GNSS) to know their locations. Consequently, UEs can accurately determine the projection centers of both the current-serving satellite and the next target satellite.

The characteristics of the channel between the satellites and the UEs are generated following the 3GPP NTN channel model described in Section 6.6 of [22]. For the signal-to-interference-plus-noise ratio (SINR), the UEs receive interference from the two neighboring satellites (TSAT and the previous SSAT) to the currently serving satellite, where they transmit at the same frequency. The strength of the signal received at the UE in (dBm) is calculated as [16]:

$$R_{UE} = \text{EIRP} - \text{PL}_{\text{total}} \tag{1}$$

where EIRP is the equivalent isotropically radiated power that represents the transmitted power and the transmit antenna gain in (dBm). The total path loss PL_{total} is given by:

$$\text{PL}_{\text{total}} = Pr_{\text{LOS}}\text{PL}_{\text{LOS}} + (1 - Pr_{\text{LOS}})\text{PL}_{\text{NLOS}} \tag{2}$$

where Pr_{LOS} is the probability of line of sight (LOS) (dB) as a function of the elevation angle according to the interpolation of Table 6.6.1-1 [22]. PL_{LOS} and PL_{NLOS} are the basic path losses due to the LOS and the non-line of sight (NLOS) paths, respectively. These path losses include free space loss, clutter loss (CL), and shadow-fading loss (SF) and are given by

$$\mathrm{PL}_{\mathrm{LOS}} = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d) + \mathrm{SF} \quad (3)$$

where the frequency f_c in GHz, and the distance d (a.k.a. slant range) can be determined based on the satellite altitude h_0 and elevation angle α by:

$$d = \sqrt{R_E^2 \sin^2(\alpha) + h_0^2 + 2h_0 \cdot R_E} - R_E \sin(\alpha) \quad (4)$$

Also, the path loss due to the NLOS path is given by

$$\mathrm{PL}_{\mathrm{NLOS}} = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d) + \mathrm{SF} + \mathrm{CL} \quad (5)$$

where R_E denotes the radius of the Earth. The values of shadow fading and clutter losses are given in Table 6.6.2-1 of [22] for reference elevation angles in dense urban scenarios. The angles are determined based on the satellite altitude h_0 and the distance between the UE and the projection center of the satellite.

III. Proposed Multi-connectivity-based Handover with CHO Approach

Considering the LEO system model introduced in the previous section, we propose to efficiently exploit multi-coverage in the overlap area between adjacent beams from satellites to construct a SHO process. This process is based on the following assumptions:1) The UEs exploit the GNSS and ephemeris data to determine their distances from the current SSAT and candidate TSATs. 2) CHO is applied with a location-based trigger criterion. 3) The UEs in the multi-coverage area are connected to both SSAT and TSAT. 4) Master cell group with split bearer option of the dual connectivity is chosen along with packet duplication. This means that the core network is connected to the MN which transmits both signaling and traffic data to the UE. After adding the SN, the traffic data is splitted and copies of the packets are transmitted from both MN and SN.

More specifically, we assume that UEs have the features and capabilities of MC. The UE first connects to the SSAT and its configured as an MN. When the UE reaches the overlap region (due to the movement of the satellites' beams) and the CHO criterion is fulfilled, the TSAT is added as an SN. Hence, the UE becomes connected to both satellites and receives traffic data from both satellites. A scheduler starts traffic duplication when the CHO criteria is satisfied, which depends on the UE's position. Furthermore, we consider that the UE will need to connect to the TSAT in a normal process as in the conventional SC-HO method where the random access protocol is applied.

The main procedure of the MC-HO is shown in Fig. 2 where the SSAT adds a request to the TSAT to be the SN. This decision is based on the measurement report received from the UE on the candidate satellites. Here we only consider one candidate satellite, which is the next one following the serving satellite in the same orbital plane.

The UE evaluates the condition criterion that is based on location. For SC-HO, this criterion is to ensure that the UE becomes closer to the TSAT. Hence, it is given by

$$d_{\text{TSAT}}(t) \leq d_{\text{SSAT}}(t) - d_{\text{offset}} \quad (6)$$

where d_{offset} is the distance offset as HO margin. Alternatively, the criterion in the proposed MC-HO is to guarantee that the UE is located inside the multi-coverage area, which can be given as

$$d_{\text{TSAT}}(t) \leq R_b - d_{\text{offset}} \quad \&\& \quad d_{\text{SSAT}}(t) \leq R_b - d_{\text{offset}} \quad (7)$$

where R_b is the radius of the beams.

When the criterion in (7) is satisfied, a random access protocol is started with the TSAT, given that the connection and traffic data are maintained from the SSAT. Note that the satisfaction of (7) activates the packet duplication (PD), where SSAT starts sending the data to the TSAT. This allows the UE to receive copies of the information through both satellites and yields to transmit diversity gain where the best link is selected based on the highest SINR (i.e., selection ratio combining scheme).

The next step is the path-switching procedure, a crucial step in which the TSAT becomes the new MN where the traffic data is routed from the core network. This proactive step prepares for the seamless release of the connection from the SSAT. To achieve this transition, after the successful transmission of the first packet from the TSAT, it sends requests to the access and mobility management function (AMF), including the MN change request. The AMF initiates bearer modification signaling with the user plane function (UPF). Once this modification is completed, the UE context-release procedure is sent to the SSAT. Consequently, the current TSAT becomes the serving SAT (i.e., MN) until the UE enters another overlap area where the procedure is repeated.

IV. Numerical Results and Discussion

This section presents the simulation results and discusses how the proposed MC-HO technique is compared with the SC-HO strategy. Referring to the system model described in Section II, we considered LEO satellites at altitudes of 600 km, and the simulation parameters are summarized in Table 1 following the set-1 configurations specified in [22]. We consider different degrees of overlap between the nearby satellite beams, which specify the inter-satellite distance between the projection centers of the satellites. The percentage of overlap ranges from 0% to 40%. The metrics evaluated here include the average number of HOs for all users per second, the average number of radio link failures (RLFs) per second, and the average system capacity. RLF represents a link outage that occurs when the SINR of the serving satellite drops below -8 dB for 0.5 seconds.

Figure 3 compares the proposed MC-HO method with the traditional SC-HO strategy, with emphasis on the average number of handover operations per second at different beam overlap percentage levels. Both systems used a location-based

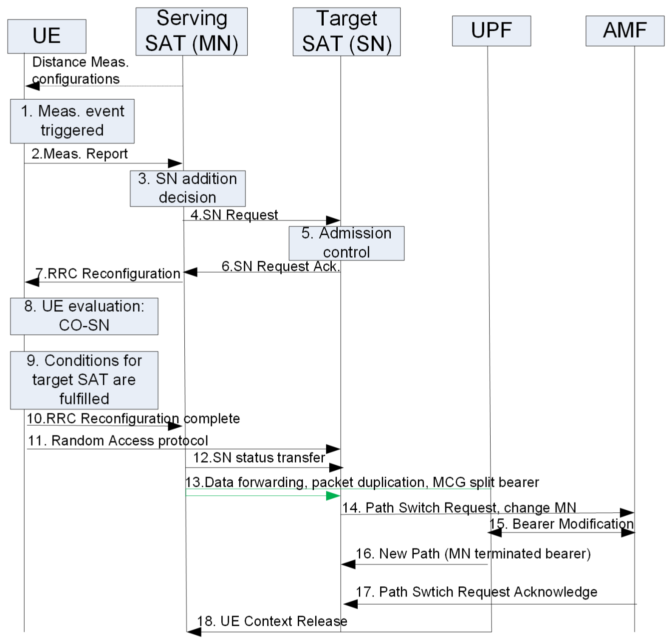

Fig. 2. Proposed handover procedures based on multi-connectivity and location-based CHO.

TABLE I
SIMULATION PARAMETERS.

Parameter	**Value**
Radius of the Earth (R_E)	6371 km
Altitude of LEO satellites (h_0)	600 km
Satellite Tx max Gain	30 dBi
Satellite beam diameter	50 km
EIRP density	34 dBW/MHz
Carrier frequency (f_c)	2 GHz (S-Band)
Bandwidth	30 MHz
Noise power	-121.4 dBm
User density	1 user/km^2
Distance offset	1 km/5 km
Satellite speed	7.56 km/s
Simulation time	200 s
Time step	0.5 s
Deployment scenario	Dense urban
Path loss parameters	Dense urban scenario [22] [6]
Shadow Fading (σ)	Based on elevation angle

CHO with a distance offset of 1 km. The results show that the MC-HO technique significantly minimizes the number of handovers due to the addition of more stability in the overlap area by connecting the UEs to the target satellite while the serving satellite is still transmitting to the UE. Hence, the HO process is delayed until the UE approaches the beam edges of both satellites.

More specifically, at 0% overlap, SC-HO and MC-HO produced the same numbers of handovers, averaging 148 HOs/s. However, as the overlap percentage increased, the benefits of MC-HO became more apparent. At 10% overlap, SC-HO and MC-HO generated 165 and 162 HOs/s, respectively, showing a modest improvement. This trend continued with an overlap 20%, where SC-HO and MC-HO reported 185 and 145 HOs/s, respectively, suggesting a more significant decrease. In particular, the advantages of MC-HO were most evident at higher overlap percentages. For example, with 30% and 40% overlap, SC-HO produced 212 and 247 HOs/s, respectively, while MC-HO obtained much lower values of 129 and 130 HOs/s.

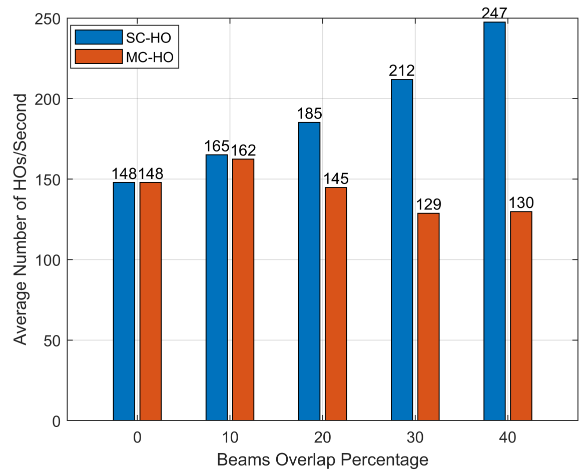

Fig. 3. Average number of handover operations per second from all users at different beam overlap percentage levels.

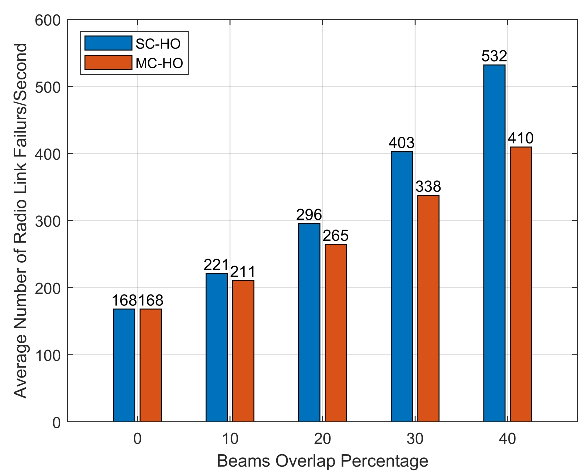

Fig. 4. Average number of radio link failures (RLF) per second from all users at different beam overlap percentage levels.

Figure 4 compares the MC-HO approach with the SC-HO strategy in terms of the average number of failures (RLFs) experienced by all users per second considering different degrees of beam overlap. Both approaches used a location-based CHO with a distance offset of 1 km. In fact, the possibility of link failures is increased at the beam-edge as long as the distance to the serving satellite is increased.
Given that both satellites transmit at the same frequency, the case of no overlap results in less RLF because the users are free of interference. In this case, the MC-HO does not

show any effect because the users have a single channel from one satellite only. However, as the overlap increased, the interference increased, making MC-HO more promising. It minimizes radio connection failures due to the use of transmit diversity through duplication of packets between the serving and the target satellites, and the highest SINR is obtained. In contrast, in the case of SC-HO, the UE is heavily influenced by interference from nearby signals as well as the reduced strength of the received signal from the serving satellite owing to the increased distance (i.e., cell edge user).

More specifically, both SC-HO and MC-HO had an average of 168 failures per second when there was no overlap. However, the advantages of MC-HO became increasingly obvious as the overlap percentage increased. With 10% overlap, SC-HO and MC-HO exhibited little improvement, with 221 and 211 failures per second, respectively. The number of failures per second recorded by SC-HO (296) and MC-HO (265) decreased significantly, with a 20% overlap. The benefits of MC-HO become increasingly evident at higher degrees of overlap, where MC-HO generated 338 and 410 failures per second, but SC-HO produced 403 and 532 failures per second, with 30% and 40% overlap.

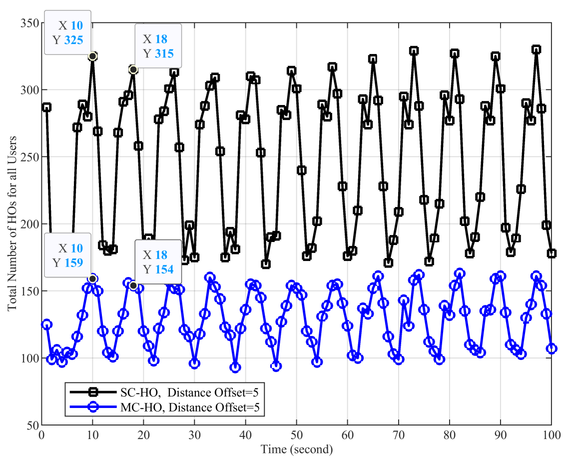

Fig. 5. Total number of HOs for all users over time at 40% beam overlap with a distance offset of 5 km is applied for the HO techniques

Figure 5 shows the total number of HOs for all users over time, comparing the SC-HO and MC-HO approaches with a distance offset of 5 km and a beam overlap of 40%. This data validates earlier findings, demonstrating that the MC-HO methodology minimizes the overall number of HOs compared to the SC-HO method. Throughout the 100-second observation period, the SC-HO approach consistently produced a larger number of handovers, ranging between 150 and 325 HO. In comparison, the MC-HO approach had a significantly lower and more consistent handover rate, ranging from 100 to 159 HOs. Moreover, it can be observed in the figure that a large number of HOs occurred after approximately 7 seconds, which is the duration of covering a specific region. This is because the LEO satellite considered here is at an altitude of 600 km, a speed of 7.56 km/s, and a beam diameter of 50 km. This relatively short stay period requires frequent handovers because the satellite rapidly moves out of the beam coverage region, resulting in an increase in the frequency of handovers. The peaks in the SC-HO graph correspond to situations in which many users demand handovers when they move out of the beam range. In contrast, the MC-HO technique exhibits a more consistent handover performance, implying that it can better manage these quick changes by offering numerous connection possibilities. This MC-HO enables smoother transitions between beams, effectively dispersing the handover burden and minimizing the effects of the satellite's rapid speed and short beam dwell times.

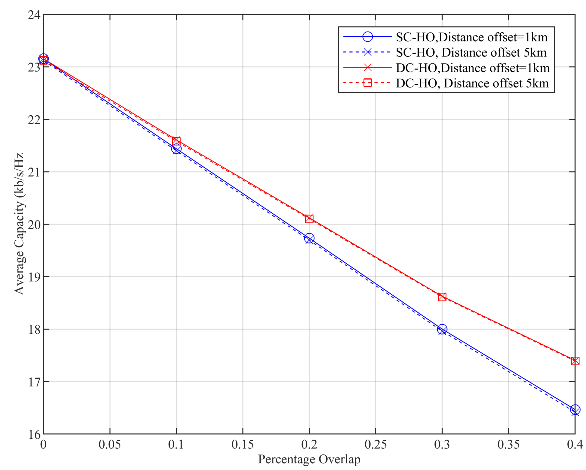

Fig. 6. Average capacity (Mb/s/Hz) versus percentage overlap for SC-HO and DC-HO with distance offsets of 1 km and 5 km.

Figure 6 shows the average capacity versus the percentage overlap for the SC-HO and MC-HO approaches with distance offsets of 1 and 5 km, respectively. As the percentage of overlap increased, the average capacity decreased under all circumstances. This tendency is expected because larger overlap percentages resulted in greater interference and worse spectral efficiency. Moreover, it also shows that increasing distance offset does not have a considerable impact on improving capacity, even though it is important to reduce the occurrence of HOs. Given that the MC-HO approach has shown its ability to minimize the frequency of HO operations and radio connection failures, Figure 6 shows that it retains more capacity than SC-HO. This is owing to the transmit diversity, which improves the SINRs. Hence, it outperforms the SC-HO method in mitigating the negative impacts of interference.

V. Conclusion

In this study, we addressed the mobility challenge of LEO satellites with Earth-moving cells by introducing a multi-connectivity-based handover (HO) (MC-HO) approach. This approach employs location-based trigger criterion with conditional HO. The MC-HO represents a soft-HO , where the

UE is connected to both the master node (MN) (i.e., the serving satellite) and the secondary node (SN) target satellite). The numerical results demonstrate that MC-HO reduces the number of handover operations and minimizes radio link failures, thus reducing the potential for service interruptions. In addition, MC-HO has the advantage of reducing the need to buffer the traffic data at the satellites during the HO process.

While the findings are encouraging, future research should look into other system configurations, such as quasi-Earth fixed beams, higher frequency bands, and larger beam diameters. Also, multi-criteria triggering conditions are a valuable method to investigate, particularly when using the CHO and MC approaches. After meeting the criteria, it is necessary to identify a more accurate scheduler that reduces the need for packet duplication, thereby lowering traffic load and signaling overhead.

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