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RESEARCH ARTICLE

Handover Solutions for 5G Low-Earth Orbit Satellite Networks

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ABSTRACT Low-Earth orbit (LEO) satellite networks are meant to be fundamental to closing the digital divide, enabling new market opportunities and providing fifth-generation (5G) New Radio (NR) connectivity everywhere at any time. Despite the advantages of LEO deployments, these systems are characterized by a high mobility and a challenging propagation channel that compromise several procedures of the current 5G standards. One of the impacted areas is the radio mobility management, which is used to ensure continuous and satisfactory service while users handover among cells. Current research shows that the measurement-based 5G NR handover (HO) procedures, designed for terrestrial networks, fail to ensure optimal mobility performance. In this work, we provide a mobility performance analysis through extensive system-level simulations of state-of-the-art HO procedures for 5G NR over LEO satellite networks with Earth-moving cells. Furthermore, this article presents a novel antenna gain-based HO solution for intra-satellite mobility that exploits the predictability of the satellites movement and the antenna gain of the satellite beams, making user equipment (UE)'s radio measurements obsolete. The system-level simulation results, which consider users in rural and urban scenarios, show that by exploiting the known satellite's trajectory, the UE eliminates service failures and undesired HO events, maximises the time-of-stay in a cell and experiences improved downlink signal-to-interference-plus-noise ratio. This article also includes a sensitivity study of the impact on the mobility performance of satellite-specific and UE-specific errors such as the UE's location error, the satellite beam's antenna radiation error and the satellite's pointing error. Finally, the impact of the UE's mobility is analyzed.

INDEX TERMS 5G systems, new radio, LEO satellites, non-terrestrial networks, mobility, handover.

I. INTRODUCTION

Internet has become something essential for society development and welfare, e.g. nowadays farmers need to be able to search for the best price to buy fertilizer and know when and where to sell their crops. Even though there has been an increase in Internet availability in recent years, a large percentage of the world's population remains unconnected; according to [1], less than 64 % of the population has Internet, which leaves 3 billion people offline. One of the main reasons for Internet access exclusion is the lack of available cellular infrastructure, especially in remote areas, where deploying fiber cable is not cost-effective.

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Satellite technology aims to bridge the digital gap. By its nature, not being geographically constrained, it is ideal to deliver broadband connectivity to any location in the globe. Tens of thousands of satellites have been proposed to be deployed in low-Earth orbit (LEO) orbits - i.e., altitudes between 500 km and 1500 km. The Starlink constellation - backed by SpaceX - is currently authorized to deploy 4408 LEO satellites while the company has already launched more than 2000 and envisions to have approximately 30 000 spacecrafts in orbit [2]. OneWeb's network, in the process of being completed in 2022, is planned to consist of 716 LEO satellites followed by a second phase with 6372 satellites [3]. Kuiper Systems, a subsidiary of Amazon, announced in 2019 a LEO deployment of 3236 satellites at altitudes between 590 km and 630 km [3]. Over the next decade, these three constellations alone envision to comprise more than 40 000 satellite systems into LEO, enabling a new time of space-based broadband services.

This new space race, driven by private companies, and the growth of demand for broadband services [1] have fueled the development of standards for non-terrestrial network (NTN) systems. Initially defined by the 3rd generation partnership project (3GPP) in [4], NTN aims to complement terrestrial networks (TNs) providing fifth generation (5G) and future sixth generation (6G) connectivity to unconnected areas through, among other systems, LEO satellites. Not limited only to provide connectivity in remote areas, NTN seeks to efficiently ensure 5G service availability anytime, anywhere, e.g. for critical communications in case of disaster and emergency, maritime communications and passengers on board of planes.

In contrast with geostationary Earth orbit (GEO) systems, LEO satellites feature high mobility but also reduced path loss, shorter transmission delays and lower production and launch costs. These systems operate in a revolving network at approximately 7.8 km/s relative to the Earth; at this speed a satellite circles the Earth in around 90 min. The movement of LEO satellites and thus signals from the radio access network (RAN) nodes leads to several issues. While in TN the RAN nodes are fixed, in LEO satellite networks, these nodes are constantly moving and triggering a high number of mobility events. Though the frequency of mobility events triggered by the satellite network will depend on the cell size - from 50 km to several hundreds of kilometers [5] -, the increment of these events might lead to an increase of the signalling overhead and potential service failures.

The target of connected-state mobility procedures is to ensure that the UE does not experience noticeable interruption or degradation of the service as it changes connection from one cell to the next one. The mobility procedure that must guarantee this is known as handover (HO). Despite the advantages mentioned above, enabling 5G New Radio (NR) access over LEO satellite networks implies important challenges for the HO procedure. Some of those challenges include high HO frequency rate - which increases the control signalling between the UE and the network (NW) -, long communication distances - which impact path loss, signal strength variation and propagation delays - and multiple high-gain beams radiated from the same satellite - which increases the downlink (DL) interference experienced by the UE. A well-designed HO procedure is required to overcome these mobility challenges and to guarantee service continuity.

A. RELATED WORK

There are research works in the literature addressing the topic of the HO over LEO satellite networks since the 1990s, which were motivated by the appearance of non-geostationary satellite projects such as Iridium and Globalstar constellations [6], [7]. These projects failed since they were not economically viable, launch costs were too high and hardware and software technologies were not mature enough.

In recent years, many companies have renewed the interest of providing ubiquitous Internet from space. A large body of investigations appeared after Starlink and OneWeb projects materialized and after the 3GPP reported in Release-15 the study to integrate satellite systems [4]. In [8], the authors proposed an inter-satellite HO strategy based on the *potential game* theory to reduce the average number of HO events and balance the constellation NW load. To reduce the HO delay and signalling cost, in [9], different HO procedures were proposed for a multi-layer network architecture which included GEO satellites, high altitude platform systems (HAPS) and terrestrial relay nodes. In [10], the authors focused on the inter-satellite HO for massive user terminals in mega-LEO constellations to maximize the quality of experience by establishing a HO model based on network-flows. A user-centric HO scheme for ultra-dense LEO satellite networks was proposed in [11]. The authors presented a solution to buffer user's downlink data in multiple satellites simultaneously to permit the terrestrial users to realize seamless HO and to address the frequent HO problem. In [12], the authors presented a reinforcement learning scheme where UEs make decisions autonomously to optimize the long-term throughput, meanwhile avoiding frequent HO events among non-terrestrial base stations. The above-mentioned proposals address approaches to optimize the HO over NTN, mainly focusing on the HO frequency problem. However, to the best of our knowledge, none of the works in the past literature considered 5G NR technology over NTN complying with the 3GPP specifications.

Based on the 3GPP technical reports [4] and [5] for Release-15 and Release-16, respectively, in [13] we demonstrated through system-level simulations that the conventional UE-assisted NW-controlled 5G NR HO - used in TNs and referred in this article as baseline HO (BHO) - cannot ensure robust service continuity in 5G LEO satellite networks with Earth-moving cells (EMC). Users experience frequent service outages due to a HO that is initiated too late when the serving cell radio link is already too weak to complete the HO process. Under the same scenario, we reported in [14] a mobility performance study of the Release-16 conditional HO (CHO) which accomplishes to eliminate the service failures due to an earlier HO initiation. However, the analysis showed a 60 % increase of unnecessary HO (UHO) events, as compared with the BHO procedure. Both mobility procedures, meant for TNs, strongly rely on UE's radio measurements. The 3GPP suggested in [5] considering additional triggering criteria based on satellite's trajectory and UE's location to enhance mobility performance. In [15], we proposed the location-based HO triggering (LHT) event to exploit the distance information given by UE's location and knowledge of satellite's trajectory. Extensive system-level simulation results proved that the LHT event reduces the signalling overhead, eliminates the service failures and maximises the time-of-stay (ToS) in a cell. The best mobility performance was achieved by the CHO procedure configured to use the LHT event; here referred as location-based CHO

(LCHO) procedure. Despite these works considered 5G NR over LEO satellite networks under 3GPP-compliant assumptions, these HO solutions were only analyzed with users in a rural environment, where radio propagation conditions are more favourable than in urban scenarios due to low and scattered buildings. Furthermore, these HO procedures are based on the reporting of the UE's radio measurements to the NW. Due to UE's radio measurement inaccuracy, this may lead to wrong HO decisions that increase the signalling overhead, which ultimately may compromise the UE's mobility performance.

B. MOTIVATION AND CONTRIBUTIONS

The motivation behind this work stems from the lack of suitable HO solutions to support the development of 5G NR over LEO satellite networks and the need for system-level simulation results to support such solutions. Furthermore, the publicly available works in the literature that meet the latter only address users in rural scenarios. Overall, the novel contributions of this article cover several gaps of the literature and are summarized as follows:

- Discuss the state-of-the-art HO procedures to support 5G LEO satellite networks and the mobility challenges that these procedures shall overcome.
- Propose a novel fully NW-controlled antenna gain-based HO (AGHO) solution for intra-satellite mobility that uses the UE's location, the antenna gain (AG) of the satellite beams and the known satellite's trajectory to avoid UE's radio measurements.
- Based on extensive system-level simulations, provide mobility performance analysis and comparison of the BHO, the CHO, the LCHO and the AGHO over 5G LEO satellite networks for users in rural and urban scenarios.
- Provide a sensitivity study that evaluates the mobility performance impact of UE-specific and satellite-specific errors on the LCHO and the AGHO solutions. The study considers the following sources of error: i) satellite beam antenna radiation, ii) satellite beam antenna steerability and iii) UE's location.

The rest of the paper is organized as follows. Section II describes the reference scenario and the main aspects impacting the HO procedure in LEO satellite networks. Furthermore, the section provides a comparison between terrestrial and LEO deployments, while it identifies the main limitations of measurement-based HO procedures. In Section III, the HO enhancements analysed in this work are explained and compared. The simulation methodology and results from system-level simulation campaigns are then provided in Section IV together with the definition of the key performance indicators (KPIs) used to evaluate the mobility performance of the different HO procedures. Finally, we draw the conclusions of this investigation and formulate recommendations for future research in Section V.

II. CONNECTED-MODE MOBILITY IN LEO SATELLITE NETWORKS

This section first describes the reference scenario, then the main challenges and limitations of the HO procedure over LEO satellite networks are introduced. Finally, the section includes a discussion on the ongoing NTN standardization activities.

A. REFERENCE SCENARIO

Fig. 1 depicts the studied reference scenario where a LEO satellite network, at an altitude of 600 km, provides 5G NR coverage to a sparse number of users on the ground. Satellite systems operate as RAN nodes that through multiple satellite high-gain beams enable NR cells on the ground with a footprint diameter of 50 km. In NTN specifications, Earth-fixed cells (EFC) and EMC are considered. The former entails that the satellite continuously adjusts the satellite beam pointing direction to fix the NR cell to a specific location on the Earth during a certain time period, while the latter option entails the satellite beam pointing direction is fixed and thus the beam footprint (i.e. NR cell) is moving on Earth. This study is carried out considering EMC, which entails highly mobile cells that will cause very frequent HO events. Fig. 1 aims to illustrate this phenomenon where stationary users continuously change serving cell due to cells movement, i.e. frequent HO events. These events can occur among cells from the same satellite, i.e. intra-satellite mobility, and among cells from different satellites, i.e. inter-satellite mobility.

As mentioned before, the connected-state mobility procedure that ensures users switching cells without noticeable service interruption is the HO procedure. The conventional HO procedure used in TNs (i.e. BHO) is based on specific reference radio signals measured by the UE, that are reported to the NW when a certain measurement-based condition is met. In this work, the BHO procedure uses the common measurement-based HO triggering (MHT) event known as NR A3 event, which is triggered when the signal strength of target cell T becomes HO margin (HOM) dB stronger than the signal strength of serving cell S for a certain time called time-to-trigger (TTT). A simplified NR A3 event is given in (1), where $P_S(t)$ and $P_T(t)$ are the reference signal received power (RSRP) measurements (in dBm) from serving cell S and target cell T, respectively. Further details of the NR measurement events can be found in [17].

$$P_T(t) > P_S(t) + \text{HOM} \qquad [\text{dBm}] \quad (1)$$

Once the above condition is met, the UE sends the measurement report (MR) to the NW via the serving cell. Based on the UE's radio measurements contained in the MR, the NW determines whether the target cell is appropriate to access and it commands the UE to initiate the HO towards that cell.

As mentioned above, the main goal of the HO procedure is to guarantee service continuity and, hence, ensure adequate

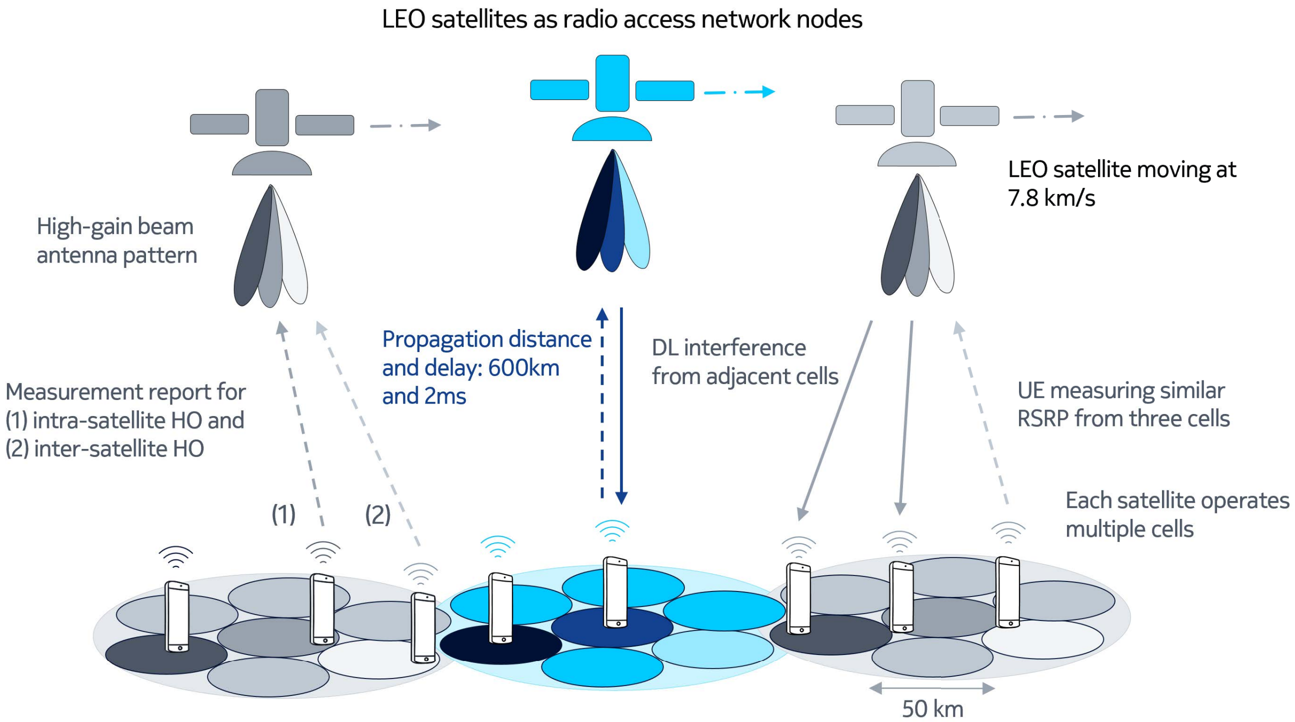


FIGURE 1. LEO satellites as radio access network nodes providing 5G NR service to users on the ground.

user's experience. In LEO satellite networks, the UE's mobility performance is mainly challenged by satellites moving at high speed and altitude, which might lead to a malfunctioning of the measurement-based NR HO procedures. The following section explains the characteristics of the reference scenario and the mobility challenges to overcome in order to design new HO solutions.

B. CHALLENGES AND LIMITATIONS

Below, the main physical differences between a typical terrestrial rural macro deployment and the reference scenario are described. Table 1 provides a summary of this comparison to support the explanation.

The NR HO procedures were designed to efficiently work in terrestrial deployments, where RAN nodes are fixed at altitudes of tens of meters, wireless communication distances are typically shorter than a few kilometers and mobility events are mainly triggered by the UE's mobility. The characteristics of LEO satellite networks are completely different. The reference scenario is characterized by LEO satellites constantly moving at an altitude of 600 km, where mobility events are mainly caused by the movement of satellites as they move much faster than UEs on the ground, approximately 7.8 km/s relative to the Earth (i.e. 28 000 km/h). While the 5G standard supports a maximum distance of 100 km, in LEO deployments the communication distances can escalate up to hundreds or thousands of kilometers. As Table 1 shows, in the reference scenario the maximum communication distance

TABLE 1. Main diifferences between the default values of the 3GPP-specific rural macro deployment in [16] and the reference LEO satellites network evaluated in this work.

Specific	Rural macro deployment	LEO satellites network
Altitude RAN node	35 m	600 km
Maximum distance UE-RAN node	10 km	610 km (79.8° elevation angle)
Maximum propagation delay	0.03 ms	2 ms
Speed of RAN node (relative to Earth)	0 km/h	28 000 km/h
Cell radius	10 km	25 km
Cell visibility time (stationary UE)	∞	3 to 7 s [15]
Cell RSRP variation in LOS (cell centre vs cell edge)	50 dB	3 dB

can be up to 610 km for a 79.8° elevation angle, as compared with the 10 km maximum distance of the rural macro deployment. Such increase in distance involves also an increase of the signal propagation delay; 0.03 s vs. 2 ms. Note that LEO satellite communications feature a propagation delay longer than a transmission slot.

1) LOW RSRP VARIATION AND UE MEASUREMENT ERROR

An important factor to consider is the RSRP variation in a cell. In TNs, there is a clear difference between the RSRP

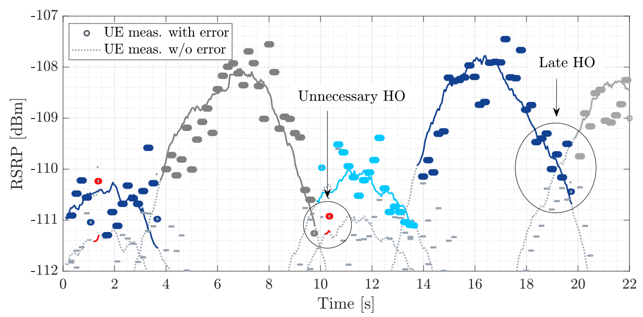


FIGURE 2. Time trace of the RSRP measured by a UE when it is connected to a LEO satellite. There is limited RSRP variation experienced between cell centre and cell edge.

measured at cell centre and at cell edge. Considering the rural case in Table 1, the communication distance ranges from a few tens of meters (i.e. cell centre) up to 10 km (i.e. cell edge). Due to the logarithmic behaviour of radio signals attenuation, the maximum distance difference results in variations of some tens of dBs. This effect is not as pronounced in LEO satellite networks, where the distance between transmitter and receiver is orders of magnitude greater, regardless of the UE's location within the cell. The satellite-user distance can be more than 10 times longer than the cell size. In our reference scenario, the AG of the satellite beams is the main element that introduces changes in the RSRP. This is because the satellite-user distance changes from 600 km at cell centre to 600.5 km at cell edge (for a UE being served by the central satellite beam), which entails hardly any change in the free-space path loss, i.e. 154.03 dB vs. 154.04 dB.

Apart from the low RSRP variation, UEs have associated a certain measurement error. The 3GPP specifies in [18] a relative RSRP accuracy requirement of ± 2 dB to be met at the input of the UE's L3 filter. The combination of these two aspects can challenge UEs to correctly distinguish the appropriate target cell to handover to. In Fig. 2, we depict the RSRP measured by a UE when using the BHO procedure. There is a maximum RSRP variation of 3 dB, where the RSRP ranges from -108 dBm at cell centre to -111 dBm at cell edge. It can be also observed that for some cells the RSRP range is even lower, i.e. approximately -110 to -111 dBm. The figure also shows the impact of the UE's measurement error. Especially in those instants when the UE is in between two cells, the UE cannot complete the HO at the optimal instant (e.g. $t = 19$ s and $t = 20$ s) or it handovers towards the wrong target cell (e.g. $t = 11$ s).

2) HIGH HO FREQUENCY AND UNNECESSARY HO EVENTS

The high frequency of HO events caused by the movement of LEO satellites is more significant in EMC-based networks. For the scenario under study, the best achievable HO rate is an average of approximately 0.2 HO/UE/s. Ergo, the NW should handle per UE roughly a HO every 5 s. The low RSRP range combined with the UE measurement error may further increase the HO rate due to wrong HO decisions. If the number of UHO events significantly increases, the mobility performance and the user experience can be compromised.

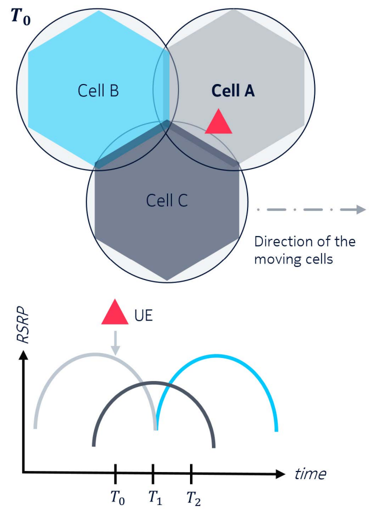
In [15], we discussed that HO procedures only based on UE's radio measurements may limit the mobility performance and increase the number of HO events towards sub-optimal target cells. Fig. 3 exemplifies some of the limitations of these procedures. The figure shows three snapshots of a scenario where a stationary UE (red triangle) is surrounded by three Earth-moving cells: *cell A*, *cell B* and *cell C*. The satellite beams radiate the cells on the ground with a circular shape. The radio coverage of the cells is depicted as an hexagon due to cells overlapping; this produces areas of a few kilometers where UEs detect similar RSRP from serving cell and neighbouring cells. The figure also includes time-traces of the RSRP variations with regards to the UE's location within the cell. In Fig. 3a, the UE is connected to *cell A* and located near the cell centre of *cell A*. As cells move from left to right due to satellite's movement, the radio coverage edge of *cell A* approaches the UE. Fig. 3b shows the UE in cell-edge conditions and located between the three cells. While the UE is in this area, it may continuously trigger measurement-based HO events due to the UE's measurement error and the low RSRP variation among cells. In order to minimize the HO rate and maximise the stay in each cell, it is optimal that the UE stays connected to *cell A* until it is close enough to handover towards *cell B*. However, the UE may connect to *cell C*, causing three undesired events:

- *Cell A→Cell C→Cell B*. Once the UE handovers from *cell A* to *cell C*, it may immediately handover to *cell B*. This results in an UHO event because it increases the signalling and makes a sub-optimal use of the available resources.
- *Cell A→Cell C→Cell A*. As in the previous case, the UE can handover back to *cell A* to immediately handover towards *cell B*.
- *Cell A→Cell C→RLF*. After handovering from *cell A* to *cell C*, the UE may attempt to handover from *cell C* to *cell B* when is too late and then the UE declares a radio link failure (RLF) and goes into idle-mode. If the UE does not execute the HO timely, the serving radio link becomes too weak because the cell moves away and the UE cannot communicate with the serving cell to initiate the HO (see Fig. 3c).

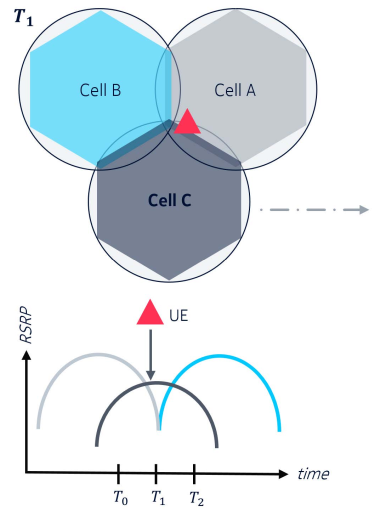
These cases are undesired and avoidable events since they increase the signalling overhead and the UE's energy consumption, lead to longer service interruptions and degrade the overall user experience.

3) LOW DL SINR

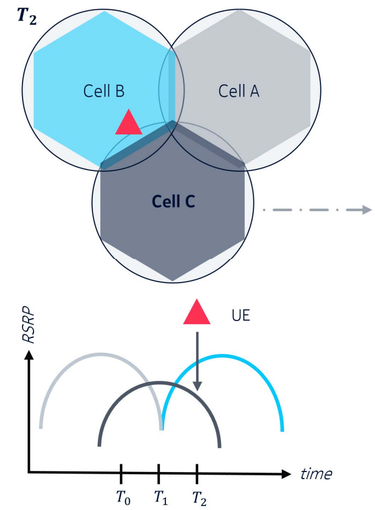
Especially when cells are deployed with a frequency reuse 1 (FR1) scheme (i.e. all cells use the same frequency resources), UEs can experience poor downlink signal-to-interference-plus-noise ratio (DL SINR) conditions when using the BHO procedure. Fig. 4 shows some of the issues of using this HO procedure to motivate the proposal of new HO



(a) UE at T_0: strong radio link with cell A



(b) UE at T_1: handover from cell A to cell C



(c) UE at T_2: radio link with cell C fails

FIGURE 3. Scenario that depicts the detected RSRP over time for a UE being covered by Earth-moving cells.

solutions. The DL SINR traces correspond to a UE impacted by a high DL interference as a result of a single satellite radiating multiple NR cells on the ground. The UE, which is randomly selected, is configured with the BHO under three sets of HO control parameters, i.e. HOM and TTT. The *optimal HO* is also included as an upper-bound of the achievable DL SINR performance (Section IV-D includes further details). None of the traces show values above 1 dB. The best DL SINR performance is achieved when the UE is configured with HOM = 0 dB and TTT = 0 s. However, this HO configuration increases the number of UHO events (e.g. $t = 12$ s). In [14] we discussed that measurement-based HO procedures are limited by such trade-off; improving the DL SINR entails an increase of UHO events. Note that the two other HO configurations present DL SINR values below −10 dB. These low values are a consequence of the inability of the BHO procedure to avoid RLFs, which strongly depend on the radio link quality experienced by the UE. Therefore, the BHO procedure is limited by a low DL SINR that increases RLFs, compromising the service continuity. Furthermore, the HO configuration that improves the DL SINR performance, increases the undesired HOs events.

As discussed above, the BHO procedure was designed to function in terrestrial scenarios, the physical characteristics of which are quite different from LEO deployments (see Table 1). These differences might cause a poor UE's mobility performance when using the BHO procedure. The key issues to address in order to design new HO solutions are summarized in the following points:

- *RSRP*. UEs detect RSRP from serving and neighbouring cells only within a 3 dB margin. If the HO procedure is purely based on UE's radio measurement, the low RSRP variation together with the UE's measurement error may cause to handover towards the wrong target cell.

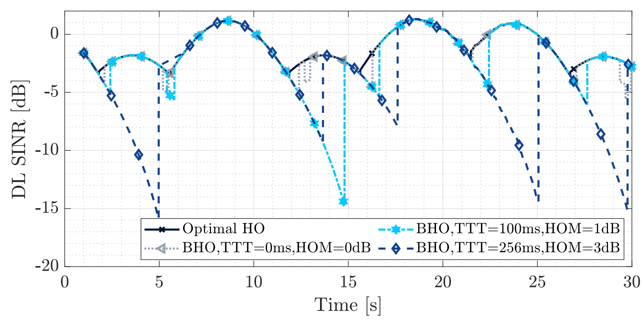


FIGURE 4. Downlink signal-to-interference-plus-noise ratio (DL SINR) as a function of time, experienced by a UE connected through a LEO satellite network. The UE is configured with the baseline HO (BHO) procedure under three HO configurations plus an optimized SINR-based HO procedure (upper-bound reference).

- *HO frequency*. The movement of LEO satellites causes a high number of HO events. We aim to minimize the HO rate and maximize the time spent in each cell because an excess of signalling overhead and measurement reporting can compromise the mobility performance and the user experience.
- *DL SINR*. Serving radio link quality is limited by a strong DL interference from neighbouring cells. This not only impacts the throughput but also the mobility performance if DL SINR falls below a certain threshold, which might cause a RLF.

C. RELATED STANDARDIZATION ACTIVITIES

The 3GPP concluded a study item on NR NTN for Release-16. The outcome, including recommendations on future work, is provided in the technical report [5]. The target was to study the support of 5G NR to users on Earth through GEO, medium-Earth orbit (MEO) and LEO satellites and

HAPS. Each platform may implement multiple beams as NR cells. Among other architecture specifications, two types of payload were accounted: *transparent* and *regenerative*. The latter implies an NTN platform, e.g. LEO satellite, acting as a base station while the former entails a platform as a relay node for base stations on Earth.

In Release-17, the 3GPP introduced for the first time the satellite technology as part of the 5G specifications. The work item in [19] defined the required changes to enable basic operations of NR over NTN in FR1. The main challenges addressed are related to the mobility of the satellites since they introduce frequent changes of serving node and high time and frequency drifts. The work done by the 3GPP focused on GEO and LEO network scenarios with transparent payload, EFC and EMC configurations and UE with global navigation satellite system (GNSS) capabilities. Using its own position and the NTN *ephemeris*, a UE could pre-compensate the Doppler frequency shift, calculate the propagation delay variation between UE and satellite to estimate the full timing advance and benefit from location-based mobility procedures. The CHO procedure was agreed as a mobility procedure for NTN and could include new triggering criteria based on cells location and timing. Even though many companies in the 3GPP proposed mobility enhancements for the CHO based on location and time conditions, there were no system-level simulation results on concrete enhancements to support the discussions.

At the time of writing, 3GPP is investigating enhancements to support NR operations over NTN in the context of Release-18. The new work item [20], started in May of 2022, will support new deployments in frequency bands above 10 GHz, enhance coverage for handset terminals with NW-verified UE location and address mobility and service continuity improvements for TN-NTN and NTN-NTN scenarios.

III. ANALYSED HO ENHANCEMENTS

This section describes three HO enhancements compared to BHO procedure in Section II-A: i) the CHO, ii) the LCHO and iii) the AGHO. Mobility performance evaluations of the CHO and the LCHO procedures are available in [14] and [15] but only for users in rural environments. This work includes a study of the novel AGHO procedure as a fully-network controlled HO strategy based on the estimated AG of the serving and target satellite beams.

A. RELEASE-16 CONDITIONAL HO

In Release-16, the 3GPP specified the CHO procedure to improve the mobility robustness in terrestrial deployments. On this basis, our work in [14] demonstrated that the CHO enhances the UE's mobility performance in LEO-based NTN by reducing the risk of RLF at the expense of increasing UHO events.

The CHO ensures a robust mobility by preparing the HO in advance (with regard to the BHO). The principal difference is that the CHO decouples preparation and execution phases by configuring the UE with up to two triggering event conditions per candidate target cell. The first condition, also called preparation condition, is used by the UE to send the MR to the NW. This condition is triggered early enough to allow the network to reach the UE when the serving cell radio link is still under favourable conditions. The second condition, or execution condition, delays the HO execution and it is used by the UE to initiate the access towards the target cell when the target cell radio link becomes sufficiently good. These two conditions are based on UE's radio measurements. The specification permits to configure different measurements quantities for each of the conditions such as RSRP and reference signal received quality (RSRQ). Furthermore, the CHO may use different NR measurement events such as the NR A3 event, i.e. target cell becomes offset better than serving cell (see Section II-A), and Event A5, i.e. serving cell becomes worse than threshold one and target cell becomes better than threshold two.

Fig. 5 illustrates the operational steps of the CHO procedure according to 3GPP specifications. In Step 1, once the first NR measurement event condition is fulfilled, the UE sends a MR to the serving cell with DL measurement details of the surrounding cells. The serving cell asks for HO preparation to the selected target cell(s) (Step 2-6). The specification allows the preparation of up to eight target cells. For the sake of simplicity, Fig. 5 shows only one target cell. The serving cell sends the CHO command comprising the radio resource control (RRC) reconfiguration information as well as the execution conditions for the prepared target cell(s) (Step 7). The execution conditions are set by the serving cell while the target cells provide the CHO command with the specific cell configuration. After reception of the CHO command, the UE does not immediately initiate the access to the target cell but evaluates the CHO execution condition (Step 8). Unlike BHO, the UE in Step 8 continues exchanging data with the serving cell until a target cell radio signal meets the CHO execution condition (Step 9). After Step 9, the UE executes the HO to access the target cell and the procedure follows as in the BHO. Fig. 5 shows a simplified signalling of the random access procedure and the HO completion since these are not part of the main focus of this paper. Further details about the CHO can be found in [21] and [17].

The main characteristics of the CHO procedure can be summarized as follows:

- *Decoupled HO preparation and HO execution phases*. This enables an earlier HO initiation when the serving cell radio link is in good conditions and delays the execution of the HO towards the target cell when the target cell radio link is strong enough.
- *Up to two HO triggering conditions purely based on UE's radio measurements*. CHO introduces preparation and execution event conditions. These events purely rely on radio measurements, which can limit the UE's mobility performance due to the reasons exposed in Section II-B.
- *Reduced risk of service failure but increased signalling overhead and measurement reporting*. An earlier HO

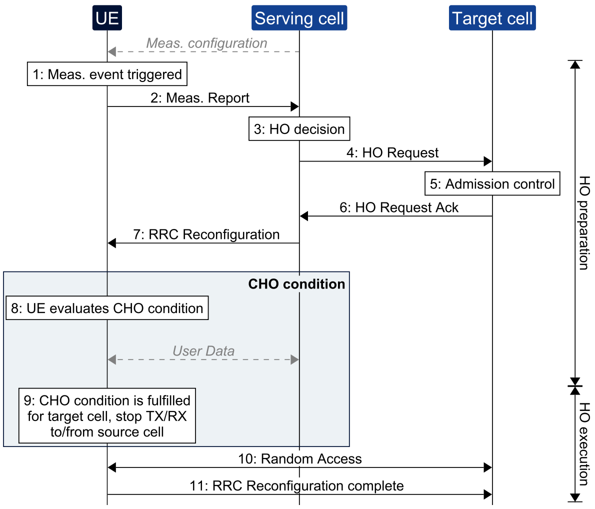


FIGURE 5. Operational steps of the conditional HO (CHO) procedure, including the preparation and the execution conditions.

initiation means a more reactive HO procedure which reduces the probability of RLF declaration but it also increases the amount of UHO events if target cells are not carefully selected.

B. LOCATION-BASED CHO

The BHO and the CHO procedures rely only on UE's radio measurements because of simplicity and effectiveness in TNs. However, in [14], we highlighted the existence of a trade-off between DL SINR and UHO events: DL SINR cannot be improved without increasing the signalling overhead and measurement reporting, which limits the stay in a cell and degrades the user experience.

LEO satellite systems follow orbits that are deterministic. The predictability of satellites movement implies that NW and/or UE may predict the cells radio coverage and exploit that information to optimize the HO procedure. Based on this principle and motivated by the discussions in [5], our work in [15] presented the LHT event, which is a novel HO triggering event that takes advantage of the cells location and UE's location.

The procedure starts with the NW broadcasting the centre locations of the moving cells. Note that in NTN, it is assumed that i) the NW has knowledge of the satellite *ephemeris* information (i.e. positions of the satellites and their orbits) and ii) the UE is aware of its own location. The UE periodically collects the satellite *ephemeris* broadcast by the NW and, together with its GNSS-based location, determines the changes of the UE-cell centre distances. This information is captured in a location-based offset, $\Phi_{S,T}(t)$, which is introduced in the NR measurement events to enhance the HO triggering process. In [15], it is proposed the following modification of the NR A3 event in (1) :

$$P_T(t) > P_S(t) + \text{HOM} + \Phi_{S,T}(t) \qquad [\text{dBm}] \quad (2)$$

where $\Phi_{S,T}(t)$ is the location-based offset (in dB) for the cell-pair S-T.

$$\delta_S(t) = d_S(t) - d_S(t\text{-}\tau) \qquad [\text{m}] \quad (3)$$

$$\delta_T(t) = d_T(t) - d_T(t\text{-}\tau) \qquad [\text{m}] \quad (4)$$

$$\Psi_{S,T}(t) = \frac{\delta_T(t)}{\delta_S(t)} \qquad [\text{dB}] \quad (5)$$

In a similar manner to DL measurements, the UE uses the location information provided by the NW to calculate distance UE-cell S' centre (d_S) and distance UE-cell T's centre (d_T) at periodic intervals τ. In (3) and (4) , the parameters δ_S and δ_T are calculated to capture the movement direction of cells S and T. A positive value of δ_S denotes that cell S is moving away from the UE, while a negative sign indicates that cell S is approaching the UE. The cells movement information given by (3) and (4) is combined to obtain the cell-pair S-T ratio $\Psi_{S,T}$, shown in (5) .

$$\Phi_{S,T}(t) = \begin{cases} \Psi_{S,T}(t) & \text{if } \Delta_S > 0 \text{ and } d_S > \gamma_S \\ & \quad \text{and } d_T < \gamma_T \\ \Theta_P & \text{otherwise} \end{cases} \qquad [\text{dB}] \quad (6)$$

The full definition of the location-based offset $\Phi_{S,T}$, given in (6) , includes the parameters γ_S, γ_T and Θ_P. The purpose of $\Psi_{S,T}$ is to leverage cells movement and prompt the HO towards those cells approaching the UE. In [15], this aspect is referred to as a *reward* strategy and it takes effect when Δ_S is positive - i.e. serving cell S is moving away - and the UE is at the geometrical edge of cell S. Distances d_S and d_T are evaluated against thresholds γ_S and γ_T. The value of γ_S is equal to half of the inter-site distance (ISD) and γ_T is used to prevent UHO events to distant target cells, which can be triggered due to antenna side-lobes when only using UE's radio measurements.

Furthermore, (6) includes the constant Θ_P to *penalize* those candidate target cells that do not meet the conditions imposed by Δ_S, γ_S and γ_T.

According to [15], the LHT event successfully captures the movement of the cells to filter undesired target cells and direct the UE towards the optimal target cells. However, UE's radio measurements are still used to detect the appropriate time for the HO. In [15], BHO and CHO procedures are analysed under three schemes of the LHT event, which depend on the values of $\Phi_{S,T}$ and Θ_P. These schemes aim to *reward*, *penalize* or both, *reward* and *penalize*, the candidate target cells. For this study we use the reported configuration achieving best mobility performance, which corresponds to the CHO procedure set with the *penalty* scheme. We refer to this configuration as the LCHO procedure.

Fig. 6 shows the operational steps to initiate the LCHO procedure. The UE not only measures reference radio signals but also periodically calculates the distances UE-Cell centre using its location and the location of the cells. Once a target cell fulfils the criteria in (6) , the UE sends the MR to the NW to initiate the HO preparation.

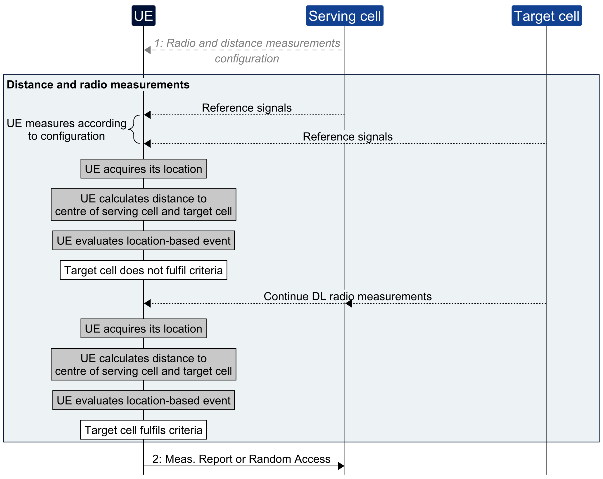


FIGURE 6. **Triggering of the measurement report or access to the target cell when using the location-based CHO (LCHO) procedure.**

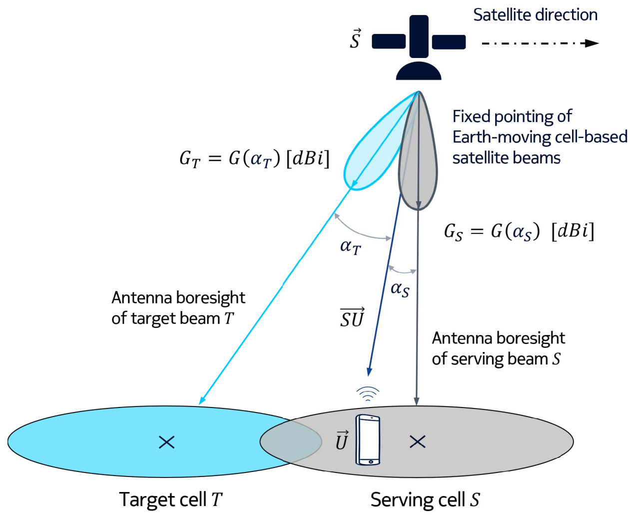


FIGURE 7. **Geometry of the antenna gain-based HO (AGHO) procedure.**

The most important features of the LCHO procedure, captured in [15], are listed below:

- *Enhances the mobility performance of the CHO procedure*. The LCHO accomplishes to eliminate service failures and UHO events and maximises the time in each cell. Thus, it overcomes the trade-off between DL SINR and signalling overhead shown by the CHO procedure.
- *Exploits the predictability of the satellites mobility*. NR measurement events are modified to exploit the deterministic movement of LEO satellites by using the distances between UE and ground centre of the cells.
- *UE's radio measurements are still relevant*. The procedure still relies on UE's radio measurements to detect the appropriate instant to handover towards the target cell. This may also account as a limitation due to UE's measurement error introduced in Section II-B.
- *Additional control signalling*. This procedure relies on the location information reported by the NW. It also involves additional signalling between UE and NW to configure distance measurements in addition to configuration and reporting of UE's radio measurements.

C. ANTENNA GAIN-BASED HO

As pointed above, specifications of the NR HO procedures can be enhanced by exploiting the predictability of the satellites movement. Initial steps were taken in [15], with a HO procedure that involves additional signalling between UE and NW to acquire cells centre and configure distance measurements. However, the procedure still relies on UE's radio measurements.

The usefulness of UE's radio measurements depends on UE's measurement accuracy. Section II-B highlights that the non-negligible measurement error, together with the low RSRP variation (see Table 1), can bring the UE to access the sub-optimal target cell. To overcome this issue, we present a novel fully NW-controlled HO solution that utilizes the AG of the satellite beams to bypass the UE's radio measurements and the effect of the measurement error. This approach is designed for intra-satellite mobility and aims to enhance the UE's mobility performance, while reducing the UE-NW signalling.

The motivation behind using the AGHO procedure stems from the fact that intra-satellite mobility represents a particular scenario where radio propagation conditions - i.e., line-of-sight, path loss and shadow fading - are assumed fully correlated between adjacent cells due to cells being radiated from the same satellite. This might result in a predictable scenario where signal conditions are static between satellite beams belonging to the same satellite. The full correlation of the radio propagation conditions together with the known movement of the cells enables a new space for novel HO solutions where the UE does not need to rely on radio measurements to reliably move among intra-satellite cells.

In the proposed approach, the NW is responsible for estimating the cells radio coverage based on the AG patterns of the satellite beams. Once an estimated target cell's AG becomes better than the serving cell's AG, the NW prepares that target cell and it sends a HO command to the UE. It is assumed that the NW knows the satellite *ephemeris* and the UE's location. In addition, the NW has knowledge of the antenna radiation pattern and the pointing vectors of the satellite beams. The AG of a satellite beam is calculated following the technical report [4], which defines the AG pattern of a typical reflector antenna with circular aperture.

The main elements of the AGHO procedure are described as follows, while Fig. 7 supports the explanation. We define $G(t)$ as the AG of a satellite beam, in dBi, at time t. The position vector of the satellite, relative to the Earth, is defined as $\vec{S}(t)$. The direction vector between satellite's location and UE's location is denoted as $\vec{SU}(t)$. The angle α refers to the angle measured from the bore-sight of a satellite beam's AG to the vector $\vec{SU}(t)$.

Given the serving satellite beam S and the target satellite beam T, the NW estimates gains $G_S(t)$ and $G_T(t)$ at time t

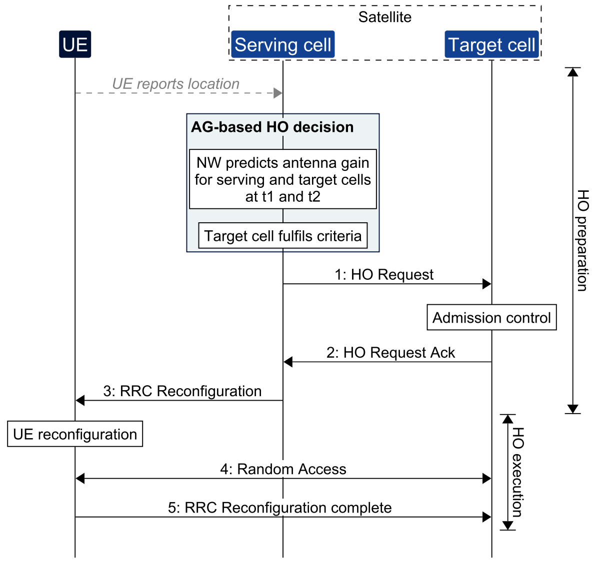


FIGURE 8. Operational steps of the antenna gain-based HO (AGHO) procedure.

based on the known AG patterns and the angle α measured for satellite beams S and T, i.e. α_S and α_T, respectively. The proposed procedure operates estimating $G_S(t)$ and $G_T(t)$ at future instants t_1, t_2. These estimations require predicting future positions of the satellite along the orbit. Note that the estimations of $\vec{S}(t_1)$ and $\vec{S}(t_2)$ are conducted using linear regression from past instants, however, this could be done using orbit propagators or any other estimator.

As shown in Fig. 8, once $G_S(t)$ and $G_T(t)$ are estimated at instants t_1, t_2, the NW evaluates two conditions to carry out the HO decision. The first condition, in (7), is to detect when target cell's AG becomes better than serving cell's AG. The second condition (8) is introduced to avoid undesired handovers by predicting the target cell's AG at t_2, i.e. $G_T(t_2)$, and identify whether $G_T(t_2)$ increases or decreases. If both conditions are fulfilled, the NW, through serving cell S, sends the HO command to the UE with instructions to initiate the access towards target cell T.

$$G_S(t_1) < G_T(t_1) \quad \text{[dBi]} \tag{7}$$
$$G_T(t_1) < G_T(t_2) \quad \text{[dBi]} \tag{8}$$

The key points of the AGHO procedure are the following:

- *Intra-satellite mobility without UE's radio measurements*. The procedure bypasses the non-negligible UE's radio measurement error and captures the crossover point among serving cell's AG and target cells' AG. Based on dual time domain, it avoids short stays in a cell and reduces UHOs events.
- *Reduced control signalling*. Reporting of UE's radio measurements can be reduced or avoided. This is important for satellites with a large number of cells; handling a heavy signalling load might require high-processing capabilities which added to a high HO frequency can compromise the UE's mobility performance.
- *Fully NW-controlled HO procedure*. Even though the NW still requires the reporting of the UE's location, the HO process is no longer assisted with UE's radio measurements. This might lead to a sub-optimal functioning in scenarios with abrupt changes of the radio propagation conditions.
- *Only for intra-satellite mobility*. The proposed solution is valid to handover among cells from the same satellite. However, it requires a different HO solution for inter-satellite mobility where radio propagation conditions are more likely to change from one cell to the next one.

TABLE 2. Summary of the HO procedures evaluated in this work.

HO procedure	Measurement quantity	Initiator	HO triggering condition
BHO	Signal strength	UE	$P_T > P_S + HOM$
CHO	Signal strength	UE	$P_T > P_S + HOM$
LCHO	Signal strength and UE-cell distance	UE	$P_T > P_S + HOM + \Phi_{S,T}$
AGHO	Satellite beam's antenna gain	NW	$G_S(t_1) < G_T(t_1)$, $G_T(t_1) < G_T(t_2)$

D. SUMMARY OF THE ANALYSED HO PROCEDURES

This section has described state-of-the-art HO enhancements to improve the UE's mobility performance of the BHO procedure. Table 7 summarizes the key aspects of the studied HO procedures. The first HO enhancement - i.e. CHO - refers to a mobility procedure fully based on UE's radio measurements which decouples HO preparation and HO execution phases, enabling an earlier HO initiation. Furthermore, it is part of the 5G NR standard since Release-16. The LCHO solution, published in [15], is built on the basis of the NR HO procedures and it modifies the NR measurement events to include location information of the UE and the centres of the cells. It requires minimum changes in the 5G NR specifications and it can be considered a hybrid HO solution since it combines UE's radio measurements and location data. The UE needs GNSS capabilities and knowledge of the cells movement, requiring additional control signalling. Finally, the third HO enhancement - i.e. the AGHO - exploits the predictability of intra-satellite scenarios as well as avoids the non-negligible UE's radio measurement error. The HO is triggered based on geometrical estimations considering that UE's mobility is negligible with regard to the movement of the satellite and that the satellite's trajectory is known by the NW. In this way, the NW does not need the radio measurements reported by the UE to make the HO decision, which reduces the HO control signalling.

The NR HO procedures, that only use UE's radio measurements, might feature sub-optimal mobility performance.

TABLE 3. System-level simulation assumptions.

Parameters	Assumption
Network deployment	LEO network with 7 satellites, 133 cells; 43.3 km of inter-site distance
UE deployment	20 UEs uniformly distributed in rural or urban environments
Channel model	Mobility NTN channel model [22]; shadow fading (σ) 0.3 to 7.4 dB
Carrier configuration	10 MHz bandwidth at 2 GHz (S-Band); FDD; FR1
PHY numerology	15 kHz sub-carrier spacing; 12 subcarriers per PRB
Satellite altitude	600 km
Satellite transmit max gain	30 dBi
Satellite beam antenna	Reflector with circular aperture (pattern in Section 6.4.1 in [4]); equivalent antenna aperture of 2 m; equivalent isotropic radiated power density of 34 dBW/MHz; 3 dB beamwidth of 4.4127°
Satellite beam diameter (on the ground)	50 km
UE transmit power	23 dBm
UE Tx/Rx antenna gain	0 dBi per element
UE noise figure	7 dB
DL/UL receiver type	LMMSE-IRC [5]
Traffic model	Full buffer
Background traffic load	25 % PRBs
Radio Link Failure [17]	Qin: −6 dB, Qout: −8 dB; T310 timer: 1000 ms; N310/N311: 1
UE's measurement error (σ)	1.72 dB [18]
L3 filter coefficient K	4
Simulation time	18 s (252 000 OFDM symbols)

Such limitation can be addressed by exploiting the deterministic movement of LEO satellites either by combining radio measurements and location information or by enabling a clever NW, that detects the correct time to handover to the appropriate target cell.

IV. SYSTEM-LEVEL PERFORMANCE EVALUATION

This section presents the mobility evaluation through system-level simulations of the HO enhancements detailed in Section III. First, the system-level simulation methodology is explained including modelling assumptions, satellite details and 5G NR settings. Then, the definition of the KPIs and the mobility performance results are given. The section closes with a discussion of the main findings.

A. SIMULATION METHODOLOGY

Table 3 contains the main assumptions used to carry out the system-level simulations. Fig. 9 depicts the simulated EMC scenario: a constellation of 7 LEO satellites with on-board gNB capabilities enabling 5G NR access to 20 users on the ground. Every satellite enables 19 NR cells through 19 satellite beams, distributed on the ground in 3 concentric tiers. The antenna of a satellite beam provides a ground coverage diameter of 50 km. Cells on the ground show an approximately ISD of 43.3 km. Satellite radio specifics are set following the assumptions in [5]. The users are static and uniformly distributed within an area of 110 km × 35 km. Since the AGHO procedure is meant for intra-satellite mobility, the users area and the simulation time (i.e. 18 s) are specifically configured to target intra-satellite mobility events (see Fig. 9). The UE's measurement error follows a normal distribution. Radio measurements are filtered by the UE at layer 1 and layer 3 according to [17]. 25 % of the available physical resource blocks (PRBs) per cell are artificially loaded to generate uniform DL interference. Further details of the simulation set-up can be found in [15].

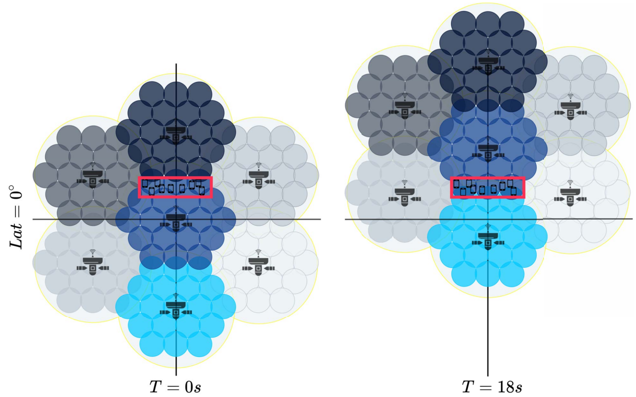


FIGURE 9. Simulation scenario: 20 static UEs are served by 7 LEO satellites operating with Earth-moving cells. Beams with the same colour belong to the same satellite. Sizes of UEs, satellites and beams footprint are not to scale.

Large-scale variations of the radio propagation conditions are modelled using the time-correlated radio propagation model reported in [22], which was designed considering the realistic changes of the propagation conditions in LEO-to-Ground links. Fast fading is not configured because it is assumed that the impact of fast fading is averaged out by UE's filtering.

The system-level simulation results are obtained with a Nokia proprietary simulation tool that models PHY and MAC layers according to NR specifications. The simulation tool offers realistic mobility analysis and it has been used in 3GPP standardization activities, e.g. [23], and research works, e.g. [24]. The simulation methodology follows a Monte Carlo approach [25]. The simulation procedure is repeated 1000 times using each time a different random seed and the simulation results are combined. The users distribution varies each simulation run with this methodology. Note that this is an important factor since the goal of this paper is to analyze UE's mobility performance and, therefore, a large number of mobility events is required.

B. CONFIGURATION OF THE HO SOLUTIONS

Each of the HO procedures is set with its optimal configuration. Table 4 contains the key HO parameters used to assess

TABLE 4. Configured HO control parameters for the evaluated HO solutions in this work.

HO procedure	Optimal HO parameters for the reference scenario
BHO	$HOM = 0\,\text{dB}, TTT = 0\,\text{ms}$
CHO	$HOM = 0\,\text{dB}, TTT = 0\,\text{ms}$ (2nd condition)
LCHO	$HOM = 0\,\text{dB}, TTT = 0\,\text{ms}$, $\Psi_{S,T} = 0\,\text{dB}, \Theta_P = 10^6\text{dB}$, $\gamma_S = 21\,\text{km}, \gamma_T = 30\,\text{km}$
AGHO	$t_1 = 0.3\,\text{s}, t_2 = 1.3\,\text{s}$

the HO solutions. The BHO and the CHO procedures are set with a HOM and a TTT equal to 0 dB and 0 ms, respectively. These values optimize the DL SINR, according to [14]. It is worth mentioning that the modelling of the CHO assumes that the CHO preparation phase is executed free of failures since it takes place when the serving cell radio link is reliable and no outages are expected. Furthermore, the system-level simulator considers any cell as a potential target cell, which means that CHO is executed without applying any filtering at NW side. More details are found in [14].

Regarding the LCHO procedure, the optimal configuration corresponds to the CHO set with the *penalty* scheme of the LHT event, i.e. $\Psi_{S,T} = 0\,\text{dB}$ and $\Theta_P = 10^6$ dB. The thresholds in (6) are set to $\gamma_S = 21$ km and $\gamma_T = 30$ km. The values were chosen considering that the $ISD/2$ is 21.65 km and the cell radius is approximately 25 km. The AGHO procedure is configured with $t_1 = 0.3$ s and $t_2 = 1.3$ s. At least 1 s of guard time is set between t_1 and t_2 to avoid UHO events and ensure that the target cell can provide sufficient time of coverage.

C. KEY PERFORMANCE INDICATORS

The following statistics were collected for this study:

- *Radio link failures* provide important information to evaluate the robustness and reliability of the radio link. A UE declares a RLF when the serving cell signal quality drops below a threshold Q_{out} during *T310* time length. Further details of the RLF mechanism can be found in [17], [23] and [21].
- *Unnecessary Handovers and Ping-pongs*. An UHO event is declared when a user stays connected in a cell for less than a certain period, e.g. 1 s. As a subset of UHOs, ping-pong (PP) events are declared when a user handovers from *cell A* to *cell B* and handovers back to *cell A* within a certain time, e.g. 1 s.
- *Geometric downlink signal-to-interference-plus-noise ratio*, in this article denoted as DL SINR, determines the quality of the received signal. This metric compares the signal strength that the user measures from the serving cell against the sum of interference power from the neighbouring cells and noise.
- *Time-of-stay* metric is defined as the time that a UE stays connected in a serving cell. It is relevant to assess the HO rate and the signalling overhead. The report [23] formally defines the ToS as the duration in *cell A* from when the UE sends a *HO complete* message to *cell A* to when the UE sends a *HO complete* message to another cell.

D. MOBILITY PERFORMANCE RESULTS

In this section we present the mobility performance of the BHO, the CHO, the LCHO and the AGHO solutions, which are tested for users in rural and urban scenarios. We also include the *optimal HO* as a reference of the best achievable performance. This *optimal HO* optimizes the DL SINR considering that the UE always receives the HO command and access the target cell with best DL SINR, at the optimal instant when target cell radio link quality becomes better than the serving cell radio link quality. There is no impact of the UE's measurement error on the *optimal HO*, control signalling propagation delays are correctly compensated and the random access procedure is executed without failures at the optimal time.

The results are organized as follows. First, the mobility performance is evaluated in terms of RLF rate. A high RLF rate indicates UEs experiencing long interruption periods and low DL SINR. Second, the UHO and PP rates provide a picture of the HO signalling overhead and the excess of measurement reporting. Some UEs could avoid RLFs but experience high rates of UHO/PP, which turns into an unnecessary use of resources and reduces the exchange of UE's data. Third, the DL SINR shows the result of the RLF performance. A consequence of reducing RLFs is the improvement of the radio link quality and, therefore, the DL SINR. Fourth, the ToS accounts for the time that a UE stays connected to the same cell. The goal is to minimize UHO and PP rates to maximise the ToS. Finally, we provide the UE-cell centre distance at HO completion time to show how close to the cell edge the UE completes the HO. Note that this metric does not distinguish among desired HO events and UHO events.

The RLF performance of users in rural and urban scenarios is depicted in Fig. 10. For the rural case, the three analysed HO enhancements are capable of eliminating the RLFs. For the urban case, the CHO is the only procedure able to keep the RLF rate close to zero. Nonetheless, the LCHO and the AGHO solutions present a rate of 0.1 operations/UE/min. The small difference is explained by the fact that CHO purely relies on UE's radio measurements and can react effectively to a channel state transition from line-of-sight (LOS) to non line-of-sight (NLOS). In contrast, LCHO and AGHO rely on geometric estimations that overlook the variations of the radio propagation conditions.

Fig. 11 provides the UHO rate and the PP rate. Similarly to the results in [14], the CHO procedure increases more than 70 % the UHO and PP rates, which results in a growth of the measurement reporting and the HO control signalling. The use of UE's location and satellite's pointing information prove to eliminate UHO events as observed for the LCHO and

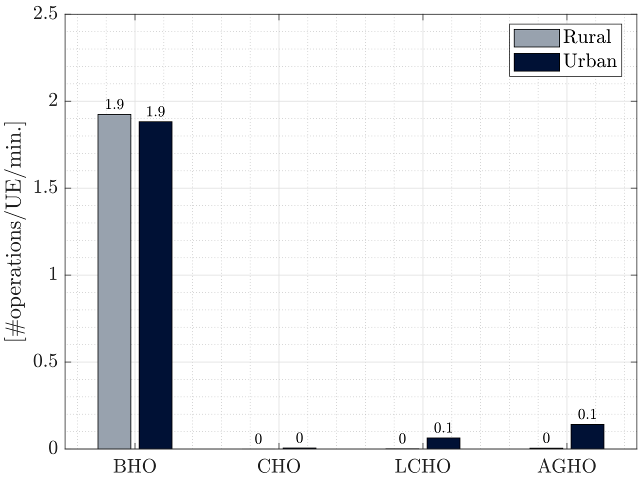


FIGURE 10. Radio link failure (RLF) rates when using the baseline HO (BHO), the conditional HO (CHO), the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) for users in rural and urban environments.

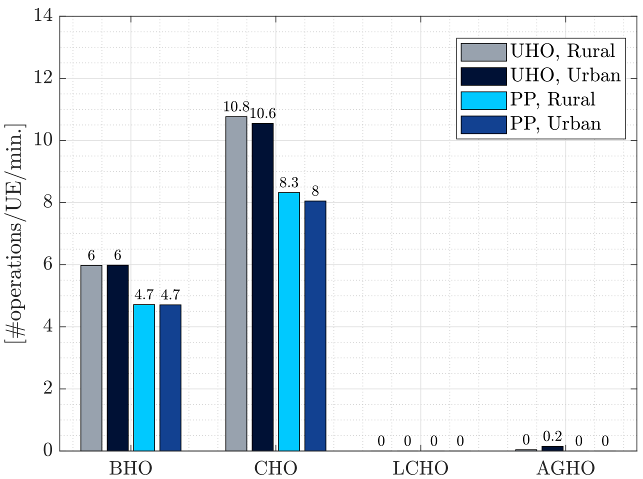


FIGURE 11. Unnecessary HO (UHO) and ping-pong (PP) rates when using the baseline HO (BHO), the conditional HO (CHO), the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) for users in rural and urban environments.

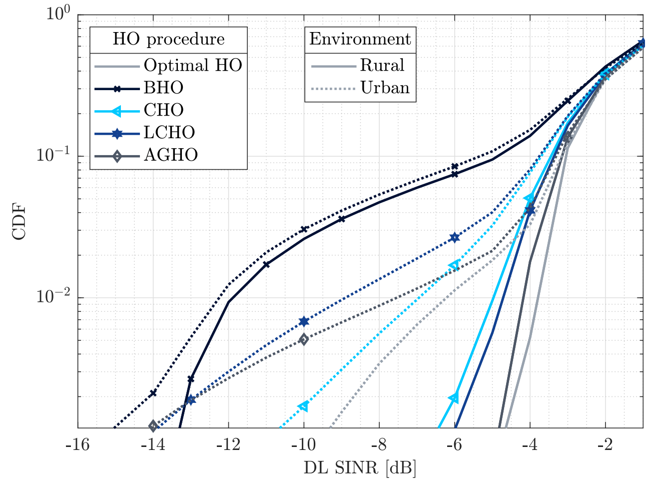


FIGURE 12. CDF of the downlink signal-to-interference-plus-noise ratio (DL SINR) when the optimal HO, the baseline HO (BHO), the conditional HO (CHO), the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) are used. Solid lines represent the performance for users in a rural environment and dotted lines refer to an urban environment.

the AGHO cases. No relevant differences are observed for the different HO procedures under rural and urban conditions.

Fig. 12 shows the cumulative distribution function (CDF) of the DL SINR corresponding to the analysed HO procedures in rural and urban scenarios. All the HO procedures present higher DL SINR values in rural conditions. As indicated in [26], in a rural scenario the likelihood of experiencing LOS conditions is higher as compared with an urban environment, where high-rise buildings might shadow users at higher elevation angles increasing the radio propagation losses. The *optimal HO* provides the upper-bound reference for both scenarios. For the rural case, where UEs are under almost-static LOS conditions, the AGHO shows the closest performance to the optimal, followed by the LCHO and the CHO procedures, respectively. This underlines the benefit of using alternative HO triggering criteria especially when radio conditions are fully-correlated among cells. Note that when urban conditions apply, in terms of DL SINR the CHO is the procedure showing a better robustness against varying LOS conditions.

Without loss of generality, the following performance results are shown only for the rural case. In Fig. 13, the CDF of the ToS is presented. LCHO and AGHO solutions achieve similar performance as compared with the *optimal HO*. As seen above, these two procedures are able to filter out UHO events, which maximises the ToS in the serving cell. Following this reasoning, when using the BHO and the CHO procedures, both with high UHO and PP rates, around 60 % of the stays in a cell are below 3 s. Note that the *optimal HO* shows a ToS performance that falls within a range between 3 s and 7 s, approximately. This provides a magnitude of the HO frequency problem in the reference scenario; even using a flawless HO procedure, a UE executes a HO every 3-7 s.

Finally, Fig. 14 shows the CDF of the distance between the UE and the serving cell's centre at HO completion. The figure includes, in light grey, the overlapping area among cells that ranges from at least $ISD/2$ - i.e. 21.65 km - to the cell radius - i.e. 25 km. These results do not consider neither the impact of radio impairments such as the UE's measurement error nor the access to an undesired target cell. However, they provide a concise overview of where the HO takes place in the cell. The *optimal HO* shows that the benchmark distance ranges from 20.5 km to 24 km. The AGHO procedure follows a similar trend to the optimal but around 2 km before. Note that this can be explained since this procedure initiates the HO based on predictions at future times t_1 and t_2 (see Section III-C). This suggests that the AGHO may be triggered shortly before the optimal time. For this evaluation, t_1 is equal to 0.3 s. Considering that the satellites moves at a speed of 7.8 km/s, this translates into a shift on the ground of 2.34 km, which

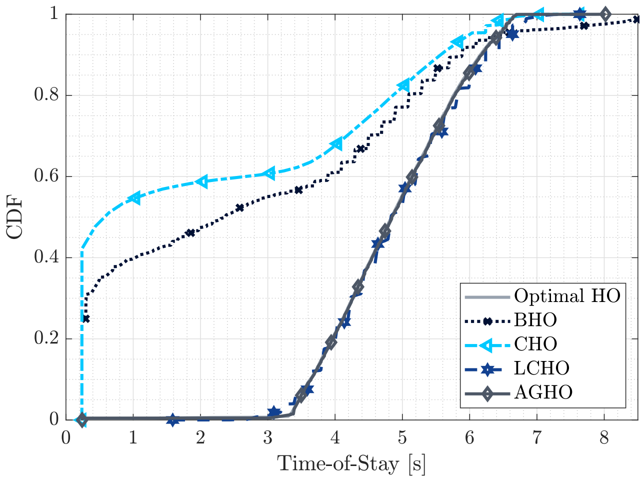


FIGURE 13. CDF of the time-of-stay (ToS) when the optimal HO, the baseline HO (BHO), the conditional HO (CHO), the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) are used in a rural environment.

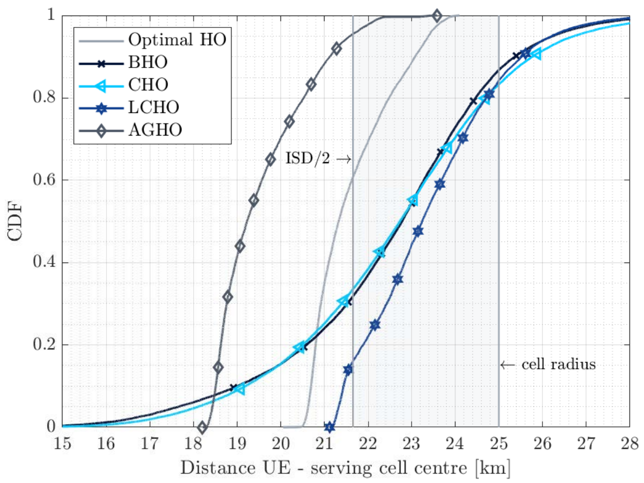


FIGURE 14. CDF of the distance UE-serving cell centre at HO completion time when the optimal HO, the baseline HO (BHO), the conditional HO (CHO), the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) are used in a rural environment.

fits with the observed in Fig. 14. It is also worth highlighting the difference among purely measurement-based procedures and geometry-based procedures, likely due to the combined impact of the UE's measurement error and the low RSRP difference between cell centre and cell edge (i.e. approximately 3 dB). The BHO and the CHO show 20 % of the HO events occurring at distances between 15 km and 20.5 km, which can be linked to the high amount of UHO/PP events seen in Fig. 11.

E. SENSITIVITY ANALYSIS

Results shown above were obtained following the 3GPP specifications in [5], which contains realistic assumptions for system-level simulations with non-terrestrial systems. Despite the 3GPP reported the importance of using location-based HO triggering criteria, none of these assumptions considered inaccuracies in the location neither from the UEs nor the satellites. This section further analyses the robustness of those HO solutions that exploit location data. We investigate the impact of errors that could deteriorate the accuracy of the location data and degrade the UE's mobility performance.

Apart from UE's radio measurements, the LCHO procedure uses the UE's location, the satellite's position and the steering angles of the beams to estimate the centre of the cells. On the other hand, the AGHO solution also exploits UE's location and satellite's attitude besides the antenna radiation pattern of the satellite beams (see Section III). Similarly as with radio measurements, these data sources could have associated a certain error that may alter the performance of the HO solutions.

To study the sensitivity of these error sources, a normally distributed error is introduced in the UE's location, the satellite's pointing accuracy and the satellite beam's antenna radiation. These errors are time-invariant and differ among UEs, satellites and satellite beams, respectively. We conduct 1000 simulations varying the pseudo-random seed to ensure a sufficiently large number of samples. The outputs from all the realizations are later combined following a Monte Carlo approach to obtain statistically reliable results.

Five cases per HO procedure are considered to study the individual and the overall impact of these errors. The first case is the benchmark where no errors are considered. Second, we introduce a UE's location error with a σ of 150 m. The 3GPP required in [27] a nominal positioning accuracy of 30 m in ideal conditions. The value for this study is set according to a worst case scenario where UEs do not feature GNSS coverage or the location is outdated due to, for example, UE's mobility. The third case covers a satellite's pointing inaccuracy of 0.35° (σ). This error translates into a shift of 3 km on the ground. The value is selected according to [28], which provides details of the Iridium's attitude, control and determination system. It is a low-accuracy case scenario since current attitude systems of LEO satellites feature more precise pointing control accuracy [2]. Fourth, an error in the antenna's radiation is introduced where the σ is equal to 0.5 dB. We set a value higher than what can be found in the literature, e.g. [29]. Finally, the fifth case shows the impact of all the aforementioned errors combined.

Table 5 presents a summary of the main findings. There are minor differences in terms of DL SINR and HO distance but, overall, no relevant impact can be observed on the mobility performance, regardless of the HO procedure or the error. It is worth underlining that only the rural environment was taken into account for this part of the investigation.

F. UE's MOBILITY

Mobility performance has been typically impacted by UE's mobility in TNs [24]. Users have different speeds which can impact RSRP, communication latency and HO rate as they move. Despite the 5G specifications support UE speeds up to 500 km/h [30], in LEO satellite networks the mobility performance is dominated by satellites movement since they move much faster, i.e. 28 000 km/h.

TABLE 5. Summary of the impact of the satellite beam's antenna radiation error, the UE's location error and the satellite's control pointing error in a rural environment.

Error source	Error [σ]	RLF [#op./UE/min]	UHO [#op./UE/min]	DL SINR 5^{th} percentile [dB]	Mean ToS [s]	Mean HO UE-cell distance [km]
			LCHO / AGHO			
None	-	0.0 / 0.0	0.0 / 0.0	-3.9 / -3.7	4.9 / 4.9	23.4 / 19.6
Antenna gain	0.5 dB	0.0 / 0.0	0.0 / 0.1	-3.9 / -3.9	4.9 / 4.9	23.4 / 19.6
UE location	150 m	0.0 / 0.1	0.0 / 0.0	-4.0 / -3.9	4.9 / 4.9	23.7 / 19.6
Satellite pointing	0.35°	0.0 / 0.0	0.0 / 0.0	-4.3 / -3.8	4.9 / 4.9	24.4 / 20.1
Antenna gain, UE location, Satellite pointing	0.5 dB, 150 m, 0.35°	0.0 / 0.1	0.0 / 0.1	-4.3 / -4.2	4.9 / 4.9	24.6 / 20.1

TABLE 6. Impact of the UE's mobility in terms of radio link failures (RLFs) and unnecessary HO (UHOs) when using the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) procedures.

HO Procedure	UE mobility [km/h]	RLF [#op./UE/min]	UHO [#op./UE/min]
LCHO	3	0.0	0.0
	30	0.0	0.0
	500	0.0	0.0
AGHO	3	0.0	0.1
	30	0.0	0.0
	500	0.0	0.1

We validate this assumption by analysing the mobility performance of users at 3, 30 and 500 km/h in a rural environment using the LCHO and the AGHO procedures. The RLF and the UHO rates, for the mentioned UE speeds and HO procedures, are provided in Table 6. The system-level simulation results confirm that UE's mobility has no relevant impact on the UE's mobility performance.

G. SUMMARY OF THE RESULTS AND DISCUSSION

Using extensive system-level simulations, this section has presented and analysed the UE's mobility performance of the BHO, the CHO, the LCHO and the novel AGHO solutions for EMC-based 5G LEO satellite networks. Furthermore, this paper contributes with a mobility analysis that considers UEs under rural and urban radio propagation conditions. The system-level simulation results support that measurement-based HO procedures require location information such as exploiting the known satellite trajectory and the UE's location.

Table 7 provides a summary of the main findings of this investigation. It is clear that LCHO and AGHO are the HO procedures achieving a mobility performance closer to the optimal. This underlines the relevance of using location data to select the appropriate target cell to handover to. Both solutions show similar performance in all the analysed KPIs. There are small differences in the distance UE-serving cell centre and the signalling load. The later intends to capture the measurement reporting and HO signalling load and is estimated considering the required signalling steps, the NR A3 event rate and the successful HO rate. Despite the AGHO shows the same signalling load as the optimal and a 25 % decrease as compared with the LCHO procedure, we consider the LCHO procedure a more suitable HO solution. This HO solution has a minimum impact on the 5G NR specifications, allows the UE to evaluate radio signal conditions and exploits the predictability of the satellites movement. Even though the AGHO has the advantage to avoid UE's radio measurements, the procedure is designed for intra-satellite mobility with continuous LOS conditions. The LCHO procedure can be used in intra-satellite and inter-satellite mobility and it is a more robust HO solution in scenarios characterized by abrupt RSRP changes, e.g. LOS to NLOS conditions.

As in TN, the environment surrounding the UE plays a part on the UE's mobility performance and the user experience. A UE in a rural environment with sparse and low clutter is likely to experience LOS conditions for longer periods since the probability of NLOS increases just for the lower elevation angles. On the other hand, urban scenarios are characterized by tall buildings, street canyons and, in essence, a shorter range of elevation angles with LOS conditions. Thus, it is important to evaluate the UE's mobility performance in rural and urban conditions to support the development of 5G LEO satellite networks. This article has contributed with novel system-level simulation results for users in rural and urban environments. With the simulation methodology used, there are no relevant differences in the results between both scenarios. This could be explained since the UE experiences a short range of elevation angles, i.e. from 79° to 101°. The used cell diameter, i.e. 50 km, combined with a low number of cells per satellite, i.e. 19, results in a satellite coverage with an approximate radius of 112 km. Considering that satellite altitude is 600 km, a UE at the edge of the satellite coverage will see a minimum elevation angle of 79.4°.

Despite the limited mobility performance differences comparing rural and urban environments, the magnitude of the mobility challenges is satellite deployment dependent. This means that the limitations of the HO procedures used in NTN

TABLE 7. Summary of the UE's mobility performance in rural and urban scenarios when using the baseline HO (BHO), the conditional HO (CHO), the location-based CHO (LCHO) and the antenna gain-based HO (AGHO) procedures. The optimal HO is included as the upper-bound performance.

HO procedure	RLF [#op./UE/min]	UHO [#op./UE/min]	DL SINR 5^{th} percentile [dB]	Mean ToS [s]	HO signalling load [#op./UE/min]
			Rural / Urban		
Optimal HO	0.0 / 0.0	0.0 / 0.1	-3.6 / -3.8	4.9 / 4.9	23.5 / 22.4
BHO	1.9 / 1.9	6.0 / 6.0	-7.8 / -8.3	2.8 / 2.7	75.4 / 73.8
CHO	0.0 / 0.0	10.8 / 10.6	-4.0 / -4.6	2.3 / 2.2	96.7 / 94.4
LCHO	0.0 / 0.1	0.0 / 0.0	-3.9 / -4.8	4.9 / 4.9	49.0 / 46.8
AGHO	0.0 / 0.1	0.0 / 0.2	-3.7 / -3.9	4.9 / 4.9	35.5 / 33.7

will change based on cell size, constellation configuration or steerability of the satellite antennas. For instance, the scenario simulated in this paper consider a LEO satellite formation, distributed in 3 polar orbits, near the equator. As satellites move to larger latitudes, e.g. near polar regions, LEO satellites will be closer to each other due to orbital propagation, which might result in more frequent HO events and higher inter-satellite interference. Thus, the UE's mobility performance can vary depending on the UE's location and the satellite formation, e.g. inclination of the satellite orbits.

V. CONCLUSION AND FUTURE RESEARCH

This article has provided a realistic system-level simulation analysis of the UE's mobility performance when using state-of-the-art handover solutions for 5G-based low-Earth orbit satellite networks. The study aims to support the development of non-terrestrial networks, thus, the simulation methodology follows 3GPP specifications and considers low-Earth orbit satellites with on-board gNB capabilities and Earth-moving cells. The baseline 5G NR handover, the 5G NR conditional handover, the location-based conditional handover and the novel antenna gain-based handover have been analyzed considering users in rural and urban environments. The antenna gain-based handover, which is a fully network-controlled handover procedure for intra-satellite mobility, exploits the known satellite's trajectory and the UE's location to avoid UE's radio measurements and, therefore, bypass the non-negligible impact of the UE's measurement error. The system-level simulation results indicated that the location-based conditional handover and the antenna gain-based handover achieved the best mobility performance, regardless of the user environment. Both procedures enhanced the handover triggering and the handover decision by eliminating radio link failures, unnecessary handovers, ping-pongs and, consequently, presented a downlink signal-to-interference-plus-noise ratio and a time-of-stay in a cell close to the optimal. Thus, the use of UE's location and satellite's movement information enhances the UE's mobility performance as compared with measurement-based handover procedures. Finally, we have presented a sensitivity analysis addressing UE-specific and satellite-specific errors that could impact the mobility performance. The system-level simulation results demonstrated that the location-based conditional handover and the antenna gain-based handover are robust against UE's location error, satellite's pointing error and satellite antenna's radiation error.

For future research directions in the field of handover procedures for low-Earth orbit satellite networks, it is worth investigating the performance of inter-satellite mobility procedures that, while exploiting the deterministic movement of these satellites, are also able to seamlessly react to abrupt changes of the received signal power due to variations of the line-of-sight conditions. Furthermore, future work should also involve the study of the proposed handover solutions under different satellite configurations such as Earth-fixed cells. The vision for future research in handover solutions should focus on developing versatile procedures able to provide robust service continuity regardless of UE's radio capabilities, constellation deployment and satellite payload characteristics.

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