5G New Radio Mobility Performance in LEO-based Non-Terrestrial Networks

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***Abstract*—As part of 3GPP standardization work for Release 17, non-terrestrial networks (NTNs) aim to bring 5G New Radio (NR) communications to unserved and isolated areas. Constellations of low Earth orbit (LEO) satellites have emerged as a promising asset for NTNs and a key enabler technology to provide truly seamless and ubiquitous connectivity through 5G. Varying and longer propagation delays compared to terrestrial networks, limited radio link budget and the inherent high-speed movement of LEO satellites introduce new challenges in the mobility management procedures. To guarantee robust service continuity and satisfactory user experience, the handover (HO) procedure in LEO satellite systems is critical. Motivated by this fact, this paper presents a first performance analysis of the conventional 5G NR HO algorithm in a LEO-based NTN deployment. We provide system-level simulations obtained for different values of HO margin and time-to-trigger. Furthermore, we compare the HO performance in NTN with two 3GPP terrestrial scenarios - urban macro and high-speed train. The simulation results show HO failures and radio link failures are a factor 10 higher for the NTN scenario, while the corresponding time in outage is 5 times longer. Finally, we analyze the key issues and suggest potential mobility enhancements.**

I. Introduction

The massive growth and demand for wireless technologies led towards the definition of a new standard known as 5G New Radio (NR). Future services such as the Internet of Things, e-Health and Industry 4.0 will play a fundamental role in the global society and economy [1]. The 5G technology sets a milestone for a technological revolution that aims to meet challenging requirements such as ultra-high reliability and global and seamless connectivity [2]. Nonetheless, according to [3], still an estimated $53\,\%$ of the world's population remains unconnected to the internet. To this end, the integration of satellite and terrestrial networks is crucial for the realization of a global and heterogeneous 5G network.

In previous mobile network generations, the integration of satellite communications was based on proprietary tailored solutions. Even when integrated solutions were addressed, the satellite network was mainly used to provide backhaul as a non-flexible and expensive transport network [4].

The definition of the 5G standard in Rel-15 and the emergence of a new space market [5] increased the interest and participation in 3GPP activities from the satellite communications industry. As a result, current 3GPP standardization efforts focus on the development of non-terrestrial networks (NTNs), where companies and organizations are convinced of the market potential. Proof of this is the completion of two study items [6] [7] as part of 3GPP Rel-16 and the work item [8] recently approved for Rel-17.

Low Earth orbit (LEO) satellites might become a key component for the realization of a communication network providing worldwide coverage and ubiquity. Unlike geostationary orbits, the use of lower orbits - from $600\,\mathrm{km}$ to $1200\,\mathrm{km}$ - allows to cut down the propagation delay, improve the radio link budget and reduce the deployment and manufacturing costs. However, LEO satellites have smaller coverage footprints and move at a very high speed relative to Earth, e.g. $7.5\,\mathrm{km/s}$ for an altitude of $600\,\mathrm{km}$. Thus, LEO systems require dense satellite constellations to guarantee continuous coverage. Commercial missions such as SpaceX's Starlink, OneWeb and Telesat were the first movers in a space market aiming to establish global networks through constellations [5].

To enable 5G through LEO satellite networks, mobility mechanisms play a key role in ensuring service continuity and a satisfactory user performance. Communication distances up to 10 times longer than in terrestrial networks, imply longer propagation delays and higher path loss. These factors, together with the satellite movement and a high downlink interference from adjacent satellite beams, might lead to a possible malfunctioning of the handover (HO) procedure, requiring enhancements.

Despite the technical report [7] discussed mobility challenges, no simulation results were provided to support the discussion. In this paper, we present, to the best of our knowledge, the first publicly available system-level simulations of the conventional 5G NR HO algorithm performance in a LEO-based NTN scenario. In a first phase, the conventional 5G NR HO is assessed under different design settings - HO margin (HOM) and time-to-trigger (TTT) - to identify the configuration achieving the best performance. In a second phase, the obtained mobility key performance indicators (KPIs) are compared against two 3GPP-compliant terrestrial environments - urban macro (UMa) and high-speed train (HST).

The remainder of the paper is structured as follows: Section II introduces the NTN concept within the 3GPP context and Section III describes the mobility issues in LEO-based NTN. Methodology and simulation results are found in Section IV and V, respectively. Section VI discusses the results, while Section VII presents potential mobility enhancements. Final conclusions are drawn in Section VIII.

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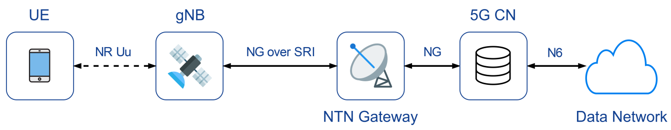
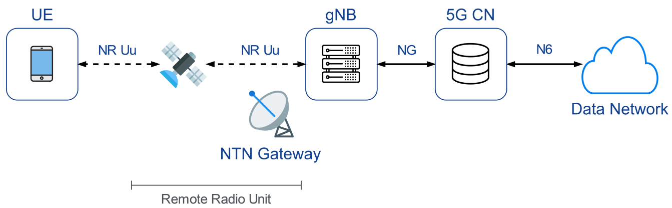


(a) Regenerative satellite payload



(b) Transparent satellite payload

Fig. 1: NTN architectures in 3GPP.

II. Non-Terrestrial Networks in 3GPP

NTNs refer to networks operating through air/spaceborne vehicles aiming to provide 5G service in unserved remote areas where the terrestrial service is not available or it is too costly to build the infrastructure. Apart from providing global service availability, it will reinforce service reliability by providing service continuity for moving platforms such as aircraft and ships as well as enabling 5G network scalability by providing multicast and broadcast resources. Initial steps were taken by 3GPP in Rel-15, where the use of satellite systems to provide global coverage was introduced. As part of Rel-16, the study items reported in [6] and [7], provided a description of the envisioned concept defining the deployment scenarios, the key potential impacts in NR as well as the challenges to tackle. Based on the outcomes of the mentioned study items, Rel-17 work item [8] aims to continue addressing new solutions and specify the enhancements identified to support NTNs for NR.

3GPP addresses not only LEO and geostationary satellites but also high altitude platforms covering altitudes from $8\,\mathrm{km}$ to $35\,786\,\mathrm{km}$. Two payload implementations are conceptualized for these platforms: transparent and regenerative [6]. In the transparent architecture, satellites work as a relay node between the user equipment (UE) and the gNB on the ground, whereas regenerative satellites embark a payload with gNB capabilities. Fig. 1 depicts the main differences between these two architectures.

III. NR Mobility in LEO-based NTN

In terrestrial networks, mobility management focuses on ensuring the service continuity for users moving in deployments with fixed cells. LEO-based NTN overturns the mobility paradigm. LEO satellites will operate as high-speed moving cells providing 5G connectivity to UEs on the ground. The satellite movement together with the long communication distances will not only trigger additional mobility events, it will challenge the UE's mobility performance.

One of the challenges of LEO-based NTN is to handle frequent HOs without resulting in an increased number of radio link failures (RLFs), HO failures (HOFs) and ping-pongs (PPs) [9]. Nonetheless, frequent mobility events are not the only driving factor. 5G NR was designed for terrestrial communications with relatively short cell-to-UE distances (i.e., a maximum distance of $300\,\mathrm{km}$). In LEO-based NTN, communication distances can reach up to $3131\,\mathrm{km}$ involving a round trip delay of $20.89\,\mathrm{ms}$ for a satellite at $1200\,\mathrm{km}$ altitude and $10°$ elevation angle. This fact has a direct impact on the link budget and the HO latency. Furthermore, the HO latency varies depending on the implemented architecture and whether HO is executed among cells of the same satellite or they belong to different satellites. Longer propagation delays can lead to outdated UE measurements, late HO decisions and, ultimately, a failure in the HO procedure. Therefore, propagation delays, fast cell mobility and a constrained link budget must be considered in the design of an optimal HO mechanism.

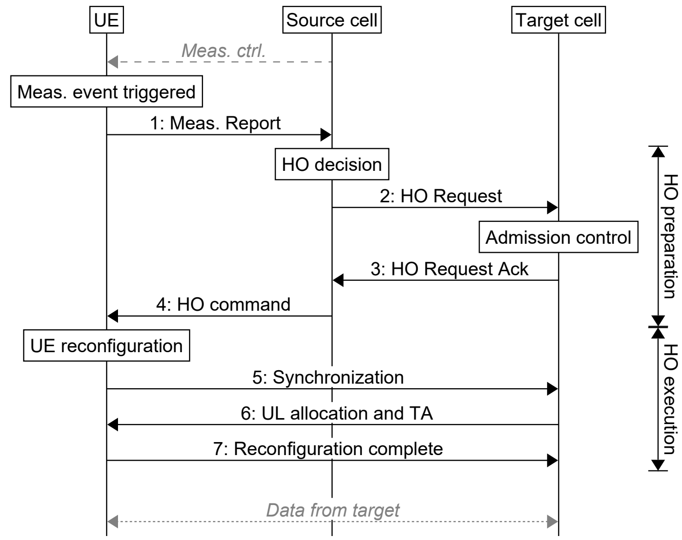


Fig. 2: Conventional UE-assisted network-controlled HO procedure.

A. Conventional Handover mechanism

The HO mechanism is designed to enable users to move from one cell to another while guaranteeing the service connectivity without noticeable service interruption. In NR, as Fig. 2 introduces, the conventional HO algorithm implements a UE-assisted, network controlled break-before-make scheme. Such scheme means that the UE experiences a certain interruption time after disconnecting from the serving cell and until the new connection with the target cell is established. The procedure uses specific downlink channel measurements performed by the UE. If certain conditions configured by the network are fulfilled, the UE sends a measurement report (MR) to the serving cell. With this information, the serving cell decides if the UE needs to be handed over to a new cell and starts the HO preparation phase. During this phase, the serving cell requests the target cell to prepare the resources to allocate the UE. Once the target cell acknowledges the UE to be handed over, the HO execution starts and the UE releases its connection with the serving cell. Then, the UE proceeds to access the target cell via the random access channel (RACH). Upon successful synchronization with the new cell, the HO is completed with a confirmation notification from the UE to the network.

The HO algorithm has been thoroughly designed to provide the best performance in terrestrial scenarios. Besides, it can be tuned according to the requirements of the network. Factors such as UE speed, radio network deployment, propagation conditions and system load are considered during the configuration of the HO. To this end, the network signals the UE with a set of HO parameters - among them there are the HOM and the TTT [10]. Furthermore, different events define the criteria for MR triggering [10]. A commonly used trigger is the NR event A3. Based upon reference signal received power (RSRP) measurements, the event A3 is triggered when the RSRP of a neighbouring cell becomes HOM dB better than the RSRP of the serving cell for a period of TTT ms.

The HO configuration needs the suitable adjustments of its control parameters to achieve optimal performance. Several mobility related KPIs are defined by 3GPP to evaluate the mobility performance [9]. The following section presents the KPIs used in this paper to conduct the HO study.

B. Mobility Key Performance Indicators

The following statistics have been collected in the course of our simulations:

- Geometric downlink signal-to-interference-plus-noise ratio (DL SINR) as a function of time [dB].
- Number of RLF events per UE over time [RLF/UE/s]. A RLF event is declared after N310 consecutive out-of-sync indications (e.g., SINR below -8dB) and expiration of timer T310 [10].
- HOF rate defined as the total number of HO failures relative to the total number of HO attempts. A HOF is counted if a RLF occurs after event A3 entering condition is satisfied but before the UE receives the HO command or a downlink control channel failure is detected after event A3 entering condition but before HO completion.
- PP rate [%]. A PP event is declared when a UE experiences a HO from cell A to B and handovers back to cell A within ping-pong-time (1 sec). The PP rate is defined as the number of PP relative to the total number of successful HO.
- Average time in outage [%] defined as the ratio between the total time in outage (i.e., interruption time during HO, HOF and radio link problems) and the total service time.

A wrong choice of HO settings can lead to unnecessary HO (i.e., PP effect), HOFs and RLFs. On the one hand, a growth in number of PPs comes with a signalling overhead including a load on the RACH of the target cell. On the other hand, RLFs and HOFs involve a long time in outage and it might cause a call drop if re-establishment fails.

IV. Methodology

A. Simulation assumptions

In this study, we evaluate a constellation of 7 LEO satellites implementing a regenerative payload. The satellite network is organized in 3 polar orbital planes with an inclination of $90°$

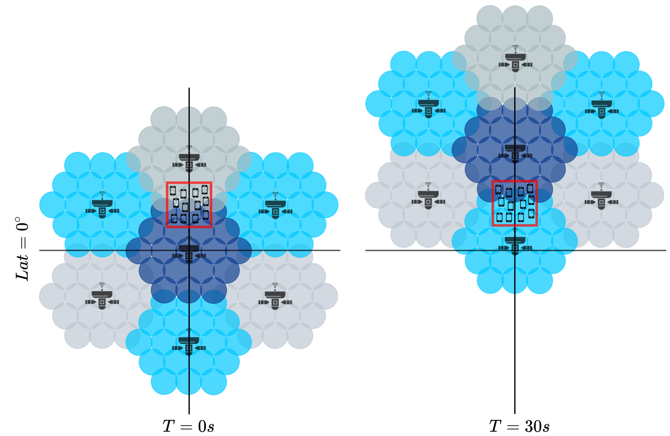


Fig. 3: Simulation scenario: stationary UEs being served by a constellation of 7 satellites operating with Earth-moving cells and a regenerative payload. Beams with the same colour belong to single satellite. Note the area and size of the UEs is not to scale, but merely included to indicate approximate location and satellite movement.

and a longitude offset of the ascending node of $1.36°$. An NR cell corresponds to a satellite beam in our study. Each LEO satellite operates 19 satellite beams with a footprint diameter on the ground of $50\,\mathrm{km}$ and an inter-cell distance of $43.3\,\mathrm{km}$. As reported in [7], a $50\,\%$ beam overlapping is used for outer beams neighbouring an adjacent satellite coverage. As it can be observed from our scenario depicted in Fig. 3, satellite beams are continuously moving on Earth. In other words, the satellite is generating beams which footprint is sweeping on the ground. Moreover, ideal Doppler compensation is assumed at satellite payload side.

From the UE's standpoint, a rural environment is used considering continuous line-of-sight (LOS) between satellite and terminal. 20 stationary UEs are uniformly distributed within an area of $55\,\mathrm{km} \times 55\,\mathrm{km}$ close to the equator. UEs establish the connection to the optimal cell based on the strongest RSRP criteria. Besides, a Gaussian error process is introduced in the UE's measurement model. Such measurements are filtered by the UE at layer 1 and layer 3 where the latter is using a single tap IIR filter [10]. We employ a simplified random access (RA) scheme, which models the RA message propagation delays but not potential RA message failures. The satellite payload characteristics and the channel propagation model are defined according to 3GPP technical report [6] and [7], respectively. An aspect to underline is the elevation angle dependency of this model. This means that both shadow fading and fast fading parameters are recalculated depending upon satellite and UE positions. Regarding the traffic network load, $30\,\%$ of the Resource Blocks available in a cell are loaded, generating uniform downlink interference conditions. The MR is triggered using the NR event A3 explained in Section III. The main simulation parameters are included in Table I.

Furthermore, we conduct system-level simulations of two terrestrial environments; UMa and HST. Although there are differences between terrestrial and non-terrestrial deployments, specially the channel conditions, we provide the terrestrial

TABLE I: System-level simulation assumptions

Parameter	Values
Satellite altitude	600 km
Satellite antenna pattern	Section 6.4.1 in [6]
Satellite equivalent isotropic radiated power density	34 dBW/MHz
3 dB beamwidth	4.4127°
Satellite Tx max Gain	30 dBi
Satellite beam diameter	50 km
UE Tx power	23 dBm
Deployment scenario [6]	NTN Rural
Shadow Fading (σ) [6]	1.79 to 0.72 dB
Fast Fading, K-factor (μ, σ) [6]	24.72 to 3.59 dB, 5.07 to 1.77 dB
Carrier frequency	2 GHz (S-Band)
System Bandwidth	10 MHz
Sub-carrier spacing	15 kHz
Traffic model	Full Buffer
Traffic load	30 %
Radio Link Failure [10]	Qin/Qout threshold: -6 dB/-8 dB T310 timer: 1000 ms N310/N311: 1
UE's measurement error (σ)	1.72 dB
L3 filter coefficient K	4
Time-to-trigger	0 ms, 100 ms and 256 ms
HO margin	0 dB, 1 dB, 2 dB and 3 dB
Simulation time	30 s

simulation results to facilitate a comparison of the NTN mobility performance with two well-known scenarios, where user mobility experience is satisfactory. To obtain the results, we use the same system-level simulator and the optimal HO configuration for each case (see Table II). The UMa scenario consists in a network composed by 21 wrapped around cells (7 sites) with 200 m ISD. UEs are uniformly distributed with random initial positions and moving at 3 km/h and 30 km/h speeds. In the HST case, UEs on board of a train at 500 km/h are simulated. The network is built upon 5 sites, with 2 cell per site and 1000 m ISD, and 2 wrap-around areas from both ends. The distance between cells and railroad track is 100 m. Both scenarios are 3GPP compliant and further details of the simulation assumptions can be found in [9] and [11].

B. Simulation tool

Performance results in this study were generated by using a fully dynamic system-level simulation tool modelling NR PHY and MAC layers with a high level of detail following 3GPP specifications. The simulator offers a realistic analysis of mobility and handovers while operating on an OFDM symbol-subcarrier resolution. It has been widely used in 3GPP standardization as well as in scientific publications [9] [12]. To obtain reliable results it includes a validated stochastic NTN channel model; implemented according to the specifications in [6] and calibrated against similar models used in 3GPP as stated in [7]. To achieve statistically stable results, 50 simulations are realized and combined for each pair of HOM and TTT values in Table I.

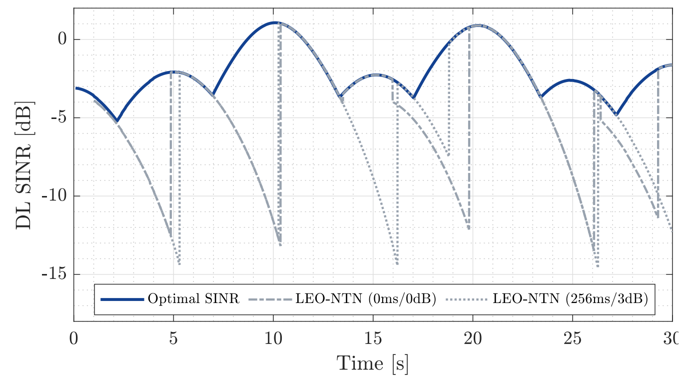


Fig. 4: Optimal and simulated DL SINR as a function of time for a UE configured with 0 dB and 3 dB HO margin and 0 ms and 256 ms time-to-trigger.

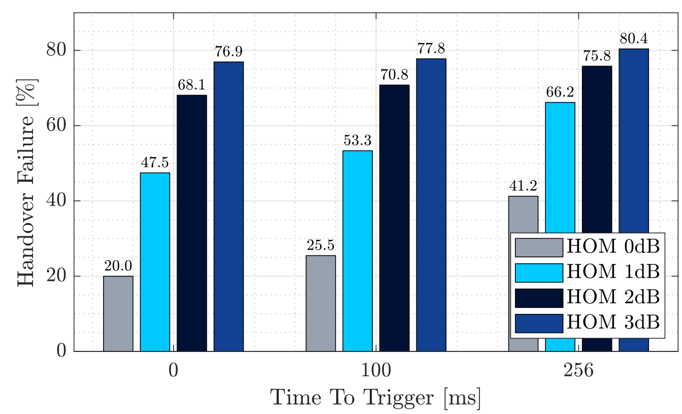


Fig. 5: HOF rate dependency on HO margin and time-to-trigger for LEO-based NTN.

V. Performance Results

A. Handover performance in LEO-based NTN

Fig. 4 shows the system-level simulated DL SINR experienced by a UE as a function of time. Two HO configurations have been included; 0 dB and 3 dB HOM and 0 ms and 256 ms TTT. Furthermore, the theoretical optimal DL SINR is included to provide a view on the upper bound. This metric is calculated by comparing the UE's best RSRP measurement per simulation step with the RSRP of all other cells. It is interesting to point the gap between the optimal and the simulated DL SINR reflecting the impact of the HO latency in the metric performance. The UE is establishing the connection to the serving cells at a late stage, i.e. when the beam signal starts to fade. Moreover, the majority of HOs occur when the DL SINR levels are very low. This might be explained by a re-establishment occurring after potential HOF or RLF.

Fig. 5 depicts the ratio of HOFs as a function of HOM and TTT. As expected, HOFs increase with HOM and TTT. Interestingly, HOM has a higher influence on the HOF metric than TTT. This fact can be observed when HOM increases from 0 dB to 1 dB, irrespectively of the TTT. The lowest HOF rates - about 20 to 40 % - are achieved when HOM is 0 dB with a global minimum of 20 % when TTT is 0 ms. Therefore,

TABLE II: HO parameters used to compare LEO-based NTN, UMa and HST scenarios

Deployment scenario	HO margin	Time-to-trigger
LEO-based NTN	0 dB	0 ms
UMa	2 dB	160 ms
HST	1 dB	0 ms

the best achievable performance is reached when HOM and TTT are both set to 0.

The RLF and PP rates are shown in Fig. 6. One can observe that both RLFs and PPs are heavily impacted by increasing the HOM and the TTT. Confirming the performance observed in Fig. 5, RLFs significantly grow with HOM. In fact, the RLF rate rises by a factor of 2 when no TTT is used and HOM transitions from $0\,\mathrm{dB}$ to $3\,\mathrm{dB}$. In contrast, the PP metric is affected by aggressive HO configurations (i.e., low HOM and low TTT) due to the effect of fading variations and the measurement model. A PP rate of $30\,\%$ can be seen when $0\,\mathrm{dB}$ HOM and $0\,\mathrm{ms}$ TTT are used and it drops to $10\,\%$ when TTT is extended. The rate is significantly reduced as soon as the HOM is non-zero with a marginal impact when HOM is set above 1 dB. Thus, a similar trade-off as in terrestrial networks can be seen when comparing RLFs and PPs. In the case under study, the best compromise is achieved when HOM is $0\,\mathrm{dB}$ and TTT is $256\,\mathrm{ms}$. Nonetheless, this HO configuration involves more than $40\,\%$ of HOFs (see Fig. 5). In general, a certain level of PPs are acceptable if RLFs are mitigated but in NTN deployments, to cope with long delays and challenging link budgets, unnecessary HOs (PPs) should be reduced.

B. Comparison with terrestrial cases

In this section, we compare the LEO-based NTN performance with UMa and HST scenarios using the HO parameters indicated in Table II. Fig. 7 reflects the HOF rate for the aforementioned deployments. Mobility optimization processes usually aim to target the HOF rate below $2\,\%$. This fact can be noted since UMa deployment establishes an upper bound for the terrestrial scenarios of $2\,\%$ of failures. In contrast, the most optimal HO configuration in LEO-NTN presents a performance loss by a factor 10 relative to the UMa case.

The results in Fig. 8 depict mobility performance in terms of RLFs and PPs. Regarding the RLFs, all the terrestrial scenarios manage to maintain a marginal number of RLFs compared to LEO-NTN where the proportion of RLFs is roughly one order of magnitude higher. Nonetheless, UMa deployment, when UEs move at $3\,\mathrm{km/h}$, show the largest PP proportion of the terrestrial scenarios and is similar to LEO-NTN performance. This can be justified by the fact that these UEs, with low mobility, will stay longer periods in cell edge conditions increasing the probability of PP. Eventually, it has to be noted that terrestrial performance present a clear trade-off between RLFs and PPs whereas LEO-NTN is not able to reach similar low RLF rate when allowing high number of PPs.

The final result in Fig. 9 demonstrates the time in outage, which is the KPI that directly impacts the user experience. The distribution reflects that in LEO-NTN $60\,\%$ of the UEs experience an outage time larger than $5\,\%$, relative to the call time. In our simulations the call time corresponds to the simulation time. In addition, $5\,\%$ of those UEs can experience outages for longer periods than $15\,\%$ of the call. Compared to terrestrial networks that show an average time in outage below $2.5\,\%$ of the call, UEs connected to a LEO-NTN deployment experiences an average time in outage from $8\,\%$ to $18\,\%$ depending upon the configuration.

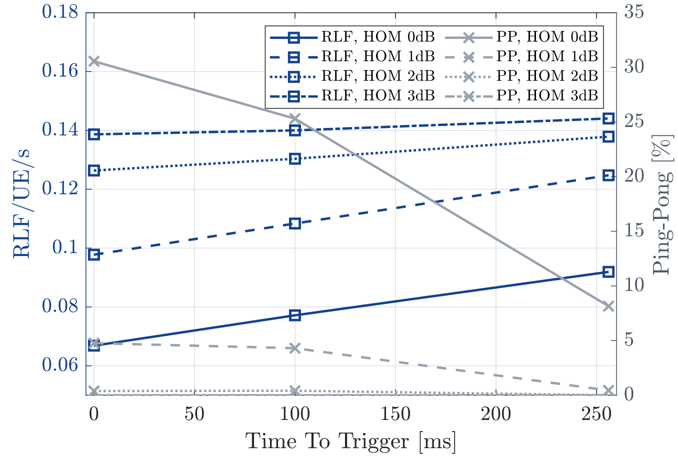


Fig. 6: RLF and PP rates dependency on HO margin and time-to-trigger for LEO-based NTN.

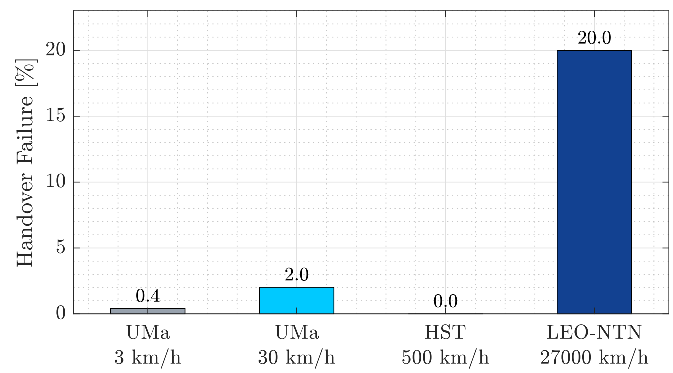


Fig. 7: HOF rate comparison for UMa, HST and LEO-NTN scenarios.

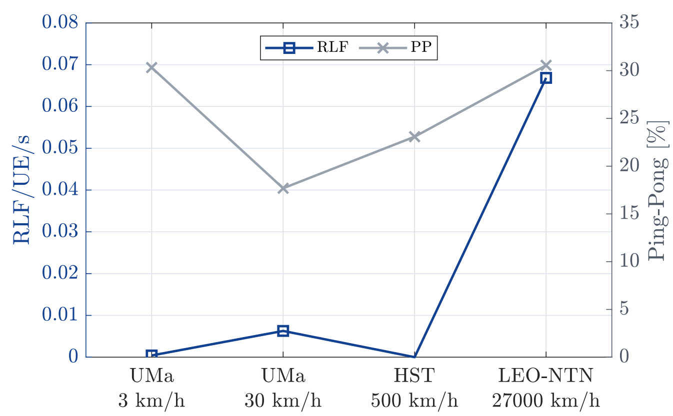


Fig. 8: RLF and PP rate comparison for UMa, HST and LEO-NTN scenarios.

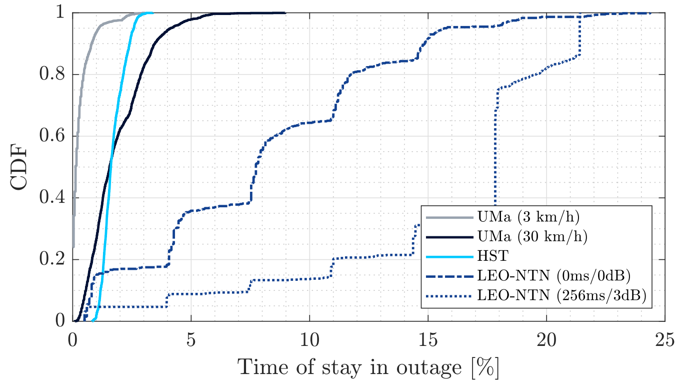


Fig. 9: Distribution of the time of stay in outage for UMa, HST and LEO-NTN scenarios.

VI. Discussion

Our simulations indicate the conventional 5G NR HO algorithm fails to provide seamless connectivity in LEO-based NTN. Even in a favourable scenario without LOS blockages, the conventional 5G NR HO cannot guarantee an acceptable user experience. The major challenge for mobility management is to address HO lateness and unnecessary HOs. Analysis of the HOF and RLF indicate a majority of failures occur during UE reception of the HO command from the serving cell. Typically in terrestrial networks, more aggressive HO configurations are used to handle HO lateness and improve the HO reliability. However, this strategy proved not sufficient in LEO-NTN. We observed that the high number of failures and PPs is due to a combination of factors but intrinsic to LEO satellites. Firstly, there is a low signal variation between the cell centre and cell edge conditions. The propagation distance is orders of magnitude longer than the cell size hindering the UE measurements. Secondly, there exists a high downlink interference from adjacent satellite beams. This fact results in a lower average DL SINR of $-2\,\mathrm{dB}$ for LEO-NTN compared to 2–$3\,\mathrm{dB}$ and $9\,\mathrm{dB}$ for UMa and HST, respectively. Thirdly, there is fast signal fading as a consequence of the high-speed cell mobility and the narrow antenna pattern. Finally, propagation delays, owing to long communication distances, delays all control messages and, hence, the HO latency.

VII. Future work

Based on the results in Section V, we conclude that LEO-based NTNs demand new mobility solutions to ensure service continuity. A promising enhancement is related to the knowledge of satellite movement. LEO constellations imply several challenges but the orbits are deterministic and, therefore, the network may predict which beam covers best a given UE, the duration that the UE will remain covered and the best next beam candidate to handover to. Such approach may optimize the triggering of the HO events and, in case of failure, improve the connection reestablishment process. The approach may be supported by the use of conditional HO (C-HO). Simulation results indicate the HO preparation phase is the most vulnerable since the HO process starts when the serving cell radio link is too weak (see Fig. 4). The C-HO enables the preparation phase to occur early, when the serving cell link is still reliable. Thus, the network may prevent HOFs due to late HOs using the C-HO and, together with the knowledge of satellites movement, foresee the most appropriate target cell.

VIII. Conclusions

This work has analysed the handover performance in a low Earth orbit based non-terrestrial network scenario. System-level simulations indicate that mobility based on a conventional 5G NR break-before-make, UE-assisted, network-controlled handover algorithm cannot guarantee robust service continuity, even under favourable propagation channel conditions. The best achievable performance is obtained by the most aggressive configuration, i.e. $0\,\mathrm{ms}$ time-to-trigger and no handover margin. The results obtained for this configuration showed a handover failure ratio of $20\,\%$ together with a ping-pong rate equal to $30\,\%$. Further analysis exposed that mobility performance is dominated by handovers happening too late. This is caused by cells moving at a relative speed of $7.5\,\mathrm{km/s}$, long communication distances and high downlink interference. Additionally, the handover performance is compared with two 3GPP terrestrial scenarios - urban macro and high-speed train - showing that non-terrestrial networks perform 10 times worse in terms of handover failures and radio link failures. Therefore, based on the simulations, it is concluded that new mobility solutions are necessary to address the challenges introduced by these satellite systems. These challenges underline the lack of scalability and robustness of the conventional terrestrial handover mechanism, which was not designed to meet non-terrestrial network requirements. Finally, some potential new directions were discussed and include a fully network-controlled handover exploiting the knowledge of satellites' movement and the use of the conditional handover.

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