

Residual Serving Time-Based Conditional Handover for Moving Beam LEO Non-Terrestrial Networks

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Abstract—Low Earth Orbit (LEO) non-terrestrial networks (NTNs) provide cellular service through moving beams whose coverage changes over time. However, conventional conditional handover (CHO) target selection mainly relies on radio-quality measurements, such as reference signal received power (RSRP), and may select a target cell with high measured RSRP but insufficient remaining service duration. Selecting such a target cell with insufficient residual serving time (RST) may require an unnecessary handover (UHO), thereby increasing CHO signaling overhead and mobility instability. This paper proposes a RST-based CHO target selection scheme for moving-beam LEO NTNs. The RST of each candidate target cell is estimated by calculating the remaining travel distance of the target-cell center until the UE reaches the cell boundary. The UE then excludes target cells whose estimated RST is shorter than the minimum time required for CHO preparation and execution, and reports the valid target-cell list to the serving gNB. network simulator-3 (ns-3) simulation results show that the proposed scheme suppresses insufficient-RST target cell selection compared with baseline CHO. In addition, the proposed scheme reduces unnecessary prepared resource blocks (RBs) while maintaining comparable target-cell RSRP and decreases handover (HO) and ping-pong occurrences. These results indicate that the RST-based criterion can reduce unnecessary CHO preparation and support more reliable mobility management in moving-beam LEO NTNs.

Index Terms—Non-terrestrial network, Low-Earth orbit, Conditional handover, Residual serving time.

I. INTRODUCTION

Low Earth Orbit (LEO) non-terrestrial networks (NTNs) provide cellular service through satellite beams that rapidly move over the ground plane [1]. Due to the high orbital velocity of LEO satellites, frequent handover (HO) events may be required to maintain service continuity for ground user equipment (UE). This mobility effect becomes more pronounced in an Earth-moving cell (EMC) scenario, where each satellite beam forms an individual cell whose footprint moves over the ground plane according to satellite motion.

Conditional handover (CHO) is a mobility enhancement mechanism in which candidate target cells and HO execution conditions are configured in advance [2]. After receiving the CHO configuration, the UE executes HO when the configured condition is satisfied. However, conventional CHO target selection mainly relies on radio-quality measurements, such as reference signal received power (RSRP). In moving-beam LEO NTNs, a target cell with high RSRP may still have insufficient remaining service duration because the beam footprint can quickly move away from the UE. Selecting such

a insufficient-RST target cell may require another HO within a short period, thereby increasing CHO signaling overhead and mobility instability.

Existing studies have investigated HO optimization, inter-beam HO triggering, and signaling load-aware CHO schemes for LEO NTN systems [3]–[5]. These approaches are useful for improving HO timing, service continuity, and mobility robustness, but they do not explicitly consider whether a prepared target cell can remain available long enough to complete CHO preparation and execution. Therefore, moving-beam LEO NTNs require a CHO target selection criterion that considers residual serving time (RST) as well as RSRP-based signal quality.

To address this limitation, this paper proposes an RST-based CHO target selection scheme for EMC-based LEO NTNs. The proposed scheme constructs a valid target-cell list by estimating the RST of candidate target cells and considering their remaining service duration. This enables the network to avoid CHO preparation for target cells with insufficient RST, thereby reducing unnecessary CHO preparation and unnecessary handover (UHO) occurrences. As a result, the proposed scheme improves HO target reliability in EMC-based LEO NTN environments.

II. SYSTEM MODEL

A. LEO NTN Network

We consider a moving-beam LEO NTN system in which LEO satellites provide cellular service using regenerative payloads with onboard gNB functionality. Each satellite projects multiple spot beams onto the ground plane, and adjacent beams partially overlap to provide continuous coverage, as illustrated in Fig. 1. Unlike an Earth-fixed cell architecture, this paper considers a moving-beam scenario where each beam footprint moves over the ground according to satellite motion.

Each spot beam is modeled as a circular moving cell on the ground plane. For the i -th beam, let $\mathbf{c}_i(t) = [x_i(t), y_i(t)]^T$ denote the ground center position at time t , and let $\mathbf{v}_i = [v_{x,i}, v_{y,i}]^T$ denote the ground velocity vector. The UE position on the ground plane is denoted by $\mathbf{p}_u = [x_u, y_u]^T$. Since LEO beam mobility is much higher than UE mobility, the UE is assumed to be stationary during the observation interval.

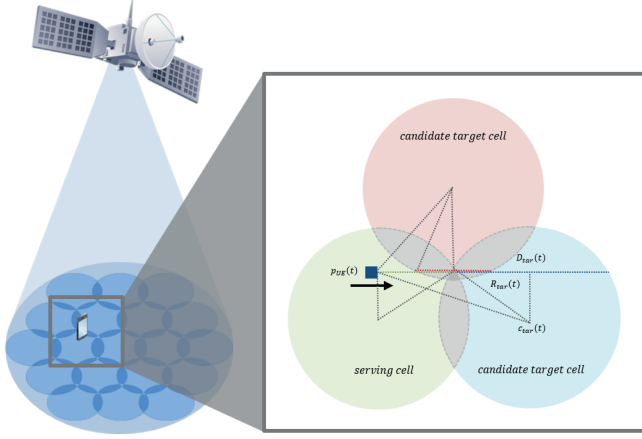


Fig. 1. System model

Under a constant beam velocity assumption, the beam center evolves as

$$\mathbf{c}_i(t) = \mathbf{c}_i(0) + \mathbf{v}_i t. \quad (1)$$

The ground distance between the UE and the i -th beam center is then given by

$$r_i(t) = \|\mathbf{p}_u - \mathbf{c}_i(t)\|. \quad (2)$$

Let R_i denote the ground coverage radius of the i -th beam. The UE is considered to be within the coverage of beam i when $r_i(t) \leq R_i$. This moving circular-cell model is used to estimate the RST of each candidate target cell.

B. Channel Model

The satellite-to-UE channel is modeled according to the rural scenario specified in 3rd generation partnership project (3GPP) TR 38.811 [1]. Depending on the existence of a direct propagation path between the satellite and the UE, the link can be classified as either line-of-sight (LOS) or non-line-of-sight (NLOS). These propagation conditions are mainly affected by the elevation angle observed at the UE and the surrounding terrain environment.

The total path loss PL is expressed as:

$$PL = PL_b + PL_g + PL_s + PL_e, \quad (3)$$

where PL_b , PL_g , PL_s , and PL_e denote the basic path loss, atmospheric gas attenuation, scintillation loss, and building entry loss, respectively.

The basic path loss PL_b is modeled by combining the LOS and NLOS components according to their occurrence probabilities as:

$$PL_b = P_{\text{LOS}}(\alpha) (FSPL + SF) + P_{\text{NLOS}}(\alpha) (FSPL + SF + CL), \quad (4)$$

where $P_{\text{LOS}}(\alpha)$ and $P_{\text{NLOS}}(\alpha)$ denote the LOS and NLOS probabilities according to the elevation angle α , respectively.

$FSPL$ denotes the free-space path loss, SF denotes shadow fading, and CL denotes clutter loss. The clutter loss represents additional attenuation caused by surrounding terrain or obstacles and is included in the NLOS component.

The free-space path loss is calculated as:

$$FSPL(d, f_c) = 32.45 + 20 \log_{10}(f_c) + 20 \log_{10}(d), \quad (5)$$

where f_c is the carrier frequency in MHz and d is the slant distance in km.

Given the satellite altitude h , the Earth radius R_E , and the elevation angle α observed at the UE, the slant distance d is given as:

$$d = \sqrt{R_E^2 \sin^2 \alpha + h^2 + 2hR_E - R_E \sin \alpha}, \quad (6)$$

where h , R_E , and d are expressed in km. The elevation angle α affects both the LOS/NLOS probabilities and the clutter loss in the rural NTN channel model.

The RSRP from cell k is calculated from the link budget as:

$$\text{RSRP}_k(t) = P_{\text{tx},k}^{\text{RS}} + G_{\text{tx}} + G_{\text{rx}} - PL_k(t), \quad (7)$$

where $P_{\text{tx},k}^{\text{RS}}$ is the transmit power allocated to the reference signal of cell k , G_{tx} is the satellite transmit antenna gain toward the UE, G_{rx} is the UE receive antenna gain, $PL_k(t)$ is the total path loss between cell k and the UE.

III. PROPOSED RST-BASED CHO TARGET SELECTION

The proposed RST-based CHO target selection scheme is designed to prevent unnecessary CHO preparation toward target cells with insufficient RST in moving-beam LEO NTN. Unlike conventional CHO target selection, which mainly relies on filtered RSRP measurements, the proposed scheme allows the UE to additionally evaluate the RST of candidate target cells before reporting valid handover candidates to the serving gNB. The operational concept is illustrated in Fig. 2.

The UE monitors the RSRP values of the serving cell and neighboring candidate target cells. When a candidate target cell satisfies the conventional RSRP-based CHO condition, the UE further examines whether the target cell can provide sufficient remaining service duration. For this purpose, the UE uses its own position, the candidate target-cell center position, the target-cell velocity vector, and the target-cell coverage radius to estimate the RST of the candidate target cell.

For a candidate target cell, let $p_{\text{UE}}(t)$, $c_{\text{tar}}(t)$, $v_{\text{tar}}(t)$, and R_{tar} denote the UE position, the target-cell center position, the target-cell velocity vector, and the target-cell coverage radius, respectively. The movement direction of the target-cell center is represented by the unit vector

$$\hat{e}_{\text{tar}}(t) = \frac{v_{\text{tar}}(t)}{\|v_{\text{tar}}(t)\|}. \quad (8)$$

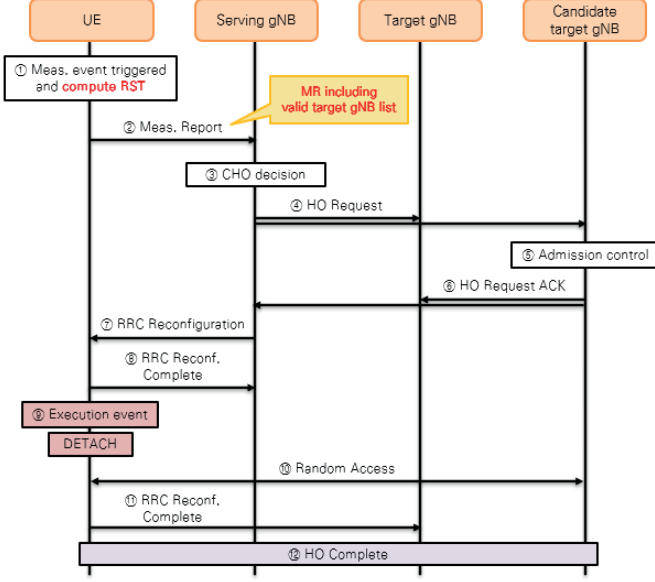


Fig. 2. Proposed RST-based CHO procedure

The relative position vector from the UE to the target-cell center is defined as:

$$g_{\text{tar}}(t) = c_{\text{tar}}(t) - p_{\text{UE}}(t). \quad (9)$$

Assuming that the target-cell center moves with an approximately constant direction and speed over a short observation interval, the future position of the target-cell center after traveling a distance $D_{\text{tar}}(t)$ along the movement direction can be expressed as:

$$c_{\text{tar}}(t) + D_{\text{tar}}(t)\hat{e}_{\text{tar}}(t). \quad (10)$$

The UE reaches the target-cell boundary when the distance between the UE and the future target-cell center becomes equal to the target-cell coverage radius. Therefore, the remaining travel distance $D_{\text{tar}}(t)$ is obtained from

$$\|g_{\text{tar}}(t) + D_{\text{tar}}(t)\hat{e}_{\text{tar}}(t)\| = R_{\text{tar}}. \quad (11)$$

Solving this equation gives

$$D_{\text{tar}}(t) = -g_{\text{tar}}^T(t)\hat{e}_{\text{tar}}(t) + \sqrt{(g_{\text{tar}}^T(t)\hat{e}_{\text{tar}}(t))^2 - (\|g_{\text{tar}}(t)\|^2 - R_{\text{tar}}^2)}. \quad (12)$$

The estimated RST of the candidate target cell is then calculated as:

$$T_{\text{RST}}(t) = \frac{D_{\text{tar}}(t)}{\|v_{\text{tar}}(t)\|}. \quad (13)$$

The UE regards a candidate target cell as a valid CHO target only when it satisfies both the RSRP condition and the

TABLE I
3GPP STUDY CASE 9-BASED SIMULATION CONFIGURATION

Parameter	Configuration
Reference scenario	3GPP Study Case 9-based LEO NTN
Satellite altitude	600 km
Satellite velocity	7.56 km/s
Payload type	Regenerative payload
Carrier frequency	2 GHz, S-band
System bandwidth	30 MHz per beam
Beam/cell model	Circular moving beam cell
Satellite EIRP density	34 dBW/MHz
Satellite antenna model	3GPP NTN antenna pattern [1]
Satellite antenna aperture	2 m
Satellite Tx antenna gain	30 dBi
UE deployment	Single stationary ground UE
UE RX antenna gain	0 dBi
Channel model	3GPP NTN large-scale channel model [1]
environment	rural scenario
TTT	0 s
Simulation duration	60 s

minimum RST condition. The RSRP condition is given by

$$\text{RSRP}_{\text{tar}}(t) > \text{RSRP}_{\text{serv}}(t) + O_{\text{CHO}}, \quad (14)$$

and the RST condition is given by

$$T_{\text{RST}}(t) \geq T_{\text{min}}, \quad (15)$$

where $\text{RSRP}_{\text{serv}}(t)$ and $\text{RSRP}_{\text{tar}}(t)$ denote the RSRP values of the serving cell and the candidate target cell, respectively. In addition, O_{CHO} is the CHO offset, and T_{min} is the minimum residual time required for CHO preparation and execution.

If a candidate target cell satisfies the RSRP condition but its estimated RST is smaller than T_{min} , the UE regards the cell as a insufficient-RST target cell and excludes it from the valid target-cell list. The UE then reports the valid target-cell list to the serving gNB through a Measurement Report (MR). Based on the reported list, the serving gNB performs CHO preparation only for target cells that are expected to provide sufficient remaining service duration. As a result, the proposed scheme avoids unnecessary CHO preparation toward target cells with insufficient RST and improves handover target reliability in moving-beam LEO NTN environments.

IV. PERFORMANCE EVALUATION

A. Simulation Environment

The performance of the proposed RST-based CHO target selection scheme is evaluated using the network simulator-3 (ns-3) simulator. The simulation follows a 3GPP system-level simulation study case 9-based LEO NTN configuration [6], where satellite beams are modeled as circular moving cells over the ground plane. The evaluation focuses on a moving-beam scenario in which a stationary ground UE observes time-varying serving and candidate target cells.

Table I summarizes the main simulation configuration, which follows the 3GPP NTN evaluation assumptions in [6]. The baseline CHO scheme selects candidate target cells based on the RSRP-based A3 condition [7], whereas the proposed scheme additionally estimates the RST of each candidate target

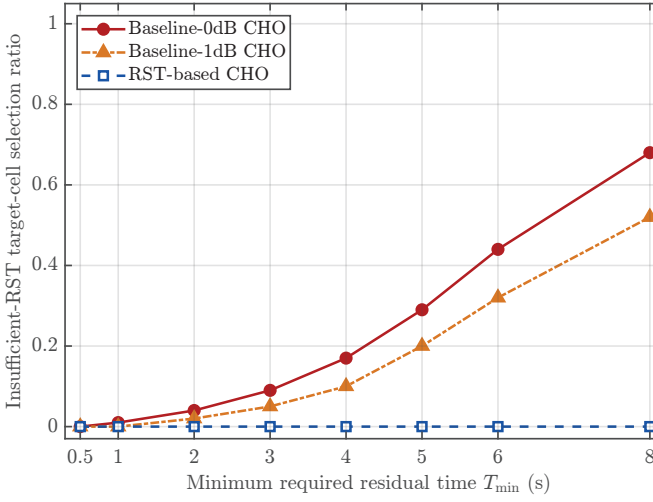


Fig. 3. Insufficient-RST target-cell selection ratio according to $T_{\min}$

cell before reporting the valid target-cell list. Therefore, the key difference between the two schemes is whether the remaining service duration of a moving target cell is considered during CHO target selection. The simulation set consists of three schemes: baseline CHO with a 0 dB offset, baseline CHO with a 1 dB offset, and the proposed RST-based CHO scheme. The two baseline schemes follow the conventional RSRP-based A3 condition, whereas the proposed scheme applies the RST criterion before reporting the valid target-cell list.

B. Key Performance Evaluation

The evaluation considers three performance metrics. The first metric is the insufficient-RST target-cell selection ratio, which measures the fraction of selected target cells whose RST is smaller than the minimum residual time requirement $T_{\min}$. In this paper, $T_{\min}$ is defined as the minimum expected service duration required for stable CHO preparation and execution, and it is varied from 0.5 s to 8 s to evaluate the sensitivity of target-cell selection to the residual-time requirement. The second metric compares the average selected target RSRP and the RB usage [8]. The RB usage represents the average number of prepared RBs per UE per second, obtained by normalizing the prepared RB count by the simulation duration. This metric is used to verify whether the proposed scheme can reduce CHO preparation overhead without degrading the radio quality of the selected target cell. The third metric is the HO usage composition, which consists of essential HO occurrences and UHO occurrences. The HO usage represents the average number of HO events per UE per second. In this paper, a UHO is declared when the UE stays in the selected target cell for less than the minimum time-of-stay (MTS) and then performs another HO to the previous or a neighboring cell. The MTS is set to 1 s to identify short-stay handovers caused by unstable target-cell selection. This metric is used to evaluate whether the proposed RST-based filtering can reduce mobility instability caused by target cells with insufficient remaining service duration.

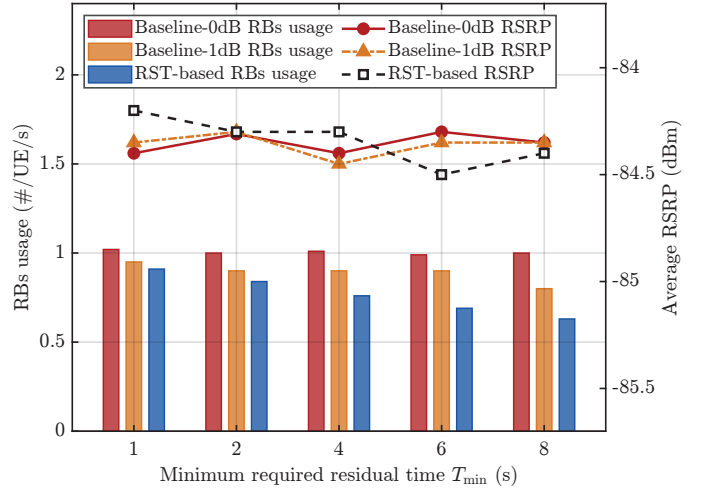


Fig. 4. Average selected target RSRP and RBs usage according to $T_{\min}$

C. Simulation Performance Results

Fig. 3 shows the insufficient-RST target-cell selection ratio according to the minimum required residual time $T_{\min}$. In the baseline CHO scheme, the insufficient-RST target-cell selection ratio increases as $T_{\min}$ becomes larger. This occurs because the baseline scheme selects target cells mainly based on RSRP-based measurements and does not evaluate how long the selected target cell can continue to serve the UE. As the residual time requirement becomes stricter, more RSRP-selected target cells fail to satisfy the minimum RST requirement. The baseline CHO with a 1 dB offset reduces the insufficient-RST target-cell selection ratio compared with the 0 dB baseline, but the ratio still increases as $T_{\min}$ becomes larger. In contrast, the proposed RST-based CHO scheme maintains a very low insufficient-RST target-cell selection ratio over the entire range of $T_{\min}$. Since the proposed scheme estimates the RST of each candidate target cell before reporting valid targets, target cells with insufficient RST are excluded from the candidate list. This result confirms that the RST criterion effectively prevents unstable target-cell selection in moving-beam LEO NTN environments.

Fig. 4 compares the average selected target RSRP and RB usage according to $T_{\min}$. The proposed scheme maintains a target RSRP level comparable to that of the baseline CHO scheme. Although increasing the CHO offset from 0 dB to 1 dB slightly reduces RB usage, the proposed RST-based CHO scheme achieves a further reduction by explicitly filtering insufficient-RST target cells. This indicates that the proposed scheme does not reduce RB usage by selecting target cells with degraded radio quality. Instead, the RST criterion is applied in addition to the RSRP-based CHO condition, so that target cells with sufficient signal quality and longer remaining service duration are preferred. The baseline CHO scheme prepares target cells mainly based on instantaneous RSRP. As a result, it may select target cells that satisfy the radio condition but provide insufficient RST. Such target-cell selections can lead to additional HOs or UHOs shortly

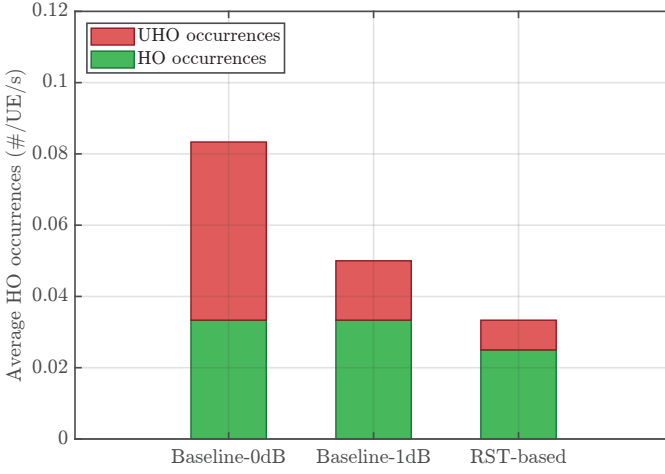


Fig. 5. HO usage composition with essential HO and unnecessary HO occurrences

after CHO execution, thereby increasing the overall CHO preparation and signaling overhead. In contrast, the proposed RST-based CHO scheme constructs the valid target-cell list by considering the remaining service duration. By avoiding insufficient-RST target cells, the proposed scheme reduces unnecessary mobility events over the simulation period. Consequently, the RB usage associated with CHO preparation is reduced while maintaining comparable target-cell RSRP. This result shows that the RB usage reduction is mainly achieved by improving the reliability of target-cell selection and reducing unnecessary HO-related preparation, rather than by relaxing the radio-quality requirement.

Fig. 5 presents the HO usage composition of the baseline CHO and the proposed RST-based CHO schemes. The 1 dB baseline reduces UHO usage compared with the 0 dB baseline, but it still shows higher UHO usage than the proposed RST-based CHO scheme. In the baseline CHO scheme, target cells are selected mainly based on RSRP-based measurements without considering their remaining service duration. Therefore, an insufficient-RST target cell may be selected, and the UE may require another HO shortly after the previous HO execution as the moving beam coverage leaves the UE location. The proposed RST-based CHO scheme reduces both total HO usage and UHO usage by excluding target cells with insufficient RST before CHO preparation. This indicates that the proposed scheme can avoid unstable HO decisions caused by target cells with insufficient RST. In particular, the reduction in UHO usage shows that the proposed scheme improves HO target reliability by preventing unnecessary subsequent HOs.

Overall, the simulation results demonstrate that the proposed RST-based CHO target selection scheme improves HO target reliability from three perspectives. First, it suppresses the selection of target cells with insufficient RST. Second, it reduces unnecessary RB usage more effectively than the baseline offset adjustment while maintaining comparable target RSRP. Third, it decreases UHO usage by avoiding unstable target cells before CHO preparation. These results confirm that RST is

an effective additional criterion for CHO target selection in moving-beam LEO NTN environments.

V. CONCLUSION AND FUTURE WORK

This paper proposed an RST-based CHO target selection scheme that filters candidate target cells with insufficient remaining service duration to reduce unnecessary CHO preparation and UHO occurrences in moving-beam LEO NTN environments. Simulation results using ns-3 showed that the proposed scheme suppresses insufficient-RST target-cell selection compared with the baseline RSRP-based CHO scheme. The proposed scheme also reduces RB usage while maintaining comparable target-cell RSRP and decreases cumulative HO and UHO occurrences by avoiding unstable target cells before CHO preparation. These results demonstrate that the RST criterion can improve HO target reliability and mobility stability in moving-beam LEO NTN environments.

As future work, the proposed RST estimation will be extended to random access channel (RACH)-less HO operation and further evaluated in realistic multi-UE and multi-satellite scenarios with dynamic traffic load, beam overlap, and resource allocation constraints.

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