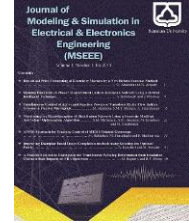




Semnan University



An Intelligent Handover Optimization Framework for Signaling Storm Reduction in 5G–Satellite Integrated Networks

Marjan Keramati^{1*}

Abstract--Low Earth Orbit (LEO) satellite networks have become an essential component of 5G and beyond non-terrestrial networks, as they enable low-latency communication and broad geographic coverage. Nevertheless, the rapid movement of LEO satellites introduces frequent handovers, substantial signaling overhead, and uneven load distribution, all of which can disrupt service continuity, particularly in scenarios involving large populations of user terminals. To address these challenges, this paper proposes a meta-heuristic-based multi-objective group handover optimization framework for LEO satellite systems. Unlike existing approaches, the proposed method jointly optimizes handover decisions at the group level while explicitly considering the RVT of satellites to ensure more stable and efficient connectivity. The simulation results show that the proposed approach effectively decreases unnecessary handovers (30%), alleviates signaling storms (70%), balances satellite loads more efficiently (10%), and prolongs the effective connectivity duration when compared with conventional baseline schemes. These findings validate the proposed framework as a more efficient solution for mobility management in highly dynamic LEO satellite network environments.

Index Terms- 5G Non-Terrestrial Networks; Group Handover; Handover Management; LEO Satellite Networks; Load Balancing.

I. INTRODUCTION

LOW Earth Orbit (LEO) satellite networks have emerged as a critical enabler for future 5G and beyond communication systems, offering low latency, extensive coverage, and global connectivity in areas where terrestrial infrastructure is limited. Despite these advantages, the rapid movement and constantly changing topology of LEO constellations result in frequent handover events, which can compromise service continuity, increase packet loss, interrupt ongoing connections, and impose additional control overhead [1], [2].

Notwithstanding these benefits, the rapid orbital motion of LEO satellites and their dynamically evolving network topology result in frequent handovers between satellites and user devices. These frequent transitions may negatively affect service reliability by increasing packet loss, interrupting active connections, and generating considerable signaling overhead. Moreover, recent studies consistently identify excessive handover rates as a critical performance limitation in LEO-based 5G non-terrestrial networks (NTNs), highlighting the need for more advanced and adaptive mobility management mechanisms [4], [5], [6].

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1. Faculty of Electrical and Computer Engineering, Semnan University, Semnan, Iran.

*Corresponding author: keramati_marjan@semnan.ac.ir

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Beyond impairing communication stability, a high rate of handovers also triggers substantial signaling overhead, particularly when large numbers of user terminals autonomously initiate handover processes. The aggregation of these control-plane exchanges may cause signaling congestion—often described as a signaling storm—which places heavy pressure on network control functions and negatively impacts quality of experience. At the same time, fluctuations in user spatial distribution combined with time-varying satellite coverage often result in uneven load conditions within the constellation, where certain satellites experience congestion while others operate below capacity. This imbalance further increases the complexity of mobility control and diminishes overall utilization of network resources [5], [6].

Traditional handover management approaches in LEO satellite networks have primarily aimed at reducing the number of handovers or optimizing individual performance metrics, such as link quality or handover latency. For example, methods based on fixed thresholds or distance criteria can successfully lower handover frequency but fail to simultaneously address both signaling overhead and load distribution challenges [4]. Likewise, strategies that organize users into groups can help alleviate signaling congestion by consolidating handover decisions. However, these techniques typically lack a comprehensive multi-objective framework capable of jointly minimizing handovers, mitigating signaling storms, and balancing satellite loads [6].

Recently, meta-heuristic optimization methods have gained attention as powerful approaches for addressing complex, high-dimensional challenges in dynamic network environments. Among these, Simulated Annealing (SA) has shown notable effectiveness in avoiding local optima and thoroughly exploring extensive solution spaces, making it well-suited for real-time decision-making in LEO networks that involve multiple, often conflicting objectives. These capabilities make SA a promising candidate for developing comprehensive handover management frameworks in satellite communication systems [7].

In this paper, a simulated annealing-based multi-objective group handover optimization framework is introduced for LEO satellite networks serving massive user terminals. The proposed framework jointly addresses three critical objectives: minimizing handover frequency, reducing signaling overhead, and maximizing the remaining visibility time (RVT) of satellites, a key factor that directly impacts service continuity and session reliability. Simulation results demonstrate that the proposed approach not only significantly reduces unnecessary handovers and alleviates signaling storm effects but also improves load balancing and extends the effective connectivity duration of user terminals compared to conventional baseline schemes. This enhancement in RVT represents a major contribution, ensuring more stable and reliable connectivity in dynamic LEO network environments.

The proposed method is among the group-based handover methods that improve the existing approaches [8] [9] and basic protocols [10] in terms of signaling storms, satellite load balancing, and service continuity.

The main contributions of the proposed method, in contrast to the current group-handover-based methods, are:

1. Simultaneous optimization of frequent handovers, signaling storm phenomena, and uneven load distribution across satellites in group-based methods.
2. Unlike some existing approaches, the proposed method jointly optimizes handover decisions at the group level while explicitly considering the RVT of satellites to ensure more stable and efficient connectivity.
3. Improving the existing mechanisms for satellite load distribution.

The remainder of the paper is structured as follows: Section II reviews related work on handover and load management in LEO satellite networks. Section III introduces the proposed Simulated Annealing-based multi-objective group handover framework. Section IV presents simulation results analyzing handover reduction, signaling overhead, load balancing, and improvements in remaining visibility time. Finally, the paper concludes with a summary of the main findings and future research directions.

II. RELATED WORKS

Mobility management in LEO satellite networks has emerged as a crucial area of research due to the high orbital speeds of satellites, which lead to frequent handover events. Early handover strategies primarily relied on signal strength or distance-based thresholds to initiate handovers, aiming to minimize service interruptions and packet loss. However, these methods often overlook the consequences of frequent handovers on signaling overhead and network scalability, particularly in dense LEO constellations that support large numbers of user terminals [11], [12].

The study in [1] has focused on inter-beam handover in 5G satellite-terrestrial integrated networks by developing conditional handover (CHO) schemes tailored to LEO satellite scenarios. Owing to rapid satellite motion, long propagation delays, and highly variable channel conditions, conventional terrestrial handover mechanisms become inadequate in such environments. Consequently, these studies typically employ realistic satellite channel models, incorporate stochastic user mobility, and propose event-driven, time-aware, and load-sensitive CHO strategies combined with various beam selection policies to limit handover frequency, mitigate ping-pong effects, and reduce handover failures. Although simulation results indicate clear performance gains over benchmark methods, most existing solutions rely on predefined rules and exhibit limited adaptability to large-scale, highly dynamic LEO constellations. In particular, signaling overhead and signaling storm effects are not explicitly considered, and global load balancing across satellites is generally absent. Moreover, the remaining visibility time of satellites is rarely included as a decision-making parameter, and handover optimization is not formulated within a unified multi-objective framework. These shortcomings highlight the need for intelligent, meta-heuristic-based group handover solutions that jointly optimize handover frequency, signaling overhead, load distribution, and visibility

time in LEO satellite networks.

Simulated Annealing-based handover approaches have been shown to effectively respond to real-time network dynamics and to escape local optima [6]. However, current research seldom incorporates remaining satellite visibility time as a direct optimization target, leaving a gap in methods that simultaneously optimize handover frequency, signaling overhead, load balancing, and satellite visibility in large-scale LEO networks.

To cope with the excessive signaling overhead and elevated handover failure rates resulting from frequent inter-satellite handovers, Authors in [8] have introduced group-based handover solutions for LEO satellite networks supporting massive user terminals. In [8], user terminals are typically clustered using hierarchical techniques based on traffic load and user-specific features, after which satellite selection and scheduling are performed through network-flow-based methods that incorporate remaining satellite visibility time to prioritize group handovers. Simulation-based evaluations report noticeable gains in terms of reduced signaling traffic, improved handover success probability, enhanced user quality of experience, and better load distribution. Despite these benefits, such schemes largely rely on deterministic clustering and scheduling mechanisms and are commonly designed for static or snapshot-based network scenarios, which limits their effectiveness in highly dynamic, large-scale LEO constellations. Furthermore, handover decision-making is not formulated within a unified multi-objective optimization framework. It therefore lacks the flexibility to dynamically balance trade-offs among handover frequency, signaling overhead, and load distribution under time-varying traffic and mobility conditions. The absence of meta-heuristic optimization techniques also constrains the exploration of a wider solution space, thereby motivating the need for adaptive, optimization-driven group handover frameworks.

Authors in [9] have explored group handover mechanisms in LEO-based non-terrestrial networks to tackle key challenges in 5G handover design, such as frequent signaling exchanges, signaling storms, and vulnerabilities arising from high satellite mobility. Secure and efficient group handover protocols have been developed to support direct-to-cell connectivity and widespread coverage, with performance assessed through custom discrete-event simulations and compared against conventional 5G handover schemes. Although these protocols demonstrate improvements in signaling efficiency, reliability, and security, they largely concentrate on protocol-level mechanisms rather than on optimization-driven handover decision-making. Specifically, they do not explicitly target reductions in handover frequency, global load balancing across satellites, or maximization of remaining satellite visibility time, nor do they frame the problem as a multi-objective optimization task. These limitations restrict their applicability to large-scale LEO constellations with massive user terminals and dynamic traffic patterns, highlighting the need for adaptive, meta-heuristic-based group handover frameworks capable of jointly optimizing signaling efficiency, load distribution, and handover performance.

The study in [13] examines the large-scale handover challenge in mega low Earth orbit (mega-LEO) satellite networks envisioned for 6G, where ultra-dense constellations, rapid satellite motion, and extensive coverage result in a large number of users simultaneously initiating handovers. To alleviate severe signaling overhead and enhance handover success rates, a double grouping-based group handover (DGGH) scheme is introduced. The proposed method first clusters users through beam-constrained hierarchical grouping and then transforms the multi-user handover management problem into a single-objective optimization formulation. This problem is addressed using a satellite grouping strategy that integrates greedy techniques with dynamic programming, followed by a group handover algorithm designed to minimize handover waiting time. Simulation results indicate that the DGGH approach significantly outperforms traditional single-user handover schemes in terms of signaling efficiency and handover success probability. Nevertheless, this solution is specifically tailored for mega-LEO scenarios characterized by extremely dense satellite deployments and large-scale concurrent handovers, which differ fundamentally from the conventional LEO environments considered in this paper. In particular, the DGGH framework does not explicitly account for RVT or satellite contact duration in its handover decisions, nor does it jointly optimize handover frequency, signaling storm mitigation, and satellite load balancing in typical LEO networks.

The proposed method in [14] addresses the handover challenge in LEO satellite networks by accounting for factors such as rapid satellite movement, bursty traffic patterns, and the large-scale nature of the system. The handover problem is modeled as a decentralized Markov decision process (DEC-MDP) and tackled using a fully distributed multi-agent reinforcement learning framework based on a multi-agent double deep Q-network (MADDQN), known as the MAF-DDQN-DIH scheme. The objective is to maximize a global reward function that jointly considers service revenue, handover cost, and packet loss, while alleviating load imbalance through decentralized decision-making at the user terminal level and addressing environmental non-stationarity via multi-agent fingerprints. However, RVT is not explicitly included as a decision metric, which restricts the framework's ability to proactively enhance connection stability and avoid unnecessary handovers. Furthermore, although handover cost is embedded in the reward formulation, the approach does not explicitly aim to minimize handover frequency, mitigate signaling storm effects, or jointly optimize signaling overhead and load distribution based on satellite visibility dynamics. In addition, the dependence on deep multi-agent reinforcement learning entails substantial computational complexity and training overhead at the terminal side, which may limit its practicality for real-time operation in large-scale LEO networks. By contrast, the proposed work directly leverages RVT within a LEO-specific optimization framework to enable more efficient, stable, and lightweight handover management. The method in [15] explores handover optimization in multi-connectivity (MC) enabled integrated terrestrial-LEO satellite

networks and introduces a deep reinforcement learning framework based on a Dueling Double Deep Q-Network, augmented with Random Ensemble Mixture and Dual Experience Replay. By jointly accounting for terrestrial base stations and LEO satellites, the method enhances handover decision accuracy in highly dynamic network environments, resulting in higher system throughput, lower latency, fewer handover events, and improved transmission success probability across various quality-of-service constraints. Nonetheless, the framework primarily targets single-user handover decisions within MC settings and depends on computationally intensive deep learning models, potentially limiting its scalability in scenarios with massive user populations. Additionally, the approach does not explicitly consider signaling overhead, group handover coordination, or signaling storm mitigation, nor does it incorporate RVT as an optimization criterion. Consequently, aspects such as load balancing across satellites and proactive handover scheduling based on satellite visibility dynamics remain insufficiently addressed—challenges that the proposed simulated annealing-based multi-objective group handover framework aims to tackle.

The study in [16] introduces a deep reinforcement learning-based handover protocol, termed DHO, which aims to address long propagation delays in LEO satellite handovers by omitting the Measurement Report (MR) phase and employing predictive models derived from pre-determined satellite orbital trajectories. The protocol achieves reductions in access delay, lower collision rates, and improved handover success when compared with conventional handover schemes, and its training behavior and convergence are evaluated across various reinforcement learning algorithms. Nevertheless, DHO primarily targets single-user handover prediction and lacks support for group-based handover strategies, limiting its scalability in networks with large numbers of user terminals. Additionally, the method does not explicitly account for signaling overhead, satellite load balancing, or RVT in its decision-making, potentially resulting in suboptimal handover timing and uneven resource utilization across satellites. While effective in minimizing MR-induced delays, the approach does not jointly optimize multi-objective handover metrics—such as handover frequency, signaling storm mitigation, and satellite load distribution.

The research in [17] examines user-centric handover mechanisms in LEO satellite communication systems and introduces an opportunistic handover strategy to mitigate congestion that arises when a large number of users independently select the same target satellite. The proposed scheme employs probabilistic satellite selection based on achievable data rates and available channel resources, enabling users to be distributed among multiple visible satellites. As a result, bottlenecks are alleviated, leading to improvements in throughput, blocking probability, and average handover efficiency in dense user environments. Nevertheless, the approach is inherently designed for individual user decision-making and does not leverage group-based handover coordination, limiting its effectiveness during large-scale mobility events. Furthermore, remaining visibility time,

satellite orbital characteristics, and signaling overhead are not explicitly incorporated into the handover decision process, restricting the scheme's ability to mitigate signaling storm effects caused by simultaneous handover requests. In addition, load balancing is achieved indirectly through probabilistic access rather than through a unified multi-objective optimization framework, leaving the joint optimization of handover frequency, signaling cost, and satellite load distribution largely unexplored.

The study in [18] explores handover optimization in Non-Terrestrial Networks through a Deep Q-Network-based approach specifically designed for LEO satellite mobility. The method adapts in real time to varying network conditions, addressing shortcomings of conventional rule-based handover schemes, and achieves higher decision accuracy alongside lower handover latency when compared to both traditional and AI-driven benchmarks. Nevertheless, the framework is primarily oriented toward single-user handover decisions and lacks support for group-based coordination or multi-user handover management, limiting its scalability in networks with large numbers of terminals. Additionally, the algorithm does not explicitly account for remaining visibility time, signaling overhead, or load balancing across satellites, nor does it provide mechanisms to mitigate signaling storms under dense user scenarios. As a result, although the approach improves per-user handover performance, it does not adopt a multi-objective optimization perspective that simultaneously addresses handover frequency reduction, signaling efficiency, and balanced satellite load distribution.

The methodology in [19] addresses frequent handovers in LEO satellite constellations supporting 5G networks by introducing a decentralized load-balancing satellite handover strategy based on multi-agent Q-learning, implemented within the NS-3 simulator. The proposed method seeks to lower both the total number of handovers and the blocking probability while achieving a more uniform distribution of load across satellites, achieving reductions in average handovers per user and the blocking rate compared to current state-of-the-art approaches. Despite these improvements in load balancing and handover frequency, the framework primarily focuses on decentralized, per-user reinforcement learning and does not explicitly incorporate remaining visibility time or satellite contact duration into the handover decisions. Additionally, it does not jointly optimize handover frequency, signaling storm mitigation, or group-based coordination, and the reliance on individual user learning may limit scalability in networks with massive user populations.

III. PROPOSED METHOD

In this paper, a simulated annealing-based multi-objective group handover framework was developed for LEO satellite networks supporting massive user terminals. The proposed framework is designed to address three key challenges in LEO mobility management: frequent handovers, signaling storm phenomena, and uneven load distribution across satellites. Unlike some existing approaches that focus on single-user handover decisions, the proposed method jointly optimizes

group-level handover decisions while explicitly considering the RVT of satellites to ensure more stable and efficient connectivity. Moreover, the proposed approach outperforms the grouping-based handover schemes presented in [8] and [9] with respect to RVT, satellite load balancing, handover frequency, and signaling overhead. A detailed evaluation supporting this claim is provided in Section IV.

A. System Model

A LEO satellite constellation is considered to be composed of multiple satellites following predefined orbital paths. A dense population of user terminals (UTs) is distributed across the service area, where satellite mobility may trigger simultaneous handover requirements for multiple users. At any given time, each UT can communicate with a limited set of satellites within its line-of-sight range, as determined by line-of-sight availability and elevation-angle constraints. The RVT represents the predicted duration during which a satellite remains accessible to a UT before the communication link is disrupted, and it is assumed to be estimable using orbital parameters (Fig. 1).

Satellite communication resources are inherently constrained, and a large volume of concurrent handover requests can lead to congestion and excessive signaling traffic. Consequently, an effective handover mechanism must jointly account for link availability, RVT, signaling overhead, and the current load conditions of the satellites, rather than relying solely on instantaneous link quality.

B. Problem Formulation

The primary objective of this paper is to simultaneously optimize RVT, satellite load balancing, handover frequency, and signaling overhead. With particular emphasis on signaling overhead, the optimization problem for minimizing conditional handover-related signaling in 3GPP systems is formulated in [20], following the specifications outlined in [10]. Building upon the framework presented in [20], this paper formulates the signaling storm optimization problem for group-based handover as expressed in (1):

$$\min (\max \sum_{g \in G} ((2 + N_{Groups}) f_{u,s}^t + w_{u,s}^t) \quad \forall t \in T, \forall s \in S) + \max (\sum_{u \in U} Sig_RRC_u) \quad (1)$$

Let $S = \{S_1, S_2, S_3, S_4, \dots, S_m\}$ be the set of m available satellites. Also, $G = \{G_1, G_2, G_3, G_4, \dots, G_K\}$ be the set of k available user groups.

$f_{u,s}^t$ is one, if s is the source satellite u of at time t and zero otherwise. $w_{u,s}^t$ is one, if s is the target satellite u of at time t and zero otherwise. N_{Groups} is the number of satellite groups. Sig_RRC_u is the RRC (Radio Resource Control) configuration signaling messages of the user agent u during handover based on [10].

Conditional signaling overhead is assumed to be triggered by reductions in RVT and satellite overload conditions. Accordingly, the key novelty of the proposed method lies in reducing signaling overhead by mitigating handover frequency.

In line with this objective, the target controller selection in the proposed scheme is designed to alleviate satellite overload while concurrently enhancing the RVT. Accordingly, during the handover process, the target controller is strategically selected to maximize the RVT of user agents and promote balanced satellite utilization, thereby effectively mitigating overload conditions, as formulated in (2).

$$obj_3 = \min (obj_1, obj_2) \quad (2)$$

$$\sum_{j \in G} x_{ij} = 1 \quad \forall i \in S \quad (3)$$

$$\sum_{j \in S} y_j \geq 1 \quad (4)$$

$$\sum_{j=1}^{|C|} x_{ij} \geq 1 \quad \forall i \in S \quad (5)$$

x_{ij} is one, if group agents G_i is connected to satellite j . m is the number of satellites. The optimization problem in (2) is a mixed integer linear programming problem. In (4), y_j indicates the existence of at least one satellite at the corresponding physical location j .

The first constraint in (3) ensures that each group of user agents is connected to a satellite. The second constraint in (4) indicates the existence of at least one satellite at each corresponding physical location. The third constraint in (5) guarantees that each group of user agents is connected to at least one satellite.

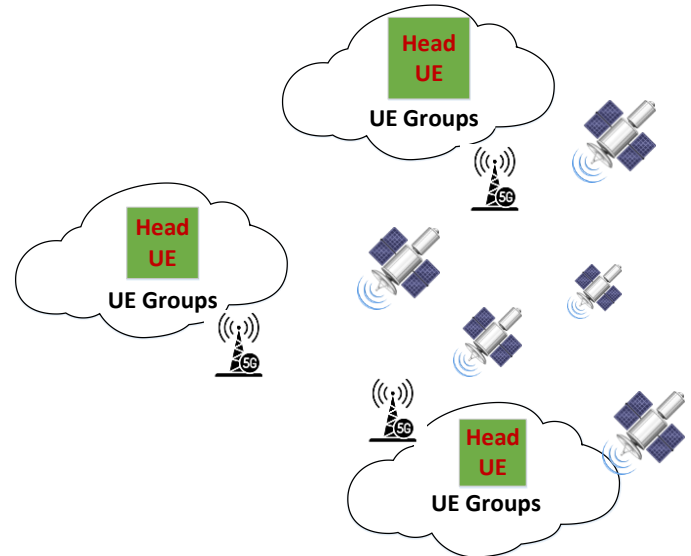


Fig. 1. System Model

$$obj_1 = \min \left(\frac{1}{l_{RVT}} \right) \quad (6)$$

$$obj_2 = \min(std_{load}) \quad (7)$$

$$l_{RVT} = \frac{1}{|G_i|} \sum_{u \in G_i} \sum_{s_j \in S} x_{ij} RVT_{(u,s_j)} \quad (8)$$

$$std_{load} = \left(\sqrt{\frac{\left(\sum_{i=1}^k \left(x_{ij} l_{d_{ij}} - \frac{\sum_{j=1}^m \sum_{i=1}^k x_{ij} l_{d_{ij}}}{m} \right)^2 \right)}{m}} \right) \quad (9)$$

In (8), l_{RVT} is the average RVT level between users and satellites. Also, $RVT(u, s_j)$ is the RVT level between users in G_i and their associated satellite. In (9), $l_{d_{ij}}$ is the employed load of group agents G_i on satellite. The optimization problem in (7) minimizes the standard deviation of satellites' load to provide more load-balanced satellites. This is done to prevent satellites from becoming overloaded and consecutive handovers from being triggered.

C. Proposed Meta-Heuristic-based method

The proposed handover optimization framework (2) is formulated as a Mixed Integer Linear Programming (MILP) problem, where binary and integer decision variables are employed to model user-satellite associations and handover decisions under linear objective functions and constraints. Due to the presence of integer variables, the resulting MILP belongs to the class of combinatorial optimization problems and is generally computationally intractable. It is well known that MILP problems are NP-hard, and solving them optimally requires exponential time in the worst case, making exact solution methods impractical for large-scale LEO satellite networks with massive user terminals. Therefore, to efficiently derive high-quality near-optimal solutions within an acceptable execution time, a meta-heuristic optimization approach is adopted in this work.

In particular, simulated annealing is employed due to its strong ability to escape local optima and handle large, complex search spaces, making it well-suited for the proposed multi-objective handover optimization problem.

Simulated annealing is a stochastic meta-heuristic inspired by the annealing process in materials, allowing exploration of the solution space and escape from local optima. The proposed handover optimization problem is formulated as an MILP and is NP-hard due to integer decision variables and combinatorial complexity.

Exact solvers are computationally impractical for large-scale LEO networks with massive user terminals. Simulated annealing is well-suited for this problem because it efficiently handles discrete and combinatorial optimization, accommodates multi-objective cost functions (handover rate, signaling overhead, load balancing, and RVT), and provides a simple yet effective approach for obtaining a high-quality near-optimal solution.

Algorithm 1 presents the simulated annealing procedure employed to solve the formulated optimization problem. The algorithm starts by generating an initial feasible solution and initializing the temperature parameter to a predefined initial value. The temperature controls the probability of accepting

non-improving solutions during the search process [7].

The proposed simulated annealing-based method is summarized in Figs. 2 and 3. The algorithm is employed in the head of each satellite group named "HEAD UE".

Fig. 3 presents the flowchart of the proposed method, outlining its main operational steps.

1. The handover process is triggered when the RVT falls below a predefined threshold or when the load of the associated satellite exceeds a specified limit.
2. The proposed meta-heuristic-based approach intelligently selects the target satellite to minimize the occurrence of consecutive handovers.
3. The group of user agents performs handover to the target satellite.

The proposed intelligent target satellite selection mechanism aims to reduce the handover rate, alleviate signaling storms, and enhance the RVT of user agents. Moreover, compared with existing group handover-based methods in [8], [9], the proposed scheme provides better satellite load balancing and minimizes the handover triggering frequency through intelligent target selection.

The validity of the above assertions is demonstrated through comprehensive experimental results, which are discussed in the next section.

Algorithm 1: Simulated Annealing Algorithm

In

Parameters Setup

S= Initial solution Construction

$T=T_0$

Out

Computation of the near optimal solution

While ($T < T_{final}$ and $N < Num_{iterations}$):

S_N =Construct a solution in the neighborhood

If ($f(S_N) < f(S)$):

$S = S_N$

else:

$\Delta = f(S_N) - f(S)$

$r = \text{random}()$

if ($r < \exp\left(\frac{-\Delta}{K * T}\right)$):

$S = S_N$

$T = T * \alpha$

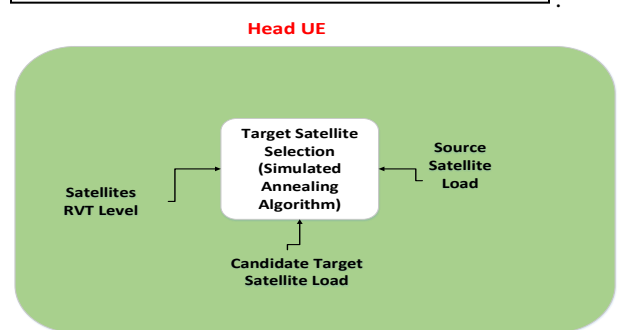


Fig. 2. Schematic of the proposed simulated annealing-based method located in the UE Header

IV. EXPERIMENTAL RESULTS

In this section, after briefly describing the test network, the performance results of the proposed method applied to a single

satellite network are presented and discussed.

A. Testbed Introduction

All simulations were conducted on a platform configured with 32 GB of RAM and an Intel® Core™ i7-10750H processor (2.80 GHz). The 5G–satellite integrated network and the proposed meta-heuristic-based target controller selection algorithm were implemented in Python. To ensure the reliability and statistical validity of the results, all experiments were independently repeated ten times, and the average performance metrics were reported.

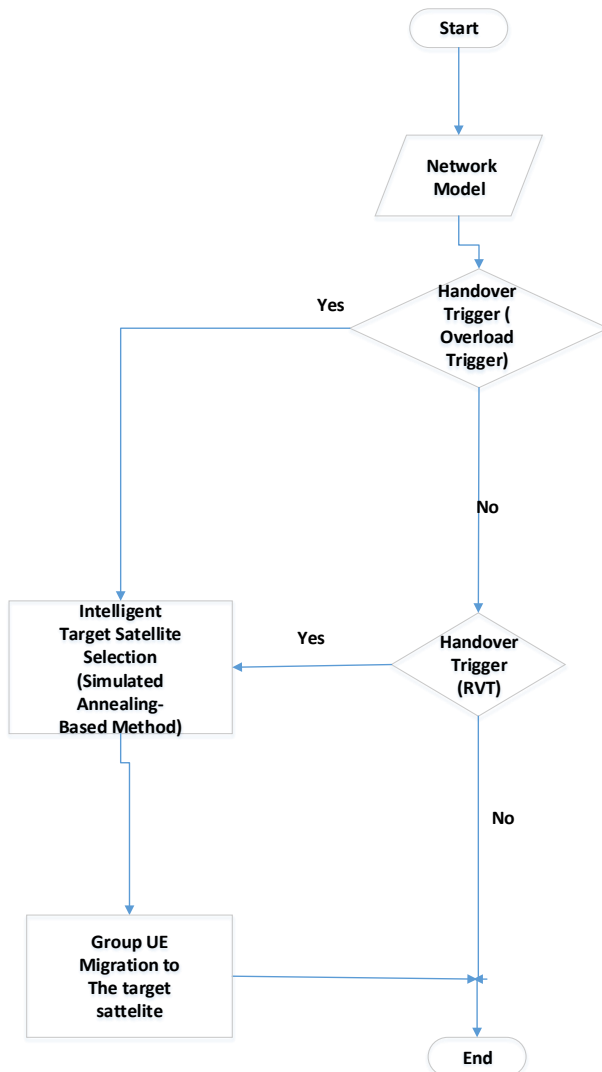


Fig. 3. Flowchart of the proposed method

The simulation parameters are presented in Table I and are mainly derived from the 3GPP TR 38.811 standard [13] and group-based handover in [8].

The proposed approach consistently outperforms the grouping-based handover schemes presented in [8] and [9] across key performance metrics, including RVT, satellite load balancing, handover frequency, and signaling overhead.

For systematic performance benchmarking and comparative evaluation, the following strategies are employed as baseline methods:

1. **3GPP TR 38.811 standard:** According to 3GPP TR [10], 38.811, a conditional handover mechanism is defined for non-terrestrial networks, in which handover conditions and candidate target cells are pre-configured at the user equipment. This design facilitates rapid handover execution while minimizing signaling overhead, which is particularly critical in a high-mobility LEO satellite environment.
2. **Group Handover Mechanism in [8]:** In [8], user terminals are typically clustered using hierarchical techniques based on traffic load and user-specific features, after which satellite selection and scheduling are performed through network-flow-based methods that incorporate remaining satellite visibility time to prioritize group handovers. Despite these benefits, such schemes largely rely on deterministic clustering and scheduling mechanisms and are commonly designed for static scenarios, which limits their effectiveness in highly dynamic, large-scale LEO constellations. Furthermore, handover decision-making is not formulated within a unified multi-objective optimization framework. It therefore lacks the flexibility to dynamically balance trade-offs among handover frequency, signaling overhead, and load distribution under time-varying traffic and mobility conditions.
3. **Group Handover Mechanism in [9]:** Authors in [9] have explored group handover mechanisms for LEO-based non-terrestrial networks to tackle key challenges in 5G handover design, such as frequent signaling exchanges, signaling storms, and vulnerabilities arising from high satellite mobility. Although these protocols demonstrate improvements in signaling efficiency, reliability, and security, they largely concentrate on protocol-level mechanisms rather than on optimization-driven handover decision-making. Specifically, they do not explicitly target reductions in handover frequency, global load balancing across satellites, or maximization of remaining satellite visibility time, nor do they formulate the problem as a multi-objective optimization task.

For clarity and brevity, the following abbreviations are adopted in the subsequent subsections:

1. Proposed method : (PM)
2. Base Protocol [10] : (BP)
3. Group Handover in [9]’: FBP
4. Group Handover in [8]: SBP

In the following sections, a comprehensive performance evaluation of the proposed method is conducted, focusing on signaling storm mitigation, balanced satellite utilization, and handover rate reduction, and comparing it against the aforementioned state-of-the-art scheme. All experiments were repeated 10 times to ensure statistical reliability and result consistency.

B. Handover Rate and Signaling Storm

The concept of group-based handover has attracted

considerable attention due to its effectiveness in mitigating handover-induced signaling storms. The proposed group-based handover strategy in this paper achieves a significant reduction in signaling storms compared to the most recent approaches available and the baseline protocol in [10]. This improvement stems from the intelligent meta-heuristic-driven mechanism employed in this work, which strategically selects target satellites to enhance the RVT and promote balanced satellite utilization. Since handover events are primarily triggered by RVT degradation and satellite overload conditions, improving

TABLE I
Network Simulation Parameters [8] and [13]

Parameters	Value
Frequency of the carrier	20 GHz
Bandwidth of the carrier	500 MHz
satellite's altitude	800, 600 Km
Number of LEO satellites	4×2
Orbital Plane Count	2×2
LEO Satellite Count in Each Orbit	2
Orbital Inclination	$60^\circ, 45^\circ$
Diameter of Beam	80, 50 Km
Per satellite beam count	19
Bandwidth of the UE's Channel	1, 4 MHz

these factors inherently reduces the handover rate and, consequently, the signaling storm intensity.

Fig. 4 illustrates the signaling storm as a function of the number of users. As anticipated from the preceding analysis, the proposed method achieves the most significant reduction in signaling storm compared to the other group-based schemes (FGM and SGM). In contrast, the Base Protocol (BP) exhibits the poorest performance because it relies on individual handovers rather than a group-based mechanism, resulting in higher signaling overhead.

The handover rate is evaluated as a function of the number of users, and the corresponding results are illustrated in Fig. 5. As can be observed, the proposed method consistently outperforms both the state-of-the-art approaches and the baseline protocol in [10], consistent with the analytical justification provided earlier.

C. Load Balancing Capability Evaluation

As discussed earlier, satellite overload constitutes one of the primary triggers for handover events. Accordingly, as formulated in (2), ensuring balanced satellite utilization is a central objective of the proposed method. This claim is validated by evaluating load-balancing efficiency using statistical measures, namely the Standard Deviation (SD) and the Coefficient of Variation (CV). The corresponding results

are presented in Figs. 6 and 7.

The use of standard deviation and coefficient of variation provides a rigorous statistical assessment of load balancing performance. Specifically, the standard deviation quantifies the absolute dispersion of traffic load across satellites, where a lower SD indicates a more uniform distribution of users. However, since SD is scale-dependent, the coefficient of variation—defined as the normalized ratio of SD to the mean load (11)—offers a relative measure of imbalance, enabling fair comparison across different user densities and network scales. Therefore, jointly analyzing SD and CV ensures a comprehensive, scale-independent evaluation of satellite load-balancing efficiency.

$$CV = \frac{\sigma}{\mu} \quad (11)$$

In (11), σ denotes the mean satellite load, and μ corresponds to the standard deviation of the satellite load distribution.

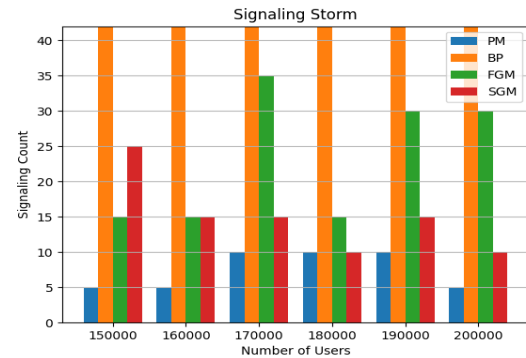


Fig. 4. Signaling storm in terms of the number of users

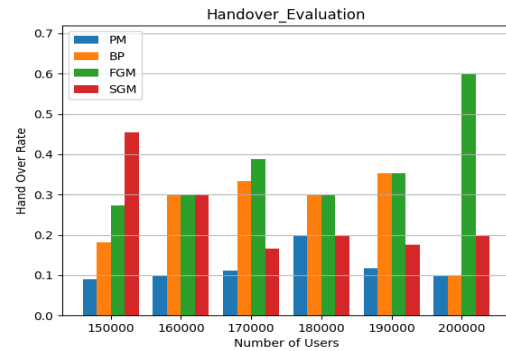


Fig. 5. Handover rate in terms of the number of users

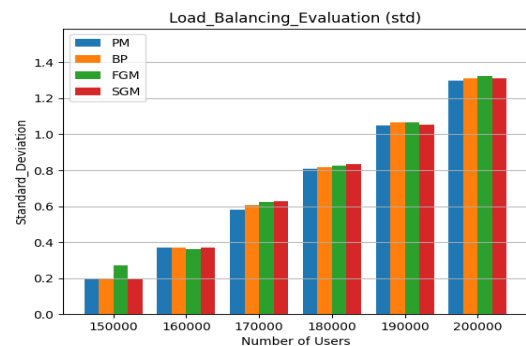


Fig. 6. Load standard deviation in terms of the number of users

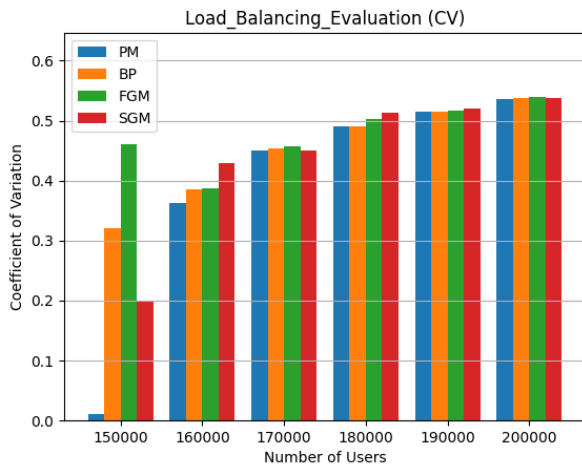


Fig. 7. Coefficient of variation in terms of the number of users

As illustrated in Figs. 6 and 7, the proposed method consistently outperforms both the state-of-the-art approaches and the baseline protocol in terms of coefficient of variation and standard deviation. This performance improvement results from the intelligent target satellite selection mechanism embedded in the proposed scheme, which effectively promotes balanced satellite utilization and minimizes load dispersion across the network.

D. RVT level evaluation

The second factor triggering handover events is the degradation of the user agent's RVT. From this perspective, the proposed method mitigates handover rates by intelligently selecting the target satellite so as to enhance the RVT level of the user agent, thereby postponing unnecessary handovers. The validity of this claim is verified by evaluating the number of handover events triggered by RVT degradation as a function of the number of users. The corresponding results are illustrated in Fig. 8. As expected, the number of handovers triggered by RVT degradation is significantly lower (it is zero) compared to the other methods. In other words, no handover events are triggered by RVT degradation under the proposed method in the

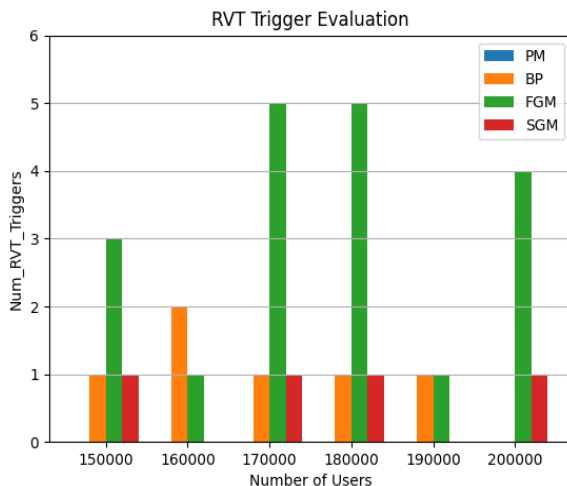


Fig. 8. Number of RVT triggers in terms of the number of users

conducted experiments.

Reducing handovers triggered by RVT degradation provides several important advantages. First, it enhances link stability by prolonging the connection duration between user agents and satellites, thereby improving communication continuity. Second, fewer RVT-induced handovers directly decrease control-plane signaling overhead, mitigating the risk of signaling storms in dense user scenarios. Third, lowering the handover frequency reduces processing burden on both satellites and ground control entities, leading to improved resource utilization and system scalability. Consequently, optimizing RVT not only improves user-level quality of service but also enhances overall network efficiency and robustness in high-mobility LEO satellite environments.

V. LIMITATIONS AND FUTURE DIRECTIONS

Here are some limitations of the proposed method:

- In the proposed method, user dynamics are ignored and will be addressed in future research.
- Signal Strength is not considered in the proposed method. Hence, the current multi-objective optimization problem will be extended in a way to include parameters such as Reference Signal Received Power (RSRP).
- Quality-of-Service requirements do not affect the handover decision in the current version and are considered as one future direction.
- Uncertainties, such as user behavior, affect the handover rate and consequently aggravate the signaling storm. Hence, in the future, such uncertainties are considered by developing a reinforcement learning-based model for handover management and signaling storm optimization.

Based on the mentioned drawbacks, the proposed method is supposed to be extended as follows:

- Enhancing the proposed method to improve the accuracy of handover policies with respect to dynamicity and RSRP.
- Developing an application-specific Quality-Of-Service-aware model for handover management.
- Implementing a reinforcement learning-based method to cover user's dynamic behavior and varying traffic patterns.

VI. CONCLUSION AND FUTURE WORK

In this paper, a meta-heuristic-based group handover framework was proposed for LEO satellite-assisted 5G networks. The handover optimization problem was formulated as a mixed integer linear programming MILP model, which is NP-hard due to its combinatorial nature and integer decision variables. To efficiently address the problem's computational complexity, a simulated annealing-based optimization approach was developed to obtain high-quality, near-optimal solutions. The proposed method intelligently selects target satellites by considering handover rate, signaling overhead,

satellite load balancing, and remaining visibility time. Simulation results demonstrated that the proposed framework significantly reduces consecutive handovers and signaling storms while improving load distribution.

Future work will focus on extending the proposed framework to dynamic multi-layer satellite architectures, including integrated LEO–MEO–GEO systems. Moreover, incorporating traffic-aware and Quality-of-Service--aware decision metrics, as well as investigating learning-based adaptive handover strategies for highly time-varying environments, constitutes an important direction for further research. The feasibility and scalability of real-time implementation in large-scale deployments will also be considered in future studies.

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CONFLICTS OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this article.

AUTHORS CONTRIBUTION STATEMENT

The author has contributed to the whole research and preparation of the manuscript.

AI DISCLOSURE

An AI-based language model, ChatGPT (OpenAI, San Francisco, CA, USA), was used solely to improve readability and expression. Final responsibility for the accuracy and integrity of the content rests entirely with the authors.

DATA AVAILABILITY

All data generated or analyzed during this study are included in this published article.

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