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Handover Strategy Based on Bipartite Graph and Hysteresis Margin in LEO Satellite

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
Génie électrique

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Ce mémoire intitulé :

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présenté par **Sahar EYDIAN**
en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*
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Jean-François FRIGON, président
Gunes KARABULUT KURT, membre et directrice de recherche
Waël JAAFAR, membre

DEDICATION

To my parents, Maryam and Mohsen…

ACKNOWLEDGEMENTS

I am sincerely grateful to the individuals listed below since their support was vital to the successful completion of my research and my master's degree. I express my profound gratitude to my supervisor, Professor Gunes Karabulut Kurt, whose deep insight and guidance in the field of study directed me throughout this research.

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RÉSUMÉ

Le mémoire présente une stratégie de transfert ("handover"; HO) innovante pour l'intégration des réseaux terrestres ("terrestrial network"; TN) avec des satellites en orbite terrestre basse ("low Earth orbit"; LEO), abordant le défi de maintenir une communication de haute qualité avec une fréquence de HO minimale. En utilisant un cadre de graphe bipartite et l'algorithme de Kuhn-Munkres (KM), l'approche garantit la qualité des liaisons et des appariements de poids maximum uniques pour chaque station passerelle et satellite, favorisant l'équilibrage de charge. Une marge d'hystérésis ("hysteresis margin"; HM) est mise en œuvre pour réduire le fréquent de HOs en modifiant l'algorithme pour prioriser les connexions existantes dans des circonstances spécifiques. Les résultats de simulation démontrent une réduction significative de la fréquence de HO - jusqu'à 40% - avec un impact minimal sur le débit et la qualité des données, atteignant des débits élevés avec une marge de 3 dB. La stratégie équilibre efficacement la continuité et la stabilité du service, améliorant la qualité de service ("quality of service"; QoS). De plus, nos résultats indiquent une performance améliorée sous diverses conditions de signal, comme le montrent les simulations avec facteur K de Rician variable. La stratégie proposée démontre également une efficacité économique en réduisant les coûts de HO. L'analyse des coûts de HO a montré que la stratégie proposée équilibre efficacement la qualité du service et les dépenses opérationnelles, en particulier avec une marge de 3 dB, tout en maintenant des débits élevés et gérant les coûts plus efficacement que les stratégies existantes. Ces résultats soulignent le potentiel de la stratégie proposée pour des applications futures dans les systèmes intégrés de réseaux terrestres et de satellites LEO, offrant une solution robuste aux défis de la mobilité dans les communications par satellite, conformément aux normes du Projet de partenariat de troisième génération ("3rd Generation Partnership Project"; 3GPP).

ABSTRACT

This thesis presents an innovative handover (HO) strategy for integrating terrestrial network (TN) with low Earth orbit (LEO) satellites, addressing the challenge to maintain high-quality communication with minimal HO frequency. Utilizing a bigraph framework and the Kuhn-Munkres (KM) technique, the approach ensures link quality and unique maximum weight matches for each gateway station and satellite, promoting load balancing. A hysteresis margin (HM) is implemented to reduce frequent HO by modifying the algorithm to prioritize existing connections under specific circumstances.

The simulation findings indicate a significant decrease in HO frequency—up to 40%—with minimal impact on data rate and quality, achieving high data rates with a 3 dB margin. The strategy effectively balances service continuity and stability, enhancing the quality of service (QoS). Additionally, our simulation results indicate improved performance under diverse signal conditions, as shown by varying Rician K-factor values. The proposed strategy also demonstrates cost efficiency by reducing HO costs. The HO cost analysis showed that the proposed strategy effectively balances service quality and operational expenses, particularly with a 3 dB margin, by maintaining high data rates and managing costs more efficiently than existing strategies. These findings underscore the potential of the proposed strategy for future applications in integrated terrestrial and LEO satellite systems, offering a robust solution to the mobility challenges in satellite communications, aligning with 3rd Generation Partnership Project (3GPP) standards.

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LIST OF SYMBOLS AND ABBREVIATIONS

5G	Fifth Generation
6G	Sixth Generation
QoS	Quality of Service
TN	Terrestrial Network
NTN	Non-Terrestrial Network
3GPP	3rd Generation Partnership Project
GEO	Geostationary Earth Orbit
MEO	Medium Earth Orbit
LEO	Low Earth Orbit
NGSO	Non-Geostationary Orbit
HAPSs	High-Altitude Platform Systems
UAVs	Unmanned Aerial Vehicles
UE	User Equipment
NR	New Radio
ISL	Inter-Satellite Link
RSS	Received Signal Strength
RSRP	Reference Signal Received Power
HO	Handover
TTT	Time-to-Trigger
HM	Hysteresis Margin
KM	Kuhn-Munkres
SNR	Signal-to-Noise Ratio
ECEF	Earth-Centered, Earth-Fixed

CHAPTER 1 INTRODUCTION

The telecommunications landscape is rapidly evolving, driven by an exponential increase in connected intelligent devices and the escalating demand for novel services characterized by strict quality of service (QoS) standards. Such needs are coupled with the imperative for ubiquitous connectivity, presenting critical challenges for terrestrial telecommunications networks. Despite significant advancements in Internet accessibility, a considerable part of the global population remains disconnected, with 67% of the world's population having Internet access. As a result, it leaves around 2.6 billion individuals offline [1]. Existing limitations of terrestrial network (TN) highlight a critical coverage gap, especially in economically unfeasible and remote regions where fibre-optic infrastructure is impossible. Furthermore, even well-equipped urban centers are vulnerable to disruptions, such as those caused by natural disasters. Thus, complicated radio resource management techniques employed by modern cellular architectures can compromise [2]. Another factor that emphasizes this trend is the increase in wireless communication applications, which is anticipated to connect up to 500 billion devices by 2030 [3]. It highlights the insufficiency of terrestrial infrastructure alone to meet the different service demands and achieve global ubiquitous communication [4]. To address these challenges, integrating non-terrestrial network (NTN) with TN offers a promising solution that enhances coverage and reliability.

The role of 3rd Generation Partnership Project (3GPP) in advancing NTNs integration is principal. 3GPP defines, [5] an NTN as operating either partially or fully for communication purposes using platforms such as geostationary Earth orbit (GEO) and non-geostationary orbit (NGSO) satellites alongside airborne platforms like high-altitude platform systems (HAPSs) and unmanned aerial vehicles (UAVs). Since Release 15 (Rel-15), 3GPP has initiated research on utilizing these platforms to enhance network stability for ground equipment [6]. This mission continued with the adaptations in Release 16 (Rel-16), [7] to improve and enable NTN functionalities through the fifth generation (5G) New Radio (NR). These efforts have significantly extended the potential for global network coverage, creating NTNs as a fundamental component for future network developments and improving connectivity in traditionally under-served regions.

1.1 Satellite Communications as a Pillar of NTNs

Satellite communications are crucial in overcoming the inherent limitations of terrestrial mobile communication networks, providing valuable key advantages for expanding global connectivity.

These systems offer extensive coverage, high flexibility to physical damage, and insensitivity to Earth and natural disasters, making them essential for reaching remote areas [8]. As a result, satellite technology is fundamental in providing ubiquitous and reliable 5G services worldwide, representing a significant evolution in network infrastructure [9]. Satellite networks are extensively utilized across various sectors [10], including military operations, disaster response, digital television, broadcasting, and mobile communications. The remarkable adaptability of satellite communications ensures stable connectivity, even under the most challenging conditions. This strong capability positions satellite communications as a core component in developing advanced network systems, potentially integrating with sixth generation (6G) wireless technology to enhance global network integration and service delivery [11].

1.1.1 Characterization of Satellite Communications Types

Satellites are primarily categorized by their orbital positions as illustrated in Figure 1.1, each type offering distinct benefits and suited for different applications:

GEO: Positioned at an altitude of around 35,786 km over the equatorial plane, GEO satellites maintain a constant position relative to the Earth. This characteristic makes them ideal for applications requiring a wide, stable coverage area, such as broadcast services and weather monitoring [8], [12]. Their expansive footprint, usually about 200 to 3500 km, enables them to provide coverage for a significant part of the Earth's surface [7].

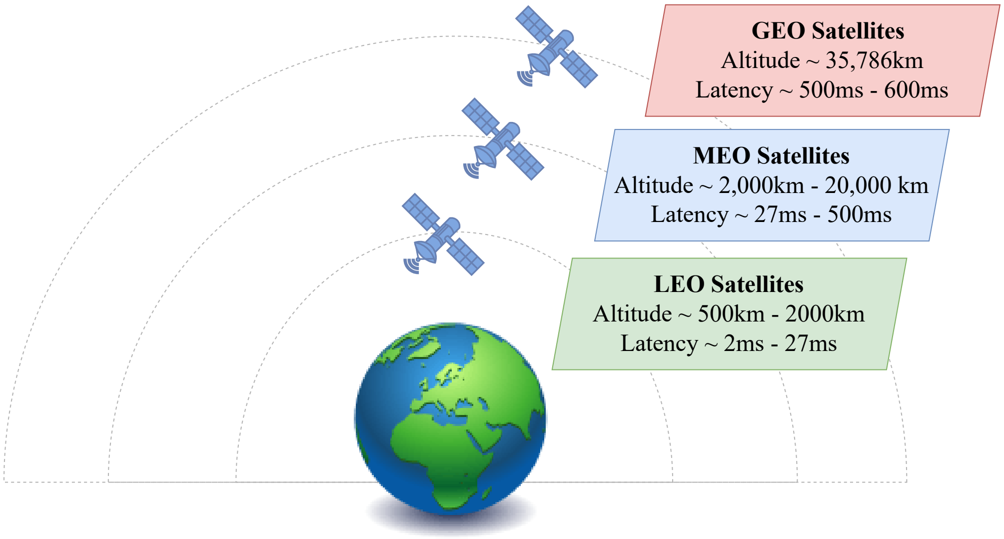


Figure 1.1 Satellite orbits (Inspired from [12]).

NGSO: It refers to the satellites operating at lower altitudes, including low Earth orbit (LEO) and medium Earth orbit (MEO). This is because their rotational velocity surpasses Earth's, making them visible as objects in motion to an observer on the ground. Their orbits are circular or elliptical, and their altitudes range from 2,000 to 20,000 km for MEO and 500 to 2,000 km for LEO. The average size of their beam footprint varies between 100 km and 1000 km [13]. Their lower altitudes reduce communication delays and may lead to higher data rates, making them well-suited for Internet services, mobile broadband, and Internet of Things (IoT) applications. However, due to their rapid motion, a constellation of satellites is required to ensure continuous coverage.

LEO satellites, utilized in various communication and network applications, are distinguished by minimal transmission attenuation and propagation delay. This characteristic ensures a broader spectrum of communication services and precise system control [14]. Their small size and lower launch power requirements decrease operational costs. In recent years, the demand for broadband connectivity has grown with massive constellations like Starlink offering low-latency (under 30 milliseconds), high-data-rate (exceeding 100 Mb/s) satellite broadband services to unreachable areas [15]. This architecture fundamentally transforms traditional communication networks by enabling network scalability and providing continuous service, wide coverage, as well as availability for crucial communications and developing applications.

1.2 Mobility Challenges in LEO Satellite Networks

Although LEO satellite deployments offer unique advantages, these networks marked by high mobility and a challenging signal propagation present compromise to certain aspects of the existing 5G protocols. Figure 1.2 illustrates that the coverage areas of each satellite can be partitioned as small cells (also known as spot beams) to facilitate the reusing of frequencies within each satellite's footprint. These spot beams are significantly smaller than the overall footprints; thereby, a spot beam is typically visible for only about 1 to 2 minutes [16]. These challenges mainly affect radio mobility management, a critical mechanism responsible for maintaining continuous, high-quality, reliable communication and service when users move among cells [17]. The role of mobility management becomes even more critical in 5G systems and needs to be studied carefully since many applications are highly dependent on network connectivity [18].

Generally, handover (HO) acts as a principal function of mobility management in wireless communication networks. HO allows the user equipment (UE) to move freely and switch between different serving cells without any interruption or losing the connection. The rapid motion in LEO satellites results in frequent HOs between satellites and beams. Mobility

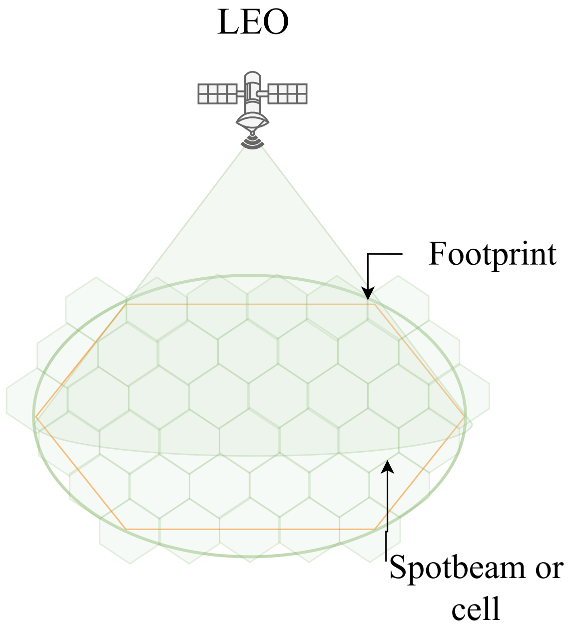


FIGURE 1.2 The spotbeams in a satellite footprint.

creates significant challenges within TN as well, such as Doppler spreading, the time-selective nature of channels, and an increase in HO events [19]. These challenges are worse in the context of LEO satellites, where the operational dynamics introduce additional complexity. Their footprint can change with velocities of 7.56 km/s [7], which are far beyond the mobility of any ground users. For instance, consider high-speed trains, which typically move with velocities of around 0.14 km/s. At this speed, LEO satellite completes one orbit around the Earth in approximately 100 minutes, resulting in any single satellite being "in view" of terrestrial equipment such as gateway stations, only a few minutes [20]. Since the footprint of a LEO satellite is constantly changing, implementation of HOs is essential to maintain uninterrupted connectivity.

1.3 Handover in LEO Satellite Networks

Providing seamless network connectivity requires advanced HO mechanisms since LEO satellites have rapid movement and varying speeds. This section first categorizes the types of HO prevalent in LEO networks and then explores the associated challenges that complicate maintaining high QoS standards.

1.3.1 Types of Handovers

Link-layer HOs in LEO satellite communications are essential for continuous service and can be broadly categorized into three types [4], [21], as shown in Figure 1.3.

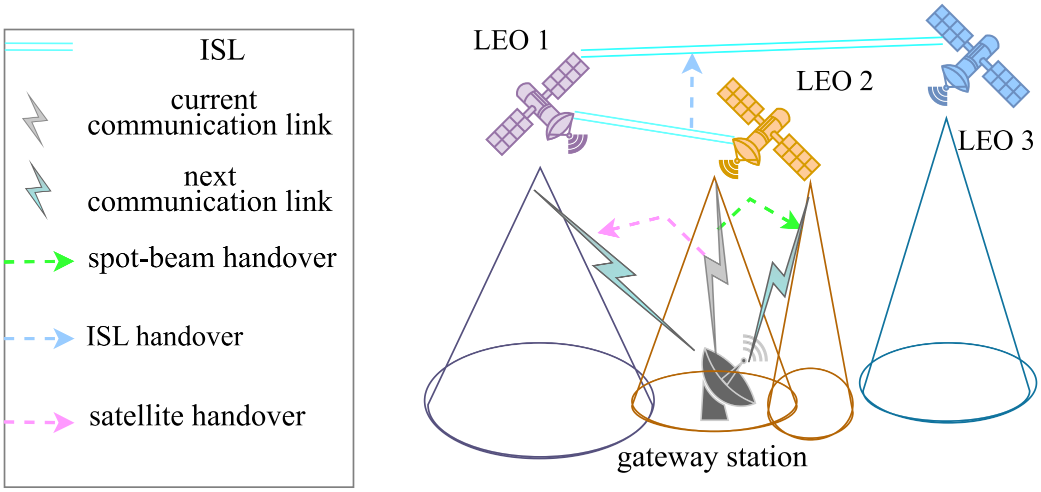


FIGURE 1.3 Handover categories in LEO satellite network.

— **Spot-beam handover (Intra-satellite):** Occurs within the same satellite when an end-user moves out of one spot-beam's coverage into another. This type of HO is necessary for managing the local capacity and coverage within a single satellite's service area.

— **Inter-satellite link (ISL) handover:** Involves switching the communication link between satellites in different orbital planes, often due to changes in distance or viewing angles.

— **Satellite handover (Inter-satellite):** This thesis focuses on satellite HO, where the communication link between ground and satellite is transferred from current satellite to another due to the serving satellite moving out of view. There are multiple strategies for spot-beam handover, and the solutions are pretty advanced. However, satellite handover has received less focus in the research community than spot-beam handover. With the increasing number of LEO satellites orbiting the Earth and more satellites being visible to users simultaneously, investigating satellite handover in LEO networks has become increasingly important. This type is critical for ensuring broader network continuity and is more challenging because of the rapid movement in LEO satellites.

1.3.2 LEO Satellite Handover Challenges

The brief presence of LEO satellites within the service range of gateway stations limits their functionality, as they are usually available for shorter duration than ongoing transmissions. In order to ensure uninterrupted communication, once the current satellite is no longer able to provide services to the gateway station, it is necessary to HO the communication link to another visible satellite as shown in Figure 1.4. According to the LEO satellite features, gateway stations usually fall within the multiple satellite coverage at a particular time [22]. This overlapping coverage requires careful selection among visible satellites at the beginning of a HO or a new call to ensure continuous network connectivity.

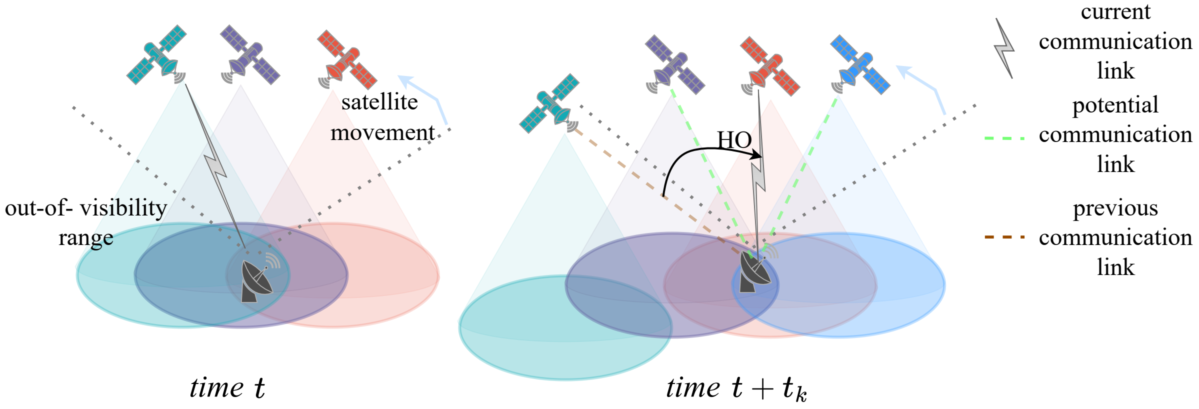


FIGURE 1.4 Illustration of consecutive times t and $t + t_k$, where handover is executed under multi LEO satellite coverage.

However, the process of satellite HO introduces several significant challenges [22], [8], [23]:

- Satellite load: Efficiently distributing the communication load among available satellites to prevent any single satellite from becoming overloaded, which can degrade service quality.
- Unnecessary HOs: Avoiding frequent and repetitive HOs and minimizing HOs to improve the network performance, thereby reducing resource wastage.
- Communication quality: Ensuring the HO decision prioritizes satellites that can offer superior channel quality to maintain high data transmission rates and reduce the likelihood of transmission errors.
- HO cost: In LEO satellite networks, when a gateway station switches from one satellite to another, it can lead to additional data transmissions and increased resource management

tasks. The network HO cost involves the process of acquiring and tracking a new path and managing session HOs at higher network layers. This cost is impacted by factors such as the HO strategy and the network's topology. Lowering HO costs not only reduces the financial burden on both the service provider and the user but also enhances network efficiency. It ensures that a greater proportion of the network's throughput is used for direct data routing rather than for intermediate routing among other satellites, thus improving data rates and potentially lowering prices for users.

— Signaling overhead: Decreasing the signalling traffic required for the HOs management puts the network infrastructure under pressure and reduces the available bandwidth for actual data traffic.

— Transmission loss and delay: Addressing the possibility for data loss and increased latency that may occur during HOs. These issues hurt user experience, especially for real-time applications.

Therefore, designing an effective HO strategy for LEO satellites is crucial. It should not only minimize the frequency and impact of HOs but also balance satellite load and ensure high communication quality. Hence, HO decision should consider multiple criteria to meet QoS requirements.

HO challenges are further complicated in environments influenced by the large cell footprints of satellites, which usually cover multiple countries and regulatory jurisdictions. This broad coverage, inherent satellite mobility, and long propagation delays can result in continuous service disruptions. Although solutions have been proposed, such as executing HOs based on specific triggering criteria like location or timing advance, these are primarily designed to limit control traffic rather than enhance overall HO quality [23], [8]. Hence, the lack of comprehensive strategy development and quantitative assessment means that the impact on user link performance remains largely unexplored.

1.3.3 Traditional Handover Strategy

In the domain of LEO satellite communications, ensuring seamless HO between satellites is most important to preserve service continuity and quality. Traditional HO strategies mainly utilize measurement-based approaches [24], where quantitative metrics, including reference signal received power (RSRP), control the decision-making process. Although measurement-based strategies are fundamental, they lead to challenges such as frequent HOs due to their sensitivity to minor fluctuations in signal strength [25]. Therefore, increased signalling overhead and a decline in the user experience may impact the network infrastructure. Additionally, these strategies fail to consider complex scenarios where various network conditions or user behaviours might impact the optimal HO decision. Such complexities can result in service disruptions or inefficiencies. Historical strategies have considered various factors such as service time, channel status, minimum distance to the satellite, Doppler shifts, and dual satellite diversity during critical conditions [4]. However, these approaches developed in the context of smaller or hypothetical legacy LEO constellations such as Globalstar, Teledesic, and Iridium. These methodologies usually focus on outdated performance indicators like call blocking probability, unsuitable for modern network demands where throughput and delay are critical.

1.3.4 Handover Control Mechanisms

In LEO satellite communication networks, HO control mechanisms consist of various techniques and parameters designed to monitor and control the HO process [26]. These mechanisms facilitate the seamless HO of a gateway station's connection from one satellite to another. They are crucial for ensuring uninterrupted and stable communication, maintaining continuous service without disruptions. Typically, the HO process involves steps of measurement, decision, and execution [27].

Measurement Mechanisms

The network configures the gateway station to conduct periodic measurements on specific cells and to submit measurement reports once predefined conditions are met. Upon receipt of a measurement report, the network might initiate various actions such as a HO, disconnection, or new measurement instructions. The initiation of a HO typically depends on the timing of the report's generation at the gateway station and the time required for the report to be transmitted to the network [26]. There are various measurement criteria, including RSRP, distance, quality, traffic volume, etc. Furthermore, different measurement events determine the timing and conditions under which reports are generated and how the network responds [28]. A typical event for initiating HOs is the A3 event [24], which ensures the gateway station remains linked to the cell that has the most robust signal. In the gateway station, the A3 event triggers a measurement report if the RSRP in the candidate cell surpasses the RSRP in the source cell for a specified duration.

Decision Mechanisms

To enhance the stability of HO decisions, control mechanisms and factors, including thresholds, time-to-trigger (TTT), and hysteresis margin (HM) are integrated into the measurement step.

Using relative RSRP with a fixed threshold helps to minimize unnecessary HOs. A HO is triggered only when the signal of the serving satellite drops under a predefined threshold and the signal of the target satellite is stronger. In contrast, HM is a crucial control mechanism in HO strategies, enhancing connection stability and reliability in dynamic environments like LEO satellite networks [28].

HM operates by setting a buffer threshold where the signal quality of the current cell should significantly and consistently drop to initiate a HO event [24]. In other words, when using a relative RSRP with a HM, the HO occurs only if the potential satellite signal becomes stronger in comparison with the current satellite by a designated HM. The connection will continue with the target satellite until its signal falls below the margin [29]. This threshold is set higher than the usual HO trigger point, ensuring that minor fluctuations in signal quality cannot lead to unnecessary HOs [30]. Therefore, it prevents unexpected HO to other satellites, maintaining a reliable and stable connection within the dynamic conditions and rapid motion of satellites. This is especially valuable in LEO networks, where the high mobility of satellites makes it challenging to maintain high service quality.

To provide a more thorough comprehension of the application and role of control mechanisms, particularly the HM, we will examine the A3 measurement event. In the A3 event, a HO from the source cell to the target cell is triggered when the RSRP in the target cell is HO-margin greater than the RSRP in the source cell for TTT [24]. Figure 1.5 describes the process of HO in A3 event. Point A indicates the moment that the target cell signal meets the condition for starting the A3 event, and it should continue for a specific time, which is equal to TTT. Finally, point C indicates the moment that HO has been completed.

Nevertheless, using these control mechanisms alone may present their unique difficulties. For example, overly conservative settings might delay necessary HOs, compromising the service quality during critical moments. On the other hand, insufficient control settings might not correctly reduce the issue of frequent and unnecessary HOs, thereby failing to address the core challenge of optimizing network resource usage and user experience.

1.3.5 Handover Decision Criteria

HO strategies used in LEO satellite networks commonly focus on criteria including service time, available channels, and elevation angle. While the maximum service time approach seeks to minimize HO frequency, it can result in an unbalanced distribution of satellite loads and decrease channel quality [23]. Strategies that prioritize the maximum number of idle satellite channels may lead to suboptimal satellite-Earth distances, thus risking the quality of service and increasing HO events [25]. In addition, exclusively considering the elevation angle can

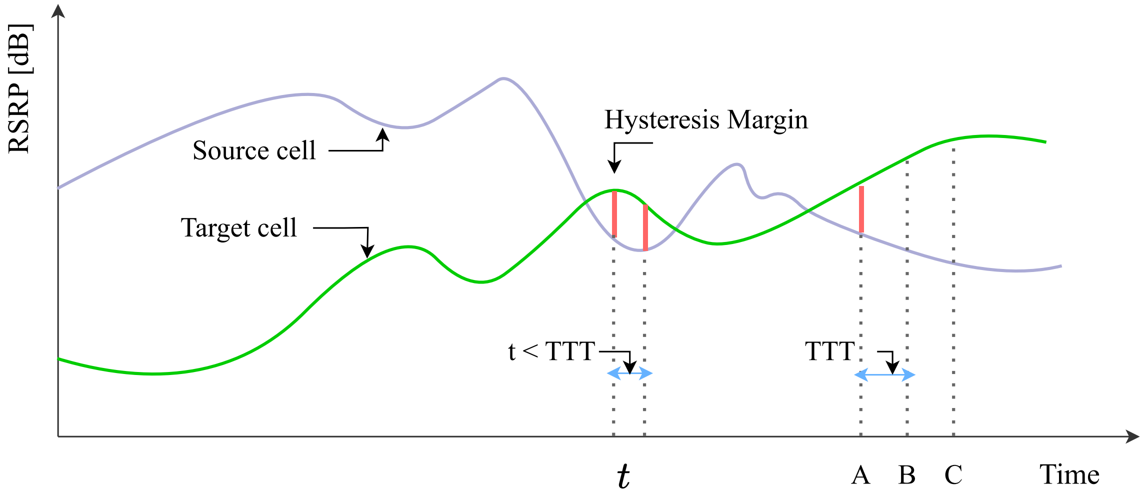


FIGURE 1.5 The A3 measurement event and HM application in handover process.

lead to the overload of certain satellites and an increase in the frequency of HOs [31]. Given these complexities, there is a pressing need for a more intelligent HO strategy. Such a strategy should enable gateway stations to select the best satellite from multiple candidates at any given time, profiting from satellite diversity to enhance service quality and prevent satellite overload. The process of selecting a candidate satellite and making decisions in satellite HO is complex. In response to the limitations of single-criterion and simple control mechanisms, recent strategies incorporate multi-attribute and conditional approaches to HO decisions.

With the emerging of 5G networks, the complexity of executing HOs escalates, mainly when utilizing high-frequency bands (like millimetre-wave) and ultradense small cells [32]. These frequency spectrums offer a wider bandwidth for utilization, thus enhancing the overall capacity of networks and reusing frequency. Nevertheless, the path loss of these frequency bands is high, which leads to a rise of ground stations with a reduced area of coverage [30]. These factors intensively increase the number of frequent HOs with growing HO probability [25]. However, the efficiency and seamlessness of the HO process are crucial, considering the stringent requirements of many applications for low latency and aiming to avoid link failures.

Frequent HOs not only compromise the capability of LEO satellite systems to guarantee user QoS, but also result in the inefficient utilization of radio resources and an increase in HO cost. Moreover, when gateway stations are covered by a common satellite, the competition between them for available channels can lead to a high imbalanced load as satellites have a limited channel budget [33]. Thus, in order to balance satellite load and prevent HO failures while maintaining a low signalling overhead, a distributed satellite HO strategy is essential.

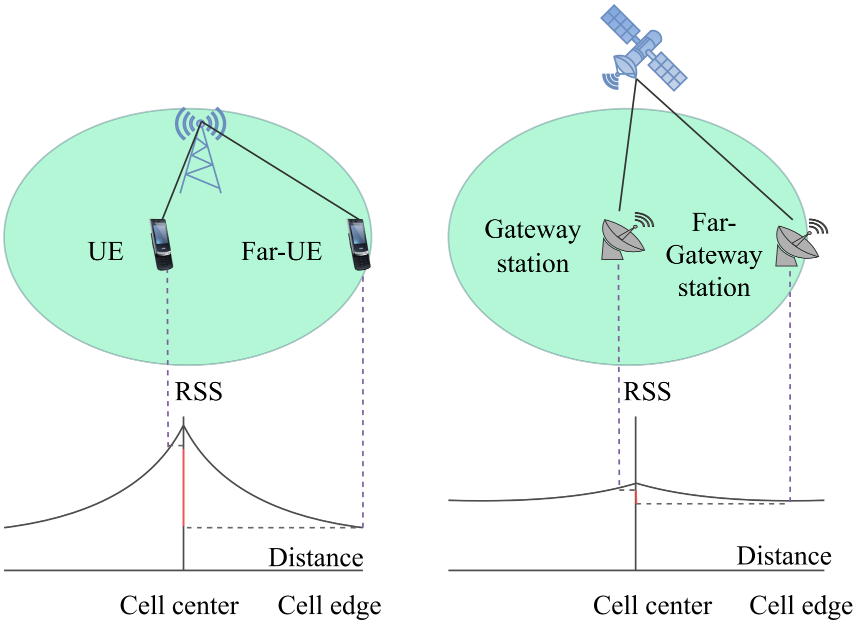


Figure 1.6 Signal strength variations in TN and NTN (Inspired from [6]).

Furthermore, the signal propagation distance between a satellite and the ground may be significantly greater than the satellite footprint [34]. Therefore, this would lead to a decrease in the variation of received signal strength (RSS) within satellite networks compared with TN [7]. In TN, a UE can initiate HO due to an apparent change in RSS as it moves from the cell center to its edge [6]. As shown in Figure 1.6, this variation in signal strength is considerably less apparent in NTN, resulting in a small difference in signal strength when two or more satellite beams overlap [35]. Direct mirroring of the HO mechanism from TN into NTN without any modifications could make it difficult for UE to identify a better target [29]. Therefore, designing more efficient HO conditions in the NTN is necessary.

The subsequent sections will provide the countribution and motivation behind this research, the specific problems that have been addressed and the objectives of proposed HO strategy in LEO satellite networks.

1.4 Motivations

In response to the growing requirements and overcome the mobility challenges throughout the 5G NR evolution, the concept of conditional HO was introduced and defined in the 3GPP Rel-16, aimed to reduce the connection and HO failures in a dynamic scenario.

While conventional HO involves a direct switch to a target cell, conditional HO enables the preparation of several candidate satellites or cells for the gateway station to monitor and select the most appropriate candidate [36]. Hence, the application of conditional HO in NTN is investigated for improving mobility during the development of the HO solution for satellite communications [7]. Given the predictable nature of LEO satellite trajectories, it is logical for the gateway station to simply implement a conditional HO strategy based on location. This strategy involves monitoring the distance between the gateway and the satellite as a condition using ephemeris data. However, the gateway station may initiate HO to a low-quality link if the conditional HO criteria are limited to distance or elevation angle without simultaneously monitoring radio condition [6]. Within NTNs frameworks, the communication link quality between ground and satellite can be affected by factors such as elevation angle, satellite load, system loss, and geographic conditions.

Therefore, the HO strategy to monitor conditions of candidate satellites should satisfy the principal requirements such as high link quality and decreasing frequent HO. Unstable link quality and frequent HOs result in increased signalling overheads and interruption throughout the service duration, thereby compromising QoS [20]. In particular, it is crucial to develop an intelligent satellite HO strategy that improves the service link's quality, addresses satellite load balancing, and reduces frequent HO.

Motivated by the above facts and considerations, this thesis proposes an intelligent HO strategy that utilizes a bipartite graph model with channel gains as weights and applies the Kuhn-Munkres (KM) algorithm to achieve best matching based on maximum weight. Thus, this approach guarantees high-quality communication and efficient load distribution. However, this inherently results in selecting satellites with high link quality at the cost of frequent HO. The proposed strategy implements a threshold mechanism within the KM algorithm by integrating a HM. This mechanism postpones the HO decision until the advantages of switching to a different satellite surpass the associated costs without compromising link quality. As a result, our strategy effectively reduces unnecessary HOs and further improves the network's performance. This methodology emphasizes the need for a dynamic assessment of multiple network aspects to enhance performance and user satisfaction across the rapidly changing domain of global satellite communications.

1.5 Objectives and Contributions

This thesis focuses on the LEO satellite HO strategy and proposes a HO strategy aiming to enhance communication link quality, reduce the number of satellite HOs, and balance satellite load. The proposed HO strategy successfully achieved the trade-off among data rate and HO frequency. Moreover, we obtained balanced satellite loads and an overall enhancement in the link quality with the proposed approach. We utilize the bipartite graph framework and KM algorithm to find maximum weight matching for HO.

The primary contributions and results of this thesis with details can be found below:

- We modeled the HO process between gateway station and LEO satellite. A bipartite graph is used to represent the connection link between gateway stations and LEO satellites at any time slot. One set of vertices in the bipartite graph displays all LEO satellites, while the other set displays all gateway stations. Furthermore, the edges in this graph indicate the communications link between the gateway stations and the LEO satellites. We consider channel gain as the weight of the communication link between a specific satellite and gateway station at a certain time.
- To maximize the overall communication quality, the KM algorithm is applied to investigate the maximum weight matching method. Besides, satellite load balancing is achieved using the KM algorithm to prevent multiple gateway stations from selecting the same target as the next serving satellite at the HO time.
- To minimize HO frequent, we introduce a HM condition and hysteresis factor to adjust the HO selection process, aiming to enhance network stability without compromising link quality. In addition, due to the flexibility of our HO strategy with adjusting HM and hysteresis factor, it can meet different needs based on the area's demand, technology, and network operators for higher data rates or lower latency. On the other hand, reducing the HO frequency in our strategy leads to reduced HO cost, which could potentially be advantageous for operators.

1.6 Thesis Organization

Chapter 2 reviews the development process and recent studies in LEO satellite HO strategies, such as various criteria and methods used in existing research. Chapter 3 details the system model, introducing the proposed HO strategy that utilizes bipartite graph matrices and incorporates HM. Additionally, it outlines the performance metrics used to evaluate the strategy, including average data rate, HO frequency, Rician K-factor, and HO cost. Chapter 4 provides the numerical findings from simulations, validating the proposed strategy's effectiveness. Chapter 5 concludes with a summary of findings, limitations, and future work directions.

CHAPTER 2 LITERATURE REVIEW

Location management and HO control are the two major aspects of mobility management in satellite communication networks. The dual motion of UE and satellites require continuous execution of both spot beam HOs [37] and satellite HOs to ensure seamless and uninterrupted service. Given the criticality of guaranteeing stable and continuous service for the deployment of 6G and global connectivity in the future of LEO satellite communication, the following review will concentrate on the recent developments to LEO satellite HOs. This research area has received considerable attention in recent studies.

2.1 Historical LEO Satellite Handover

Since the 1990s, various research studies in the literature have explored HO mechanisms in LEO satellite networks. This interest was driven by the emergence of NGSO satellite constellations, such as projects of the Globalstar and Iridium [38], [32]. Despite their innovative nature, these constellations were unsuccessful due to their high launch costs, uneconomic viability, and immature technologies [22]. However, in recent years, the appearance of projects like OneWeb and Starlink has generated a new level of interest in offering ubiquitous Internet from space. This interest was further stronger by the 3GPP reported in Release-16, which included a study on integrating satellite systems into existing telecommunications networks [5], leading to a significant increase in research activities in this domain.

In the field of 5G networks, various functions related to mobility management have been established and developed in an effort to address challenges associated with mobility issues [39–43]. Mobility management is essential for an efficient HO process and involves the optimization of HO control parameters. However, the traditional measurement-based HO mechanisms may lose effectiveness in NTNs due to reduced RSS variation, leading to challenges in ensuring reliable service continuity in LEO satellites. For enhancing mobility efficiency, the 3GPP has proposed considering additional triggering criteria that take into account the gateway's location and the satellite's trajectory [7].

2.2 Handover Criteria and Methods

As satellites in different orbital planes overlap in coverage within a common terrestrial area, users have the opportunity to select between multiple satellites when a HO is required. Several satellite HO approaches have been presented in the literature utilizing different decision criteria. Furthermore, the criteria and methods considered in HO decisions primarily include maximum service time, elevation angle, system loss, HO failure, signal strength, and latency. Several methods were developed and implemented to improve the mentioned metrics in satellite HO, with each method concentrating on improving a different aspect of the HO process. Table 2.1 represents an overview of satellite handover methods.

TABLE 2.1 Overview of satellite HO methods.

Method	**Reference**
Graph theory	[31]- [44–49]
Learning algorithm	[30], [23], [33, 50]
Architecture and protocols design	[51–53]
HO schemes design	[54]
Decision technique	[55, 56]
Game theory	[45]- [47]

Some efforts of recent literature in satellite HO strategies have been enumerated in Table 2.2; these HO decisions involve aspects of metrics and methods, which we investigate in detail in a subsequent section.

2.3 Decision Criteria-Based Strategies

In satellite communication networks, these satellite HO criteria significantly impact the QoS of the gateway stations. For instance, the maximum service time significantly impacts the number of satellite HOs and minimizes the number of HOs [23]. The maximum satellite elevation angle can achieve high communication quality. The strongest signal strength maintains high communication quality and system stability and guarantees service quality [25]. Additionally, the total available channels which a satellite can provide might impact the overall network performance and facilitate load balancing in the system [30]. Through using the shortest distance criteria, the selection of satellites is optimized to reduce the risk of link failures by choosing the nearest satellite. The mentioned evaluation criteria can generate the other evaluation criteria. However, most research considered a specific HO criterion, resulting in a lack of a comprehensive solution that could consider all the HO factors. The decision strategies based on criteria focus on specific measurable or estimable metrics to decide on HOs.

2.3.1 Signal Strength Strategy

The RSS has been broadly discussed in the literature as one of the most prevalent metrics. In [57], authors propose a hybrid adaptive HO scheme that optimizes decisions for NGSO satellite systems by utilizing real-time signal strength and channel conditions. Although the scheme aims to minimize service disruptions and optimize network resources, it fails to consider critical elements such as satellite load and user density. These gaps may significantly impact the network's overall performance. The study in [58] employs fuzzy logic to optimize HO parameters based on user mobility and signal strength. It effectively decreases unnecessary HOs and enhances throughput, preventing the ping-pong effect. However, lacking load balancing considerations might lead to potential QoS reductions when network traffic distribution is inappropriate. Additionally, the complexity of the approach and dependence on accurate user mobility modelling could cause challenges in real-world scenarios.

Table 2.2 Recent literature on LEO satellite HO strategies including considered metrics, objects, and methods.

	Category	**Reference**
Objects	Service time	[31]- [46]- [30]- [23]- [56, 59–61]
	Elevation angle	[31], [44, 45], [59]
	Channel status	[31]- [44]- [30]- [23] - [54–56]
	HO failure	[46]- [30]- [33]- [51]- [55]
	HO rate	[44, 45]- [30]- [33, 50]- [56]
	Latency/delay	[44]- [30]- [51, 52]- [55]- [61]
	QoS/QoE	[45]- [47]- [54]
	Load	[47]- [33]- [56, 59]
	Throughput	[51]- [55]
	Buffer	[23]- [54]
	Packet loss	[62]
Methods	Graph-based	[31]- [44–49]
	Learning-based	[30]- [23]- [33, 50]
	Architecture and protocol design	[51–53]- [56]
	Game-based	[45]- [47]
	Optimization	[55]
	Buffering and measurement-based	[54]- [62]

2.3.2 Remaining Service Time Strategy

The strategies that rely on the maximum service time and utilize ephemeris data to measure service time [60], [61] is an effort to highly reduce delay, number of HO, and signalling cost. This strategy considers the remaining service time of a satellite before handing it over to another, as shown in Figure 2.1. For instance, the authors in [60] developed a basic real-time HO technique that leverages the Global Positioning System (GPS) system along with several satellites to reduce the number of HO. Similarly, [61] proposes a distributed HO method that considers the effects of routing. This approach reduces propagation delay while maintaining acceptable HO times. Additionally, [46] proposes a velocity-aware HO prediction technique to identify target satellites that have maximum service duration. Moreover, to improve the reliability of HO prediction and find the shortest path, they proposed a time-extended graph. Although this method minimizes the number of HOs and the failure rate of HO, it doesn't consider the network quality. As a consequence of this oversight, the ability to ensure the QoS for users is compromised.

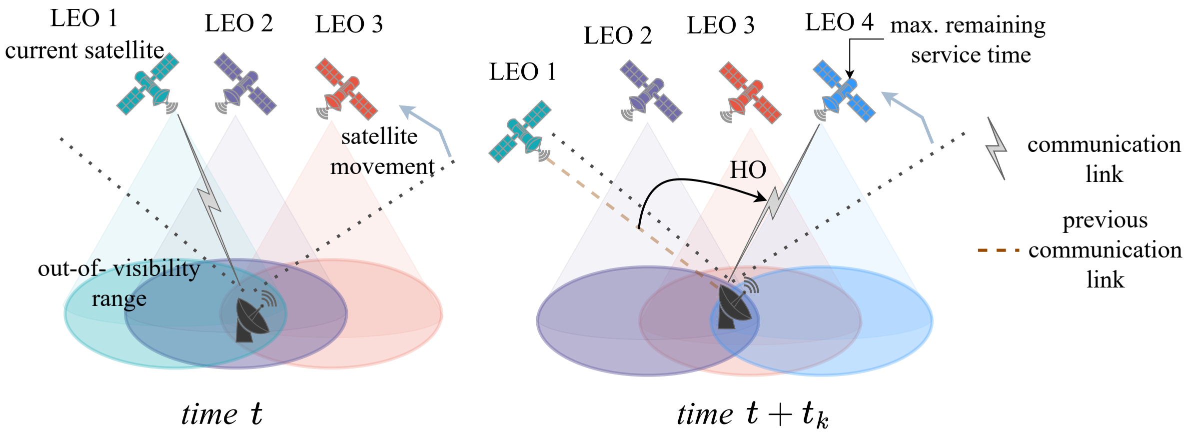


FIGURE 2.1 Illustration of consecutive times t and $t + t_k$, where a HO is performed according to the maximum visibility time of the satellite.

2.3.3 Number of Idle Satellite Channel Strategy

A significant cause of ongoing call drops or blocks is the congestion driven by multi-user competition, which seriously disrupts communication performance. Therefore, some research has utilized the number of channels as a HO decision criteria [59], [63] and has allocated specific and constant channels for transferring the UEs. The maximum idle channels approach prioritizes satellites with the highest channel availability to optimize connectivity, selecting the target satellite that has the most accessible channels. Thus, this approach facilitates balanced load distribution across satellite systems and efficiently utilizes limited network resources. In [63], the authors proposed a dynamic prioritization technique for HO that relies on Doppler to predict the satellite's load. The authors in [64] have employed UE location data to estimate channel requirements; however, with the increasing number of UEs, this method may place major computational demands on satellite resources.

2.3.4 Elevation Angle Strategy

The maximum elevation angle of the satellite about the user or gateway station is considered by this strategy when making HO decisions. The highest elevation angle is used as the primary criteria in [65], [66]. In [66], an approach based on maximum elevation angles as HO decision metrics is proposed for satellite HO, which evaluates and selects the candidate satellite with the highest service time. However, the highest angle that the satellite is placed in relation to the ground equipment may not always indicate the actual quality of the link, resulting in sub-optimal HO performance of the strategy. In [65], the authors proposed a hard HO strategy based on the dual satellite diversity to postpone satellite HO as long as possible. This method can reduce the frequent HOs. However, it does not guarantee call quality, and there is potential to decrease further the number of satellite HOs.

Since the above studies only focus on one aspect and attribute for monitoring and selecting a target satellite, they fail to effectively balance the trade-offs among HO frequency, satellite system load, and communication link quality. In LEO communications, the HO decision is complex and challenging. It is obvious that considering a single factor is not comprehensive. To achieve optimal satellite selection, some researchers assigned weights to various factors. It is essential to carefully investigate various HO strategies for different objectives, leveraging the satellite diversity advantages and ensuring the QoS.

2.4 Handover Methods and Mechanisms

The corresponding HO methods are challenged to offer a comprehensive satellite HO solution due to each HO metric being implemented to address a specific issue. Therefore, many studies prefer to develop mechanisms to consider multi-criteria for satellite HO decision and assign weights to various factors to achieve optimal satellite selection. Several methods and mechanisms have been developed to enhance the metrics in satellite HO; these can be broadly classified into two approaches, as detailed below.

2.4.1 Design and Architectural Approaches

These methods involve broader considerations related to the design of network architecture and HO protocols.

Decision Algorithm

In [55], a comprehensive architecture for managing HO across multiple layers is proposed, along with several methods that rely on HO prediction. These methods can potentially decrease both HO latency and signalling cost. Additionally, they implemented an optimized HO technique that considers channel gains, load flow, and data rate demands.This approach is designed to decrease the HO failure and ensure the QoS for UE. The authors in [56] introduced a strategy for LEO satellite HO and spot beam HO that relies on a multi-attribute decision approach. They integrate three key criteria, including signal strength, remaining service time, and free channels as weight. Based on these criteria, this method selects the satellite with the highest weight and performance, resulting in reduced handover frequency, balanced satellite load, and maintained high signal quality. This approach is designed to decrease the HO failure and ensure the QoS for UE.

Design of Handover Schemes

In [54] the authors presented a HO strategy that buffers user data across multiple satellites, ensuring seamless transitions and optimal link quality through real-time signal measurements and satellite updates. The HO decision considers three criteria: maximal service time, highest elevation angle, and satellite load. This approach significantly outperforms traditional methods, enhancing throughput and reducing delays while smoothly managing satellite switches to maintain stable network operations among high satellite mobility.

2.4.2 Algorithmic and Theoretical Approaches

These methods include more complex computational or theoretical models used to optimize HO processes.

Learning-Based Method

In recent years, the rise of intelligent algorithms and their applications, such as machine learning, has increased interest in utilizing them within satellite communication networks. Therefore, some studies have investigated the application of these algorithms for HO decisions optimization and improvement in LEO satellite HO [23], [30,33], [50]. In [30], authors developed a quality of experience (QoE)-driven intelligent HO algorithm that uses reinforcement learning to optimize mobile satellite network HOs by considering factors like service time and channel resources. This approach, which predicts user and satellite motion, significantly improves HO success rates, reduces delays and minimizes communication disruptions. The authors in [33] proposed a load-aware satellite HO method that utilizes a multi-agent Q-learning algorithm with a combined Boltzmann exploration to optimize HO processes in LEO satellite networks. This strategy minimizes HOs and reduces user blocking rates by considering real-time satellite load and coverage.

Graph-Based and Game-Based Methods

In detail, graph theory and game theory play a critical role in analyzing and optimizing HO strategies within network systems. Graph theory provides a structured way to represent and examine the relationships within a network, which is essential for developing effective HO schemes that minimize disruptions and optimize the utilization of network resources. Meanwhile, game theory offers insights into the strategic relationships between network components, which helps to predict their decisions in competitive environments, such as the HO process. Together, they enable an enhanced awareness of complex network behaviours and the establishment of HO mechanisms that balance user demands with network efficiency.

Within the field of graph theory, two main graph frameworks—directed graphs and bipartite graphs—are commonly utilized in literature [31], [44], [45], [47–49].

Directed Graph Framework:

Let us first define the directed graph, known as a digraph, and its application in satellite HO. Figure 2.2 shows a simple digraph consisting of a set of vertices (also known as nodes or points) and a series of directed edges connecting ordered pairs of vertices. Digraphs help to model directional relationships and flow within networks, which are utilized for tracing the paths of communication and understanding the dynamics of satellite HOs. Specifically, the literature mostly considers coverage of satellites for specific ground stations as vertices and weighted the edge of pair vertices with HO criteria.

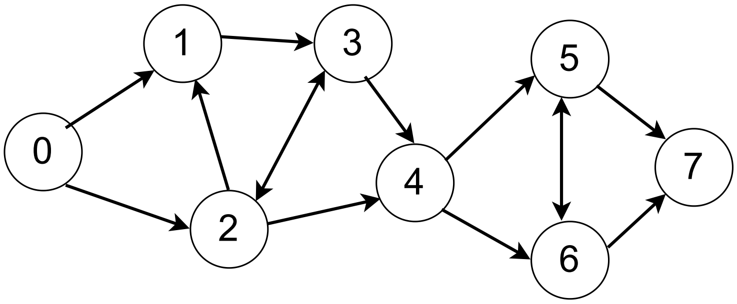


Figure 2.2 Simple directed graph example.

Bipartite Graph Framework:

On the other hand, let us look at and define the bipartite graph, also called a bigraph, and its application in satellite HO. A bigraph is a type of graph in which vertices can divide into two independent and separate sets U, and V; each edge connects a vertex in set U to one in set V [45]. Figure 2.3 shows a simple bigraph, and the vertices have been coloured based on whether they belong to which set. bigraphs are highly advantageous when it comes to representing the interrelationships between two separate sets, such as ground stations and satellites. This capability enables the analysis of possible HOs and interactions, optimizing network resource utilization and reducing disruptions. The studies in the literature utilized a bigraph-based framework to express network communication links by representing the LEO satellites and the ground equipment as two disjoint and independent sets. Therefore, the link between the satellite and gateway station as edge could be weighed by HO criteria and factors.

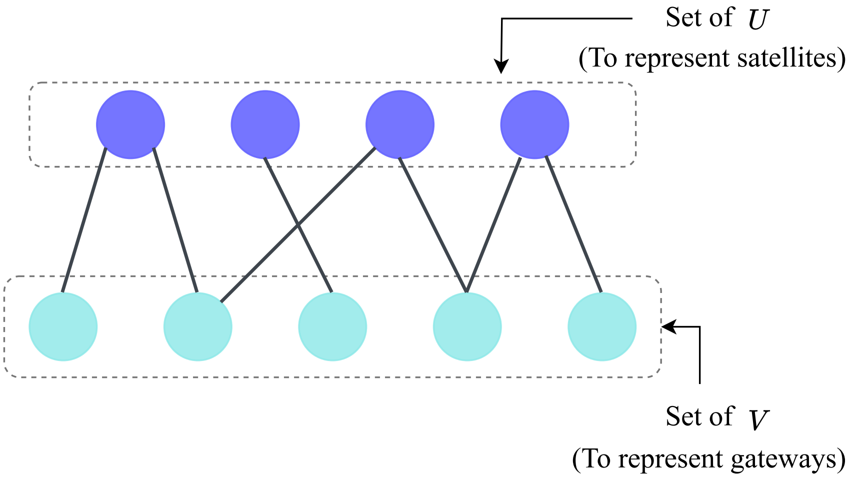


FIGURE 2.3 Simple bipartite graph example.

Below, we review the recent effort based on graph theory and game theory in literature.

Directed Graph Studies:

— In [31], the authors developed and mapped the HO process as a path finding problem for LEO satellite networks utilizing a digraph model.

Methodology: In this framework, nodes represent the coverage periods of satellites, and edges denote potential HOs between these periods. The strategy theoretically allows for integrating pre-established criteria such as elevation angle, service time, and available channels to optimize HO paths.

Results and Limitations: The authors utilized shortest path algorithms to investigate the performance of their strategy, focusing primarily on the shortest distance as a criterion for HO decisions. This approach aims to optimize the satellite HO process by integrating various HO criteria into a unified framework, enhancing flexibility and effectiveness. While the framework is designed to handle multiple criteria simultaneously, the study evaluates its performance using the shortest distance for a single metric, thereby not fully assessing its capacity to manage more complex, multi-criteria scenarios. In addition, the assignment of weights to different HO criteria presents a challenge, which is critical for implementing the framework in real-world scenarios.

— The authors in [44] developed a multi-attribute dynamic graph HO framework between LEO satellite networks and TN.

Methodology: This study introduces a novel HO scheme within LEO Satellite-TN that utilizes a multi-attribute dynamic graph to manage satellites mobility, prevent frequent link switching, and enhance the QoS. The framework models the network in a way that dynamically selects optimal HO paths based on multiple attributes such as elevation angle, coverage time, and channel state. In addition, the research employs a Floyd algorithm with multiple weights on edges, enabling the computation of shortest paths in the graph while considering various HO criteria. This approach improves the ability to adapt HO decisions more closely to the network's conditions and requirements.

Results and Limitations: The proposed framework effectively identifies available switching paths and uses the Floyd algorithm to select the optimal HO path, which reduces HO delays and unnecessary HOs. The approach aims to balance the need for quick HO processes with the demand for maintaining high service quality across dynamic satellite and TN. While the framework demonstrates promise and ability in theoretical simulations, implementing a multi-weighted Floyd algorithm suggests a complex method for handling multiple criteria in determining the optimal HO paths.

— In [49] author proposed a multi-attribute digraph HO framework for LEO satellite networks.

Methodology: This study presents an advanced HO scheme for LEO satellite networks utilizing a multi-attribute graph and a genetic algorithm. The multi-attribute graph incorporates critical attributes such as elevation angle, coverage time, and free channel state. This approach represents the HO process and optimizes path selection by considering a comprehensive set of satellite attributes. This approach effectively integrates multiple criteria into a single-objective optimization problem using a genetic algorithm, which selects the most efficient HO path based on calculated weights for each attribute.

Results and Limitations: The implementation of this multi-attribute HO framework significantly reduces communication delays and the number of unnecessary HOs, enhancing the QoS within LEO satellite networks. This approach supports higher network efficiency and better resource allocation by optimization of HO decisions and demonstrates its effectiveness through simulation outcomes. While the framework is robust in theory, its practical application may face computational demands and scalability challenges, especially in large-scale satellite networks.

Bipartite Graph Studies:

— In [48], the authors introduced a bigraph HO model for LEO satellite networks that evaluate the quality of service provided by the satellites.

Methodology: The study introduces a novel satellite HO strategy using a weighted bigraph, where the nodes represent satellites and users, and the edges reflect potential HO opportunities. The methodology incorporates the QoS provided by satellites as weights on the edges in the bigraph. In this strategy for solving multi-objective optimization problems, the authors utilized the entropy technique to compute and assign weights to each HO objective. Furthermore, they convert these objectives into a single issue and prioritize the highest weight when selecting candidate satellites and making HO decisions. This approach evaluates multiple factors that impact HO decisions, including service time, channel quality, and system load.

Results and Limitations: The entropy-based weighting mechanism optimizes HO decisions by balancing multiple objectives, leading to enhanced service quality and effective load management throughout the network. The findings from the simulation indicate that this method outperforms existing strategies in decreasing HO times, improving signal-to-noise ratio (SNR), and achieving a balanced load distribution. Although the entropy-based HO strategy demonstrates promise in simulations, its practical application may compromised by high computational complexity, which may impact real-time operations. Additionally, the strategy strongly relies on data precision and timeliness, both of which are critical factors in the accurate computation of entropy weights. Moreover, the scalability of this method in massive and complex satellite networks is not considered, raising questions about its feasibility in expansive operational scenarios.

Some studies have utilized the bigraph model along with game theoretical models like the potential game [45] and the matching game [47] to facilitate HO decision-making. By developing these models, it is possible to identify solutions that decrease the occurrence of HOs and improve communication quality.

— In [47], the authors introduced a bigraph HO model and multiple-input multiple-output (MIMO) technology for LEO satellite networks.

Methodology: The paper introduces a HO strategy utilizing a weighted bigraph framework in LEO satellites network. This model connects satellites and gateway stations, where the weight of each link is determined by the QoS, incorporating factors like channel quality and system load. The strategy employs the KM algorithm for maximum weight matching to optimize the allocation of satellites to gateway stations, ensuring high communication quality and efficient load balancing. Additionally, the strategy integrates MIMO technology to enhance communication rates and overall network performance.

Results and Limitations: The proposed strategy significantly improves the overall communication quality and load distribution within the satellite network. Through the implementation of MIMO technology and the optimization of HO decisions using the KM algorithm, the approach successfully maintains high data rates while efficiently distributing network load. This method represents a considerable advancement compared to conventional HO methods. While the KM algorithm effectively maximizes the overall communication quality by selecting the best available satellite links, it can potentially lead to increased HO occurrences. This paper did not address this aspect, which could lead to frequent HOs that disrupt service continuity and increase operational complexities. Furthermore, the study didn't properly consider the different commercial demands of users and operators' requirements, which could affect the efficacy of the HO strategy in various real-world scenarios.

— The authors in [45] presented a bigraph HO approach in LEO satellite that utilizes game theory.

Methodology: This paper introduces a satellite HO strategy for LEO satellite networks that utilizes a potential game approach. The strategy is designed to address the HO challenges in a high-speed LEO environment by modelling the HO process as a game where mobile terminals compete for satellite resources. The game theoretical model aims to optimize the allocation of satellite resources efficiently, thus reducing HO times and enhancing communication reliability. The HO decision-making is displayed as a bigraph, where one set of vertices corresponds to mobile terminals and the other represents satellites. The interactions are managed through a software-defined satellite network (SDSN) architecture, which supports dynamic control and efficient resource management.

Results and Limitations: The strategy effectively minimizes the average number of HOs and balances network load across the satellite constellation. The proposed method effectively minimizes HO delays, optimizes network resource utilization, and maintains communication quality, as demonstrated by simulations performed on the Iridium satellite network. Reduced call-dropping probabilities and better management of the constellation network load verify these improvements.

The overview and comparison of the mentioned studies are presented in Table 2.3.

2.5 Objective of The Thesis in Comparison with The Existing Works

Existing works on LEO satellite HO strategies have explored various criteria and methods to manage mobility with the aim of improving the QoS, reducing HO frequency, and balancing network load. These strategies often employ multiple criteria, including service time, channel status, and elevation angle, through different methods such as graph theory, learning-based approaches, and game theory. However, there are several gaps in these approaches, which this thesis aims to address.

Key Gaps in The Existing Works

- Complexity and Trade-offs of Multiple Criteria Approaches: Many existing strategies rely on multiple criteria to make HO decisions. While these approaches can enhance certain aspects of network performance, they also introduce complexity and may not always achieve an optimal balance across all desired outcomes. For instance, focusing on multiple criteria like elevation angle and service time may lead to increased computational demands and potential conflicts between criteria, complicating the HO decision process. Moreover, there is often a trade-off between data rate and HO rate, where improving one may adversely affect the other, leading to a compromise between continuity (fewer HOs) and stability (higher data rates).
- Lack of Flexibility: Existing strategies often lack the adaptability needed to meet the variable demands of users and network operators. The utilization of fixed criteria and thresholds in these strategies may not effectively account for the dynamic nature of satellite communication environments. Such inflexibility may lead to less-than-ideal performance in the face of changing conditions and user demands.
- Limited Across Channel Models: Many studies concentrate on a particular channel model, limiting their findings' applicability. The performance of HO strategies under different channel conditions, such as variable Rician K-factors, is not thoroughly investigated; as a result, the impact of environmental changes on HO decisions and the overall performance

of the network may be overlooked.

Contributions of This Thesis

Our proposed strategy addresses these gaps by integrating the KM algorithm with a HM, focusing on channel gain as a main criterion for HO decisions. This integration achieves multiple objectives:

- Simplified and Efficient Decision-Making and Trade-Off Management: By concentrating on channel gain, our strategy simplifies the HO decision process while effectively managing service time and reducing HO frequency through the application of a HM. This approach leverages the advantages of the KM algorithm to achieve high-quality connections and balanced load distribution across the network, addressing the primary goals of QoS, HO reduction, and load balancing efficiently. The proposed scheme simplifies the trade-offs among data rate and frequency of HO, ensuring a more balance between continuity and stability.
- Enhanced Flexibility and Adaptability: Our strategy can adapt to various operational demands due to the implementation of adjustable HM. Network operators can fine-tune the HM parameter to prioritize either low HO frequency or high data rates, depending on the specific needs of the users and network. This flexibility makes our strategy adaptable to various scenarios, enhancing its applicability in real-world environments.
- Robust Performance Across Different Channel Models: Our strategy demonstrates robust performance under different channel conditions, as indicated by our evaluation using various Rician K-factors. The ability to maintain good performance across various channel models offers the adaptability and reliability of our approach. It ensures reduced HO numbers and high-quality connections even under challenging signal conditions, a significant advantage over existing strategies limited to specific channel models.

As a result, this thesis provides a HO technique that effectively addresses the limitations of existing approaches in LEO satellite networks. By focusing on channel gain, integrating the KM algorithm with HM, and providing flexibility, scalability, and robust performance across different channel models, our strategy achieves high-quality service, reduced HO frequency, and balanced network load. Additionally, the adaptability to future technologies, potential for energy efficiency, and decreased HO cost make our strategy a comprehensive and practical solution to the challenges of mobility management in LEO satellite networks. These advancements contribute significantly to satellite communication, offering a practical and efficient solution to LEO satellites mobility challenges.

Table 2.3 Comparison of existing handover strategies.

Ref.	**Serv. Time**	**Idle Channel**	**Elev. Angle**	**Channel Quality**	**Method-Factors**	**Performance**
[59]	✓	✓	✓			reduce HO load balance link quality
[46]	✓				velocity-aware	reduce HO time shortest path
[60]	✓					reduce HO
[61]	✓				routing delay	reduce delay reduce HO
[31]	✓	✓	✓		shortest path digraph	QoS reduce HO load balance
[55]		✓			decision alg. rate demand	QoS reduce drop rate
[45]	✓		✓		access alg. bigraph game theory	reduce HO reduce call-drop link quality
[33]	✓	✓			learning-based load-aware	load balance low signal overhead
[56]	✓	✓			decision alg. signal strenght	QoS reduce HO load balance
[48]	✓	✓		✓	entropy method bigraph	load balance reduce HO guarantee SNR
[30]	✓	✓			Learning-based routing delay	reduce HO, failure rate, transition delay
[54]	✓	✓	✓		buffering	reduce HO reduce delay high throughput
[44]	✓	✓	✓		multi-weighted dynamic graph	reduce HO reduce delay load balance QoS
[49]	✓	✓	✓		genetic alg. critic alg. digraph	reduce HO load balance QoS
[47]				✓	MIMO KM alg.	QoS load balance

CHAPTER 3 SYSTEM MODEL

This chapter investigates the system model of the proposed downlink LEO satellite HO strategy, which is based on a weighted bigraph framework. This model provides comprehension of the dynamic interactions between gateway stations and satellites, which is essential for maintaining reliable communication links. Subsequently, we examine the processes for obtaining the LEO satellites that have coverage over each gateway station, the weighting of the communication link, the maximum weight matching algorithm, and the integration of the HM into the KM algorithm. Finally, we analyze performance metrics to evaluate the proposed HO strategy.

3.1 Graph Model

In this thesis, according to the existent satellite HO frameworks, the dynamic network topology of LEO satellites and their interaction with gateway stations is modelled as a bigraph, which is illustrated in Figure 3.1. As we discussed, the bigraph in satellite communication consists of one set of vertices representing LEO satellites and another set representing gateway station points. Furthermore, the edges of the bigraph indicate the communication link and connection between the gateway stations and the LEO satellites.

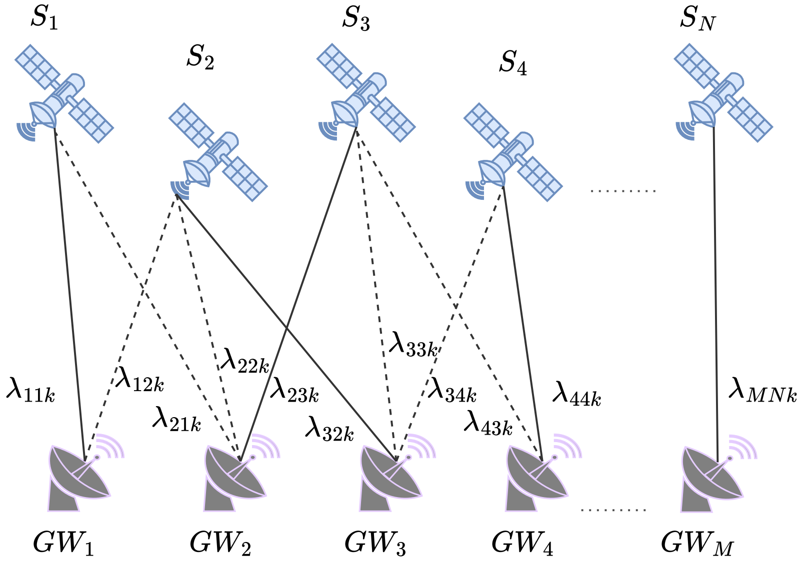


Figure 3.1 System model.

We consider the downlink of an LEO satellite network composed of a total of N LEO satellites, and the S_j indicates the j-th LEO satellite, where $j = 1, 2, \ldots, N$. Similarly, the model contains the total of M gateway stations, and GW_i indicate the i-th gateway station, where $i = 1, 2, \ldots, M$. The corresponding weight for the communication link at time slot t_k between GW_i and S_j is λ_{ijk}. Before delving into the details of how this system operates, let us summarize the notation employed within the thesis, as it will be essential for understanding the framework's descriptions in Table 3.1.

TABLE 3.1 Overview of notation utilized in the thesis.

Parameter	Description
S_j	j-th satellite
GW_i	i-th gateway station
λ_{ijk}	Weight of the link between GW_i and S_j at t_k
N	Number of satellites
M	Number of gateway stations
θ_{ijk}	Elevation angle of S_j relative to GW_i at t_k
t_{ij}^{in}	Entering time of S_j coverage area of GW_i
t_{ij}^{out}	Leaving time of S_j coverage area of GW_i
t_k	$k-th$ time slot in T
G_{ijk}	Channel gain between GW_i and S_j at instant t_k
F_H	Hysteresis factor
HM	Hysteresis margin
c_{light}	Speed of light
f_c	Carrier frequency
d_{ij}	Distance between GW_i and S_j
$A(d)$	Atmospheric fading
φ_{ijk}	Rician small-scale fading between GW_i and S_j at t_k
σ	Large value related to hysteresis factor
$\mathcal{F}_k$	Set of matching elements at instant t_{k-1}
$G_{ij}^{'}$	Initial channel gain between GW_i and S_j
$\mathcal{G}(:,:,k)$	Initial bigraph Matrix at t_k
$\mathcal{G}'(:,:,k)$	Adjusted bigraph Matrix at t_k
$\mathcal{M}(:,:,k)$	Matching matrix driven by KM algorithm
w_{ijk}	Weight of the link between GW_i and S_j at t_k in $\mathcal{M}(i,j,k)$
$\{i,j,k\}$	Selected S_j for specific GW_i at $\mathcal{M}(i,j,k)$ as paired matching elements
(i,j,k)	CandidateS_j for specific GW_i at $\mathcal{G}(i,j,k)$ as potential matching elements

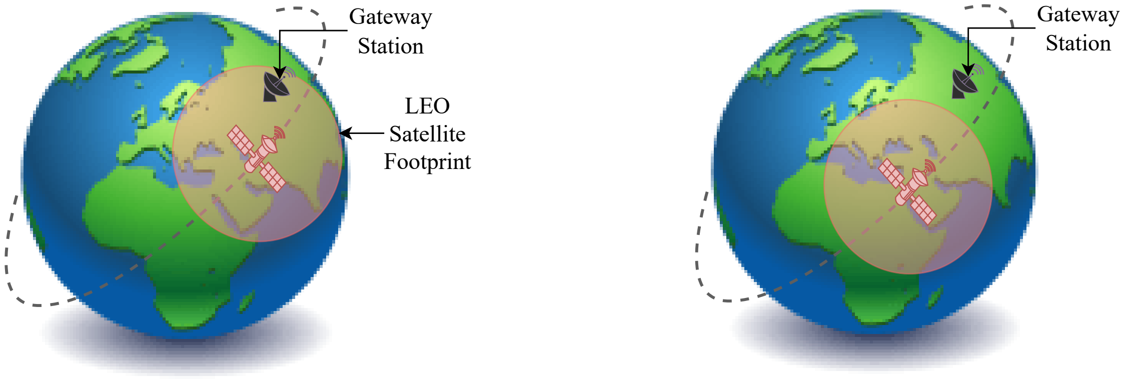
3.2 Identifying Candidate LEO Satellites

Advancements in communication technology have significantly transformed the future outlook of satellite communications, centered by LEO satellites. Reduce in the orbital altitude leads to higher operational velocities and lower service range for these satellites.

3.2.1 Visible Satellite From Gateway Stations Perspective

The satellite's coverage area over the Earth is determined by its specific orbital parameters, which include altitude, inclination, and orbital path. As illustrated in Figure 3.2a, only when the gateway stations are within the satellite's footprint communication between the gateway stations and LEO satellites is possible.

The service time and the duration that each LEO satellite could be visible from the perspective of a gateway station varies. This variability is due to the satellite's orbital parameters and the relative positions of the satellite and the gateway station. As the satellite moves, its footprint also shifts, finally moving beyond the gateway station and resulting in a loss of communication, as illustrated in Figure 3.2b.



(a) The gateway station under the LEO coverage area.

(b) The gateway station out off the LEO coverage area.

FIGURE 3.2 LEO satellite coverage (Inspired from [67]).

Figure 3.3 illustrates the basic geometric relationship between a satellite and a gateway station. In this figure, the satellite (labelled as SAT), the gateway station (denoted as GW), and the Earth's center are marked as key points. The horizon plane is shown by a line that intersects point GW, and T indicates the point of the sub-satellite [67]. Therefore, the central angle, denoted by (β), is the angle between the horizon plane at GW point and T point. Besides, the nadir angle is represented by (α), and the slant range is denoted by (d). Hence, the elevation angle, represented by (θ), is the angle between the horizon plane at the GW point and line (d). For the satellite to be visible to a gateway station at a given time, its ground trace must fall within the station's visibility area [67]. For this reason, the elevation angle of the satellite relative to the gateway station should satisfy the minimum required angle, denoted as $\theta_{\min}$, which is illustrated as approximately 15° in Figure 3.3.

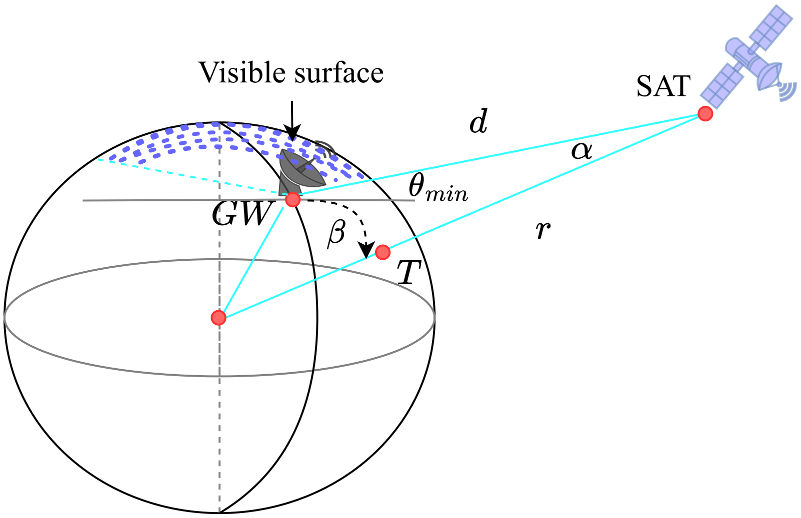


FIGURE 3.3 Gateway station station geometry (Inspired from [67]).

The satellite constellation is expanding to meet the increasing demands for global coverage and maintain reliability. Given the predictability of the LEO satellite's trajectory, the gateway station can identify and get information on the satellites passing within its visibility range using the methodology suggested in [34].

The coverage information for the satellites passing over gateway station GW_i can be expressed as follows

$$Coverage\ Table\, GW_i = \begin{bmatrix} S_1 & S_2 & S_3 & \dots & S_N \\ t_{i1}^{in} & t_{i2}^{in} & t_{i3}^{in} & \dots & t_{iN}^{in} \\ t_{i1}^{out} & t_{i2}^{out} & t_{i3}^{out} & \dots & t_{iN}^{out} \end{bmatrix}, \tag{3.1}$$

where the first row represents the indices of the covering satellites, the second row indicates the enter time of satellite S_j to the visibility range of gateway station GW_i by the element t_{ij}^{in}, and the third row indicates the leave time of satellite S_j from the visibility range of gateway station GW_i by the element t_{ij}^{out}. To prevent disruptions to ongoing communications, the gateway station shifts to an alternative satellite upon exiting the current serving satellite's coverage area.

Since we achieve HO management and control with this proposed strategy, let us assume that the HO may occur only in two situations.

— When the serving satellite leaves from the visibility range of the gateway station.

— When the new candidate satellite enters the visibility range of the gateway station.

3.2.2 Establishing Bipartite Graph in Each Time Slot

For gateway stations to maintain connectivity with certain QoS requirements, a HO sequence among the passing satellites is required for a time period, T. Let's assume that the time period T is divided into K identical time intervals, where each interval is denoted as t_k, representing the kth time slot in T. Thus, T is indicated as $T = [t_1, t_2, \ldots, t_k, \ldots, t_K]$. As a result, the ground station can uniformly manage the access and HOs of the gateway station.

As shown in Figure 3.1, from the perspective of the gateway station, at a given time, there is often more than one satellite available to access simultaneously. In this figure, solid lines indicate active connections between the gateway stations and satellites, while dotted lines indicate potential connections to candidate satellites. These indicate that although the satellite can provide services to the gateway stations, the quality of service might not be optimal at the moment.

For instance, consider that the connectivity at a specific moment, t_k, is denoted by $\mathcal{G} = \langle X, E, Y\rangle_{t_k}$, where $X = \{GW_1, GW_2, \ldots, GW_M\}$ and $Y = \{S_1, S_2, \ldots, S_N\}$ represents the sets of gateway stations and satellites, respectively [45]. The set E reflects the connection status between gateway stations and satellites. In case that gateway station GW_i is within the coverage area of satellite S_j, a value of 1 is assigned to the corresponding matrix element E_{ij}; otherwise, it is initialized to 0 in the absence of coverage. To obtain the various levels of service quality provided by different candidate satellites to gateway stations, we multiply λ_{ijk} by E_{ij} to obtain a new accurate value as a weight for bipartite graph $\mathcal{G} = \langle X, E', Y\rangle_{t_k}$.

To establish a bipartite graph for each time slot t_k, focusing on the communication status between S_j and GW_i, the following analysis should be considered

— If $t_{ij}^{in} \leq t_k < t_{ij}^{out}$, then S_j is within the visibility range of GW_i, indicating that GW_i can select S_j at t_k.

— If $t_k < t_{ij}^{in}$ or $t_k \geq t_{ij}^{out}$, then S_j is outside the visibility range of GW_i, indicating that S_j is not a candidate satellite for GW_i at t_k.

Based on these conditions, the initial bigraph matrices, denoted by $\mathcal{G}(,:,k)$, that reflects the communication link status between GW_i and S_j at time t_k defined as follows

$$\mathcal{G}(i,j,k) = \begin{array}{c} \\ GW_1 \\ GW_2 \\ \vdots \\ GW_M \end{array} \begin{array}{c} \begin{array}{cccc} S_1 & S_2 & \dots & S_N \end{array} \\ \begin{bmatrix} \lambda_{11k} & \lambda_{12k} & \dots & \lambda_{1Nk} \\ \lambda_{21k} & \lambda_{22k} & \dots & \lambda_{2Nk} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{M1k} & \lambda_{M2k} & \dots & \lambda_{MNk} \end{bmatrix} \end{array}, \tag{3.2}$$

where each array represents the weight of the communication link between each satellite and the corresponding gateway station at t_k. The λ_{ijk}, which represents the weight of the communication link between GW_i and S_j at time slot t_k, can be determined according to the following rule

$$\mathcal{G}(i,j,k) = \lambda_{ijk}, \begin{cases} \lambda_{ijk} > 0, & \text{if } t_{ij}^{in} \leq t_k < t_{ij}^{out}, \quad S_j \text{ is candidate satellite for } GW_i \\ \lambda_{ijk} = 0, & \text{if } t_k < t_{ij}^{in} \text{ or } t_k \geq t_{ij}^{out}, \quad S_j \text{ is not candidate satellite for } GW_i. \end{cases} \tag{3.3}$$

In the case if the value of λ_{ijk} is greater than zero, then S_j becomes a possible candidate for HO to GW_i during the time slot t_k. Otherwise, if λ_{ijk} is equal to zero, then S_j cannot be considered as a potential HO option for GW_i at t_k. Therefore, the sequence of bipartite graph matrices for each time slot from t_1 through to t_k can be generated and represented as $\mathcal{G}(:,:,k)$ where $k \in \{1, \dots, K\}$.

3.3 Handover Decision via Adjustable Weight and Maximum Weight Matching

The communication channels between the gateway stations and satellites have variations. Besides, the process of satellite HO is inherently competitive. Therefore, applying a binary link weight of 1 or 0 within the bipartite graph framework [45] fails to accurately describe the difference in channel quality, thus preventing the development of a stable and seamless communication network. On the other hand, considering only channel quality as the weighting criterion without monitoring service time leads to frequent HO.

Hence, to effectively identify and quantify the different levels of service provided by various satellites to gateway stations, ensuring network stability and continuity, we consider λ_{ijk} as weight in our method. The λ_{ijk} is a function of channel quality and hysteresis factor as link weight for S_j and GW_i at instant t_k. It can be represented by

$$\lambda_{ijk} = G_{ijk} \times F_H, \tag{3.4}$$

where G_{ijk} denotes the channel gain between GW_i and S_j at instant t_k, reflecting the link quality. F_H denotes the hysteresis factor between GW_i and S_j at instant t_k, responsible for maintaining connections to satellites as long as they provide high-quality service. The value of F_H is defined by HM condition as follows

$$F_H = \begin{cases} \sigma, & \text{if } S_j \text{ satisfies HM condition for } GW_i, \\ 1, & \text{if } S_j \text{ does not satisfy HM condition for } GW_i. \end{cases} \tag{3.5}$$

where σ is a large value that enhances the weight of S_j if it satisfies the hysteresis condition, ensuring stable connectivity. Otherwise, F_H remains 1, and the selection is based on G_{ijk}.

3.3.1 Channel Quality as Initial Weight

The first component of λ_{ijk} configuration is defined with channel gain to represent the channels quality variations. Therefore, in the case of elements λ_{ijk} within $\mathcal{G}(:,:,k)$ that are greater than zero, we assign the absolute value of $|G_{ijk}|$ to λ_{ijk}. A higher-quality channel corresponds to a larger weight, indicating that such channels have a competitive advantage in the satellite HO strategy. The channel gain is calculated by considering factors such as the elevation angle and the distance, fading and free space path loss. These parameters can be determined through the satellite ephemeris data and the gateway station location [19]. The channel gain, G_{ijk}, between GW_i and S_j at t_k is given by [42].

$$G_{ijk} = \left(\frac{c_{light}}{4\pi d_{ijk} f_c}\right)^2 A(d)\varphi, \tag{3.6}$$

where c_{light} represents the speed of light, while f_c denotes the carrier frequency. The variable d represents the distance from the satellites to the gateway station. $A(d)$ and φ are the atmospheric fading and the Rician small-scale fading, respectively.

3.3.2 Hysteresis Margin and Algorithm Enhancement

The only reliance on channel gain as the weighting criterion for HO decision results in the continuous selection of the channel with the highest quality. Therefore, it overlooks the stability and continuity of the system, leading to an increased number of HO and causing disruptions to the overall network performance and user experience. Figure 3.4 illustrates the evaluation process of a gateway station for various candidate satellites before the conditional HO event and after applying the HM condition.

At time t_k, under multi-satellite coverage, each candidate's gain G_{ijk} can be obtained using

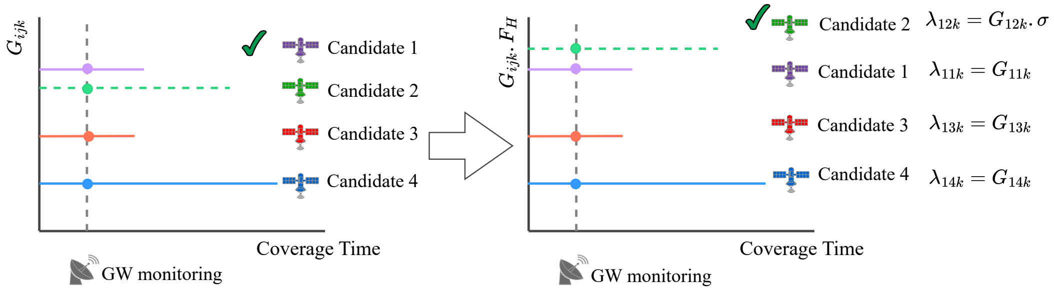


FIGURE 3.4 Weight adjustment and monitoring using hysteresis margin.

equation (3.6) and through ephemeris data. Typically, the gateway station selects the candidate with the greatest G_{ijk}, as shown on the left side of Figure 3.4. For instance, Candidate 1 provides the highest G_{ijk} and would be the preferred choice based on channel gain alone. However, if candidate 1 has a short service duration, the gateway station must quickly switch to an alternative candidate, which increases the frequency of HO and an interruption in service. Therefore, we introduce the HM as an additional factor in the weight configuration, aimed at improving the stability of HO decisions. The HM defines the threshold at which a satellite connection is maintained even if another candidate offers slightly better link quality.

To address the issue of frequent HOs while maintaining high link quality, the F_H is introduced as a control factor in the HO decision process. The role of F_H is to ensure that a satellite connection is maintained as long as the satellite provides good service quality. The value of F_H is determined by the HM conditions. If a satellite meets the HM condition, meaning its link quality exceeds a predefined threshold, F_H is set to σ, a large value that boosts the weight of the satellite and prioritizes it for selection. This mechanism, as applied to Candidate 2 (selected at the previous time slot t_{k-1}), prevents unnecessary HO even when other candidates offer slightly better link quality in the short term. On the other hand, if a satellite does not meet the HM condition, F_H remains 1, meaning no additional weight is applied, and the selection decision relies solely on the channel gain G_{ijk}.

On the right side of Figure 3.4, the weight of Candidate 2 is artificially increased to $G_{12k} \cdot \sigma$, allowing it to remain the preferred option, despite Candidate 1 having a higher initial link gain G_{ijk}. This approach achieves a balance between reducing the number of HOs and maintaining a high-quality communication link. The fairness mechanism integrated into the system ensures that the HO decision process does not blindly favor previously selected satellites or prioritize marginally better channel gains. Instead, it seeks to improve overall network performance by considering both service continuity and link quality. While Candidates 1, 3, and 4 maintain their original weights, the adjustment made to Candidate 2 helps balance high link quality with reduced HO frequency, ensuring fairness in the network's resource allocation and stability.

$\mathcal{F}_k$ Set Selection:

First of all, $\mathcal{F}_k$, an important data structure in our model, is initialized. $\mathcal{F}_k$ stores the status of the network at each time slot, including information on paired satellite and gateway stations, with their corresponding initial channel gains. This configuration is crucial for maintaining continuity and stability in network operations throughout the operational period.

Purpose: $\mathcal{F}_k$ tracks the historical status of connections to assist in HOs decision-making by storing the pairs and their channel gains obtained from the previous time slot.

Initial setup: During the initial setup, the system selects satellites with the highest link quality to make HO decisions, without applying the HM. In this phase, gateway stations prioritize satellites based on channel gain to establish initial connections. Thus, $\mathcal{F}_k$ records the matching data of satellites and gateway stations based on the highest link quality during initial step.

Each selected S_j for each specific GW_i, called paired matching elements (i, j, k), and each candidateS_j for each specific GW_i at $\mathcal{G}(i, j, k)$, called potential matching elements $\{i, j, k\}$. The set $\mathcal{F}_k$ stored data regarding paired components $(j, i, k-1)$ at instant t_{k-1}.

$$\begin{cases} \{i,j,k\} & \in \mathcal{F}_k, \text{ then } \lambda_{ijk} = G_{ijk} \times F_H \\ \{i,j,k\} & \notin \mathcal{F}_k, \text{ then } \lambda_{ijk} = G_{ijk}. \end{cases} \tag{3.7}$$

Hence, the weight in the bigraph matrices representing the relationship between S_j and GW_i at t_k can be adjusted and denoted as the matrix $\mathcal{G}'(:,:,k)$.

$$\mathcal{G}'(i,j,k) = \lambda_{ijk}, \begin{cases} \lambda_{ijk} = G_{ijk} \times F_H, \quad \text{where } F_H = \sigma, \\ \quad \forall\{i,j,k\} \in F_k \wedge G_{ijk} \geq G'_{ij} + H, \\ \\ \lambda_{ijk} = G_{ijk} \times F_H, \quad \text{where } F_H = 1, \\ \quad \forall\{i,j,k\} \in F_k \wedge G_{ijk} < G'_{ij} + H, \\ \\ \lambda_{ijk} = G_{ijk}, \\ \quad \forall\{i,j,k\} \notin F_k. \end{cases} \tag{3.8}$$

where $G^{'}_{ij}$ represents the channel gain between GW_i and S_j at the very first time paired matching element, HM is hysteresis margin, and σ is large value for F_H. Therefore, we can achieve our updated bipartite graph matrices by adjusting weights for each time slot from t_1 to t_k, denoted as $\mathcal{G}'(:,:,k)$ where k varies from 1 to K. Integrating a HM into the HO mechanism significantly enhances our selection performance by introducing a criterion for service stability.

Our intelligent strategy evaluates whether the paired matching elements at t_{k-1} remain as qualified candidates at the current instant t_k. This step ensures that we consider the system's past condition, thereby adding a layer of continuity to the selection process.

Weight Adjustment Operation:

The proposed method verifies the presence of any potential matching elements $\{i, j, k\}$ in $\mathcal{F}_k$, resulting in one of the following two scenarios.

I. For those $\{i, j, k\}$ found in set F_k, meaning that S_j has continued coverage from previous time slot t_{k-1} till time slot t_k for corresponding GW_i.

II. For those $\{i, j, k\}$ not found in set F_k, meaning that S_j did not have coverage or was not the best candidate for the corresponding GW_i during time slot t_{k-1}.

In the first scenario, the proposed algorithm evaluates the HO margin condition as indicated in equations (3.7) and (3.8). Our method compares the current channel quality of potential matching elements $\{i, j, k\}$ with its initial value to examine the HM condition at t_k. If S_j satisfies the specified requirements for corresponding GW_i, it can be considered qualified to continue providing service for GW_i among other candidate satellites. Therefore, by maintaining S_j for GW_i at time slot t_k, while the overall communication link has high quality, it effectively prevents frequent HO. To this end, our algorithm increases the weight of the communication link within the weighted bipartite graph. This enhancement is achieved by the implementation of a large hysteresis factor, σ, and by modifying the weights in our new bipartite matrices $\mathcal{G}'(i, j, k)$. This strategic adjustment prioritizes S_j as the preferred HO candidate for GW_i at t_k, thus emphasizing service reliability above temporary quality improvements, as demonstrated in Figure 3.4.

On the other hand, if S_j fails to satisfy the HM condition for the corresponding GW_i, it indicates that S_j may not be eligible to continue service GW_i compared to other candidate satellites. Moreover, this situation implies that S_j can no longer provide high-quality service for GW_i. As a result, GW_i needs to identify a qualified alternative satellite at t_k. Therefore, we keep the same G_{ijk} as weight in $\mathcal{G}'(i, j, k)$, enabling the proposed algorithm to select satellite with high-quality link among candidates for GW_i using the maximum weight matching (MWM) method.

In second scenario, since GW_i wasn't under coverage of S_j or didn't select S_j as target satellite, we keep the G_{ijk} as weight in $\mathcal{G}'(i,j,k)$. Therefore, we maintain the same G_{ijk} as weight in $\mathcal{G}'(i,j,k)$, and let the proposed algorithm implement HO decision for selecting high-quality satellite among candidates.

Finally, the updated bipartite matrices $\mathcal{G}'(i,j,k)$ are obtained after the implementation and evaluation of these two scenarios, as well as the adjustment of weights. This strategy ensures that while channel quality remains a crucial factor, the system also considers the service duration of satellites and aims to reduce frequent HOs. As illustrated in the right of figure 3.4, the adjusted weight λ_{ijk} provides a more accurate representation of the candidate satellite's potential for stable service. As a result, our method effectively implements HO decision that balances the requirements for service stability and network efficiency with the need for high channel quality.

3.3.3 Maximum Weight Matching

The rapid expansion in communication demands, which results from ever-increasing communication terminals, creates significant pressure on satellite resources. Therefore, to prevent resource wastage and overloading, it is essential to not only maintain high-quality links but also ensure that the operational load is uniformly distributed among satellites. With the bigraph matrices $\mathcal{G}'(:,:,k)$ developed for each time slot from t_1 to t_K, our objective is to achieve high link quality with balanced load distribution across the satellite network.

Within this particular scenario, the concept of matching within a bipartite graph becomes essential. This graph defines a match as a subset of edges where no two edges share a common vertex. The objective of the MWM is to identify a pairing that maximizes the total weight of the edges included in the matching. This method with KM algorithm is particularly well-suited for our system model, which prioritizes load balancing and link quality.

KM Algorithm Objective

The KM algorithm, also known as the Hungarian algorithm, is a polynomial-time algorithm with a complexity of $O(|V|^3)$, where $|V|$ is the number of vertices in a bipartite graph. It efficiently solves the MWM problem, ensuring optimal resource utilization and communication quality.

Given a complete weighted bipartite graph $\mathcal{G}'(i,j,k)$, the goal of the KM algorithm is to find a matching $\mathcal{M}$ that maximizes the total weight, defined as

$$\text{Maximize } w(\mathcal{M}) = \sum_{(i,j)\in\mathcal{M}} \lambda_{ijk}. \tag{3.9}$$

This matching optimizes communication link quality and load balancing between gateway stations and satellites. By utilizing the KM technique to our weighted bigraph $\mathcal{G}'(:,:,k)$, we derive the matching matrices, represented as $\mathcal{M}(:,:,k)$. Hence, the outcomes derived from the KM method are stored in $\mathcal{F}_k$ to be utilized in the subsequent time slot. This matrix represents the most efficient combination of gateway stations and satellites in order to:

- **Load Balancing:** Each satellite allocates its capacity to a suitable number of gateway stations. The KM method guarantees that each satellite is exclusively chosen by a gateway station during the time slot t_k, thus preventing overload and facilitating a fair distribution of network traffic.
- **Link Quality:** By applying MWM, the total weight in $\mathcal{M}(:,:,k)$ become maximized. This implies that the HO decisions are designed to enhance the overall channel quality at time t_k. The decisions involve selecting the most optimal available links, considering the current satellite positions, channel conditions, and system loss.

The matching matrix $\mathcal{M}(:,:,k)$, is defined as

$$\mathcal{M}(i,j,k) = \begin{cases} w_{ijk} = \lambda_{ijk}, & \text{if } GW_i \text{ matches } S_j \\ w_{ijk} = 0, & \text{if } GW_i \text{ does not match } S_j, \end{cases} \tag{3.10}$$

where w_{ijk} represents the weight of the communication link between GW_i and S_j at time slot t_k in $\mathcal{M}(i,j,k)$.

By consistently implementing the KM method for each time slot, we guarantee that each gateway station is matched with the satellite that has the highest link quality according to the most recent data. Additionally, our approach facilitates the effective utilization of satellite resources. This dual emphasis on service quality and load balancing is essential for maintaining the robustness and reliability of future satellite communication networks in the face of changing demands and operational limitations. The proposed method and HO decision process are illustrated by Algorithm 1.

Algorithm 1 Satellite Handover Decision Process with Hysteresis Margin

```
Initialize visibility of satellites $S_j$ for each gateway $GW_i$.
Initialize hysteresis margin $HM$ and factor $F_H$.
Define and initialize set $\mathcal{F}_k$ to track matched pairs.
for all time slots $k$ in operational time $T$ , $k = 1, 2, \dots, K$. do
    Establish initial bipartite matrices $\mathcal{G}(:, :, k)$, with weights $\lambda_{ijk}$ initialized.
    for each potential matching element $\{i, j, k\}$ in $\mathcal{G}(:, :, k)$ do
        if $\lambda_{ijk} > 0$ then
            Set $\lambda_{ijk} = G_{ijk}$ using Eq.(3.5)
        end if
    end for
    Weight adjustment operation:
    for each $\{i, j, k\}$ in $\mathcal{G}(:, :, k)$ do
        if $\{i, j, k\}$ is found in $\mathcal{F}_k$ then
            Check HM condition
            if HM condition is met then
                Increase weight by multiplying $\sigma$ in $G_{ijk}$ using Eq.(3.8)
                Adjust the weight in $\mathcal{G}'(:, :, k)$
                HO does not occur.
            else
                Maintain $G_{ijk}$ as weight in $\mathcal{G}'(:, :, k)$
            end if
        else
            Use the same $G_{ijk}$ as weight in $\mathcal{G}'(:, :, k)$
        end if
    end for
    Compute $\mathcal{M}(:, :, k)$ using the KM method to enhanced $\mathcal{G}'(:, :, k)$
    Update $\mathcal{F}_k$ with the results from $\mathcal{M}(:, :, k)$ for the next time slot
end for
```

Steps of the KM Algorithm

1. Initialization: A bipartite graph $\mathcal{G} = (V, E)$ consists of two disjoint sets of vertices, X and Y, such that $V = X \cup Y$ and $E \subseteq X \times Y$. The sets X and Y are defined as follows

— $X = \{GW_1, GW_2, \ldots, GW_M\}$ represents the set of gateway stations.

— $Y = \{S_1, S_2, \ldots, S_N\}$ represents the set of satellites.

Each vertex $v \in V$ represents either a gateway station $v \in X$ or a satellite $v \in Y$.

Each edge $(GW_i, S_j) \in E$ is assigned a weight λ_{ijk}, which represents the communication link quality between gateway station GW_i and satellite S_j at time t_k.

If $N > M$, dummy rows with edges assigned weights $\lambda_{ijk} = 0$ are added to balance the bipartite graph.

2. Feasible Labeling: The KM algorithm assigns labels to the vertices in the bipartite graph to maintain a feasible weighted cover. A vertex labeling is defined as a function $\ell : V \to \mathbb{R}$, where each vertex in the graph is assigned a real-valued label [40]. The label of each gateway station GW_i, denoted $\ell(GW_i)$, and the label of each satellite S_j, denoted $\ell(S_j)$, must satisfy the following condition

$$\ell(GW_i) + \ell(S_j) \geq \lambda_{ijk}, \quad \forall i, j. \tag{3.11}$$

The labels are initialized as follows

— $\ell(GW_i) = \max \lambda_{ijk}, \quad \forall i \in \{1, 2, \ldots, M\}$.

— $\ell(S_j) = 0, \quad \forall j \in \{1, 2, \ldots, N\}$.

The labeling ensures that the difference between labels for any matched edge satisfies the following equality

$$\ell(GW_i) + \ell(S_j) = \lambda_{ijk}. \tag{3.12}$$

3. Constructing an Equality Graph: The algorithm constructs the equality graph $\mathcal{G} = (V, E_\ell)$ from the labeled graph. An edge (GW_i, S_j) is included in the equality graph if it satisfies the following condition

$$E_\ell = \{(GW_i, S_j) : \ell(GW_i) + \ell(S_j) = \lambda_{ijk}\}. \tag{3.13}$$

After constructing the equality graph, the algorithm checks for a perfect matching. A perfect matching means that every gateway station is connected to exactly one satellite. According to the KM theorem, if the labeling ℓ is feasible and the matching $\mathcal{M}$ is a perfect matching in

E_ℓ, then $\mathcal{M}$ is also the MWM. In this case, the algorithm terminates. If no perfect matching is found, the algorithm proceeds to the next step.

4. Finding an Augmenting Path: The algorithm searches for an augmenting path. An augmenting path alternates between matched and unmatched edges, starting and ending at unmatched vertices. If an augmenting path is found, the matching is updated by reversing the matched and unmatched edges along the path, thereby increasing the size of the matching. If no augmenting path is found, the algorithm proceeds to adjust the labels.

5. Adjusting Labels: If no augmenting path exists, the algorithm improves the labeling from ℓ to ℓ', such that $E_\ell \subset E_{\ell'}$. Let ℓ be a feasible labeling. Define the neighbor of $u \in V$, and set $P \subseteq V$, which represents the set of gateway stations involved in the current search for an augmenting path. The neighbor function is defined as [46]

$$N_\ell(P) = \bigcup_{u \in P} N_\ell(u), \quad \text{where} \quad N_\ell(u) = \{v : (u, v) \in E_\ell\}. \tag{3.14}$$

Let $P \subseteq X$ and define $U = N_\ell(P)$, where U is a proper subset of Y (i.e., $U \neq Y$).

- **Set** P**:** Contains the unmatched gateway stations (free vertices) involved in the search for an augmenting path. If a gateway station is connected to a satellite that is already matched with another gateway station, that gateway station remains unmatched, and hence becomes part of P.
- **Set** U**:** Represents the set of satellites (neighbors) connected to vertices in P through edges in the equality graph. U is a proper subset of Y, meaning that not all satellites will necessarily be included in U.

Once P and U are defined, the slack α_ℓ is calculated. The slack α_ℓ is defined as the smallest difference between the sum of labels and the edge weight for edges not in the equality graph

$$\alpha_\ell = \min_{GW_i \in P, S_j \notin U} \left(\ell(GW_i) + \ell(S_j) - \lambda_{ijk}\right). \tag{3.15}$$

The labels are updated as follows

$$\ell'(v) = \begin{cases} \ell(v) - \alpha_\ell & \text{if } v \in P \\ \ell(v) + \alpha_\ell & \text{if } v \in U \\ \ell(v) & \text{otherwise.} \end{cases} \tag{3.16}$$

This means

- — For vertices in P, the label is decreased by α_ℓ.
- — For vertices in U, the label is increased by α_ℓ.
- — For all other vertices, the label remains unchanged.

This adjustment ensures that new edges are added to the equality graph $E_{\ell'}$, increasing the chances of finding an augmenting path. After updating the labels, the algorithm returns to Step 1 to search for a new augmenting path.

6. Repeat Steps 3-5: The process of finding augmenting paths and adjusting labels is repeated until a maximum weight matching is found, where each gateway station is matched to a satellite with the maximum total weight $w(\mathcal{M})$.

7. Output: The final output is the matching matrix $\mathcal{M}(i, j, k)$, representing the optimal matching between gateway stations and satellites at time t_k, which maximizes total communication quality.

Example of Maximum Weight Matching Using the KM Algorithm

Consider a network with five gateway stations $GW_1, GW_2, GW_3, GW_4, GW_5$ and five LEO satellites S_1, S_2, S_3, S_4, S_5. The objective is to find the MWM using the KM algorithm.

Step 1: Initialization

The following weight matrix represents the communication link quality λ_{ijk} between the gateway stations and satellites at time slot t_k.

$$\mathcal{G}(i, j, k) = \begin{bmatrix} 10 & 3 & 8 & 2 & 5 \\ 7 & 6 & 5 & 9 & 2 \\ 4 & 9 & 6 & 1 & 3 \\ 5 & 2 & 7 & 6 & 4 \\ 8 & 7 & 3 & 4 & 7 \end{bmatrix}.$$

Step 2: Feasible Labeling

The algorithm begins by labeling the vertices. Each gateway station GW_i is assigned an initial label equal to the maximum edge weight connected to that vertex. The satellites are initialized with a label of 0.

The initial labels for the gateway stations are as follow

— $\ell(GW_1) = \max(10, 3, 8, 2, 5) = 10$.

— $\ell(GW_2) = \max(7, 6, 5, 9, 2) = 9$.

— $\ell(GW_3) = \max(4, 9, 6, 1, 3) = 9$.

— $\ell(GW_4) = \max(5, 2, 7, 6, 4) = 7$.

— $\ell(GW_5) = \max(8, 7, 3, 4, 7) = 8$.

The initial labels for the satellites are as follow

— $\ell(S_1) = \ell(S_2) = \ell(S_3) = \ell(S_4) = \ell(S_5) = 0$.

Step 3: Construct the Equality Graph

The next step constructs the equality graph by selecting edges that satisfy $\ell(GW_i) + \ell(S_j) = \lambda_{ijk}$. For each gateway station, the equality condition is checked for each satellite as follows

— $\ell(GW_1) + \ell(S_1) = 10 + 0 = 10$, matches λ_{11k}, so $(GW_1, S_1) \in E_\ell$.

— $\ell(GW_2) + \ell(S_4) = 9 + 0 = 9$, matches λ_{24k}, so $(GW_2, S_4) \in E_\ell$.

— $\ell(GW_3) + \ell(S_2) = 9 + 0 = 9$, matches λ_{32k}, so $(GW_3, S_2) \in E_\ell$.

— $\ell(GW_4) + \ell(S_3) = 7 + 0 = 7$, matches λ_{43k}, so $(GW_4, S_3) \in E_\ell$.

— $\ell(GW_5) + \ell(S_1) = 8 + 0 = 8$, matches λ_{51k}, so $(GW_5, S_1) \in E_\ell$.

Thus, the equality graph contains the following edges

$$E_\ell = \{(GW_1, S_1),\ (GW_2, S_4),\ (GW_3, S_2),\ (GW_4, S_3),\ (GW_5, S_1)\}$$

Step 4: Finding an Augmenting Path

The KM algorithm then checks whether the matching $\mathcal{M}$ in the equality graph $\mathcal{G} = (V, E_\ell)$ is a perfect matching. Since both GW_1 and GW_5 are matched to the same satellite S_1, and S_5 remains unmatched, the matching is not perfect. Therefore, the next step is to adjust the labels.

Step 5: Adjusting Labels

Since the matching is not perfect, the KM algorithm proceeds to adjust the labels. To do this, the algorithm finds the sets P and U.

First, it identifies the unmatched gateway stations. Since both GW_1 and GW_5 are matched to the same satellite S_1, these vertices are included in the alternating tree.

Starting with the free vertex GW_5, the sets are defined as

$$P = \{GW_5\}, \quad U = N_\ell(P) = \{S_1\}.$$

The algorithm then attempts to find other neighbors of P. Since GW_1 is matched with S_1, it is added to P

$$P = \{GW_1, GW_5\}, \quad U = N_\ell(P) = \{S_1\}.$$

At this point, $P = \{GW_1, GW_5\}$ and $U = \{S_1\}$, and since $U \neq Y$ (i.e., U is not equal to the entire set of satellites), the next step is to adjust the labels. Hence, the slack α_ℓ is calculated, defined as the smallest difference between the sum of labels and the edge weight.

$$\alpha_\ell = \min_{GW_i \in P, S_j \notin U} \left(\ell(GW_i) + \ell(S_j) - \lambda_{ijk}\right).$$

For the example, the slack is calculated as follows

$$\alpha_\ell = \min \begin{cases} \ell(GW_1) + \ell(S_2) - \lambda_{12k} = 10 + 0 - 3 = 7, \\ \ell(GW_1) + \ell(S_3) - \lambda_{13k} = 10 + 0 - 8 = 2, \\ \ell(GW_1) + \ell(S_4) - \lambda_{14k} = 10 + 0 - 2 = 8, \\ \ell(GW_1) + \ell(S_5) - \lambda_{15k} = 10 + 0 - 5 = 5, \\ \ell(GW_5) + \ell(S_2) - \lambda_{52k} = 8 + 0 - 7 = 1, \\ \ell(GW_5) + \ell(S_3) - \lambda_{53k} = 8 + 0 - 3 = 5, \\ \ell(GW_5) + \ell(S_4) - \lambda_{53k} = 8 + 0 - 4 = 4, \\ \ell(GW_5) + \ell(S_5) - \lambda_{53k} = 8 + 0 - 7 = 1. \end{cases}$$

Thus, $\alpha_\ell = 1$.

Now, the labels are updated as follows

$$\ell'(v) = \begin{cases} \ell(v) - \alpha_\ell & \text{if } v \in P \\ \ell(v) + \alpha_\ell & \text{if } v \in U \\ \ell(v) & \text{otherwise.} \end{cases}$$

For the vertices in P

$$\ell'(GW_1) = \ell(GW_1) - 1 = 10 - 1 = 9,$$
$$\ell'(GW_5) = \ell(GW_5) - 1 = 8 - 1 = 7.$$

For the vertex in U

$$\ell'(S_1) = \ell(S_1) + 1 = 0 + 1 = 1.$$

For all other vertices, the labels remain unchanged.

After updating the labels, the algorithm returns to Step 3 to update the equality graph. By checking the equality condition for GW_1 and GW_5 with the updated labeling values, the equality graph is updated as follows

— $\ell'(GW_1) + \ell'(S_1) = 9 + 1 = 10$, matches λ_{11k}, so $(GW_1, S_1) \in E'_\ell$.
— $\ell'(GW_5) + \ell'(S_1) = 7 + 1 = 8$, matches λ_{51k}, so $(GW_5, S_1) \in E'_\ell$.
— $\ell'(GW_5) + \ell(S_2) = 7 + 0 = 7$, matches λ_{52k}, so $(GW_5, S_2) \in E'_\ell$.
— $\ell'(GW_5) + \ell(S_5) = 7 + 0 = 7$, matches λ_{55k}, so $(GW_5, S_5) \in E'_\ell$.

$$E_\ell = \{(GW_1, S_1),\ (GW_2, S_4),\ (GW_3, S_2),\ (GW_4, S_3),\ (GW_5, S_5)\}.$$

Now, GW_5 can be matched with S_5, completing the perfect matching.

Step 8: Final Output

With the perfect matching $\mathcal{M}$ achieved, the total weight of this matching, representing the maximum communication link quality between the gateway stations and satellites, is calculated.

$$\mathcal{M} = \{(GW_1, S_1),\ (GW_2, S_4),\ (GW_3, S_2),\ (GW_4, S_3),\ (GW_5, S_5)\}.$$

The final matching matrix is

$$\mathcal{M}(i, j, k) = \begin{bmatrix} 10 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 9 & 0 \\ 0 & 9 & 0 & 0 & 0 \\ 0 & 0 & 7 & 0 & 0 \\ 0 & 0 & 0 & 0 & 7 \end{bmatrix},$$

where each non-zero entry represents the matched gateway station and satellite with the corresponding weight, while the zeros indicate unmatched pairs.

The total weight of the matching is calculated by summing the link qualities for each matched pair as follows

$$\begin{aligned} w(\mathcal{M}) &= \lambda_{11k} + \lambda_{24k} + \lambda_{32k} + \lambda_{43k} + \lambda_{55k} \\ &= 10 + 9 + 9 + 7 + 7 \\ &= 42. \end{aligned}$$

Thus, the total communication quality (maximum weight) of the matching is $w(\mathcal{M}) = 42$.

This example demonstrates the application of the KM algorithm for solving the given problem and finding the MWM in a bipartite graph, ensuring high communication link quality between the gateway stations and the LEO satellites.

3.4 Analyzing Performance Metrics

This section examines critical performance metrics for LEO satellite network operations in the context of HO strategies. These metrics include the average data rate, HO rate, the impact of the Rician K-factor, and the HO cost of the strategy. Understanding these metrics is essential for evaluating the effectiveness and performance of the proposed satellite HO strategy and ensuring stable and reliable communication within the satellite network.

3.4.1 Channel Model

The channel model is an important key factor in evaluating the performance metrics within the LEO satellite network. The channel model contains multiple critical factors, including Rician small-scale fading, path loss, and atmospheric attenuation [42]. Such factors are crucial since they significantly impact the link quality and the system performance. The large-scale fading primarily results from the path loss of free space and additional attenuation resulting from weather and atmospheric conditions [42]. However, small-scale fading in the satellite system is mainly characterized by Rician fading due to the direct line-of-sight (LoS) connections between the satellites and various service locations. The channel model is expressed as follows

$$G_{ijk} = \left(\frac{c_{light}}{4\pi d_{ijk} f_c} \right)^2 A(d) \varphi_{ijk}, \tag{3.17}$$

where $A(d)$ represents the atmospheric fading, based on the distance from the satellite to the gateway station within the coverage area, and φ_{ijk} represents small-scale fading.

Atmospheric Fading

The atmospheric fading component, $A(d)$ [42], is defined as

$$A(d) = 10^{\frac{3 d_{ijk} \chi}{10h}}, \tag{3.18}$$

where χ represents the attenuation due to rainfall and clouds, measured in dB/km. The distance d_{ijk} between the satellite and the gateway station at t_k can be computed from their coordinates in the Earth-Centered, Earth-Fixed (ECEF) system [55], calculated by

$$d_{ijk} = \sqrt{(X_{j,k} - X_{i,k})^2 + (Y_{j,k} - Y_{i,k})^2 + (Z_{j,k} - Z_{i,k})^2}. \tag{3.19}$$

Rician Small-Scale Fading

In satellite communication systems, small-scale fading refers to rapid fluctuations in signal strength caused by multipath propagation and relative motion of satellites. The fading is modeled as Rician fading since the links consist of both LoS and non-line-of-sight (NLoS) components. The probability of having a strong LoS component increases with the elevation angle, reaching its maximum when the satellite is directly overhead (90° elevation).

For the purpose of modeling, it is assumed that the channel conditions remain static over a coherence time interval τ_c, thus allowing the use of a flat fading (non-frequency selective) model. This assumption simplifies analysis by ensuring that the fading uniformly affects the entire bandwidth, which is valid when the coherence bandwidth exceeds the signal bandwidth.

The Rician fading channel gain, φ_{ijk}, is expressed as follows [68]

$$\varphi_{ijk} = \sqrt{\frac{K_{ijk}}{K_{ijk}+1}} e^{j\phi_{ijk}} + \sqrt{\frac{1}{K_{ijk}+1}} h_{ijk}^{\text{NLoS}}, \tag{3.20}$$

where

- — K_{ijk} is the Rician K-factor, representing the ratio of the power of the direct LoS path to that of the scattered NLoS components.
- — ϕ_{ijk} is the phase of the LoS component, uniformly distributed as $\phi_{ijk} \sim \mathcal{U}[-\pi, \pi]$.
- — $h_{ijk}^{\text{NLoS}} \sim \mathcal{CN}(0, 1)$ represents the Rayleigh fading component, modeling the NLoS multipath scattering.

The first term of equation (3.20) corresponds to the deterministic LoS component, while the second term models the stochastic NLoS scattering. The Rician K-factor K_{ijk} is crucial for characterizing the relative strength of the LoS and NLoS components, with higher K-values indicating stronger LoS paths and lower K-values reflecting a greater influence of NLoS scattering.

Received Power Calculation

The received power, denoted by $P_{rx,k}$, is crucial for calculating the SNR and data rates. $P_{rx,k}$ is defined as

$$P_{rx,k} = P_{tx,k} \times G_{tx,k} \times G_{rx,k} \times G_{ijk}, \tag{3.21}$$

where, the variables $P_{tx,k}$, $G_{tx,k}$, and $G_{rx,k}$ represent the transmit power, the transmitter antenna gains, and antenna gains of the receiver at t_k respectively. The channel gain includes factors such as path loss and fading.

3.4.2 Average Data Rate

The SNR for the link between GW_i and the corresponding S_j at t_k is determined by using the received power relative to the noise. It is represented as

$$SNR_{ij}(t_k) = \frac{P_{rx,ij}(t_k)}{N_0 \times B}, \tag{3.22}$$

where $P_{rx,ij}(t_k)$ is the received power for GW_i and S_j at t_k, N_0 indicate the noise spectral density, and B represents the bandwidth.

The achievable data rate for each pair of gateway stations and satellite can be calculated using the following formula

$$R_{ij}(t_k) = B \times \log_2\left(1 + SNR_{ij}(t_k)\right). \tag{3.23}$$

To calculate the average data rate at t_k across all gateway stations, we could sum the rates of all active pairs of gateways and satellites and divide it by the total number of gateway stations. The average data rate is defined as follows

$$\overline{R}(t_k) = \frac{1}{M}\sum_{i=1}^{M} R_{ij}(t_k). \tag{3.24}$$

In this context, M signifies the total count of active gateway stations at t_k. This computation assumes that each gateway station is paired with only one satellite at any given time.

3.4.3 Handover Rate

The HO rate is a crucial metric in satellite communication networks and evaluates the efficiency of HO strategies to ensure uninterrupted service. This rate quantifies the frequency of HOs per unit of time or session, providing insights into the network's ability to respond and stability under different conditions. A lower HO rate indicates a higher level of stability in connections, resulting in fewer interruptions and enhanced user satisfaction. While a higher HO rate may indicate better adaptability to changes in satellite positions and user movements, it comes with many challenges, such as signalling overhead, service interruption, and HO cost. The HO rate is determined based on simulation data and measures the total number of HOs within a specific duration. Therefore, it provides a dynamic perspective on the trade-offs between service quality and operational efficiency. We aim to improve HO strategies to balance effective connectivity with minimized disruptions, enhancing overall network performance.

3.4.4 Rician K-Factor

The ratio of the signal power coming from the direct line-of-sight to the signal power coming from multipath scattering is known as the Rician K-factor [39]. The Rician K-factor serves as a key parameter of a wireless channel analysis and is critical in evaluating satellite HO strategies. A high K-factor values indicate the presence of strong line-of-sight components, resulting in enhanced signal stability and reliability. This is essential for maintaining continuous and robust communication links. In contrast, lower K-factor values, indicative of prevalent scattering, can degrade the signal quality. We investigate the impact of variable K-factors, ranging from -10dB to 25dB, to simulate real-world environmental changes, such as atmospheric disruptions. This analysis evaluates the flexibility and adaptation of our HO strategies over various signal conditions. It guides the optimal configuration of HM to effectively balance HO frequency with data rate. We aim to distinguish the impact of fluctuations in line-of-sight conditions on the overall network efficiency and user experience by comparing these variable conditions to a constant K-factor of 20 dB. Thus, this will provide essential insights for adapting HO mechanisms to dynamic operational environments.

3.4.5 Handover Cost

In satellite network operations, especially within large constellations such as Starlink, analyzing HO cost is crucial. This metric identifies the resource utilization involved in managing satellite HOs and is essential for evaluating the operational efficiency and economic consequences of HO strategies. As the current serving satellite approaches the end of its coverage, the communication link need to HO to a new satellite. This satellite HO process involves operations such as acquiring and tracking new paths at network levels, which leads to HO costs. It is crucial to emphasize that the HO cost is not solely related to reducing the number of HOs occurrences [69]. The HO cost involves complex dynamics such as LEO satellite network topology, the distance that data needs to travel during each HO and the corresponding signalling efforts. During the satellite HO process, the transmission of data from the current serving satellite to the next candidate satellite could require multiple hops. This is often due to the satellite's travel direction and its ability to establish connections with neighbouring satellites.

The cost for a single HO is defined as $d_h + \nu$, where d_h represents the number of hops between the current serving LEO satellite and the next LEO satellite [69]. The term ν denotes a constant that indicates the link setup cost. This assumes that the new path will route through the current existing satellite to the new candidate satellite, which may not always be the optimal routing scheme.

The set $\mathcal{H}$ includes all HO events that occur during the simulation time and the total number of HO events denoted by $\mathcal{N}$. Each element, h, within this set, represents a specific HO where a gateway station switches from the serving satellite to the target satellite due to the satellite moving out of coverage or other operational needs. This could be defined as follows

$$\mathcal{H} = \{h | 1 \leq h \leq \mathcal{N}\}. \tag{3.25}$$

Based on the methodology presented in [69], the overall HO cost for a strategy is calculated by summing the costs of all individual HOs, expressed through the following formula

$$Cost(\text{strategy}) = \sum_{h \in \mathcal{H}} (d_h + \nu), \tag{3.26}$$

where d_h denotes the delay or hop count for each handover h, and ν is a constant representing the setup cost for each handover h, here assumed to be 10. This setup cost refers to the required fundamental resource to connect adjacent satellites.

This context highlights the complex relationship between HO frequency, satellite spatial configuration, and the economic feasibility of satellite network operations.

The hop count specifies the number of satellites that data must cross when transferring from the serving satellite to the next candidate satellite. This distance is critical as longer paths through multiple satellites increase resource consumption and operational costs. It emphasizes that only reducing the HO frequency does not directly decrease overall HO costs. Our model assumes that each satellite is equipped with four ISL terminals, which can establish connections within a maximum range of 5000 km. This assumption defines the spatial dynamics in which satellites might interact, affecting both the frequency and the cost of HOs.

This sort of analysis allows for the accurate quantification of the HO costs related to various strategic implementations, providing a comprehensive evaluation of their economic feasibility and efficiency. By applying this model, we aim to identify HO strategy that reduces operational costs and maintains high standards of connectivity and service reliability. Thus, it enhance the competitive edge of satellite network services.

CHAPTER 4 NUMERICAL RESULTS

This chapter presents several simulations to validate the efficacy of the proposed HO strategy for LEO satellite communication systems. The simulations are implemented in Python, using various libraries and custom modules to model and evaluate satellite HOs within the Starlink Phase I constellation. The constellation consists of 1,584 satellites, distributed across 22 orbital planes, with 72 satellites per orbit, at an altitude of 550 km.

4.1 Simulation Setup

In this simulation, we model the downlink of a LEO satellite communication network, focusing on the performance of the satellite HO strategy. The simulation environment includes three gateway stations, each covered by multiple LEO satellites over different time slots. These gateway stations are geographically distributed across the region of Montréal, Canada. The geographical coordinates of the gateway stations are as follows

- Laval, Canada : 45.6066° N, -73.7124° W
- Longueuil, Canada : 45.5319° N, -73.5183° W
- Montréal-Est, Canada : 45.6325° N, -73.5076° W

Figure 4.1 Geographical locations of the gateway stations used in the simulation.

The simulation duration is set to 45 minutes. A gateway station is considered to be within the coverage area of a satellite if the elevation angle between the satellite and the station is 15°

or higher. In this simulation, the HM condition is based on the dynamic channel gain $G_{ij-init}$ between GW_i and S_j, which is calculated at the initial matching between each gateway station and satellite. The HM is applied to ensure that as long as the current channel gain between GW_i and S_j does not fall below $G_{ij-init}$ by more than the HM value, the satellite connection is maintained. This adaptive approach eliminates the need for a fixed minimum signal threshold (such as RSRP) and allows the system to dynamically adjust based on real-time channel conditions.

4.2 Simulation Process

The simulation code and implementation details for the proposed HO strategy are available in the GitHub repository at: `https://github.com/sahar19921371/LEO-Satellite-Handover`. To model the satellite constellation and its interactions with the gateway stations, the following steps were taken.

Coordinate Systems and Positioning

The gateway stations' positions are represented using geodetic coordinates in the World Geodetic System (WGS 84), which serves as the standard reference ellipsoid for the GPS. Therefore, the position of each gateway station is specified by the tuple $(\mathrm{Lat}_i, \mathrm{Lon}_i, \mathrm{Alt}_i)$, where the latitude is within the range of $[-90°, 90°]$, the longitude ranges from $[-180°, 180°]$, and the altitude is measured in meters.

For satellite simulations and to compute precise distances, the geodetic coordinates are transformed from the WGS 84 system (EPSG: 4326) to the ECEF coordinate system (EPSG: 4978). This transformation, performed using the *pyproj* library, converts the geodetic coordinates (latitude, longitude, altitude) into Cartesian coordinates (x, y, z) in meters. The ECEF system is more suitable for mathematical operations involved in satellite tracking and distance calculations.

Satellite Positioning via TLE Data

The satellite orbits are determined using publicly available two-line element (TLE) data, sourced from platforms like *NORAD* and *CelesTrak*. TLE data includes essential orbital parameters, such as inclination, eccentricity, right ascension of the ascending node (RAAN), and true anomaly, which define the satellite's trajectory and position over time. These parameters enable precise predictions of satellite positions relative to the gateway stations at any given moment. The TLE files are regularly updated to ensure accuracy in satellite trajectory forecasts.

Inclination defines the angle between the satellite's orbital plane and the equator, while eccentricity describes the orbit's shape, indicating how circular or elliptical it is. The RAAN specifies the horizontal orientation of the orbital plane, and the true anomaly details the satellite's position within the orbit at a particular time. Together, these parameters are crucial for determining when a satellite will be visible to a gateway station, allowing for accurate HO predictions. For the purposes of our simulation, the *pyorbital* library is used to process the TLE data and predict satellite positions at specific time intervals. This enables real-time tracking of satellite movements and facilitates the computation of satellite visibility and HO decisions between satellites and gateway stations throughout the simulation.

Time Interval Generation

The simulation time is divided into evenly spaced intervals to model the dynamic interactions between the satellites and gateway stations. The simulation starts at a predefined initial time, and subsequent time points are generated at regular intervals using *datetime* and *timedelta* libraries. The total duration of the simulation is 45 minutes, with a specific number of time slots generated to capture satellite visibility at each gateway station over this period.

To ensure accurate temporal resolution, NumPy's *linspace* function is employed to generate an array of timestamps that are evenly distributed between the initial and final time points. These timestamps are critical for evaluating the satellite-to-gateway link status and making HO decisions during each time interval.

Link Metrics Calculation

For each satellite-gateway pair, the distance and elevation angle are calculated in the ECEF system. A satellite is considered to be in coverage if its elevation angle exceeds 15°. The channel gain is calculated based on free-space path loss, atmospheric fading, and Rician small-scale fading. Using the channel gain, the received power and achievable data rate are computed using the Shannon theorem, which are essential for optimizing communication quality and minimizing HO disruptions.

Satellite Coverage and Handover Timetable

The simulation generates coverage matrices that track the visibility of satellites from each gateway station. These matrices determine the time periods during which a satellite is within coverage and guide the HO decisions. A HO timetable is created to ensure smooth transitions between satellites as they enter and exit the coverage area.

Algorithm Enhancement Using the KM Algorithm and HM

HO decisions are managed iteratively for each time slot t_k by constructing a weighted bipartite graph, where the vertices represent satellites and gateway stations. Historical connection data is retrieved, and the HM is applied to prioritize maintaining connections with previously matched satellite-gateway pairs, reducing unnecessary HOs.

The *scipy.optimize* library is used to implement the KM algorithm, specifically the 'linear sum assignment' function, which solves the MWM problem. This function ensures optimal satellite-gateway assignments, improving link quality while reducing the frequency of HO occurrences.

At each time step, the weight matrix is updated based on current and historical conditions. The updated matching is then used to guide future HO decisions, allowing the simulation to adapt dynamically to changing satellite positions and link conditions.

4.2.1 Simulation Parameters

The system settings have been determined in accordance with the works and recommendations in [7] and the implementation trends of the LEO satellite [70]. The LEO satellite environment parameters are summarized in Table 4.1.

TABLE 4.1 Simulation parameters.

Parameter	**Value**
Simulation time	45 minutes
Minimum coverage elevation angle	15°
Altitude	550 km
Transmit power	400 watts
Carrier frequency	11.9 GHz
BW	10 MHz
Noise power spectral density	-173 dBm/Hz
Atmospheric fading's attenuation	0.05 dB/km
Rician K-factor	20dB
σ (Large value of F_H)	10dB

4.3 Simulation Results

This section evaluates the performance of the proposed HO strategy using various essential metrics. Let us begin with data rate, a critical factor that directly impacts the QoS, user experience, and network efficiency. Subsequent sections investigate metrics such as the HO rate, the impact of the Rician K-factor, and the HO cost.

4.3.1 Average Data Rate Across Different Strategies

The data rate is crucial for evaluating the effectiveness of HO strategies in LEO satellite networks. This metric reflects the ability of our method to maintain high data rates among dynamic satellite coverage and various network conditions. In Figure 4.2, the average data rate of four approaches is displayed, including the proposed satellite HO strategy, enhanced KM strategy in [47], shortest HO path strategy in [31], and maximum service time strategy. The enhanced KM strategy, implemented in [47], utilizes maximum weight matching with channel coefficients as weights to optimize link quality. As shown in Figure 4.2, this strategy maintains competitive data rates. However, this approach does not consider HO frequency, potentially leading to service interruptions and degraded user experience.

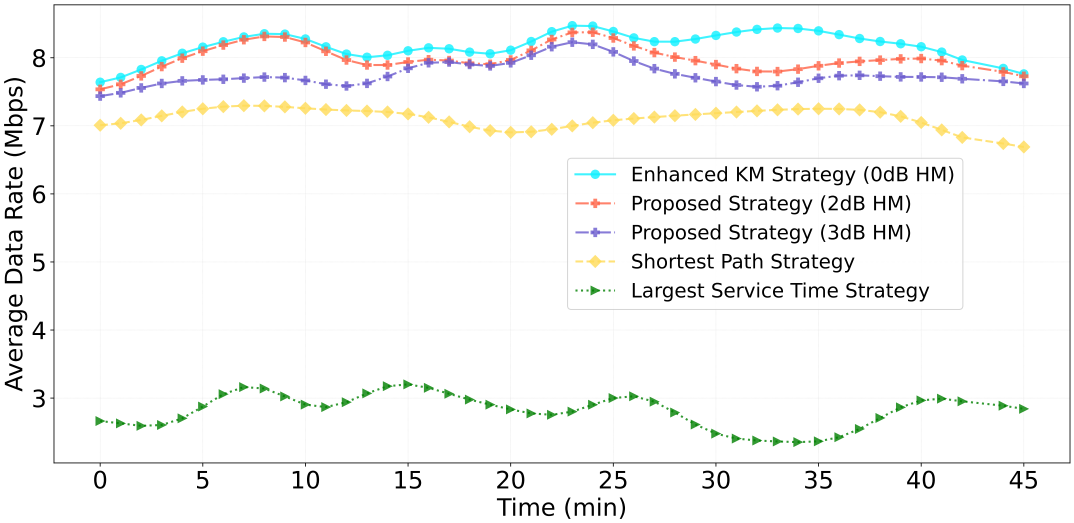


FIGURE 4.2 Average data rate of handover strategies

Our proposed strategy introduces HM of 2 dB and 3 dB to effectively balance the link quality with the HO frequency. It is shown in Figure 4.2 that the average data rate of the proposed scheme, especially with the 2 dB margin, closely matches that of the enhanced KM strategy. Furthermore, our scheme demonstrates the effective HO management without compromising data rate performance. In addition, it offers a robust method that improves network stability while maintaining a high level of QoS.

The shortest path strategy, discussed in [31], aims to minimize path length in a directed graph by considering service time and elevation angle factors. Our findings from simulation demonstrate in Figure 4.2 that the proposed method with both the 2 dB and 3 dB margins continuously outperforms the shortest path strategy in terms of data rates. Hence, it highlights our model's ability to effectively leverage the benefits of satellite diversity and dynamic HO thresholds. The strategy focusing on the largest service time, which inherently minimizes HO occurrences, shows lower average data rates, as expected. This result emphasizes the trade-off between reducing HOs and maintaining a high data rate. Besides, it refers that excessive reduction of HOs might affect the network's capability to maintain high data rates.

4.3.2 Average Data Rate Across Different HM

This subsection analyzes the proposed strategy's efficacy under various HM. The HM setting is critical to achieve a trade-off between low HOs and high data rates in our scheme. Therefore, the impact of different HM on the average data rate is shown in Figure 4.3, with each curve representing a distinct HM setting.

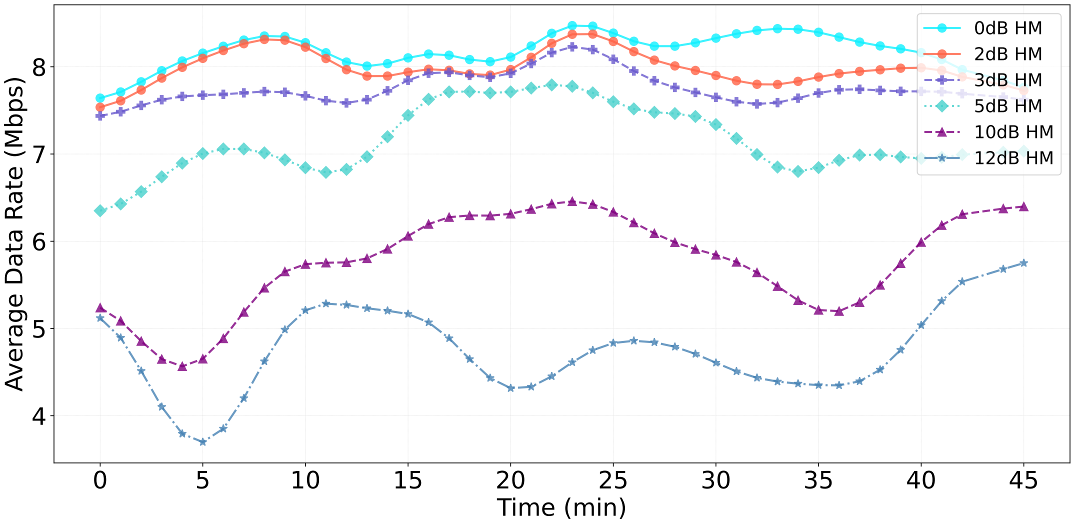


FIGURE 4.3 Average data rate across different HMs

Figure 4.3 displays that the average data rate drops as the margins increase. Furthermore, the fluctuation of the curves escalates with higher margins as a result of the close competition between HM conditions and the KM algorithm in HO decisions. In particular, smaller margins such as 2 dB and 3 dB maintain high data rates with stable performance as demonstrated in Figure 4.3. These results indicate that the KM algorithm mostly manages HO decisions, while the HM improves service continuity without compromising channel quality. Therefore, these settings can be ideal for environments where high data rate is critical and minor HO rates are acceptable.

When dealing with medium margins, such as 5 dB, the main focus is to enhance continuity of service, which is essential for scenarios that prioritize minimizing HO costs and delays. Figure 4.3 shows that at the 5 dB margin, the average data rate decreases compared to lower margins. This occurs because the role of HM in HO decisions has increased. In addition, the trajectory of the 5 dB curve demonstrates a well-balanced approach that efficiently reduces

HO frequency while taking advantage of high-quality channels. This configuration ensures uninterrupted connectivity while reducing frequent switching.

Furthermore, applying higher thresholds, such as 10 dB and 12 dB, decreases the average data rate and causes significant fluctuations. The initial downward trends in their curves indicate a reduced role of the KM algorithm that triggers a HOs almost with the end of satellite coverage. While this configuration further decreases the number of HOs, it also decreases service quality. These settings are not suitable for applications that require high-quality and stable connections.

4.3.3 Overall Average Data Rates Across Different HM

To further examine the impact of HM on network reliability, Figure 4.4 displays the overall data rates for various HM settings.

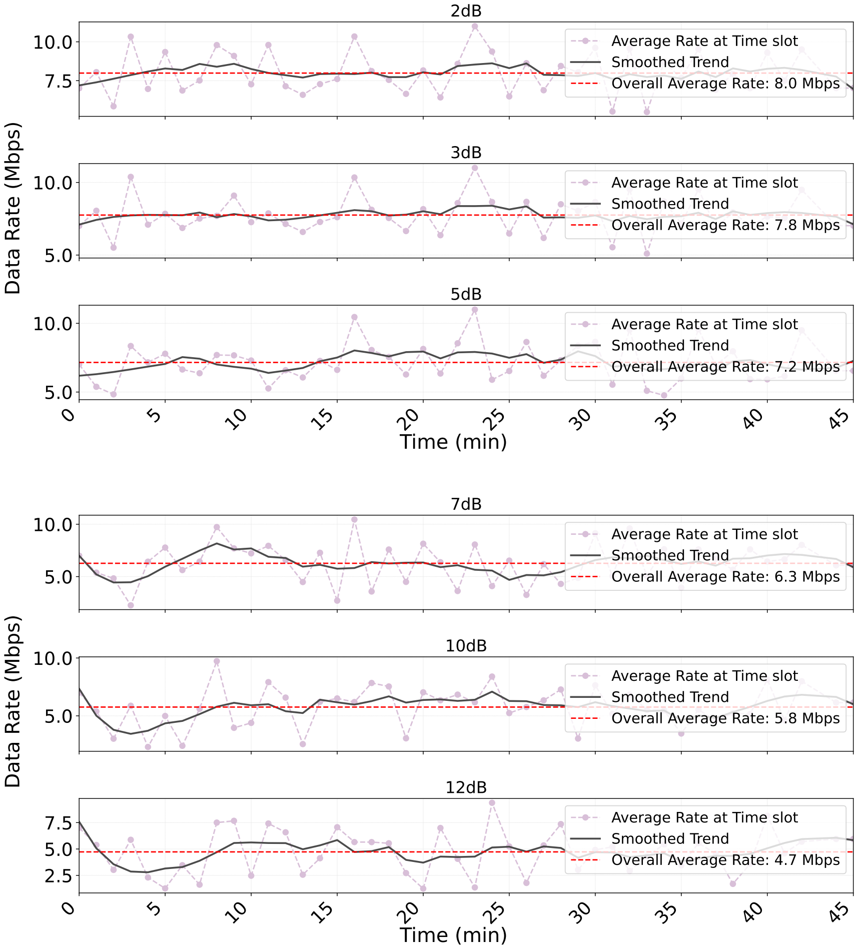


FIGURE 4.4 Comparison of overall average data rates for various HM settings.

The HM needs to be carefully adjusted to fulfill the specific operational requirements of the satellite network. Figure 4.4 shows that lower margins, especially 2 dB and 3 dB, provide the highest service quality with overall data rates of 8.0 Mbps and 7.8 Mbps, respectively. On the other hand, margins from 5 dB to 7 dB result in overall data rates varying from 6.3 Mbps to 7.2 Mbps. Thus, they might be suitable for scenarios prioritizing seamless and uninterrupted service. When the margins exceed 7 dB, the average rates are close to those achieved by the maximum service time method.

Generally, it is not beneficial to utilize these margins as they increase service duration with lower data rates, which may not be ideal for scenarios that require continuous high-speed connectivity. The flexibility of our method in configuring HM is essential for improving network performance by efficiently managing the trade-off between high data rates and low HO rates. Thus, operators and companies are able to enhance network quality and efficiency based on their unique service requirements and operating conditions.

4.3.4 Handover Times Across Three Different Strategies

This subsection evaluates the satellite HO number via three different approaches during connection duration. Figure 4.5 indicates that with increasing the connection duration, the frequency of HO occurrences across these three methods rises almost linearly.

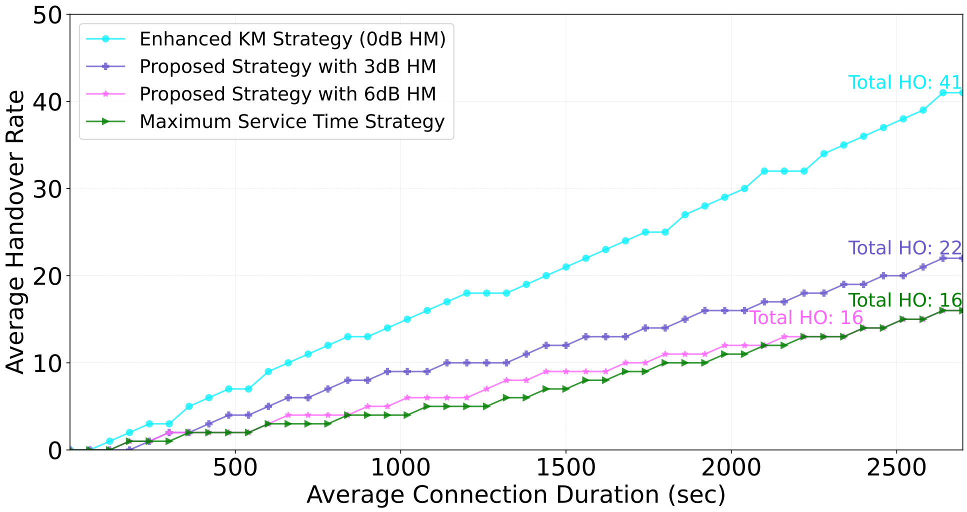


Figure 4.5 Comparison of three strategies handover times

By examining these strategies, it has been shown the maximum service time approach shows the slowest increase in the number of HO, while the enhanced KM approach experiences the quickest increase. On the other hand, the number of HO in our proposed method, with 3 dB and 6 dB margins, increase at a rate between those approaches and remaining close to the service time approach. Additionally, the 6 dB margin aligns closely with the number of HOs in the maximum service time method.

The 3 dB margin significantly reduces the number of HO. It improves service continuity while providing a high service quality comparable to the enhanced KM approach. This margin is appropriate for environments where both high service quality and low HO frequency are essential. Meanwhile, the 6 dB margin achieved by limiting the number of HOs is suitable for scenarios that prefer continuous service over peak service performance.

The number of HOs is critical for both users and systems as it directly impacts the QoE and the system's signalling overhead. Frequent HOs can lead to increased connection drops and the need for various signalling interactions, which can waste system resources and increase operational costs.

4.3.5 Number of Handovers Across Different HM

Here, we examine the variation in the frequency of HOs across different HM settings. Figure 4.6 clearly demonstrates that increasing the HM reduces the number of HOs within the network.

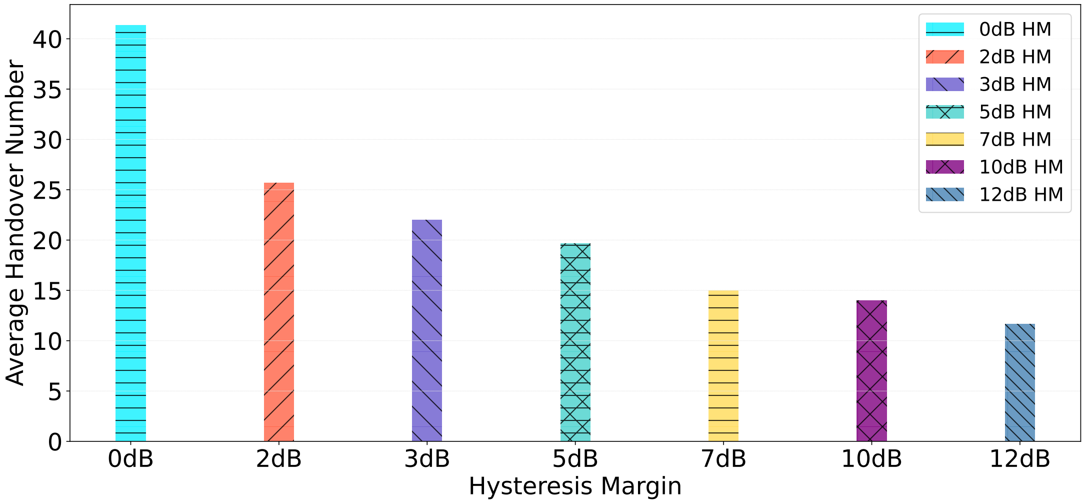


Figure 4.6 Average number of handover events across different HMs.

Figure 4.6 demonstrates that the 2 dB and 3 dB margins, central to our proposed strategy, significantly decrease the number of HO. These margins reduce the number of HO occurrences by 45% to 50% compared to the enhanced KM strategy while maintaining almost the same level of communication quality. This displays their performance to achieve a balance between QoS and operational efficiency. Figure 4.6 also shows that utilization of 5 dB to 7 dB margins decreases 25% to 27% in HO numbers compared to using 2 dB and 3 dB margins. However, this setting is accompanied by a minor reduction in link quality. While these settings effectively decrease service interruptions by limiting HOs, the slight degradation in communication quality indicates that they should applied with caution, particularly in scenarios in which a high data rate is crucial.

The margins of 10 dB and 12 dB result in the highest decrease in HO frequency, almost reducing the HO number in half compared to the 2 dB and 3 dB margins as displayed in Figure 4.6. However, the significant decrease in HOs seriously affects the quality of links, making these settings inappropriate for network performance. The analysis highlights the importance of selecting a HM that could effectively meet the requirement for minimizing HO events while maintaining high-quality communication, especially in dynamic satellite communication environments.

4.3.6 Impact of Various Rician K-factor on Handover Strategy

This section investigates the impact of varying Rician K-factors, ranging from -10 dB to 25 dB, on our satellite HO strategy. The aim is to evaluate the effectiveness of the proposed approach in the presence of varying signal conditions that reflect real-world environmental changes, such as atmospheric disruptions or physical obstacles. This analysis evaluates the performance of our scheme under variable K-factors compared to a baseline of a constant 20 dB K-factor. The examination focuses on the metrics, such as the number of HO and the overall data rate, across different HM configurations.

Impact on Overall Average Data Rate

By comparing the two curves displayed in Figure 4.7, it can be found that the average rate has generally increased in all HM for the variable Rician K-factor. Figure 4.7 demonstrates that in the scenario with a variable Rician K-factor, the data rate of bigger margins, such as 10 dB, experiences a considerable increase. The enhancement is mainly due to our method's ability to leverage high-quality links during moments of peak K-factor. Unlike the constant K-factor scenario, where the channel gains between a specific satellite and gateway station usually decrease over time, the variable K-factor provides the possibility of improvements or stability in channel quality within subsequent time slots. Therefore, the higher HM can keep satellites with enhanced line-of-sight conditions longer while reducing the HO frequency.

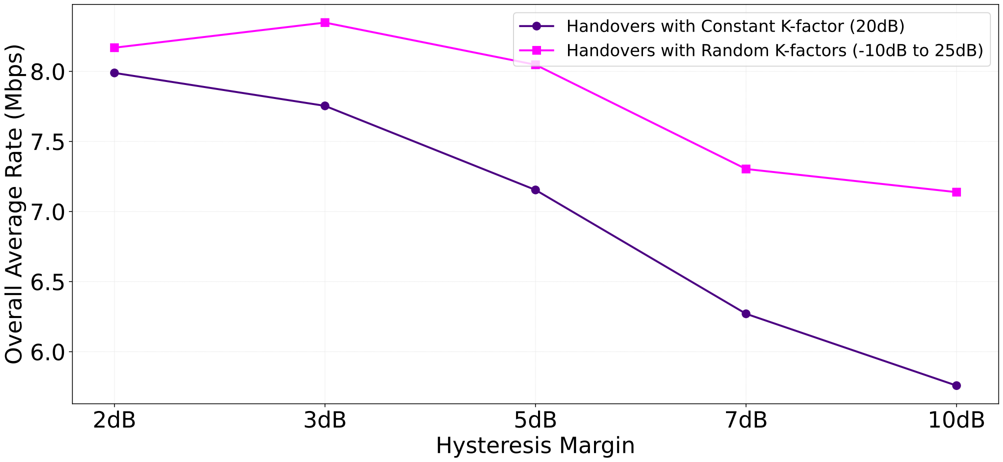


FIGURE 4.7 Overall average data rates vs HMs

In contrast, at a lower margin, such as 2 dB, the improvement of the overall rate is less visible. This occurs because the KM algorithm prioritizes selecting high-quality links and plays a more significant part in HO decisions within smaller margins. Connections are regularly adjusted at these lower thresholds to guarantee the best quality, thus minimizing the impact of the variable K-factor.

These findings indicate that satellite network operators should adjust HM settings based on their specific operational environments. The 3 dB and 5 dB margins are particularly effective, maintaining high data rates even in various signal conditions while reducing the frequency of HO. The 3 dB margin is ideal for scenarios demanding stability, high quality and user experience, whereas the 5 dB margin provides further robustness against signal variability. The proposed approach optimizes the trade-off between service continuity and link quality, thus enhancing QoS and user experience.

Impact on Average Handover Number

Figure 4.8 highlights the impact of variable Rician K-factors on the number of HO across different HM. Figure 4.8 displays that at lower margins (2 dB and 3 dB), the number of HO significantly decreases. This trend can be attributed to the possibility of signal improvement over time for specific satellites and gateway stations, resulting in the maintenance or enhancement of link quality. The enhanced signal quality enables the current satellite link to stay connected for longer durations without facing the specific conditions that usually trigger a HO.

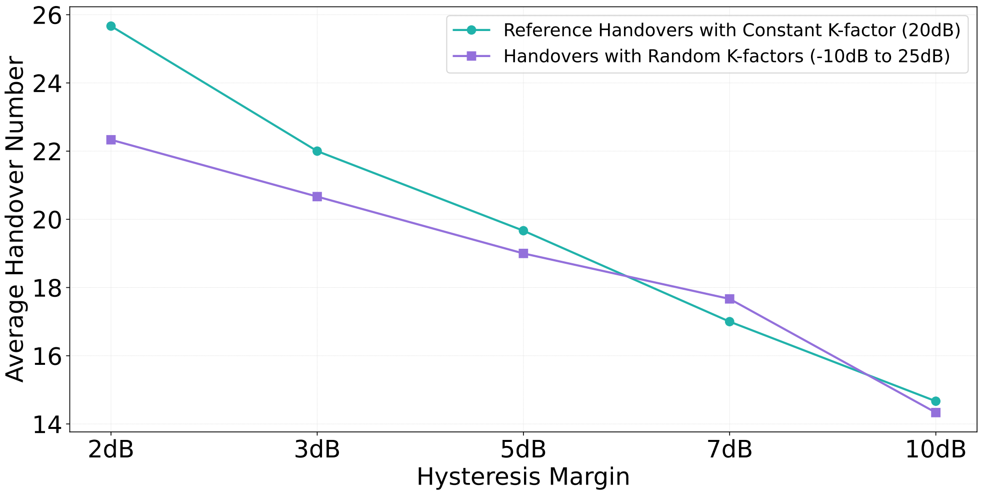


Figure 4.8 Average handover number vs HMs.

This effect is especially visible at lower margins, where the system is more sensitive to changes in signal quality. The 3 dB margin effectively demonstrates this effect by significantly reducing HOs as represented in Figure 4.8. Furthermore, the 3 dB margin achieves higher overall data rates, as Figure 4.7 shows. In contrast, higher margins have already reduced the occurrence of HO to a minimum. Therefore, the variation in K-factors does not significantly affect the frequency of HO. This finding highlights the efficacy of a 3 dB margin in maintaining a balance between service continuity and stability in the presence of fluctuating signal conditions.

4.3.7 Handover Strategy Cost

In Figure 4.9, we examine the HO costs associated with three strategies within a LEO satellite network: the enhanced KM approach, represented by (EKM); the maximum service time approach represented by (MST); and our proposed approach with 3 dB margin, represented by (KMHM). As mentioned before, the MST strategy minimizes HOs but may compromise the link quality. The ratios β and α quantify the HO cost of our strategy and the enhanced KM strategy relative to the MST strategy. These ratios are defined as:

— $\alpha =$ (HO cost of EKM strategy)/(HO cost of MST strategy)

— $\beta =$ (HO cost of KMHM strategy)/(HO cost of MST strategy)

Figure 4.9 illustrates significant variations in HO cost across the strategies. The EKM strategy (α) continually achieves a ratio much greater than 1, indicating higher costs resulting from

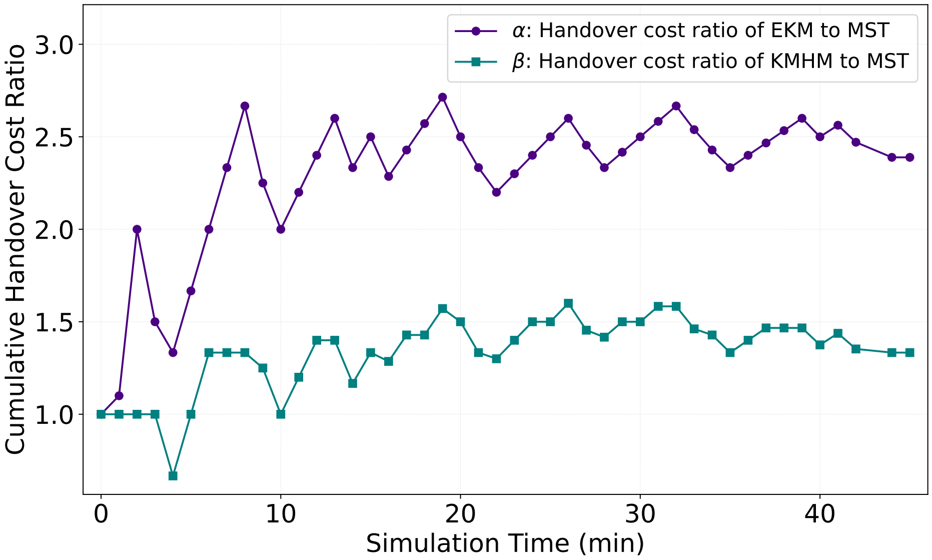


Figure 4.9 Handover cost ratios vs simulation time.

frequent HOs. The fluctuations in the α curve indicate periods of high HO costs due to frequent switching between satellites to maintain high service quality. This strategy focuses on selecting the highest link quality without considering the satellite service time, leading to ping-pong HOs—where a satellite HO occurs back and forth between satellites due to minor variations in link quality or the short service time of satellites. These frequent HOs may involve multiple hops due to the network's dynamic topology, thereby increasing the operational costs and causing fluctuations in the HO cost ratio.

In contrast, the proposed KMHM strategy (β) mostly keeps closer to 1 and indicates that our approach effectively reduces HO costs. Therefore, the proposed scheme, especially with the 3 dB margin, reduces operational costs and unnecessary HO through strategic delays in HO decision-making. Moreover, our method provides high service quality and data rates with adaptability under various channel conditions. This balance emphasizes that our proposed method is highly efficient for scenarios that require an assured combination of robust network performance and cost-efficiency. Therefore, it is an ideal choice for network operators that aim to manage both cost and service quality effectively.

As discussed in the performance metrics chapter, reducing the number of HOs does not necessarily lead to a decrease in HO costs, as their relationship is not entirely linear. However, the flexibility of our proposed strategy with adjustable HM allows for further improvement based on specific network requirements. By accurately adjusting the margin, network operators may evaluate different trade-offs in order to decrease frequent HO and HO costs while enhancing the quality of the link.

CHAPTER 5 CONCLUSION

In this thesis, we proposed a HO strategy for LEO satellite networks based on a bipartite graph model, aiming to maximize overall communication quality, minimize HO number, and balance network load. Additionally, we introduced a novel implementation of HM, providing a flexible, robust, and adaptable framework to meet different network requirements. The proposed approach applies a HM in the maximum weight matching method, leveraging channel gain as the primary criterion for HO decisions and reducing frequent HO without compromising channel quality. The utilization of the KM algorithm ensures high-quality links between satellites and gateway stations, providing a robust and efficient solution for dynamic network conditions. By its nature, the KM algorithm guarantees a unique match for each gateway station and satellite in each time slot, meaning that each satellite can only serve one gateway station at a time. This unique matching prevents any single satellite from serving multiple gateway stations simultaneously, thereby promoting load balancing across the network. On the other hand, HM create a threshold that should be met before a HO is executed to keep the satellite with the highest service quality for the maximum possible time. By combining these two techniques, our approach maintains high-quality communication links while significantly reducing the number of HOs, improving overall network performance and user experience. Simulation results show that the average data rate of our proposed strategy closely matches that of the enhanced KM strategy and outperforms the shortest HO path strategy. Furthermore, our scheme significantly reduces the number of HOs and HO costs compared to the enhanced KM strategy.

5.1 Main Insights, Contributions and Findings on the Proposed Analysis

This section outlines key insights and contributions of the proposed HO strategy for the LEO satellite networks. The achievement and effectiveness of the HO model, performance metrics outcomes, adaptability and flexibility under various network demands, and economic benefits of the proposed approach have been explored. Each segment explores specific aspects of the research, emphasizing the theoretical and practical effects of the proposed strategy, thereby expressing the importance of the contributions made to improve LEO satellite communication efficiencies. In particular

- HO Modeling and Enhancement: We modelled the HO process between gateway stations and LEO satellites using a bigraph, where each vertex set represents LEO satellites and gateway stations, and the edges denote communication links weighted by channel gain. The KM algorithm was applied to achieve maximum weight matching, ensuring high-quality communication and balanced satellite load distribution. The integration of an HM condition further enhances the algorithm by delaying HO decisions until the benefits of switching outweigh the service time, thereby reducing unnecessary HOs and enhancing network stability. Our simulations demonstrated that the proposed method effectively managed the dynamic nature of LEO satellite networks, balancing the need for high data rates with the requirement to minimize HO frequency.

- Performance Metrics and Simulation: We evaluated the proposed strategy using various performance metrics, including average data rate, number of HO, Rician K-factor, and HO cost. Simulations were conducted within the Starlink Phase I constellation using Python, covering different HM settings to balance the trade-off between minimizing HOs and maintaining high data rates. The results demonstrated that lower HM settings (2 dB and 3 dB) maintained high data rates with stable performance, while moderate HM settings (5 dB) provided a balanced approach, minimizing HO frequency without significantly compromising service quality. Specifically, our strategy with 2dB and 3dB margins reduced the HO number by approximately 45% to 50% compared to the enhanced KM strategy, demonstrating a significant improvement in maintaining stable communication links. The simulation results confirmed that the proposed method could balance performance and efficiency well, adapting to various channel conditions while ensuring high-quality service.
- Flexibility and Adaptability: The configurable HM provide a compatible framework for various operational demands, enabling network operators to prioritize either reduced HO frequency or higher data rates. This flexibility makes the strategy adaptable to different scenarios, enhancing its applicability in real-world environments. Additionally, the strategy demonstrated robust performance under varying channel conditions, including different Rician K-factors, ensuring high-quality connections and reduced HO numbers even under challenging signal conditions. This adaptability is crucial for practical deployments, where network conditions can vary widely, and the ability to dynamically adjust the HO strategy can lead to better overall performance and user satisfaction.
- Economic Efficiency: By integrating the HM into the KM algorithm, the proposed strategy reduced unnecessary HOs, improving network performance and decreasing operational costs. The simulation results showed that the proposed strategy, especially with the 3 dB HM margin, effectively balanced service quality and high data rates while managing costs more efficiently than existing strategies. The reduction in HO frequency decreases operational costs, signalling overhead, and resources that are required for managing HOs. This cost-effectiveness, combined with improved performance metrics,

might make the proposed strategy attractive for network operators looking to enhance satellite communication networks.

5.2 Limitations and Future Work

While the proposed strategy shows significant promise, several areas warrant further investigation and development:

Multi-Objective Optimization and Pareto Front: Future work should focus on multi-objective optimization to address multiple conflicting objectives, such as minimizing HO frequency, maximizing data rates, and optimizing energy efficiency. A multi-objective optimization approach would ensure that the network performs efficiently across all these dimensions. Additionally, identifying the Pareto Front for different hysteresis margin settings could provide valuable insights into the best trade-offs between conflicting objectives like data rate and HO rate. By selecting optimal hysteresis margins that balance these conflicting factors, future HO strategies could be even more effective.

Multi-Connectivity: In the proposed approach, each satellite can serve only one gateway station per time slot. Although this ensures load balancing, it does not fully utilize the satellite's capacity. Given the long distance between satellites and gateway stations, the fading of the communication channel is significant and requires high transmission power. Future LEO satellites, which will be smaller with lower transmission power, will benefit from strategies that maximize their communication capabilities. Implementing multi-connectivity in the satellite HO strategy could improve performance by enabling full utilization of satellite resources. In scenarios where a satellite is in an advantageous geometric position relative to multiple gateway stations, it could serve them simultaneously, improving data rates and further reducing HO frequency. This approach would combat channel fading and enhance communication quality, making the network more resilient and efficient.

Hysteresis Margin Sensitivity and Advanced Technologies: The strategy's performance is sensitive to the HM settings. Improper tuning of the HM can lead to frequent HOs or sub-optimal link quality. Future research should focus on developing adaptive HM settings that dynamically adjust based on real-time network conditions to maintain optimal performance. Leveraging advanced technologies such as machine learning and artificial intelligence can further enhance the HO strategy by predicting network conditions and optimizing HM settings. Algorithms using machine learning have the potential for analyzing massive data sets to predict network conditions, discover optimal HM settings, and make real-time adjustments to improve HO decisions. This integration could significantly enhance the strategy's efficiency and reliability.

Energy Efficiency: Investigating the impact of the proposed strategy on energy consumption and exploring energy-efficient implementations is crucial for future satellite networks. Reducing the overall power consumption while maintaining high performance will be essential as LEO satellites become smaller and more energy-constrained. Developing strategies that optimize power usage without compromising communication quality will be crucial for future research.

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