

Project CubeSat Programming

CubeSat Ground Station Handover Simulation

Task 2:

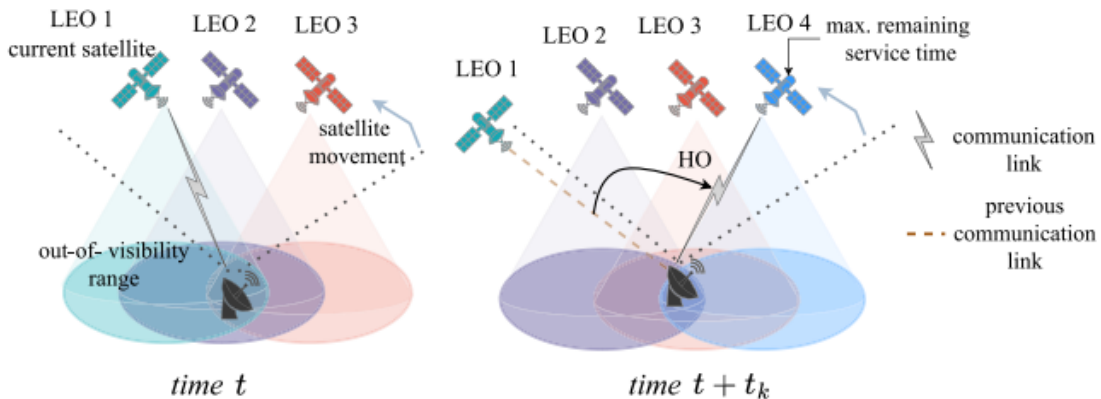
Model a scenario where one ground station hands off tracking to another as the CubeSat moves. Find the time when the elevation of one station drops below 0 degrees and next rises above 0 degrees.

Propagate the cubesat orbit, compute the elevation vs time for each ground station, detect where one station's elevation drops below zero degrees while another rises above zero degrees, mark that timestamp as the handover event.

Handover Strategy for LEO Satellite Networks Using Bipartite Graph and Hysteresis Margin

SATELLITE communications play an important role in providing seamless global connectivity and overcoming the inherent limitations of terrestrial mobile communications. The low Earth orbit (LEO) constellations, with orbits deployed at altitudes between 500 km and 1500 km, allow lower transmission latency and higher throughput compared to geostationary earth orbit (GEO) satellites . Furthermore, the low altitude of the satellites reduces power requirements and minimizes signal attenuation, which is critical to reducing the size of ground equipment . In recent years, the demand for broadband services offered by large constellations of LEO satellite networks (e.g., Kuiper, Starlink, OneWeb, and Lightspeed) has increased. For example, Starlink provides low-latency (i.e., below 30 ms), high-data-rate (i.e., above 100 Mb/s) satellite broadband services to inaccessible areas.

Therefore, the LEO constellation will be a key component in the evolution of communication systems



Hysteresis margin and Algorithm enhancement:

Frequent handovers disrupt communication quality and elevate operational costs. This subsection introduces the application of the HM condition, which adjusts weights to create updated matrices that prioritize stable connections while maintaining link quality. To investigate the HM condition for those $\{i, j, k\}$ found in set F_k , the proposed method compares the current channel quality of the $\{i, j, k\}$ with its initial value at t_k to adjust the weight and achieve the new bipartite matrix $G(:, :, k)$. Therefore, by applying the HM condition, the weight in $G(:, :, k)$ can be adjusted and expressed as a new matrix $G(:, :, k)$ as follows:

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

represents the updated weight of the communication link between G_{Wi} and S_j at time slot t_k , incorporating the HM condition. G_{ij} represents the channel gain between G_{Wi} and S_j at the first time, H is the hysteresis margin, and σ is a large value for F_H . In the first case, the proposed algorithm evaluates the handover margin condition. If S_j

satisfies the specified requirements for the corresponding GW_i , it can be considered qualified to continue providing service for GW_i among other candidate satellites. Therefore, the proposed scheme effectively prevents frequent handover while ensuring a highquality connection by maintaining S_j for GW_i at time slot t_k . To this end, we increase the link weight by multiplying a large hysteresis coefficient, σ , in G_{ijk} at $G(i, j, k)$. This strategic adjustment prioritizes S_j as the preferred handover candidate for GW_i at t_k , thus emphasizing service reliability above temporary quality improvements. In contrast, if S_j fails to satisfy the HM condition for the corresponding GW_i , it implies that S_j may not provide high-quality service to GW_i compared to other candidate satellites. As a result, GW_i may needs to identify a qualified alternative satellite at t_k , thereby the algorithm assigns the default weight G_{ijk} to $G(i, j, k)$. In the second case, since the coverage of serving satellite S_j for GW_i at t_{k-1} has ended at t_k , GW_i must switch to other satellites. Thus, we assign G_{ijk} as the weight in $G(i, j, k)$ to find the best target satellite for GW_i at t_k . The HM mechanism reduces unnecessary handovers and enhances network stability, making it a crucial component of the proposed scheme.

Maximum weight matching:

In this subsection, a MWM approach is employed to achieve high-quality links and balanced load distribution. This design addresses resource conflicts and enhances overall communication quality. 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 $G(:, :, k)$ 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. Given a complete weighted bipartite graph $G(i, j, k)$, the

$$w(\mathcal{M}) = \sum_{(i,j) \in \mathcal{M}} \lambda'_{ijk}.$$

goal of the KM algorithm is to find a matching M that maximizes the total weight, defined as

This matching improves communication link quality and load balancing between gateway stations and satellites. By utilizing the KM technique to our weighted bigraph $G(:, :, k)$, we derive the matching matrices, represented as $M(:, :, k)$. The outcome matching matrices $M(:, :, k)$ from KM algorithm, is defined as

$$\mathcal{M}(i, j, k) = w_{ijk}, \begin{cases} w_{ijk} = \lambda'_{ijk}, & \text{if } GW_i \text{ matches } S_j \\ w_{ijk} = 0, & \text{if } GW_i \text{ does not match } S_j. \end{cases} \quad (1)$$

The proposed method and the handover decision process are depicted in Algorithm 1. The KM algorithm maximizes the sum of weights in the for each gateway station, and reduces the handover number by integrating HM. By consistently implementing the KM method for each time slot, we ensure that each gateway station matches the satellite with the highest link quality based on the latest data. The proposed method also facilitates the efficient use of satellite resources and significantly reduces the handover rate. Finally, the outcomes derived from the KM method are stored in F_k to be utilized in the subsequent time slot. The MWM process enhances link quality and load distribution, effectively addressing key challenges in dynamic LEO satellite

networks. matching matrix $M(:, :, k)$, selects the best link quality

Algorithm 1 Proposed Satellite Handover Decision Process

```

1: Initialize satellites coverage  $S_j$  for gateway  $GW_i$ .
2: Initialize  $H$  and  $F_H$ .
3: Define and initialize set  $\mathcal{F}_k$ .
4: for all time slots  $k$  in  $T$ ,  $k = 1, 2, \dots, K$  do
5:   Establish initial bipartite matrices  $\mathcal{G}(:, :, k)$ .
6:   Weight adjustment operation:
7:   for all  $\{i, j, k\}$  in  $\mathcal{G}(:, :, k)$  do
8:     if  $\{i, j, k\}$  is found in  $\mathcal{F}_k$  then
9:       Check HM condition
10:      if HM condition is met then
11:        Increase the weight of  $\{i, j, k\}$  using (6).
12:        Adjust the weight in  $\mathcal{G}'(:, :, k)$ .
13:        Handover does not occur.
14:      else
15:        Assign  $G_{ijk}$  as weight in  $\mathcal{G}'(:, :, k)$ .
16:      end if
17:    else
18:      Assign  $G_{ijk}$  as the weight of in  $\mathcal{G}'(:, :, k)$ 
19:    end if
20:  end for
21:  Compute  $\mathcal{M}(:, :, k)$  using the KM to  $\mathcal{G}'(:, :, k)$ 
22:  Update  $\mathcal{F}_k$  with the results from  $\mathcal{M}(:, :, k)$  for the
    next time slot.
23: end for

```

Results and Discussions:

Fig. 5 demonstrates the performance of the proposed strategy under varying HM values. The HM setting is crucial in balancing between reducing handovers and maintaining high data rates. As the HM increases, the average data rate generally declines. Lower margins, such as 2 dB and 3 dB, maintain relatively high data rates and stable performance, indicating a balance between service continuity and channel quality, making them suitable for environments where high data rates are prioritized. Moderate margins, like 5 dB, effectively balance reduced handover frequency with a slight drop in data rate, highlighting their potential for minimizing handover costs. Higher

margins, such as 10 dB, result in further declines in data rate and greater fluctuations, indicating reduced service quality and a dominant role of HM over the KM algorithm in the handover process. These higher thresholds are less ideal for scenarios requiring stable, high-quality connections.

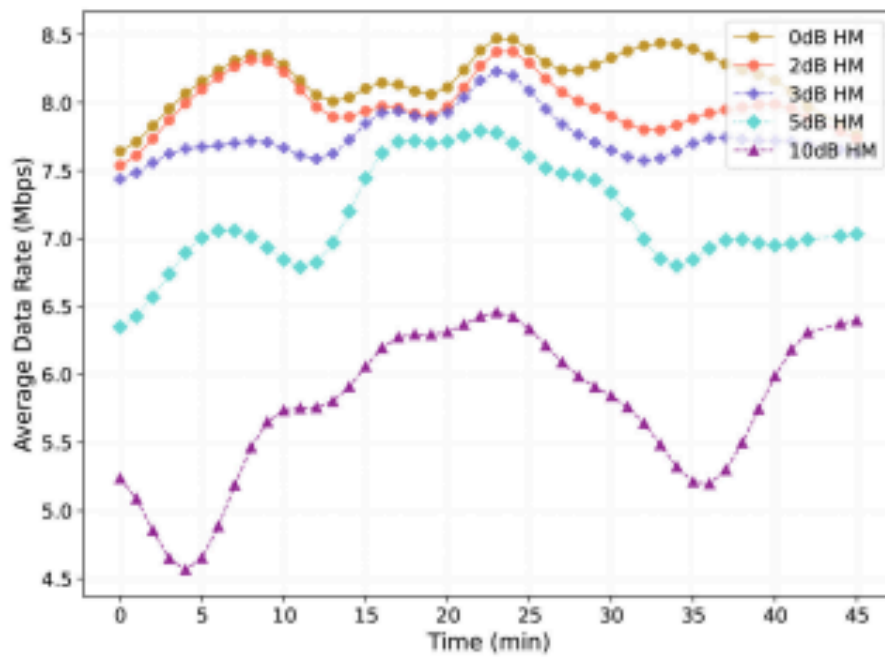


FIGURE 5. Average data rate across different HMs.

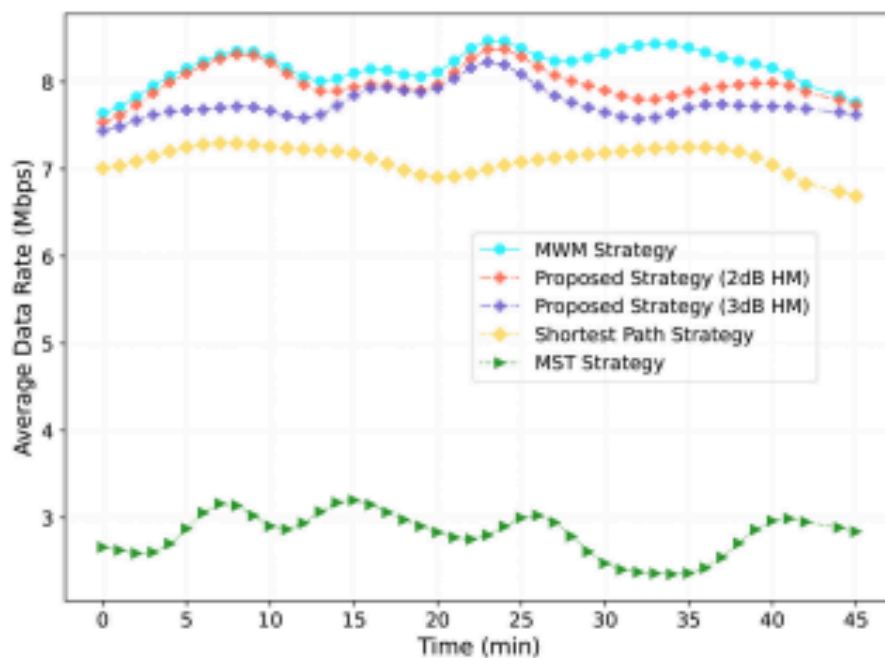


FIGURE 6. Average data rate of handover strategies.

Fig. 6 represents the average data rates for four strategies: the proposed handover strategy, the MWM strategy from [1], the shortest handover path strategy from [2], and the MST strategy. The MWM strategy achieves competitive data rates but overlooks frequent handover, risking service interruptions and user experience degradation. The proposed strategy, incorporating 2 dB and 3 dB margins, effectively balances link quality and handover frequency. As shown, the average data rate of our scheme, especially with the 2 dB margin, closely matches that of the MWM strategy and managing handovers effectively without sacrificing performance. Additionally, it offers robust network stability and high QoS. The proposed scheme with both margins consistently outperforms the shortest path strategy in data rates, demonstrating its ability to leverage satellite diversity and dynamic handover thresholds. In contrast, the MST strategy results in lower data rates, illustrating the challenge of balancing reduced handover numbers with maintaining high data rates.

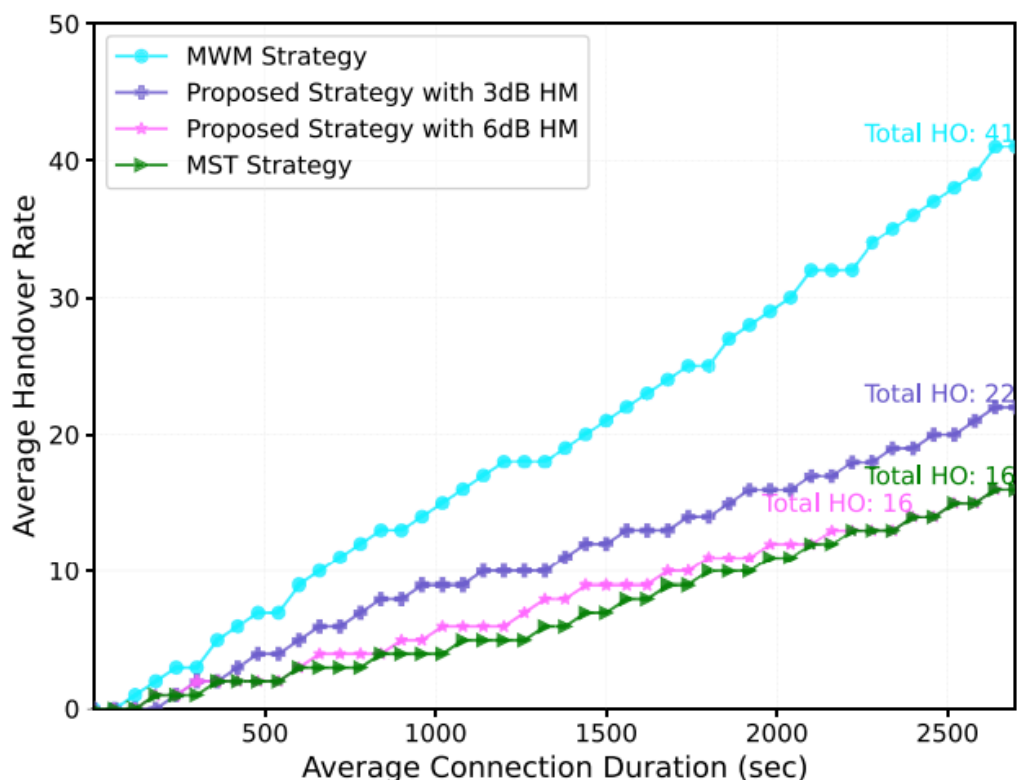


FIGURE 7. Comparison of handover rate across three techniques.

Fig. 7 shows that the number of handover times increases approximately linearly with the increase of connection duration across three different approaches. By examining these strategies, it has been shown the MST approach shows the slowest increase in the number of handover, while the MWM approach experiences the quickest increase. The handover number of 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. It can also be found that the 6 dB margin aligns closely with the number of switches in the MST strategy. The 3 dB margin significantly reduces the number of handovers and improves service continuity while providing a high service quality comparable to the MWM approach. The 3 dB margin is ideal for environments where both high service quality and low handover frequency are essential. Meanwhile, the 6 dB margin suits scenarios prioritizing continuous service over peak service performance. The number of handovers is critical for users and systems as it directly impacts the QoE and the system's signaling overhead. Frequent handovers can lead to increased connection drops, signaling interactions, operational costs, and waste system resources. Fig. 8 demonstrates that increasing the HM reduces the number of handovers within the network. The optimal margins (i.e., 2 dB and 3 dB) of our proposed method significantly reduce handovers by 45% to 50% compared to 0 dB margin, while preserving comparable communication quality. It displays their performance to achieve the perfect balance between QoS and operational efficiency. Moreover, utilization of 5 dB to 7 dB margins further reduces handovers by 25% to 27% compared to the 2 dB and 3 dB margins. However, this setting is accompanied by a minor

degradation in link quality and should be

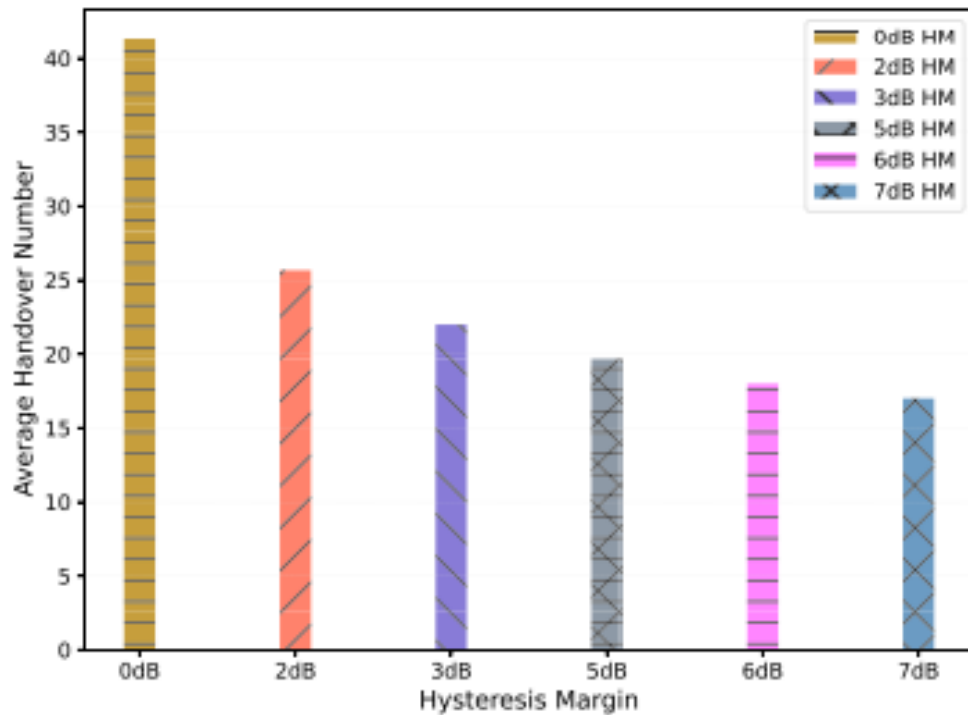


FIGURE 8. Average handover numbers vs different margins.

applied cautiously where high data rates are crucial. This analysis highlights the importance of selecting an appropriate HM to minimize handover events while maintaining high quality communication in dynamic satellite communication environments.

Fig. 9 evaluates the impact of varying Rician K-factors, uniformly distributed on a linear scale between -10 dB and 25 dB, compared to a constant K-factor baseline of 20 dB. The results show a decrease in handover rates as HM increases across both scenarios. However, under random K-factors, the reduction in handover rates is more pronounced at lower margins, such as 2 dB and 3 dB. This behavior is attributed to dynamic improvements in link quality. In real-world scenarios, satellite movement and changing geometrical configurations can temporarily boost the K-factor, enhancing link quality in subsequent time slots. At lower margins, the algorithm adapts effectively to these signal improvements, maintaining connections with the current satellite and avoiding unnecessary handovers. At higher margins, this adaptability becomes less impactful as the strict HM thresholds inherently reduce

handovers regardless of signal fluctuations.

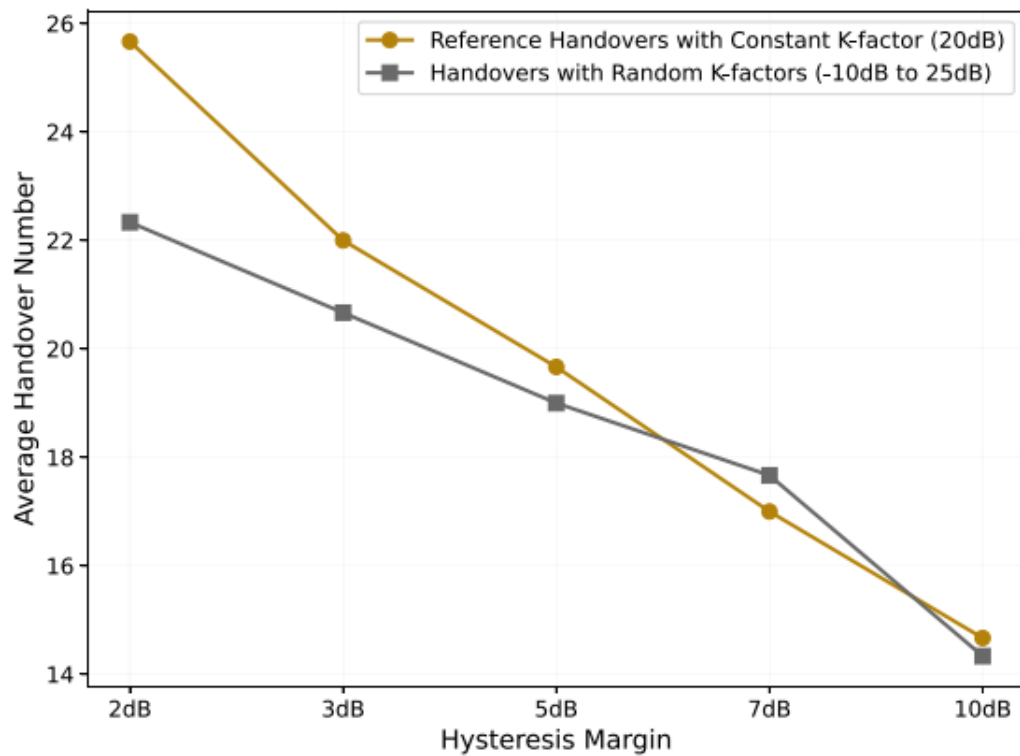


FIGURE 9. Average handover number vs margins.

Conclusion:

In this paper, we proposed a handover strategy for LEO satellite networks based on a bipartite graph model, aiming to maximize the overall communication quality, minimize the handover rate, and balance the network load. Furthermore, we introduced a novel integration of HM with KM algorithm, which provides a flexible, robust, and adaptable framework to meet different network requirements. The provided simulation results show that the average data rate of the proposed scheme closely matches the MWM strategy while outperforming the shortest handover path strategy. In addition, our scheme significantly reduces the handover rate and handover costs, and communication latency, while achieving energy consumption levels comparable to the MWM strategy. These improvements highlight the proposed strategy's ability to deliver stable, efficient, and low-latency communication. Future investigations should implement multi-connectivity in the satellite handover strategy to fully utilize satellite resources and improve data rates. Moreover, exploring

multi-objective optimization techniques, such as optimizing data rates, handover frequency, and energy efficiency simultaneously, would help in effectively balancing system performance metrics. Pareto front analysis could identify the best configurations to balance these conflicting objectives. Moreover, developing dynamic, re-configurable HM settings based on real-time network conditions through advanced technologies such as machine learning can further enhance the handover strategy and adapt it to varying operational environments.

References:

- “Handover Strategy for LEO Satellite Networks Using Bipartite Graph and Hysteresis Margin” -
<https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=10884973>

THANK YOU

Anant Nagari - 251ec109