

AoI-Aware Beam Count Optimization in Beam-Hopping LEO Multibeam Satellite Networks

Asfar Ahmad and Haejoon Jung

Department of Electronics and Information Convergence, Kyung Hee University (KHU), Yongin 17104, South Korea.

Email: {asfarahmad,haejoonjung}@khu.ac.kr

Abstract—Beam hopping (BH) allows flexible use of downlink resources in low Earth orbit (LEO) multibeam satellite systems by selectively activating a subset of beams for each transmission slot. Most existing BH frameworks focus on optimizing throughput or energy efficiency. However, the effect of choosing the number of beams on information freshness is still an unresolved issue. This paper jointly optimizes number of active beams and the beam scheduling policy for each slot to reduce the worst-case Age of Information (AoI) across all served cells. We identify a U-shaped relationship between the maximum network AoI and the number of activated beams. This arises from the balance between coverage limits at low beam counts and rate limits at high beam counts, establishing the existence of an optimal beam configuration. We evaluate four scheduling policies: greedy max-AoI, round-robin, periodic hopping, and random scheduling. The following is done under a diverse elevation angle channel model. The results show that the greedy policy achieves the lowest worst-case AoI and the best scheduling fairness among all considered baselines.

Index Terms—Age of information, beam hopping, LEO satellite, resource allocation, scheduling fairness.

I. INTRODUCTION

The rapid deployment of LEO satellite mega-constellations has made non-terrestrial networks (NTN) a key part of the new 6G wireless ecosystem. LEO satellites offer reduced propagation delay and global coverage in areas that lack terrestrial infrastructure [1], 3GPP has officially standardized NTN support starting with Release 17 for IoT, broadband, and mission-critical services [2]. In multibeam LEO satellite systems, only a specific number of B beams can be activated per slot due to hardware limits. To address this, beam hopping (BH) rotates beam assignments across time slots [3]. This offers a good balance between scheduling flexibility and hardware complexity [3], [4]

Existing studies on BH mainly concentrate on throughput or energy efficiency. In the literature, convex optimization and successive convex approximation techniques have been applied for joint beam scheduling and power allocation [5], while deep reinforcement learning addresses LEO-specific dynamic channel conditions [6]. Latency-aware formulations have also been explored [7]. However, a critical dimension has been overlooked: the *freshness* of information delivered to ground users.

The age of information (AoI) quantifies this by measuring elapsed time since the last successful status update [8], which is directly relevant for satellite IoT applications such as

environmental monitoring and maritime tracking [9]. Greedy max-weight scheduling is known to be optimal for AoI minimization under symmetric channels, while the Whittle-index policies extend this to heterogeneous settings [10]. However, none of these frameworks address the BH beam count selection problem, leaving the interaction between B , scheduling policy, and AoI entirely unexplored.

Motivated by this limitation, this paper addresses the joint beam count and scheduling optimization to minimize worst-case AoI. Activating too few beams starves dark cells (*coverage bottleneck*); too many beams narrows per-user bandwidth below the decoding threshold (*rate bottleneck*). An optimal B^* balancing these effects is shown to exist. The main contributions are summarized as follows:

- 1) We formulate the BH beam count selection as a minimax AoI optimization, jointly determining the number of simultaneously illuminated beams and the per-slot scheduling policy π to minimize the worst (maximum) AoI among all users, subject to bandwidth, power, and cardinality constraints.
- 2) We identify and characterize the U-shaped dependence of maximum network AoI on B , establishing the existence of an optimal beam configuration B^* .
- 3) Through Monte-Carlo simulation with $N_{mc} = 500$ realizations, we show that greedy max-AoI scheduling achieves the lowest maximum AoI and the highest Jain's fairness index (JFI), outperforming round-robin, periodic hopping, and random scheduling.

II. SYSTEM MODEL

A. Network Model

We consider a downlink BH-enabled LEO satellite communication system, as illustrated in Fig. 1. A single LEO satellite equipped with multiple steerable spot beams serves a geographical region partitioned into C virtual ground cells. Each cell contains K user terminals randomly distributed within the beam footprint. Due to the limited number of simultaneously active beams, the satellite dynamically illuminates only a subset of cells during each transmission slot through beam hopping. Such a BH architecture improves spectral efficiency and enables flexible resource utilization across heterogeneous traffic regions [11].

Let $\mathcal{C} = \{1, 2, \dots, C\}$ denote the set of ground cells and $\mathcal{B}(t) \subseteq \mathcal{C}$ represent the subset of illuminated cells

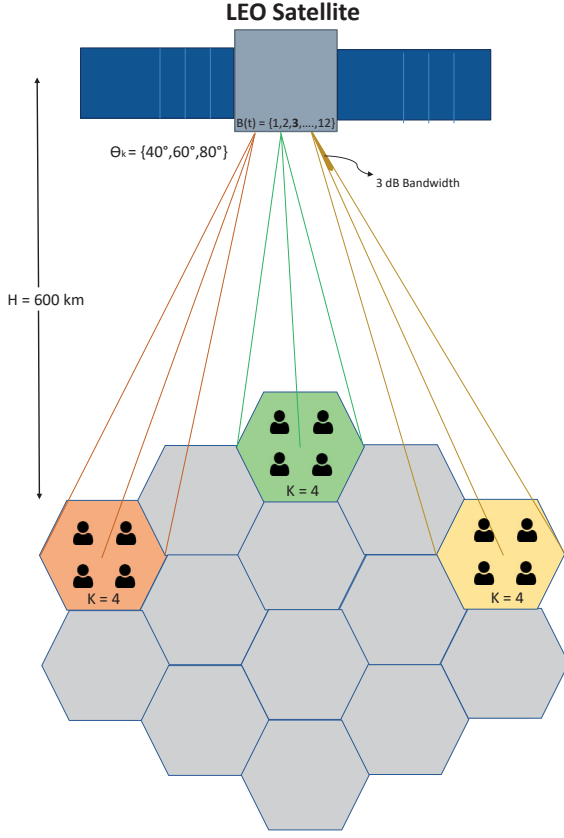


Fig. 1: BH-enabled LEO multibeam satellite downlink system model.

during transmission slot t . The considered system operates in a time-slotted manner, where scheduling and transmission decisions are updated at the beginning of each time slot. In addition, the key system parameters investigated in this work are summarized in Table I.

B. Channel Model

To characterize the satellite downlink channel, large-scale propagation effects, including free-space path loss and shadow fading, are considered. Since LEO satellite communications typically experience dominant line-of-sight (LoS) propagation due to the high orbital altitude and limited terrestrial blockage, the free-space path loss model accurately captures the dominant propagation attenuation [12]. Moreover, the long satellite-to-ground transmission distance significantly impacts the achievable transmission reliability and information freshness performance.

The free-space path loss between the satellite and user k is expressed as

$$L_k^{\text{FS}} = 32.45 + 20 \log_{10}(f_c) + 20 \log_{10}(d_k), \quad (1)$$

where f_c denotes the carrier frequency in GHz and d_k represents the slant distance between the satellite and user k in kilometers.

The slant distance depends on the satellite altitude, user position, and elevation angle. Following the geometric LEO satellite model, the reference distance between the satellite projection point and the Earth-origin reference is first calculated as

$$d_o = \sqrt{(R_E \sin \theta_k)^2 + H^2 + 2HR_E - R_E \sin \theta_k}, \quad (2)$$

where R_E denotes the Earth radius, H is the satellite altitude, and θ_k represents the elevation angle corresponding to user k .

Let $d_{k,o}$ denote the horizontal distance between user k and the beam center. Then, the slant range between the satellite and user k is given by

$$d_k = \sqrt{d_o^2 + d_{k,o}^2 - 2d_o d_{k,o} \cos(\theta_k)}, \quad (3)$$

which captures the geometric relationship between the satellite position, beam footprint, and user location.

In practical satellite systems, the wireless channel is additionally affected by environmental variations and atmospheric impairments. Therefore, log-normal shadow fading is incorporated into the propagation model [13]. Accordingly, the total large-scale propagation loss is modeled as

$$L_k = L_k^{\text{FS}} + X_{\text{sf}} + L_{\text{margin}}, \quad (4)$$

where $X_{\text{sf}} \sim \mathcal{N}(0, \sigma_{\text{sf}}^2)$ represents the shadow fading component with standard deviation σ_{sf} .

The satellite employs a directional spot-beam antenna pattern, where the transmit antenna gain depends on the off-axis angle between the user location and the beam boresight. Following the practical multibeam antenna model in [6], the transmit antenna gain is expressed as

$$G_T(\theta_k^{\text{off}}) = G_T \left(\frac{J_1(u_k)}{2u_k} + \frac{36J_3(u_k)}{u_k^3} \right)^2, \quad (5)$$

where $J_1(\cdot)$ and $J_3(\cdot)$ denote the first- and third-order Bessel functions of the first kind, respectively. Moreover, u_k is defined as

$$u_k = \frac{2.07123 \sin(\theta_k^{\text{off}})}{\sin(\theta_{3\text{dB}})}, \quad (6)$$

where $\theta_{3\text{dB}}$ denotes the antenna 3-dB beamwidth. The maximum boresight antenna gain is calculated as

$$G_T = \zeta \left(\frac{70\pi}{\theta_{3\text{dB}}} \right)^2, \quad (7)$$

where ζ represents the antenna efficiency factor.

The off-axis angle θ_k^{off} is determined according to the relative geometric position between the user and the beam center. Let $\mathbf{v}_m$ and $\mathbf{v}_k$ denote the beam boresight vector and user direction vector, respectively. Then, the off-axis angle is computed as

$$\theta_k^{\text{off}} = \cos^{-1} \left(\frac{\mathbf{v}_m^T \mathbf{v}_k}{\|\mathbf{v}_m\| \|\mathbf{v}_k\|} \right). \quad (8)$$

Due to beam-hopping operation and non-uniform user distribution within each beam footprint, users experience different

beamforming gains depending on their angular separation from the beam boresight [6]. Consequently, users located closer to the beam center generally achieve stronger channel conditions compared to edge users.

Based on the above propagation and antenna models, the overall downlink channel power gain between the satellite and user k is expressed as

$$g_k = 10^{-L_k/10} \cdot G_T(\theta_k^{\text{off}}) \cdot G_{\text{rx}}, \quad (9)$$

where $10^{-L_k/10}$ denotes the propagation gain corresponding to the total path loss as stated in eq.(4), $G_T(\theta_k^{\text{off}})$ is the satellite transmit antenna gain, and G_{rx} denotes the receiver antenna gain at the user terminal.

C. Communication Links and AoI

Assuming additive white Gaussian noise (AWGN), the received signal-to-noise ratio (SNR) of user k is calculated as

$$\gamma_k = \frac{P_k g_k}{\sigma^2}, \quad (10)$$

where P_k denotes the transmit power allocated to user k , while σ^2 represents the receiver noise power.

According to Shannon's capacity theorem, the achievable downlink transmission rate of user k is obtained as

$$R_k = W_k \log_2(1 + \gamma_k), \quad (11)$$

where W_k denotes the bandwidth allocated to the corresponding user.

A successful packet transmission occurs when the achievable transmission rate satisfies the minimum quality-of-service (QoS) requirement. Accordingly, the scheduling indicator of user k at transmission slot t is defined as

$$\delta_k(t) = \begin{cases} 1, & R_k(t) \geq R_{\text{th}}, \\ 0, & \text{otherwise,} \end{cases} \quad (12)$$

where R_{th} denotes the minimum target transmission rate threshold. Specifically, $\delta_k(t) = 1$ indicates that user k successfully receives a fresh information update during slot t , whereas $\delta_k(t) = 0$ represents a transmission outage caused by insufficient channel quality or limited resource availability.

To evaluate information freshness, the AoI metric is adopted. Let $A_k(t)$ denote the AoI of user k at transmission slot t . The AoI evolution is modeled as

$$A_k(t+1) = \begin{cases} 1, & \delta_k(t) = 1, \\ A_k(t) + 1, & \delta_k(t) = 0. \end{cases} \quad (13)$$

Since the considered system focuses on fairness-aware information freshness, the cell-level AoI is defined as the maximum AoI among all users within a cell, given by

$$A_c(t) = \max_{k \in \mathcal{U}_c} A_k(t), \quad (14)$$

where $\mathcal{U}_c$ denotes the set of users associated with cell c . This metric captures the worst-case freshness condition within each beam coverage region and is particularly suitable for fairness-oriented beam scheduling in satellite IoT systems [14].

TABLE I: System parameters and their configurations for the simulation.

Parameter	Value
Number of cells, C	12
Users per cell, K	4
Satellite altitude, H	600 km
Carrier frequency, f_c	2 GHz
Total system bandwidth, W_{total}	20 MHz
Total transmit power, P_{total}	53 dBm
Antenna efficiency factor, ζ	0.5
Receiver antenna gain, G_{rx}	16 dBi
Shadow fading standard deviation, σ_{sf}	4 dB
Noise spectral density	-174 dBm/Hz
Receiver noise figure	7 dB
Cell elevation angles, θ_k	80°, 60°, 40°
Target transmission rate, R_{th}	12 Mbps
Number of transmission slots, T	200

To evaluate the effectiveness of the proposed BH-LEO satellite framework, multiple beam scheduling strategies are considered, including greedy AoI-based scheduling, round-robin scheduling, periodic beam hopping, and random beam selection. These benchmark schemes provide different trade-offs between information freshness and fairness across the satellite coverage region. The system performance is analyzed under different numbers of simultaneously active beams, where the primary evaluation metrics include the maximum AoI, JFI for AoI, and JFI for throughput.

III. PROBLEM FORMULATION

Based on the system model described in Section II, the considered BH-LEO satellite system aims to efficiently allocate limited beam resources while maintaining fairness-aware information freshness among users. Since only a subset of beams can be simultaneously activated during each transmission slot, the number of active beams significantly affects both the achievable transmission performance and the AoI evolution across the coverage region.

Let B denote the number of simultaneously illuminated beams during a transmission slot, such that $1 \leq B \leq C$. Due to the fixed total system bandwidth and transmit power, increasing the number of active beams improves spatial coverage but reduces the communication resources allocated to each beam. Since each active beam simultaneously serves K users, the bandwidth and transmit power allocated to each user are respectively given by

$$W_k = \frac{W_{\text{total}}}{B \times K}, \quad (15)$$

and

$$P_k = \frac{P_{\text{total}}}{B \times K}. \quad (16)$$

Therefore, the beam selection process introduces an inherent trade-off between spatial beam coverage and per-user transmission reliability. Specifically, activating a larger number of beams increases the number of simultaneously

served cells while reducing the available power and bandwidth per user. Conversely, activating fewer beams improves the achievable transmission rate per user but decreases service opportunities for non-illuminated cells, potentially increasing the AoI.

To investigate this trade-off, four benchmark beam scheduling strategies are considered in this work, namely greedy AoI-based scheduling, round-robin scheduling, periodic beam hopping, and random beam selection. The greedy scheduling policy prioritizes cells with the largest AoI values in order to reduce worst-case information staleness. In contrast, round-robin and periodic beam hopping provide cyclic service opportunities across all cells to improve temporal fairness, while random scheduling serves as a baseline benchmark without deterministic prioritization. For a given transmission slot t , let $\mathcal{B}(t)$ denote the set of selected beams satisfying $|\mathcal{B}(t)| = B$.

The primary objective of the considered BH-LEO framework is to minimize the worst-case information freshness across the network by optimally selecting the number of simultaneously active beams. Accordingly, the optimization objective is formulated as

$$\min_B \max_{c \in \mathcal{C}} A_c(t) \quad (17a)$$

$$\text{s.t. } 1 \leq B \leq C, \quad (17b)$$

$$R_k(t) \geq R_{\text{th}}, \quad \forall k \in \mathcal{U}_c, \quad (17c)$$

$$\mathcal{B}(t) \subseteq \mathcal{C}. \quad (17d)$$

The optimization problem in (17a) aims to determine the beam configuration that minimizes the maximum cell AoI while satisfying transmission reliability constraints. Since the number of simultaneously active beams directly affects user scheduling opportunities and resource allocation, different beam counts lead to distinct information freshness characteristics across the network.

To evaluate the effectiveness of the considered beam scheduling schemes, the system performance is first analyzed under varying numbers of active beams using the maximum AoI metric. Subsequently, the fairness performance is evaluated at the optimal beam configuration that achieves the minimum maximum AoI. In particular, JFI for AoI is utilized to characterize fairness among different cells in the considered BH-LEO satellite network.

IV. SIMULATION RESULTS

In this section, the performance of the proposed BH-LEO satellite framework is evaluated under different beam scheduling strategies and varying numbers of simultaneously active beams. The simulations are conducted using the parameters summarized in Table I. To provide a comprehensive comparison, four benchmark scheduling schemes are considered, namely greedy AoI-based scheduling, round-robin scheduling, periodic beam hopping, and random beam selection.

Fig. 2 presents the maximum AoI performance as a function of the number of simultaneous active beams B . We show that the number of active beams creates a fundamental trade-off

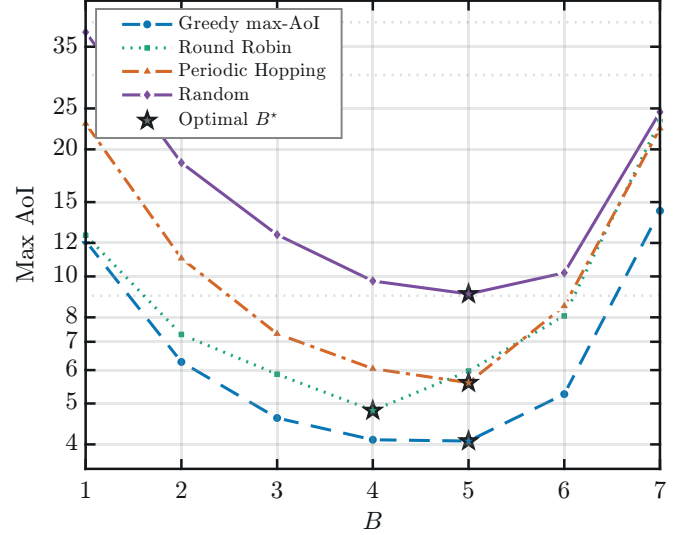


Fig. 2: Maximum AoI versus the number of active beams B for different beam scheduling techniques.

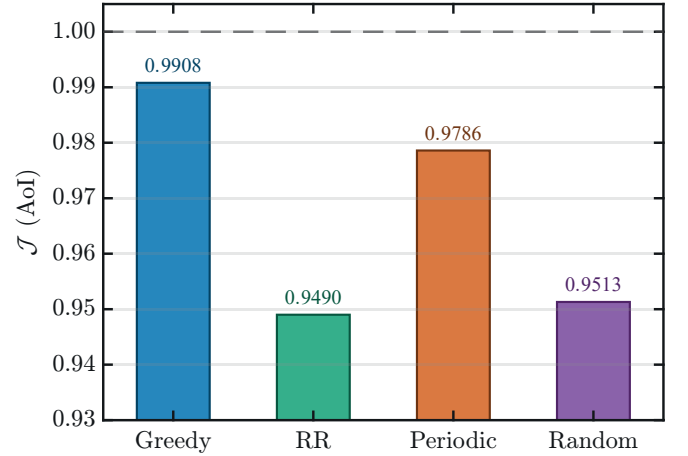


Fig. 3: JFI for AoI evaluated at the optimal beam configuration B^* for different scheduling techniques.

between spatial service coverage and per-user transmission reliability. when the number of active beams is small, a limited subset of cells can be illuminated during each transmission slot, which results in long service delays for several users and thus large AoI values. When B increases, more cells are served at the same time, thus improving the update opportunities and reducing the overall information staleness in the network.

However, going past a certain point in the number of active beams negatively influences performance. This happens because more beams mean that available system bandwidth and transmit power is now divided among more users and beams, and this decreases both the possible data rate and the chances of packet loss. Thus, the AoI begins to raise again with larger B values. This observation suggests that there is

an optimal beam configuration that can achieve a trade-off between the spatial coverage and communication reliability.

The greedy scheme for scheduling based on AoI consistently proves to be the most effective in terms of worst-case information freshness among all schemes that we analyzed. In particular, it is worth noting that the minimum value of maximum AoI established by the greedy approach is achieved at the optimal value of beam configuration, namely $B = 5$, which is equal to almost 4.074 AoI. Meanwhile, the values of minimum maximum AoI reached by the round-robin scheduling method, periodic beam hopping, and random scheduling are equal to around 4.812, 5.600, and 9.088 respectively. Thus, the results clearly prove that AoI-aware beam prioritization produces a very positive effect on the mitigation of outdated information in the network.

The superior performance of the greedy scheduling strategy can be attributed to its ability to adaptively allocate its resources. In contrast to both the cyclic setting and random scheduling methods, the greedy method takes a dynamic approach to place important cells higher in the priority list, thus avoiding serious data aging in the areas where access to the service is limited. Therefore, it gives great improvements in terms of the worst case freshness results and uses beam resources available in the BH-LEO satellite system to the fullest extent possible.

Furthermore, Fig. 3 shows the JFI for AoI at the optimal beam configuration obtained by each scheduling scheme. The results show that the greedy scheduling policy provides the highest level of fairness, achieving a JFI of 0.9908, which is very close to the ideal value of 1. By comparison, periodic beam hopping achieves a JFI of 0.9786, while round-robin and random scheduling yield JFI values of 0.9490 and 0.9513, respectively.

The fairness results back this up as well. Since the greedy scheduling policy always serves the most outdated cells first, AoI gaps across the network stay manageable and no user falls too far behind. Combining this with the right beam count turns out to be a simple yet effective way to keep information fresh and fairly distributed in beam-hopping LEO satellite networks particularly for IoT applications where delays matter.

V. CONCLUSION

In this paper, we studied the problem of information freshness optimization for a BH enabled LEO satellite network via adaptive beam scheduling and optimal beam count selection. By establishing the BH-LEO satellite system model, which takes into account the propagation features of space links, directional beam patterns, reliability constraints of communication links, and AoI dynamics, we evaluated the impact of scheduling policy and simultaneous active beam count on the system AoI performance. Multiple scheduling strategies, including greedy AoI-based scheduling, round-robin scheduling, periodic beam hopping, and random beam selection, were evaluated under different number of beams.

Numerical results show that there exists an optimal number of beams balancing the spatial coverage and the communication reliability, while the greedy scheduling framework always achieves the lowest maximum AoI and the highest fairness among all benchmarks. These observations emphasise the importance of intelligent beam scheduling for future delay-sensitive satellite IoT applications, providing an effective solution to enhance information freshness in next-generation BH-enabled LEO satellite communication systems.

ACKNOWLEDGEMENT

This work was supported by Institute of Information & communications Technology Planning & evaluation (IITP) grant funded by the Korea government (MSIT) (No. RS-2024-00359235, Development of Ground Station Core Technology for Low Earth Orbit Cluster Satellite Communications).

REFERENCES

- [1] Z. Xiao, J. Yang, T. Mao, C. Xu, R. Zhang, Z. Han, and X.-G. Xia, "LEO satellite access network (LEO-SAN) toward 6G: Challenges and approaches," *IEEE Wireless Commun.*, vol. 31, no. 2, pp. 89–96, 2022.
- [2] N. Zhang, P. Chen, L. Ma, J. Zhao, and M. Yang, "Performance evaluation and application exploration of nb-iot-based IoT-NTN," in *Prof. IEEE ICICN*, pp. 388–394, IEEE, 2024.
- [3] L. Chen, V. N. Ha, E. Lagunas, L. Wu, S. Chatzinotas, and B. Ottersten, "The next generation of beam hopping satellite systems: Dynamic beam illumination with selective precoding," *IEEE Trans. Wireless Commun.*, vol. 22, no. 4, pp. 2666–2682, 2022.
- [4] J. Chen, Q. Jiang, and M. Yan, "A beam hopping scheme based on adaptive beam radius for LEO satellites," *Sensors*, vol. 24, no. 20, p. 6574, 2024.
- [5] Z. Shuang, Z. Xing, W. Peng, and W. Wenbo, "Joint beam scheduling and power optimization for beam hopping leo satellite systems," *China Commun.*, vol. 21, no. 10, pp. 1–14, 2024.
- [6] D. Kim, H. Jung, I.-H. Lee, and D. Niyato, "Dnn-based energy-efficient resource management for beam-hopping leo satellite Commun.," *IEEE Internet of Things J.*, 2025.
- [7] L. Chen, L. Wu, E. Lagunas, A. Wang, L. Lei, S. Chatzinotas, and B. Ottersten, "Joint power allocation and beam scheduling in beam-hopping satellites: A two-stage framework with a probabilistic perspective," *IEEE Trans. Wireless Commun.*, vol. 23, no. 10, pp. 14685–14701, 2024.
- [8] S. Kaul, R. Yates, and M. Gruteser, "Real-time status: How often should one update?," in *Proc. IEEE INFOCOM*, pp. 2731–2735, IEEE, 2012.
- [9] F. Chiariotti, O. Vikhrova, B. Soret, and P. Popovski, "Information freshness of updates sent over LEO satellite multi-hop networks," *arXiv preprint arXiv:2007.05449*, 2020.
- [10] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh, and E. Modiano, "Scheduling policies for minimizing age of information in broadcast wireless networks," *IEEE/ACM Trans. Networking*, vol. 26, no. 6, pp. 2637–2650, 2018.
- [11] O. Markovitz and M. Segal, "Leo satellite beam management algorithms," *Computer Networks*, vol. 214, p. 109160, 2022.
- [12] B. Mao, X. Zhou, J. Liu, and N. Kato, "On an intelligent hierarchical routing strategy for ultra-dense free space optical low earth orbit satellite networks," *IEEE Journal on Selected Areas in Commun.*, vol. 42, no. 5, pp. 1219–1230, 2024.
- [13] J. Choi, J. Park, J. Lee, and N. Lee, "Coverage analysis for downlink satellite networks: Effect of shadowing," in *Proc. IEEE ICC*, pp. 2601–2606, IEEE, 2023.
- [14] X. Xie, B. Feng, Z. Chen, L. An, and Q. Zhang, "Aoi-aware scheduling and resource control via hierarchical DRL in beam hopping LEO satellite," in *Proc. VTC2025-Fall*, pp. 1–6, 2025.