MANAGING USER AND GATEWAY LINK SPECTRAL COEXISTENCE IN LEO SATELLITE SYSTEMS VIA HAND-OVER

***Marcele O. K. Mendonça*[1]*, Eva Lagunas*[1]*, Ana Perez-Neira*[234]*, Juan A. Vásquez-Peralvo*[1]*, Joel Grotz*[5]*, Symeon Chatzinotas*[1] *and Bjorn Ottersten*[1]**

[1]*SnT - University of Luxembourg, Luxembourg.*
[2]*Centre Tecnologic de Telecomunicacions de Catalunya (CTTC/CERCA), Castelldefels, Spain*
[3]*ICREA Academia*
[4]*Universitat Politecnica de Catalunya (UPC), Barcelona, Spain*
[5]*SES S.A., Luxembourg*
Corresponding Author: marcele.kuhfuss@uni.lu.

Keywords: SPECTRUM SHARING, NGSO HAND-OVER, INTERFERENCE.

Abstract

The reduced latency and ubiquitousness of NGSO satellite systems make them an attractive option for the high-speed broadband services when comparing to terrestrial networks. However, due to the spectrum shortage problem in satellite communications, NGSO operating gateway (GW) feeder links and user terminal (UT) links are sharing the same frequency bands. Interference becomes then a critical concern, especially when UTs are situated in close proximity to GWs. Motivated by this interference issue, we investigate satellite hand-over to reduce the interference between GW and UT in this work. Through empirical analysis and simulations, our work sheds light on the feasibility and efficacy of employing satellite hand-overs to enhance the overall performance of NGSO-based communication networks under the spectrum sharing between Gws and UTs.

1 Introduction and Background

With the ability to offer omnipresent wireless coverage, satellites have been seen as a potential solution to meet the increasing number of various applications and services either as a stand-alone system, or as an integrated satellite-terrestrial network [1]. The offered coverage area and communication delays depends on the orbital altitude of the satellite. Geostationary earth orbit (GEO) satellites, orbiting at an altitude of 35,678 km, offer an expansive footprint that can span continents and appear at the same position in the sky from the UT perspective. However, their high altitude introduces significant challenges. The signal propagation delay due to the extended distance can lead to latency issues, impacting real-time applications such as video conferencing or online gaming. Additionally, the atmospheric attenuation faced by signals traveling such vast distances can result in signal degradation. On the other hand, non-geostationary (NGSO) satellites such as Medium earth orbit (MEO), at 10,000 km, and low earth orbit (LEO) satellites, between 350 and 1,200 km, present an alternative solution to these challenges [2]. These satellites offer reduced over-the-air delay and path loss due to their closer proximity to Earth. As a result, they are promising for applications requiring low latency and high data rates, making them particularly suitable for emerging technologies such as Internet of Things (IoT) devices and real-time remote sensing.

The integration of NGSO satellites into 5G and future communication networks presents an opportunity for global connectivity. However, when compared to traditional GSO satellite systems, NGSO satellite systems face several challenging technical issues. As the NGSO satellites move quickly, the UTs may need frequent hand-over [3]. In this sense, new conditional hand-over management schemes can be adopted to reduce hand-over signaling while maintaining system performance [4].

Furthermore, spectrum scarcity is one of the key challenges faced by satellite systems as the demand for new services continues to grow [5]. As a result, spectrum sharing emerges as a possible option to optimize the utilization of limited spectral resources. In this context, GWs and UTs are driven to operate in the same band [6]. However, interference between feeder links and user links can arise due to the spectrum sharing and spatial proximity, as illustrated in Figure 1. While beamforming strategies can help mitigate this interference by dynamically adjusting the beam shape, this approach might be unpractical [6]. Continuously reshaping beams for interference mitigation may impose computational overhead and complicate system management.

In this work, we explore satellite hand-over strategies as a solution to address interference between GW and UT and maintain seamless communication. The idea is to strategically transition a UT's communication link from one satellite to another, thereby mitigating interference and ensuring the optimal link quality. For instance, in the illustrative scenario of Figure 1, the UT could switch from satellite 2 to satellite 3 to reduce the interference. This proactive hand-over approach aligns with the evolving landscape of satellite communication, where dynamic adaptation becomes essential for delivering reliable and efficient connectivity.

The rest of this paper is as follows. We describe the system model regarding the scenario, satellite beam pattern and link quality assessment in Section 2. Section 3 comprises the two well known hand-over criteria based on the maximum service time or visibility and minimum distance [7], and the proposed hand-over approach based on the C/I. Then, the proposed method is evaluated considering different scenarios via simulations results, and we provide some insights regarding how the interference elements impact the C/I and hence the hand-over in Section 4. Finally some conclusion remarks are included in Section 5.

2 System Model

We consider the downlink from N_{S} LEO satellites to N_{GW} GWs and N_{UT} UTs. We consider a Delta-Star constellation, but the proposed approach can be generalized to any type of satellite constellation. The GW is assumed to operate in the whole range of bandwidth between 17.7 GHz and 20.2 GHz in the Ka-band, as feeder links typically aggregate traffic from multiple UTs. The GW downlink's bandwidth is B_{i}. The UT is assumed to operate in the same spectrum but with reduced bandwidth of $B_{\mathrm{w}} < B_{\mathrm{i}}$. Both ground stations can receive coverage from the LEO satellites by having their own pencil-shaped beams assigned to them. In theory, interference between beams should be avoided by narrow beam-pattern and geographical distance, however when the UT is close to the GW, the pencil-type beams splash.

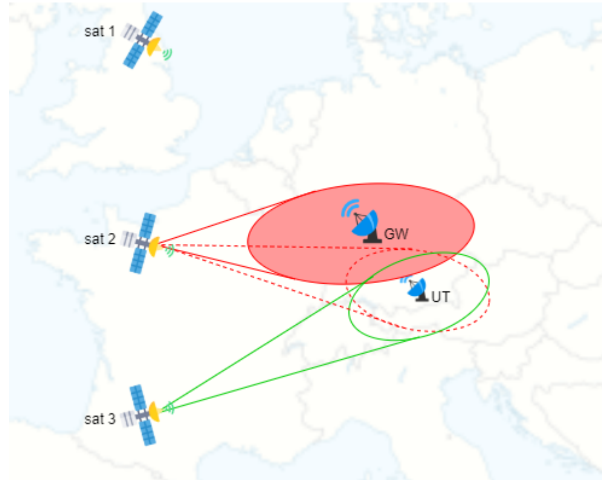


Fig. 1: Illustration of the interference problem.

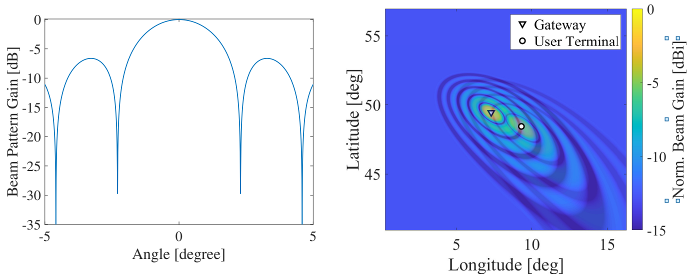
2.1 *Satellite Beam Pattern*

The generated beams correspond to a Direct Radiating Array (DRA) utilizing a planar array configuration to simplify the satellite system as in [6]. The resulting antenna beam pattern is shown in Figure 2a. Figure 2b shows the projection of the DRA-generated beam pattern when centered over the GW and UT locations, where the projected beam at GW interferes with the projected beam at UT.

2.2 *Link Quality*

To assess the quality of the link, we consider the carrier-to-interference power ratio (C/I) at the UT defined in [8] as

$$\mathrm{C/I[dB]} = 10\,\log_{10}\left(\frac{S_{\mathrm{UT}}}{S_{\mathrm{I_{TOT}}}}\right), \qquad (1)$$



(a) Main beam

(b) Projected beams

Fig. 2: (a) Main beam generated with a planar array and (b) Projected beams at GW and UT.

where S_{UT} is the intended received signal power for UT and $S_{\mathrm{I_{TOT}}}$ is the total interference signal power in Watts. The intended received signal power for UT in dBW is given by

$$S_{\mathrm{UT}}[\mathrm{dBW}] = \mathrm{EIRP}_{\mathrm{UT}}[\mathrm{dBW}] - L_{\mathrm{UT}}[\mathrm{dB}] + G_{\mathrm{rx,UT}}[\mathrm{dBi}], \tag{2}$$

in which $\mathrm{EIRP}_{\mathrm{UT}}$ is the effective isotropic radiated power for the UT, L_{UT} is the path loss towards UT, and $G_{\mathrm{rx,UT}}$ is the composite receive gain at UT.

The interference signal coming from one ground station in dBW is given by

$$S_{\mathrm{I}}[\mathrm{dBW}] = \mathrm{EIRP}_{\mathrm{I}}[\mathrm{dBW}] - L_{\mathrm{I}}[\mathrm{dB}] + G_{\mathrm{rx,I}}[\mathrm{dBi}] + \\ + 10\log\left(\min\left(1, \frac{B_{\mathrm{UT}}}{B_{\mathrm{I}}}\right)\right), \tag{3}$$

where $\mathrm{EIRP}_{\mathrm{I}}$ is the EIRP for the interfering carrier, L_{I} is the path loss, $G_{\mathrm{rx,UT}}$ is the composite receive gain for the interfering carrier, B_{UT} is the carrier bandwidth and B_{I} is the interfering carrier bandwidth in Hertz. The composite receive gain can be expressed as

$$G_{\mathrm{rx}}[\mathrm{dBi}] = G_{\mathrm{Rmax}}[\mathrm{dBi}] - L_{\mathrm{R}}[\mathrm{dBi}], \tag{4}$$

where G_{Rmax} is the antenna receive gain at boresight, and L_{R} is the off-axis gain loss.

3 Proposed Min C/I based hand-over

When the UT is close to other ground stations operating in the same frequency band, the beam projections can overlap, resulting in inter-beam interference, as depicted in Figures 1 and 2b. In order to prevent this interference from causing link degradation, we propose a Min C/I based hand-over approach.

In the proposed approach, the GWs have priority to select the closest satellite to assign. The satellite system continuously assesses the link quality by estimating the C/I defined in equation (1). The satellite link at instant index k is at risk if

$$\mathrm{C/I}_k < \mathrm{C/I}_{\mathrm{min}}, \tag{5}$$

where $\mathrm{C/I}_{\mathrm{min}}$ is the minimum accepted C/I.

Then, the UT selects the satellite with the highest estimated C/I ratio. By prioritizing satellites with superior C/I ratios, the UT enhances its resilience to interference, enhancing the overall communication quality. The UT hand-overs to the satellite with greatest C/I whenever the link is at risk as indicated in equation (5). This dynamic approach prevents degradation by proactively switching to a satellite that offers a more favorable C/I ratio, ensuring uninterrupted communication.

Three alternative hand-over mechanisms are also considered for comparative evaluation. The first is the min-dist based hand-over, where the UT selects the nearest satellite upon C/I threshold violation. The second is the visibility based hand-over, in which the closest satellite is selected when the current satellite is no longer visible to the UT. When compared to these two methods, the proposed Min C/I based hand-over can minimize link quality degradation as it explicitly considers the minimum C/I as condition to hand-over.

Finally, the third one is the Best C/I based hand-over, in which the satellite with the greatest C/I is selected at each time index. When compared to the Best C/I based hand-over, the proposed Min C/I based hand-over tends to reduce more the hand-over frequency since it only triggers a hand-over when the minimal C/I is not satisfied.

4 Simulation Results

The simulation is based on a Delta-Star constellation. We consider a constellation with 12 planes containing 20 LEO satellites at an altitude of 600 kilometers. The system operates at a frequency of 19.5 GHz. The Effective Isotropic Radiated Power Spectral Density of the satellite is -48 dBW. The satellite's antenna employs a planar array with 50 elements. The bandwidth for the GW link is 2 GHz, whereas the bandwidth for the UT link is 200 MHz. The GW and UT use antenna dishes with a diameter of 3.5 meters and 0.6 meters, respectively.

The minimum elevation angle between the satellite and the station is set to 10 degrees. The receiver antennas have an efficiency of 0.6 and maximum gain of 35 dBi.

The composite receive gain in equation (4) is obtained using the ITU recommendation S.1528 for LEO satellites [9]. Figure 3 shows the obtained composite receive gain using the ITU recommendation S.1528, and compares it with the one obtained using the ITU recommendation S.465-6 for GEO satellites [10]. As expected, LEO satellites require ground station antennas with wider radiation pattern.

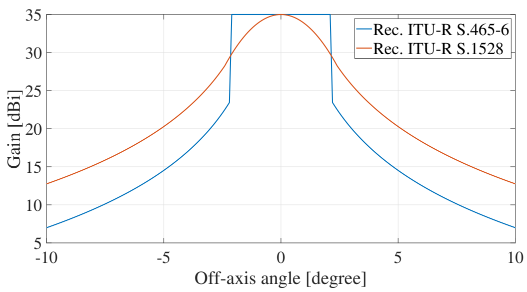
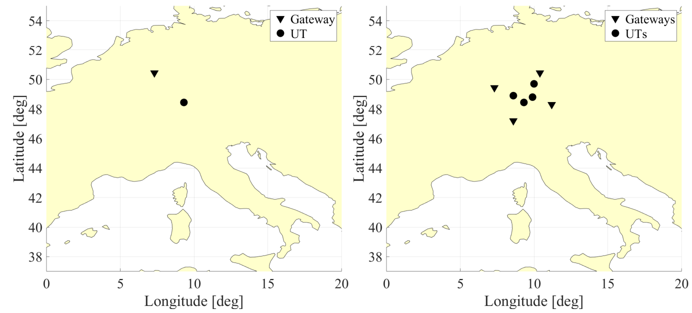


Fig. 3: Composite receive gain as a function of the off-axis angle.



(a) Scenario 1 and 2 (b) Scenario 3

Fig. 4: GW and UT locations for considered scenarios.

4.1 *Scenario 1: One GW and one UT + No pointing loss*

In this scenario, we consider one GW and a single target UT, as illustrated in Figure 4a. Therefore, the GW is the only source of interference at the target UT. In this scenario, we assume the absence of pointing loss at the UT, that is, when the UT is pointing to a specific satellite and the interference comes from a satellite that the UT is not pointing to, the pointing loss is considered zero.

In this case, we assume that when the UT is aligned with one satellite and experiences interference from another satellite that it's not pointing to, there is no pointing loss. With no pointing loss, the composite receiver gain in equation (4) is maximum and the intereference received by the satellite is also maximized.

Figure 5 illustrates the evolution of the C/I metric over time. When the C/I is below the prescribed C/I threshold $C/I_{\text{tresh}} = 13$ dB, the target UT selects an alternative satellite. We can observe that the UT starts by selecting the satellite with index 136, but eventually it does not satisfy the C/I threshold of 13 dB. If no hand-over is done at this point, the UT link will be at risk. It is essentially what happens when using the Visibility hand-over: the UT experiences severe link degradation after time index 30. The proposed Min C/I, the min-dist and the Best C/I based hand-over methods are able to satisfy the threshold of 13 dB. For simple scenario, selecting the satellite with the greatest C/I ratio is equivalent to selecting the closest satellite to the UT.

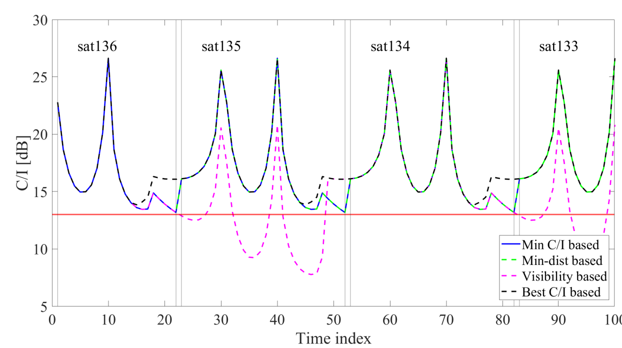


Fig. 5: Instantaneous C/I (dB) metric for scenario 1.

Figure 6 depicts the C/I values of each visible satellite at discrete time intervals, offering a panoramic view of their temporal dynamics. The interference in this scenario is intense, just a portion of the satellites offer a C/I above the threshold of 13 dB.

The chosen satellites are also highlighted for each hand-over procedure in Figure 6 and the number of hand-overs is shown in Table I. For this simple scenario, the proposed Min C/I based hand-over performs comparably to the Min-dist and Best C/I based hand-overs in terms of number of satellite switching.

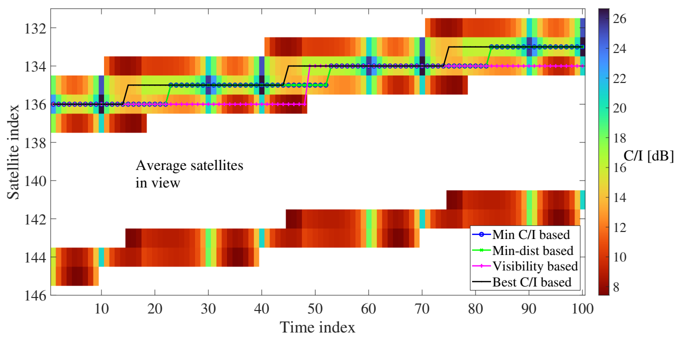


Fig. 6: Satellite selection for each hand-over method in scenario 1.

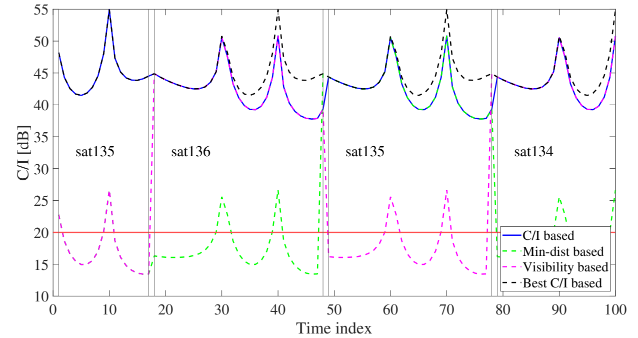


Fig. 7: Instantaneous C/I (dB) metric for scenario 2.

TABLE I: Number of hand-overs required for each method.

	# hand-overs		
Method	**Scenario 1**	**Scenario 2**	**Scenario 3**
Min C/I based	3	3	6
Min-dist based	3	2	2
Visibility based	1	1	1
Best C/I based	3	6	12

4.2 Scenario 2: One GW and one UT + Pointing loss

In the second scenario, we maintain the simplicity by keeping our attention focused on a single GW and a single target UT. However, an important modification is introduced: the pointing loss is considered in the composite receive gain in equation (4).

Figure 7 shows the C/I evolution when the pointing loss is considered. A notable trend emerges: some satellites now offer higher C/I values, when compared with the previous scenario. This occurs as a result of the UT seeing less interference from satellites with large off-axis angles. It becomes clear that the pointing loss integration has a significant influence on the UT's hand-over choices. Satellites with large off-axis angles are associated with low interference, thereby rendering them more favorable candidates for being selected by the UT.

From this more complex scenario, we can observe that the most favorable satellite may not always be the one that is closest to the UT. Indeed, the proposed C/I based hand-over outperforms both the visibility based hand-over and the min-dist based hand-over in this more realistic scenario as shown in Figure 7. The Best C/I based hand-over occasionally performs better than the Min-based C/I, but it requires more hand-overs as shown in Table I.

Figure 8 complements the narrative by offering a view of each satellite's C/I value at distinct time points. Notably, the proposed C/I based hand-over avoids the satellites with poor C/I. By introducing pointing loss, this scenario amplifies the complexity of satellite selection. Nevertheless, the proposed Min C/I-based hand-over strategy emerges as a robust solution.

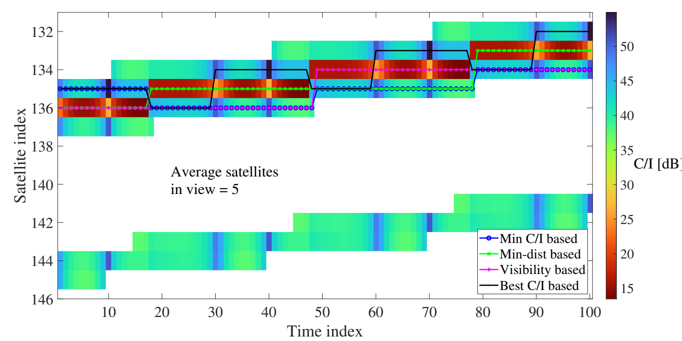


Fig. 8: Satellite selection for each hand-over method in scenario 2.

4.3 Scenario 3: Four GWs and four UTs + Pointing loss

For this scenario, we consider four GWs, a single target UT, and three additional users. The location of the GWs and UTs is presented in Figure 4b. In this way, the four GWs and three UTs combine to cause interference at the target UT. With the inclusion of these extra interference events, the overall C/I reduces as illustrated in Figure 7.

The performance obtained with the Min C/I based hand-over is superior that both the visibility based and the min-dist based hand-overs. Although the Best C/I based hand-over outperforms the Min-

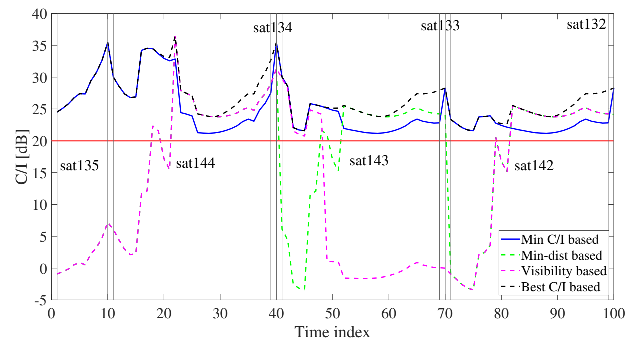


Fig. 9: Instantaneous C/I (dB) metric for scenario 3.

based C/I method, the satellite switching is more frequent as shown in Table I.

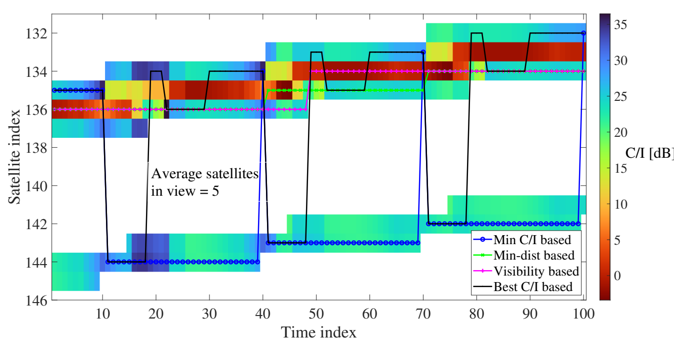


Fig. 10: Satellite selection for each hand-over method in scenario 3.

5 Conclusion and Future Work

In this work, we motivated satellite hand-over to reduce the interference between UT and GW in LEO systems. The simulation results indicate that the proposed Min C/I-based hand-over approach offers a promising solution to address beam splash-induced link degradation, championing interference resilience and communication continuity within NGSO satellite systems. The selection performed by the UT is impacted not only by the satellite distance, but also by the pointing loss. For future work, more congested scenarios with more GW and more UT, and different NGSO constellations would be considered. Also, the integration of machine learning techniques offers exciting prospects for further refining hand-over strategies by maximizing the C/I and minimizing the number of hand-overs over time.

6 Acknowledgment

This research was funded by the Luxembourg National Research Fund (FNR) under the project SmartSpace (C21/IS/16193290), by the Spanish ministry of science and innovation under project IRENE (PID2020-115323RB-C31) funded by MCIN/AEI/10.13039/501100011033, and also by the ICREA Academia program funded by the Catalan government. Please note that the views of the authors of this paper do not necessarily reflect the views of SES S.A. For the purpose of open access, the author has applied a Creative Commons Attribution 4.0 International (CC BY 4.0) license to any Author Accepted Manuscript version arising from this submission.

References

[1] A. I. Perez-Neira, M. A. Vazquez, M. B. Shankar, S. Maleki, and S. Chatzinotas, "Signal processing for high-throughput satellites: Challenges in new interference-limited scenarios," *IEEE Signal Processing Magazine*, vol. 36, no. 4, pp. 112–131, 2019.

[2] H. Al-Hraishawi, H. Chougrani, S. Kisseleff, E. Lagunas, and S. Chatzinotas, "A survey on non-geostationary satellite systems: The communication perspective," *IEEE Communications Surveys & Tutorials*, 2022.

[3] P. Boedhihartono and G. Maral, "Evaluation of the guaranteed handover algorithm in satellite constellations requiring mutual visibility," *International journal of satellite communications and networking*, vol. 21, no. 2, pp. 163–182, 2003.

[4] X. Lin, S. Cioni, G. Charbit, N. Chuberre, S. Hellsten, and J.-F. Boutillon, "On the path to 6g: Embracing the next wave of low earth orbit satellite access," *IEEE Communications Magazine*, vol. 59, no. 12, pp. 36–42, 2021.

[5] T. Darwish, G. K. Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, "Leo satellites in 5g and beyond networks: A review from a standardization perspective," *IEEE Access*, vol. 10, pp. 35 040–35 060, 2022.

[6] E. Lagunas, A. Perez-Neira, J. Grotz, S. Chatzinotas, and B. Ottersten, "Beam splash mitigation for ngso spectrum coexistence between feeder and user downlink," in *WSA & SCC 2023; 26th International ITG Workshop on Smart Antennas and 13th Conference on Systems, Communications, and Coding*. VDE, 2023, pp. 1–6.

[7] E. Papapetrou, S. Karapantazis, G. Dimitriadis, and F.-N. Pavlidou, "Satellite handover techniques for leo networks," *International Journal of Satellite Communications and Networking*, vol. 22, no. 2, pp. 231–245, 2004.

[8] G. Maral, *VSAT networks*. John Wiley & Sons, 2004.

[9] International Telecommunication Union , "Satellite antenna radiation patterns for non-geostationary orbit satellite antennas operating in the fixed-satellite service below 30 GHz ," International Telecommunication Union, Tech. Rep. ITU-R S.1528, 2001.

[10] International Telecommunication Union, "Reference radiation pattern for earth station antennas in the fixed-satellite service for use in coordination and interference assessment in the frequency range from 2 to 31 GHz ," International Telecommunication Union, Tech. Rep. ITU-R S.465-6, 2010.