Outage Performance of Fluid Antenna Systems for LEO Satellite Downlinks in SAGIN

Md Mahdir Mim, Wooyeol Choi
School of Computer Science and Engineering
Chung-Ang University, Seoul, Republic of Korea
{mahdirmim, wchoi}@cau.ac.kr

Abstract

Fluid antenna systems (FAS) enable dynamic port selection across a compact antenna array, offering spatial diversity gains through position-based diversity. This paper presents an initial outage probability analysis of FAS enabled low Earth orbit (LEO) satellite downlinks for space-air-ground integrated networks (SAGIN). Using a simplified baseline channel model based on Jake's spatial correlation, Monte Carlo simulations indicate that a 10-port FAS provides an approximately 3.8 dB SNR gain relative to a fixed antenna at an outage probability of 10^{-3}. Results show modest diversity gains due to strong spatial correlation in compact FAS geometries.

Ⅰ. Introduction

Space-air-ground integrated networks (SAGIN) enable ubiquitous 6G connectivity with LEO satellites playing a central role in providing global coverage and low-latency services [1], [2]. Operating at 500-2000 km altitudes, LEO links face high path losses, significant Doppler shifts, and frequent handovers [3]. Fluid antenna systems (FAS) achieve spatial diversity by dynamically reconfiguring a single antenna across multiple ports within a compact space [4]. The position-based diversity offered by FAS presents a potential solution to mitigate fading effects in challenging satellite propagation environments. Despite growing interest in both technologies, their intersection remains relatively unexplored. While recent work identified FAS-aided non-terrestrial networks as promising [5], [6], limited prior work characterizes FAS outage for LEO downlinks using correlated fading models. This baseline study combines Jake's spatial correlation with LEO link parameters to quantify diversity gains via Monte Carlo simulation

Ⅱ. Method

We consider a LEO satellite (altitude 550 km, frequency 12 GHz, path loss 168.8 dB) transmitting to an N-port FAS with aperture size W wavelengths. We adopt correlated Rayleigh fading with Jake's isotropic scattering [7], [8], where correlation between ports separated by distance d wavelengths is:

$$\rho(d) = J_0(2\pi d) \tag{1}$$

where J_0 is the zero order Bessel function. Correlated channels are generated via Cholesky decomposition of the correlation matrix. The terminal selects the port with maximum channel gain. Outage probability for target rate R (requiring minimum SNR threshold $\gamma_{\text{th}} = 2^R - 1$)

$$P_{\text{out}} = \Pr(\max_{n=1}^{N} |h_n|^2 < \gamma_{\text{th}}/\bar{\gamma}) \tag{2}$$

where $\bar{\gamma}$ is average received SNR and h_n is the channel at port n.

Ⅲ. Results

Monte Carlo simulations with 10^5 trials are conducted for R = 1bit/s/Hz and W = 1.5λ, comparing N ∈ {1, 5, 10, 25} ports, where N = 1 is the fixed antenna baseline. Each configuration is evaluated across average received SNR values ranging from 0 to 30 dB to characterize outage behavior under varying link conditions. Figure 1 demonstrates modest diversity gains due to strong spatial correlation in compact FAS geometries. The outage curves exhibit the expected monotonic decrease with increasing SNR, with clear separation between different FAS configurations. Specifically, 5 ports yield 2.5 dB improvement at 10^{-3} outage, while 10 and 25 ports achieve 3.8 dB and 5.0 dB respectively. Diminishing returns beyond N = 10 stem from high correlation with W = 1.5λ and 25 ports,

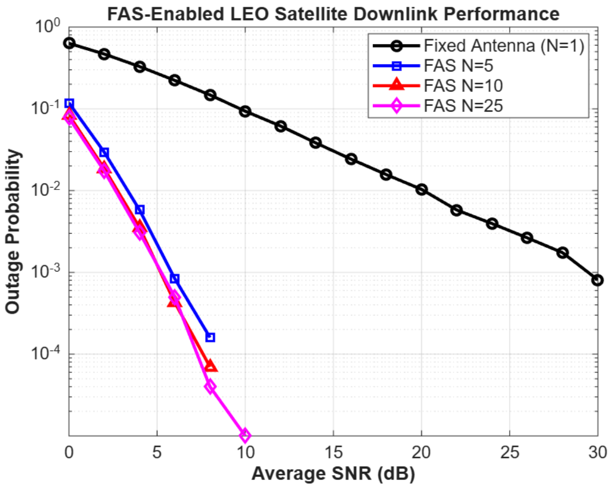

Fig. 1. Outage probability vs. SNR: A 10-port FAS achieves 3.8 dB gain at 10^{-3} outage.

neighboring ports separated by only 0.0625λ exhibit correlation coefficients exceeding 0.95 (computed via Jake's model), severely limiting effective diversity order. These modest gains are consistent with selection combining under heavily correlated channels and suggest that larger apertures or alternative diversity techniques may be needed for substantial performance improvements in practical LEO terminals. Limitations: This baseline study employs correlated Rayleigh fading; Rician fading components, shadowing effects, and elevation-dependent propagation characteristics are left for future work.

IV. Conclusion

This research presented an initial outage analysis of FAS for LEO satellite downlinks in SAGIN using a simplified correlated Rayleigh baseline. Monte Carlo simulations indicate 2.5-5 dB SNR gains over fixed antennas, with performance primarily limited by strong spatial correlation in compact geometries. The results demonstrate that while FAS can provide meaningful diversity benefits for satellite communications, the compact form factor required for mobile terminals inherently constrains the achievable gains due to high channel correlation between adjacent ports. Nevertheless, the improvement observed suggests that FAS technology warrants further investigation for next-generation SAGIN terminals, particularly in scenarios where link reliability is critical and space constraints limit the deployment of traditional multi-antenna systems. Future work will incorporate more realistic LEO channel models, including Rician fading, elevation-dependent effects, handover dynamics, and adaptive port selection strategies.

ACKNOWLEDGMENT

This research was supported by the Chung-Ang University Research Grants in 2025.

REFERENCES

[1] J. Chen, H. Zhang, and Z. Xie, "Space-Air-Ground Integrated Network (SAGIN): A Survey," 2023, arXiv. doi: 10.48550/ARXIV.2307.14697.

[2] O. Kodheli et al., "Satellite Communications in the New Space Era: A Survey and Future Challenges," IEEE Commun. Surv. Tutorials, vol. 23, no. 1, pp. 70–109, 2021, doi: 10.1109/COMST.2020.3028247.

[3] J.-H. Lee, C. Park, S. Park, and A. F. Molisch, "Handover Protocol Learning for LEO Satellite Networks: Access Delay and Collision Minimization," IEEE Trans. Wireless Commun., vol. 23, no. 7, pp. 7624–7637, July 2024, doi: 10.1109/TWC.2023.3342975.

[4] W. K. New, K.-K. Wong, H. Xu, K.-F. Tong, and C.-B. Chae, "Fluid Antenna System: New Insights on Outage Probability and Diversity Gain," IEEE Trans. Wireless Commun., vol. 23, no. 1, pp. 128–140, Jan. 2024, doi: 10.1109/TWC.2023.3276245.

[5] T. Xu et al., "Advancing Fluid Antenna-Assisted Non-Terrestrial Networks in 6G and Beyond: Fundamentals, State of the Art, and Future Directions," 2025, arXiv. doi: 10.48550/ARXIV.2511.00569.

[6] H. Yang, M. Derakhshani, S. Lambotharan, and L. Hanzo, "Performance Analysis of Fluid Antenna System Aided OTFS Satellite Communications," IEEE J. Sel. Areas Commun., pp. 1–1, 2025, doi: 10.1109/JSAC.2025.3615566.

[7] M. Khammassi, A. Kammoun, and M.-S. Alouini, "A New Analytical Approximation of the Fluid Antenna System Channel," IEEE Trans. Wireless Commun., vol. 22, no. 12, pp. 8843–8858, Dec. 2023, doi: 10.1109/TWC.2023.3266411.

[8] P. Ramírez-Espinosa, D. Morales-Jimenez, and K.-K. Wong, "A New Spatial Block-Correlation Model for Fluid Antenna Systems," IEEE Trans. Wireless Commun., vol. 23, no. 11, pp. 15829–15843, Nov. 2024, doi: 10.1109/TWC.2024.3434509.