

Optical and Aerial RISs-Enabled Hybrid FSO/RF Space-Air-Ground Integrated Network

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Abstract—Space-air-ground integrated networks (SAGINs) are revolutionizing wireless communications by integrating space, aerial, and terrestrial networks, providing global connectivity, aiding underserved regions, and enabling 6G applications. This paper proposes a dual reconfigurable intelligent surfaces (RISs)-assisted cooperative hybrid free space optical (FSO)/ radio frequency (RF) communication framework for SAGINs to address the reliable communications challenges. The framework integrates an optical RIS on a low Earth orbit satellite and an RF aerial RIS, enhancing FSO link performance and mitigating RF line-of-sight blockages. The system uses selection combining to dynamically choose the stronger signal between FSO and RF links, ensuring robust communication in varying conditions. We derive analytical expressions for key performance metrics such as outage probability, average symbol error rate, and ergodic capacity, considering pointing errors and atmospheric turbulence effects on the FSO link. Simulation results verify the analytical derivations, highlighting the critical role of RISs in enhancing the system performance.

Index Terms—Space-air-ground integrated networks (SAGINs), reconfigurable intelligent surfaces (RISs), free space optical (FSO), radio frequency (RF), outage probability, average symbol error rate, and ergodic capacity.

I. INTRODUCTION

SPACE-air-ground integrated networks (SAGINs) are revolutionizing wireless communications by integrating space, aerial, and terrestrial networks to achieve global connectivity, particularly benefiting underserved regions and 6G applications like maritime communications [1]. The space segment, comprising satellite constellations, provides varying coverage and latency based on orbital altitude. The aerial segment enhances network flexibility by acting as relays, especially in remote areas. The terrestrial segment offers high-capacity, low-latency connectivity but struggles in remote terrains [2]. Reconfigurable intelligent surfaces (RISs) have received significant attention in wireless communications due to their ability to dynamically adapt to changing wireless environments [3]. Comprising a planar array of cost-effective near-passive reflecting elements, RISs can transform wireless networks by improving signal coverage, minimizing interference, optimizing spectrum efficiency, and strengthening security mechanisms [4]–[6]. In SAGINs, RISs are crucial in mitigating severe attenuation while improving spectral efficiency through intelligent signal redirection [7].

Several studies have explored integrating hybrid communication technologies within SAGINs to enhance system per-

formance. In [8], a SAGIN system incorporating an adaptive combining scheme for RF and free-space optical (FSO) links was proposed to improve network efficiency. To further extend coverage and enhance transmission capacity, a hybrid FSO/RF-based SAGIN was investigated in [9], where FSO and RF links were utilized complementary within the satellite-high-altitude platform station (HAPS)-ground network. The integration of RIS into hybrid networks has also been explored. An uplink RIS-assisted FSO/RF hybrid satellite-terrestrial network was proposed in [10], where the impact of imperfect channel state information (CSI) on the RIS system was analyzed. In [11], an aerial RIS (ARIS) was deployed to passively reflect uplink signals from ground stations to HAPS, which subsequently relayed the signals to satellite networks via hybrid FSO links. Similarly, a hybrid FSO/RF-based HAPS-assisted SAGIN was presented in [12] to mitigate the impact of adverse weather conditions and improve link reliability.

Hybrid FSO/RF-based systems enhance SAGINs by combining FSO's high capacity and security with RF's resilience and coverage. However, FSO is affected by pointing errors, turbulence, and weather, while RF faces interference and bandwidth constraints. Recent research efforts have integrated RISs into hybrid FSO/RF networks to enhance system performance. Despite these advancements, existing research has primarily considered either RF-based RISs or FSO-based systems, without a comprehensive framework integrating optical and RF RISs for cooperative hybrid communications. Moreover, prior works often assume a fixed relay architecture, lacking dynamic adaptation to environmental conditions and network demands. The proposed system model introduces a dual RIS-assisted cooperative hybrid FSO/RF communication framework in SAGINs, integrating both optical RIS (ORIS) and RF ARIS for enhanced performance. The main contributions of this paper are listed below:

- We introduce a novel hybrid FSO/RF transmission framework by deploying an ORIS on a low Earth orbit (LEO) satellite and an RF ARIS on an unmanned aerial vehicle (UAV), where the ORIS enhances and amplifies the reflected optical signal in the FSO link, while the ARIS enables dynamic RF beam steering to mitigate LoS blockages in urban environments.
- The proposed system employs selection combining (SC) to choose the stronger signal between the FSO and RF links, ensuring robust communication that adapts to

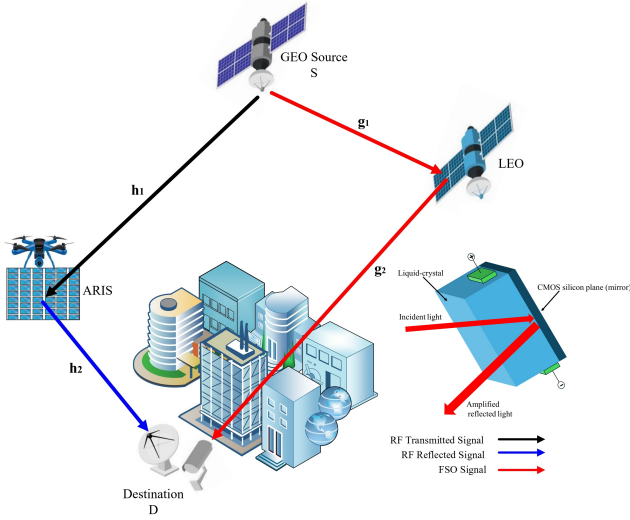


Fig. 1: System model.

environmental variations.

- We investigate the outage probability, P_{out} , average symbol error rate, ASER, and ergodic capacity, C , and derive exact closed-form expressions for these metrics. Additionally, we examine the impact of atmospheric turbulence on the FSO link and its overall effect on system performance.
- We validate and confirm our analysis through extensive Monte Carlo simulations.

II. SYSTEM AND CHANNEL MODELS

A. System Model

We explore the integration of optical and RF RISs to enhance cooperative FSO/RF communications in SAGINs using a combining scheme, as illustrated in Fig. 1. The system architecture comprises a geostationary (GEO) satellite functioning as the source node (S), an ORIS mounted on an LEO satellite, an RF ARIS mounted on a UAV, and a ground station serving as the destination node (D). Due to the challenging environmental conditions that impact signal propagation, the system establishes dual communication links between the GEO satellite and the destination: an FSO link via the ORIS on the LEO satellite and an RF link via the ARIS. In the FSO link, the GEO satellite transmits optical signals from a laser diode to the ground station through an LEO satellite equipped with an ORIS, which amplifies the signals before reflection. Both the GEO satellite and the destination node are equipped with optical antennas for FSO signal transmission and reception. Meanwhile, in the RF link, the GEO satellite transmits RF signals to the ARIS, which redirects them to D. Deploying the ARIS helps avoid problems caused by buildings and other urban structures that block the direct line of sight (LoS) path between the satellite and the ground station. The GEO satellite and the destination node are assumed to be also equipped with RF antennas. At D, the received FSO and RF signals are processed and combined to enhance communication reliability.

The system employs the SC technique, which dynamically selects the stronger signal between the FSO and RF signals to ensure robust signal reception. As a result, the system's resilience and reliability are improved for SAGIN applications.

1) *Received Optical Signal:* At D, the received signal for the optical link via the ORIS is given by

$$y_D^{\text{FSO}} = \Lambda P_S^{\text{FSO}} \mathcal{I} A x_S + z_D^{\text{FSO}}, \quad (1)$$

where x_S denotes the transmitted signal with an average power constraint of $\mathbb{E}\{|x_S|^2\} = 1$, P_S^{FSO} represents the transmit power of the FSO signal, while Λ corresponds to the responsivity of the photo-detector. The channel coefficient for the FSO link is denoted by $\mathcal{I}$, and A indicates the optical amplification gain provided by the ORIS. Furthermore, z_D^{FSO} represents the additive white Gaussian noise (AWGN) of the FSO link, characterized by a variance σ_D^{FSO} . At D, the detection of FSO signals is carried out using both intensity modulation with direct detection (IM/DD) and heterodyne detection (HD) techniques. In this work, we examine the integration of ORIS within the FSO link, where the ORIS is precisely configured to ensure that the incident optical signal aligns with the reflection angle. Under optimal phase shift conditions, the ORIS acts as an ideal reflective surface, effectively redirecting the optical signal toward the intended destination with maximum efficiency. For the ORIS-aided FSO link, the signal-to-noise ratio (SNR) at D, Ξ_D^{FSO} , is given by

$$\Xi_D^{\text{FSO}} = \frac{A (\Lambda P_S^{\text{FSO}} \mathcal{I}_1 \mathcal{I}_2)^v}{\sigma_{\text{FSO}}^2} = A \bar{\gamma}_{\text{FSO}} (\mathcal{I}_1 \mathcal{I}_2)^v, \quad (2)$$

where $\bar{\gamma}_{\text{FSO}} = \frac{(\Lambda P_S^{\text{FSO}})^v}{\sigma_{\text{FSO}}^2}$, $\mathcal{I}_1$ and $\mathcal{I}_2$ denote the channel coefficients of the $S \rightarrow \text{ORIS}$ and $\text{ORIS} \rightarrow D$ links, respectively, and $v \in \{1, 2\}$ related to HD and IM/DD techniques, respectively.

2) *Received RF Signal:* At D, the received signal for the RF link via the ARIS is expressed as

$$y_D^{\text{RF}} = \sqrt{P_S^{\text{RF}}} \sqrt{\Psi_{\text{SD}}} \left[x_S \sum_{i=1}^N h_{1,i} \exp(j\phi_i) h_{2,i} \right] + z_D^{\text{RF}}, \quad (3)$$

where P_S^{RF} denotes the RF transmit power, z_D^{RF} represents the AWGN at D for the RF link, modeled as $z_D^{\text{RF}} \sim \mathcal{NC}(0, \sigma_{\text{RF}}^2)$. The phase adjustment introduced by the i -th reflecting element (RE) of the ARIS is denoted by ϕ_i . Additionally, the term Ψ_{SD} represents the combined path loss between S and the ARIS, and between the ARIS and D. The channel gains associated with the RF transmission are represented by $h_{1,i}$ and $h_{2,i}$ corresponding to the links from S to the i -th RE and from the i -th RE to D, respectively. These gains can be expressed as $h_{1,i} = \mathcal{V}_i \exp(-j\varphi_i)$ and $h_{2,i} = \mathcal{B}_i \exp(-j\delta_i)$, where φ_i and δ_i represent the phases of $h_{1,i}$ and $h_{2,i}$, respectively, and $\mathcal{V}_i$ and $\mathcal{B}_i$ denote their corresponding amplitude components. It is assumed that the ARIS has perfect CSI for the RF link, enabling precise reflection of the RF signals toward the receiver [13], which is a common assumption in the existing literature [4], [14]. Therefore, the phase shifts at the ARIS can be optimized to fully compensate for the cumulative phase

errors of the channels, i.e., $\phi_i = \delta_i + \varphi_i$ [4]. Consequently, (3) can be rewritten as $y_D^{\text{RF}} = \sqrt{P_S^{\text{RF}}} \sqrt{\Psi_{\text{SD}}} \left[x_S \sum_{i=1}^N \mathcal{V}_i \mathcal{B}_i \right] + z_D^{\text{RF}}$. As a result, the SNR at D for the ARIS-aided RF link, Ξ_D^{RF} , can be expressed as

$$\Xi_D^{\text{RF}} = \frac{P_S^{\text{RF}} \Psi_{\text{SD}}}{\sigma_D^2} \left| \sum_{i=1}^N \mathcal{V}_i \mathcal{B}_i \right|^2 = \bar{\gamma}_{\text{RF}} \left| \sum_{i=1}^N \mathcal{G}_i \right|^2 = \bar{\gamma}_{\text{RF}} \mathcal{M}^2, \quad (4)$$

where $\bar{\gamma}_{\text{RF}} = \frac{P_S^{\text{RF}} \Psi_{\text{SD}}}{\sigma_D^2}$, $\mathcal{G}_i = \mathcal{V}_i \mathcal{B}_i$ and $\mathcal{M} = \sum_{i=1}^N \mathcal{G}_i$, with $\mathcal{V}_i \sim \text{Nakagami}(m_1, \Omega_1)$, and $\mathcal{B}_i \sim \text{Nakagami}(m_2, \Omega_2)$.

B. Channel Models

1) *FSO Channel Model*: The cascaded FSO channel for the ORIS-assisted $S \rightarrow D$ link is given by $\mathcal{I} = \mathbf{g}_1 \mathbf{g}_2$, where $\mathbf{g}_1$ and $\mathbf{g}_2$ represent the channel coefficients of the $S \rightarrow \text{ORIS}$ link and $\text{ORIS} \rightarrow D$ link, respectively. The overall channel can be expressed as $\mathcal{I} = \mathcal{I}_l \mathcal{I}_p \mathcal{I}_a$, where $\mathcal{I}_l$, $\mathcal{I}_p$, and $\mathcal{I}_a$ denote the effects of attenuation, pointing errors, and atmospheric turbulence, respectively. The FSO link attenuation can be modeled according to the Beer-Lambert's law as $\mathcal{I}_l = \exp(-\Omega_l d_l)$, where d_l is the link distance and Ω_l is the attenuation coefficient. $\mathcal{I}_l$ highlights the impact of atmospheric absorption and scattering on the optical signal. Moreover, pointing errors in the FSO link arise from beam jitter and ORIS jitter due to misalignment. The probability density function (PDF) of pointing errors can be expressed as [15], $f_{\mathcal{I}_p}(z) = \frac{\zeta^2}{\mathcal{A}_0^{\zeta^2}} z^{\zeta^2-1}$, $0 \leq z \leq \mathcal{A}_0$, where $\mathcal{A}_0$ quantifies pointing loss and ζ is the ratio of beam radius to jitter deviation. Furthermore, The Gamma-Gamma distribution is widely utilized to model FSO channels under atmospheric turbulence, capturing signal fluctuations due to varying attenuation and phase distortion. The PDF for both S-ORIS and ORIS-D subchannels is given by [16],

$$f_{\mathcal{I}_a}(z) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} z^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta} \left(2\sqrt{\alpha\beta} z \right), \quad (5)$$

where $K_q(\cdot)$ corresponds to the modified Bessel function of the second kind of order q [17, eq. (8.407.1)], α and β are the large and small-scale turbulence effects, and $\Gamma(\cdot)$ refers to the Gamma function [17, eq. (8.310.1)].

2) *RF Channel Model*: The RF $S \rightarrow D$ link is modeled using the Nakagami- m distribution, which provides flexibility in characterizing diverse fading conditions. Notably, the Nakagami- m distribution generalizes the Rician distribution through appropriate parameter selection. The model is particularly valuable for satellite communications as its shape parameter m enables precise representation of fading severity across different scenarios. Thus, The PDF and cumulative distribution function (CDF) for both S-ARIS and ARIS-D subchannels are given by $f_Z(z) = \frac{2m^m}{\Gamma(m)\Omega^m} z^{2m-1} \exp\left(-\frac{m}{\Omega} z^2\right)$, and $F_Z(z) = \frac{\gamma\left(m, \frac{m}{\Omega} z^2\right)}{\Gamma(m)}$, respectively, where $m > 0$, $\Omega > 0$, and $Z \in \{\mathcal{V}_i, \mathcal{B}_i\}$, $\gamma(a, x) = \int_0^x t^{a-1} \exp(-t) dt$ denotes the lower incomplete Gamma function defined by [17, Eq. (8.350.1)].

III. PERFORMANCE ANALYSIS

The performance analysis of the proposed RIS-enabled hybrid FSO/RF for SAGIN is introduced in this section. The SC scheme enhances reliability in the proposed system model by selecting the link, FSO or RF, with the highest instantaneous SNR for data transmission. The instantaneous SNR for the SC scheme is expressed as $\Xi_{\text{SC}} = \max(\Xi_{\text{FSO}}, \Xi_{\text{RF}})$. Therefore, the CDF and PDF of Ξ_{SC} are given by $F_{\Xi_{\text{SC}}}(z) = F_{\Xi_{\text{FSO}}}(z) F_{\Xi_{\text{RF}}}(z)$, and $f_{\Xi_{\text{SC}}}(z) = f_{\Xi_{\text{FSO}}}(z) F_{\Xi_{\text{RF}}}(z) + F_{\Xi_{\text{FSO}}}(z) f_{\Xi_{\text{RF}}}(z)$, respectively.

A. Outage Probability

The outage probability in a hybrid FSO/RF system using the SC technique, P_{out} , is defined as the probability that Ξ_{SC} drops below a specified threshold, γ_{th} . Since Ξ_{SC} represents the maximum SNR between the FSO and RF links, P_{out} is given by $P_{\text{out}} = \Pr(\Xi_{\text{SC}} < \gamma_{\text{th}}) = F_{\Xi_{\text{SC}}}(\gamma_{\text{th}})$.

Theorem 1: The P_{out} can be derived as

$$P_{\text{out}} = \frac{\zeta_1^2 \zeta_2^2 v^{\alpha_1 + \alpha_2 + \beta_1 + \beta_2 - 4}}{(2\pi)^{2(v-1)} \Gamma(\alpha_1) \Gamma(\beta_1) \Gamma(\alpha_2) \Gamma(\beta_2) \Gamma(N\Omega_{\mathcal{G}})} \\ \times G_{2v+1, 6v+1}^{6v, 1} \left[\frac{(\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2)^v \gamma_{\text{th}}}{v^{4v} ((\zeta_1^2 + 1)(\zeta_2^2 + 1))^v \bar{\gamma}_{\text{FSO}}} \middle| 1, \Delta_1 \right] \\ \times G_{1, 2}^{1, 1} \left[\Theta_{\mathcal{G}} \sqrt{\frac{\gamma_{\text{th}}}{\bar{\gamma}_{\text{RF}}}} \middle| 1, N\Omega_{\mathcal{G}}, 0 \right], \quad (6)$$

where $G_{p, q}^{m, n}[x | \cdot]$ is the Meijer G function [17, (9.301)], $\Delta_1 = \frac{\zeta_1^2 + 1}{v}, \dots, \frac{\zeta_1^2 + v}{v}, \frac{\zeta_2^2 + 1}{v}, \dots, \frac{\zeta_2^2 + v}{v}$, and $\Delta_2 = \frac{\zeta_2^2}{v}, \dots, \frac{\zeta_2^2 + v - 1}{v}, \frac{\alpha_2}{v}, \dots, \frac{\alpha_2 + v - 1}{v}, \frac{\beta_2}{v}, \dots, \frac{\beta_2 + v - 1}{v}, \frac{\zeta_1^2}{v}, \dots, \frac{\zeta_1^2 + v - 1}{v}, \frac{\alpha_1}{v}, \dots, \frac{\alpha_1 + v - 1}{v}, \frac{\beta_1}{v}, \dots, \frac{\beta_1 + v - 1}{v}$.

Proof: See Appendix A. ■

B. Average Symbol Error Rate

The ASER is a critical performance indicator in communications systems, measuring the probability of symbol error detection at D. For the SC scheme employing M-ary phase shift keying (MPSK) modulation, the ASER can be mathematically expressed as

$$\text{ASER} = \frac{\sin\left(\frac{\pi}{M}\right)}{\sqrt{\pi}} \int_0^\infty \frac{\exp\left(-z \sin^2\left(\frac{\pi}{M}\right)\right)}{\sqrt{z}} F_{\Xi_{\text{SC}}}(z) dz. \quad (7)$$

Theorem 2: The ASER can be derived as in (8) at the top of the next page.

Proof: See Appendix B. ■

C. Ergodic Capacity

Ergodic capacity is an essential performance measure representing the average data rate in bits per unit of time and frequency that a communication channel can reliably maintain. For the FSO/RF SAGIN system utilizing the SC technique, the ergodic capacity, C , is expressed as in (9)

$$\text{ASER} = \frac{\zeta_1^2 \zeta_2^2 v^{\alpha_1 + \alpha_2 + \beta_1 + \beta_2 - 4}}{\sqrt{\pi} (2\pi)^{2(v-1)} \Gamma(\alpha_1) \Gamma(\beta_1) \Gamma(\alpha_2) \Gamma(\beta_2) \Gamma(N\Omega_G)} \times \sum_{i=1}^n \left[G_{2v+1, 6v+1}^{6v, 1} \left[\frac{(\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2)^v \omega_i}{v^{4v} (\zeta_1^2 + 1)^v (\zeta_2^2 + 1)^v \bar{\gamma}_{\text{FSO}} \sin^2\left(\frac{\pi}{M}\right)} \middle| \Delta_2, 0 \right] G_{1,2}^{1,1} \left[\Theta_G \sqrt{\frac{\omega_i}{\bar{\gamma}_{\text{RF}} \sin^2\left(\frac{\pi}{M}\right)}} \middle| N\Omega_G, 0 \right] \frac{H_i}{\sqrt{\omega_i}} \right]. \quad (8)$$

$$\mathcal{J}_1 = \frac{2\zeta_1^2 \zeta_2^2}{v \Gamma(\alpha_1) \Gamma(\beta_1) \Gamma(\alpha_2) \Gamma(\beta_2) \Gamma(N\Omega_G)} \sum_{k=1}^{\infty} \frac{(-1)^{k+1} v^\mu 2^{2k+N\Omega_G-\frac{3}{2}}}{k (2\pi)^{2v-\frac{3}{2}} \left(\Theta_G \sqrt{\frac{1}{\bar{\gamma}_{\text{RF}}}} \right)^{2k} G_{2v+4, 6v+2}^{6v+2, 2}} \left[\frac{4 (\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2)^v \Phi_1}{v^{4v} ((\zeta_1^2 + 1) (\zeta_2^2 + 1))^v} \middle| \bar{\Delta}_1, \bar{\Delta}_2 \right], \quad (10)$$

$$\mathcal{J}_2 = \frac{\zeta_1^2 \zeta_2^2 v^{\alpha_1 + \alpha_2 + \beta_1 + \beta_2 - 4} \Theta_G^{N\Omega_G} \left(\frac{2}{\bar{\gamma}_{\text{RF}}} \right)^{\frac{N\Omega_G-2}{2}}}{2\sqrt{\pi} (2\pi)^{2(v-1)} \Gamma(\alpha_1) \Gamma(\beta_1) \Gamma(\alpha_2) \Gamma(\beta_2) \Gamma(N\Omega_G) \left(\Theta_G \sqrt{\frac{1}{\bar{\gamma}_{\text{RF}}}} \right)^{N\Omega_G-2}} \sum_{k=1}^{\infty} \frac{(-1)^{k+1}}{k} \left(\frac{\Theta_G^2}{4\bar{\gamma}_{\text{RF}}} \right)^{-(k+1)} \times G_{2v+3, 6v+1}^{6v, 3} \left[\frac{4^3 (\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2)^v \bar{\gamma}_{\text{RF}}^2}{v^{4v} ((\zeta_1^2 + 1) (\zeta_2^2 + 1))^v \bar{\gamma}_{\text{FSO}} \Theta_G^4} \middle| 1, -\left(k + \frac{N\Omega_G-2}{2}\right), -\left(k + \frac{N\Omega_G-1}{2}\right) \right], \quad (11)$$

where $\mu = \alpha_2 + \beta_2 + \alpha_1 + \beta_1 - 3$, $\bar{\Delta}_1 = \frac{1-2k-N\Omega_G}{2}, \frac{2-2k-N\Omega_G}{2}, \frac{1-2k}{2}, \frac{2-2k}{2}, \bar{\Delta}_2 = \frac{\zeta_1^2+1}{v}, \dots, \frac{\zeta_1^2+v}{v}, \frac{\zeta_2^2+1}{v}, \dots, \frac{\zeta_2^2+v}{v}, \bar{\Delta}_3 = \frac{\zeta_2^2}{v}, \dots, \frac{\zeta_2^2+v-1}{v}, \frac{\alpha_2}{v}, \dots, \frac{\alpha_2+v-1}{v}, \frac{\beta_2}{v}, \dots, \frac{\beta_2+v-1}{v}, \frac{\zeta_1^2}{v}, \dots, \frac{\zeta_1^2+v-1}{v}, \frac{\alpha_1}{v}, \dots, \frac{\alpha_1+v-1}{v}, \frac{\beta_1}{v}, \dots, \frac{\beta_1+v-1}{v}, \bar{\Delta}_4 = \frac{-2k}{2}, \frac{1-2k}{2}$, and $\Phi_1 = \frac{\bar{\gamma}_{\text{RF}}}{\bar{\gamma}_{\text{FSO}} \Theta_G^2}$.

$$C = \frac{1}{\ln 2} \int_0^\infty \ln(1+z) f_{\Xi_{\text{sc}}}(z) dz = \frac{1}{\ln(2)} (\mathcal{J}_1 + \mathcal{J}_2). \quad (9)$$

Theorem 3: The C can be obtained as in (9), where $\mathcal{J}_1$ and $\mathcal{J}_2$ can be derived as in (10) and (11), respectively, at the top of this page.

Proof: See Appendix C. ■

IV. RESULTS AND DISCUSSION

In this section, through simulation results and analytical analysis, the performance of the proposed system model is evaluated. Unless otherwise stated, the main parameters used for the simulation and numerical results are defined as $\Omega = 1$, $m = 2$, $\gamma_{\text{th}} = 20$ dB, $\alpha = 4$, $\beta = 3$, $\zeta = 8$, $\lambda = 0.05$ m, $\mathcal{A}_0 = 1$, $d_1 = 33000$ km, $d_2 = 1000$ km, and $\Omega_l = -45$ dB/km [8].

In Fig. 2, the P_{out} is illustrated as a function of the average SNR for various N at the ARIS with a fixed amplification gain, $A = 5$ dB, for the ORIS. The results obtained are investigated using two FSO link detection techniques, namely HD and IM/DD. The results demonstrate that increasing N at the ARIS from 3 to 5 significantly reduces the P_{out} across all average SNR levels, enhancing beamforming gain and diversity in the RF link. For example, for the HD technique, at 10 dB SNR, P_{out} improves from approximately 10^{-2} for $N = 3$ to approximately 10^{-3} for $N = 5$. The HD technique consistently outperforms the IM/DD technique due to its superior noise resilience, while IM/DD shows higher outages due to its limitations under atmospheric turbulence and multipath fading. The hybrid FSO/RF system, aided by ORIS and ARIS, ensures resilience in SAGINs, especially in obstructed or turbulent

environments. Both analytical and simulation results match very well, demonstrating the validity of our analysis.

In Fig. 3, the ASER is shown versus the average SNR. The results demonstrate the impact of M-ary modulation order, M , and ARIS reflecting elements, N , on the ASER in the RIS-enabled hybrid FSO/RF SAGIN system. As an illustration, at 0 dB SNR, $M = 4$ with $N = 4$ achieves ASER $\approx 10^{-3}$ while $M = 16$ with $N = 2$ shows ASER ≈ 0.3 , highlighting the trade-off between spectral efficiency and reliability. The system's compensation for atmospheric impairments relies on N and A . Increasing N significantly improves the ASER by enhancing spatial diversity and beamforming in the RF link. The ORIS amplification gain, $A = 5$ dB, also helps mitigate FSO link attenuation. These results highlight the critical role of ARIS and ORIS configurations in enabling reliable high-order modulation for hybrid FSO/RF systems operating under realistic atmospheric conditions. Figure 4 demonstrates the ergodic capacity, C , performance under varying A and N , where it can be seen that either parameter enhances C . For instance, at 8 dB SNR, the configuration with $A = 10$ dB and $N = 10$ achieves $C \approx 12.5$ bits/s/Hz, approximately 25% improvement over the $A = 6$ dB and $N = 5$ case, which achieves $C \approx 10$ bits/s/Hz, highlighting the benefits of higher A and N . The performance gains are attributed to the ORIS's ability to compensate for FSO link impairments through amplified reflected signal, while the increased ARIS elements provide enhanced beamforming and diversity for the RF link. The 3D results in Fig. 5 thoroughly characterize how the FSO atmospheric turbulence parameters, α and β , influence the key performance metrics of the RIS-enabled hybrid FSO/RF SAGIN system under fixed ORIS amplification, $A = 5$ dB, and ARIS elements, $N = 5$. Under light

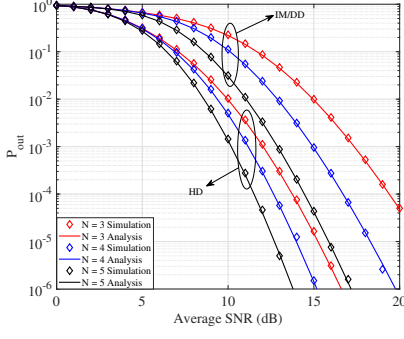
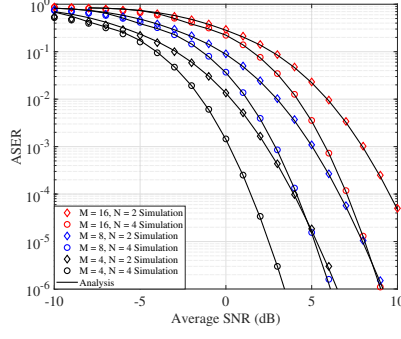

 Fig. 2: The P_{out} vs. average SNR.


Fig. 3: The ASER vs. average SNR.

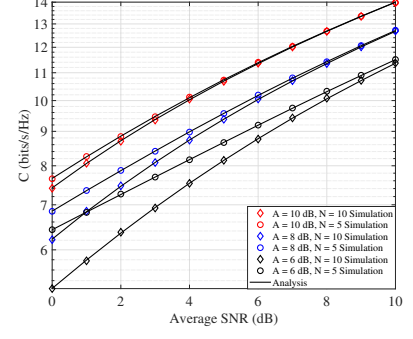
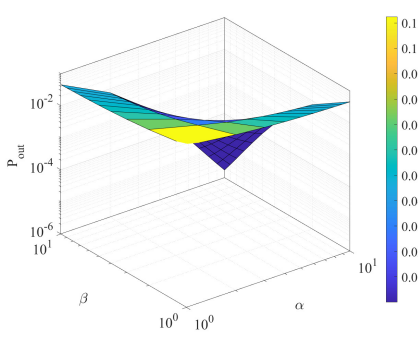
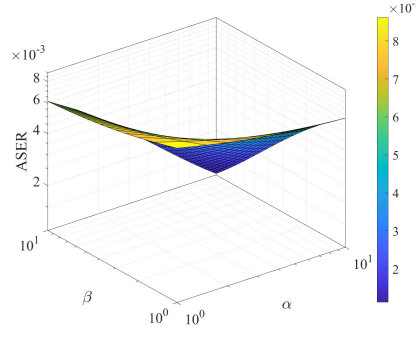
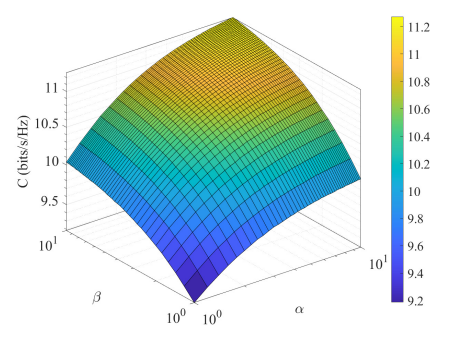

 Fig. 4: Ergodic capacity, C , vs. average SNR.

 (a) Outage probability, P_{out} , vs. α and β .

 (b) ASER vs. α and β .

 (c) Ergodic capacity, C , vs. α and β .

 Fig. 5: The effect of the FSO atmospheric turbulence parameters, α and β , on the hybrid FSO/RF SAGIN performance.

turbulence, high α and β values, performance is optimal, with very low $P_{out} < 10^{-6}$ in Fig. 5a, minimal ASER $\approx 10^{-3}$ in Fig. 5b, and high $C \approx 11$ bits/s/Hz in 5c. In moderate turbulence, the performance declines but remains acceptable, $P_{out} \approx 10^{-4}$, ASER $\approx 4 \times 10^{-3}$, $C \approx 10$ bits/s/Hz. However, in high turbulence, low α and β values, the performance drops significantly, $P_{out} > 10^{-2}$, ASER $> 10^{-3}$, $C < 9$ bits/s/Hz. These results demonstrate how atmospheric turbulence limits the achievable performance of SAGINs.

V. CONCLUSION

This paper presented a hybrid FSO/RF communication framework for SAGINs, integrating optical and RF RISs to enhance the system performance. An ORIS mounted on an LEO satellite improves and amplifies the optical reflected signal, while an ARIS installed on an UAV enables dynamic RF beam steering to mitigate LoS blockages. The system employs SC to choose the stronger signal, ensuring robust communication. The outage probability, ASER, and ergodic capacity were analyzed, and closed-form expressions were derived. The impact of atmospheric turbulence was also examined. Results reveal that increasing the number of ARIS elements and the ORIS amplification gain substantially improves link reliability, spectral efficiency, and robustness. Notably, the system maintains strong performance under light

and moderate atmospheric turbulence, and HD at the receiver yields consistently better results than IM/DD.

APPENDIX

Appendix A

The PDF and CDF of Ξ_D^{RF} can be obtained as [18]

$$f_{\Xi_D^{RF}}(z) = \frac{\Theta_G^{N\Omega_G} \left(\frac{z}{\gamma_{RF}} \right)^{\frac{N\Omega_G-1}{2}}}{2\Gamma(N\Omega_G) \sqrt{\gamma_{RF}z}} \exp\left(-\Theta_G \sqrt{\frac{z}{\gamma_{RF}}}\right), \quad (12)$$

and

$$F_{\Xi_D^{RF}}(z) = \frac{\gamma \left(N\Omega_G, \Theta_G \sqrt{\frac{z}{\gamma_{RF}}} \right)}{\Gamma(N\Omega_G)}, \quad (13)$$

respectively, where $\Omega_G = \frac{(\mu_{G_i}(1))^2}{\mu_{G_i}(2) - (\mu_{G_i}(1))^2}$, $\Theta_G = \frac{\mu_{G_i}(1)}{\mu_{G_i}(2) - (\mu_{G_i}(1))^2}$. The q -th moment of $\mathcal{G}_i$, $\mu_{G_i}(q) \triangleq \mathbb{E}[\mathcal{G}_i^q]$, can be expressed as $\mu_{G_i}(q) = \frac{\Gamma(m_1 + \frac{q}{2})\Gamma(m_2 + \frac{q}{2})}{\Delta^q \Gamma(m_1)\Gamma(m_2)}$. On the other hand, the PDF and CDF of Ξ_D^{FSO} can be obtained respectively as [16]

$$f_{\Xi_D^{FSO}}(z) = \frac{\zeta_1^2 \zeta_2^2}{v\Gamma(\alpha_1)\Gamma(\beta_1)\Gamma(\alpha_2)\Gamma(\beta_2)z} \times G_{2,6}^{6,0} \left[\frac{\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2 z^{\frac{1}{v}}}{(\zeta_1^2 + 1)(\zeta_2^2 + 1)\bar{\gamma}_{FSO}^{\frac{1}{v}}} \middle| \begin{matrix} \zeta_1^2 + 1, \zeta_2^2 + 1 \\ \zeta_2^2, \alpha_2, \beta_2, \zeta_1^2, \alpha_1, \beta_1 \end{matrix} \right], \quad (14)$$

and

$$F_{\Xi_{\text{FSO}}}^{\text{FSO}}(z) = \frac{\zeta_1^2 \zeta_2^2 v^{\alpha_1 + \alpha_2 + \beta_1 + \beta_2 - 4}}{(2\pi)^{2(v-1)} \Gamma(\alpha_1) \Gamma(\beta_1) \Gamma(\alpha_2) \Gamma(\beta_2)} \times \quad (15)$$

$$G_{2v+1, 6v+1}^{6v, 1} \left[\frac{(\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2)^v z}{v^{4v} ((\zeta_1^2 + 1) (\zeta_2^2 + 1))^v \bar{\gamma}_{\text{FSO}}} \middle| 1, \Delta_1 \right] \left[\Delta_2, 0 \right].$$

By utilizing (13), (15), and using [19, Eq. (07.34.03.0275.01)], the P_{out} can be derived as in (6).

Appendix B

The ASER for MPSK can be obtained by plugging (13) and (15) into (7) and using [19, Eq. (07.34.03.0275.01)] as

$$\text{ASER} = \frac{(2\pi)^{-2(v-1)} \zeta_1^2 \zeta_2^2 v^{\alpha_1 + \alpha_2 + \beta_1 + \beta_2 - 4} \sin\left(\frac{\pi}{M}\right)}{\sqrt{\pi} \Gamma(\alpha_1) \Gamma(\beta_1) \Gamma(\alpha_2) \Gamma(\beta_2) \Gamma(N \Omega_{\mathcal{G}})} \quad (16)$$

$$\int_0^\infty \frac{\exp\left(-z \sin^2\left(\frac{\pi}{M}\right)\right)}{\sqrt{z}} G_{1,2}^{1,1} \left[\Theta_{\mathcal{G}} \sqrt{\frac{z}{\bar{\gamma}_{\text{RF}}}} \middle| \frac{1}{N \Omega_{\mathcal{G}}}, 0 \right]$$

$$G_{2v+1, 6v+1}^{6v, 1} \left[\frac{(\zeta_1^2 \alpha_1 \beta_1 \zeta_2^2 \alpha_2 \beta_2)^v z}{v^{4v} ((\zeta_1^2 + 1) (\zeta_2^2 + 1))^v \bar{\gamma}_{\text{FSO}}} \middle| 1, \Delta_1 \right] \left[\Delta_2, 0 \right] dz.$$

Due to the complexity of computing the integral in (16), we have utilized the Gauss-Laguerre quadrature approximation method given by $\int_0^\infty \exp(-x) f(x) dx \approx \sum_{i=1}^n H_i f(\omega_i)$ [20, Eq. (25.4.45)], where H_i is the corresponding weight coefficient given by $H_i = \frac{\omega_i}{(n+1)^2 (L_{n+1}(\omega_i))^2}$, with ω_i being the i -th zero of the Laguerre polynomial $L_n^0(\cdot)$ given by $L_n^0(x) = \sum_{i=0}^n (-1)^i \binom{n}{i} \frac{x^i}{i!}$ [17, Eq. (8.970)]. By utilizing the Gauss-Laguerre quadrature technique, and after simple algebraic manipulations, the ASER can be derived as in (8).

Appendix C

The ergodic capacity, C , can be obtained as $C = \frac{1}{\ln(2)} (\mathcal{J}_1 + \mathcal{J}_2)$, where

$$\mathcal{J}_1 = \int_0^\infty \ln(1+z) f_{\Xi_{\text{FSO}}}^{\text{FSO}}(z) F_{\Xi_{\text{D}}}^{\text{RF}}(z) dz, \quad (17)$$

and

$$\mathcal{J}_2 = \int_0^\infty \ln(1+z) F_{\Xi_{\text{D}}}^{\text{FSO}}(z) f_{\Xi_{\text{D}}}^{\text{RF}}(z) dz. \quad (18)$$

Utilizing the Taylor series expansion, we have $\ln(1+z) = \sum_{k=1}^\infty (-1)^{k+1} \frac{z^k}{k}$ [17, (1.511)]. By substituting (13) and (14) in (17) and with some mathematical manipulations and the help of [19, Eq. (07.34.21.0013.01)], $\mathcal{J}_1$ can be derived as in (10). By substituting (12) and (15) in (18), with the help of [19, Eq. (07.34.03.0606.01)] and [19, Eq. (07.34.21.0013.01)], and with some mathematical manipulations, $\mathcal{J}_2$ can be derived as (11). The ergodic capacity, C , is then obtained as in (9).

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