

Optimizing Aerial Nodes Placement for Minimized Outage in Satellite-Ground FSO Links

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Abstract—In 6G era, Satellite-Ground (S-G) free-space optical (FSO) links will be critical in achieving global coverage and high data rate communication. Key 6G applications like quantum key distribution and distributed computing will depend heavily on the reliability of these S-G FSO connections. However, atmospheric turbulence remains a significant challenge. This paper introduces a novel Optimal Aerial Nodes Placement (OAP) framework to enhance the reliability of S-G FSO links with an objective of turbulence aware path length balancing. We explore three deployment configurations, namely, serial, parallel, and OAP. We evaluate two cooperation protocols, amplify-and-forward (AF) and decode-and-forward (DF). Comparative analysis reveals that the proposed OAP framework performs better under DF mode compared to AF and achieves a 20 dB performance improvement over serial transmission in DF mode, thus demonstrating the effectiveness of OAP in boosting FSO link reliability.

Index Terms—Space-ground FSO links, aerial node placement, turbulence-aware communication, outage performance.

I. INTRODUCTION

Integration of non-terrestrial nodes (NTNs) into evolving 6G wireless ecosystem is crucial for ensuring service availability and continuity across diverse environments. However, this integration is challenging because the characteristics of NTNs, such as orbit type, altitude, coverage area, vary significantly based on the platform, which ranges from geostationary, medium, and low earth orbit (GEO, MEO, LEO) satellites to unmanned aerial vehicles (UAVs) and high altitude platforms (HAPs). Another futuristic research direction has been aerial base stations utilizing free-space optical (FSO) communication which present a promising technology for bridging NTNs and terrestrial nodes (TNs), enabling high-speed, low-latency, and reliable transmissions. However, FSO link reliability significantly decreases with increased path lengths and atmospheric turbulence induced losses [1].

This paper focuses on enhancing the satellite-ground (S-G) FSO link reliability by identifying optical channel aware-optimal aerial nodes placement for integrating NTNs with TNs as illustrated in Fig. 1. Several recent studies have investigated multi-hop FSO systems to improve link reliability by addressing challenges in areas like routing, network architecture, and resource allocation. For example, [2] analyzed optimal relay spacing in terrestrial dual-hop FSO systems under log-normal turbulence, but assumed fixed 2D relay placement with no altitude optimization. [3] studied multi-layer airborne FSO configurations but relied on pre-defined layer positions

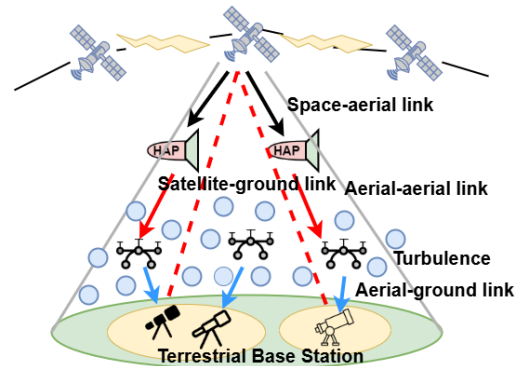


Fig. 1: Turbulence aware aerial nodes deployment for enhancing S-G FSO link reliability.

with power adjustment rather than spatial optimization. Other works, such as [4] and [5], explored SAG-FSO architectures using HAPs and site diversity, yet adopted fixed aerial geometries. Similarly, [6] and [7] developed detailed outage and latency models under various turbulence conditions, assuming static relay deployments. In a different line of work, [8] applied genetic algorithms (GAs) to tune beam parameters in FSO links, but did not address relay positioning. While these studies provide valuable insights, most of them treat relay locations as fixed and do not leverage the spatial deployment flexibility of NTNs, particularly in the vertical dimension.

In contrast, this work introduces a turbulence-aware 3D aerial node placement framework that jointly optimizes both horizontal and vertical positioning of aerial nodes to improve S-G FSO link reliability. By adopting an optical channel-aware design strategy, our method explicitly incorporates distance-dependent turbulence effects into the optimization process, an aspect largely overlooked in prior studies. The key contributions of our work are as follows: (1) We propose an Optimal Aerial Node Placement (OAP) framework that arranges aerial nodes in layered configurations to exploit log-amplitude turbulence variance, enhancing end-to-end S-G FSO performance. (2) We formulate and solve aerial node's placement optimization problem to find the optimal aerial node locations that minimize the outage of S-G FSO link. (3) We conduct extensive numerical evaluations comparing serial, parallel, and OAP transmission strategies under amplify-and-forward (AF) and decode-and-forward (DF) protocols. Outage performance results reveal the benefits of using proposed OAP scheme over serial and parallel transmission schemes.

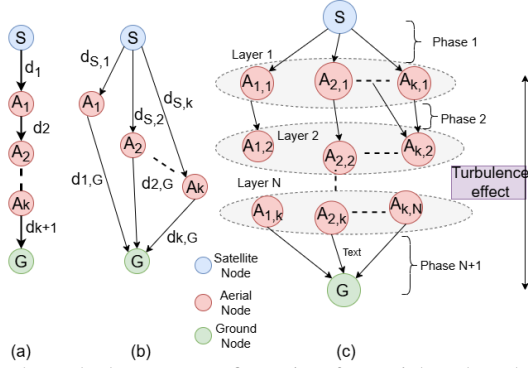


Fig. 2: Three deployment configuration for aerial nodes placement between S-G link: (a) Serial transmission, (b) Parallel transmission, (c) Proposed OAP transmission.

II. SYSTEM MODEL

We consider a satellite-to-ground vertical FSO system with k aerial nodes positioned in between. The satellite operates with a predictable trajectory, while the aerial nodes are assumed to maintain quasi-static positions during the entire communication window. We focus on a design-time planning scenario where aerial nodes placements are optimized before deployment. In the serial transmission configuration, illustrated in Fig. 2(a), the satellite signal reaches the ground node after passing through $k + 1$ hops. In DF mode, each aerial node decodes and remodulates the received signal before transmitting. In AF mode, the aerial node amplifies the signal and forwards it without decoding. In the parallel transmission setup, the satellite simultaneously sends the same signal to k aerial nodes, as shown in Fig. 2(b). In the third configuration, we introduce a hybrid mesh network that combines serial and parallel transmissions among aerial nodes as shown in Fig. 2(c). As in previous configurations, satellite signal reaches ground through k aerial nodes, but here we organize nearby nodes into N layers. The satellite node utilizes a multi-laser transmitter and each laser is directed at a corresponding aerial node in the first layer. Since the number of aerial nodes per layer may vary, all nodes (except in the first layer) and the ground terminal use wide apertures to capture overlapping diffraction patterns from multiple sources.

A. S-A FSO Channel Modeling

We consider optical beam propagation from a satellite to a ground station via k aerial nodes at different altitudes. The S-A FSO link experiences negligible attenuation due to stable upper-atmospheric conditions, i.e., $h_{S-A} \approx 1$ [4], [9].

B. A-G FSO Channel Model

Unlike S-A link, the aerial-to-ground (A-G) FSO channel is strongly affected by atmospheric turbulence due to varying temperature and pressure gradients near the surface. This causes spatially varying irradiance fading, with near-ground turbulence being isotropic and spherical, but as altitude increases, these eddies become more anisotropic and elongated, resulting in directionally dependent fading of optical beam. These effects introduce stronger scintillation and beam distortion, making A-G links more sensitive to node placement and local conditions. Recognizing these altitude-based variations,

the authors in [1] proposed segmenting the vertical FSO channel into parallel layers and developed a channel model that relies on a cascaded structure of fading coefficients for each layer $h_{t,n}$. The overall fading coefficient is modeled as $h_T = \prod_{n=1}^N h_{t,n}$. In our work, we have considered the fading coefficient for each layer $h_{t,n}$ is independent and non-identically distributed and follows lognormal distribution with μ_{x_n} be the mean and $\sigma_{x_n}^2$ represent the log-irradiance variance of n^{th} layer. $X_n = 0.5 \ln I_n$ is log-amplitude coefficient of n^{th} layer. The PDF of the overall fading coefficient $I_H = \prod_{n=1}^N I_n$ follows lognormal distribution, given by

$$p_{I_H}(I_H) = \frac{1}{I_H \sqrt{2\pi(\sigma_H^2)}} \exp\left[-\frac{[\ln(I_H) - \mu_H]^2}{2\sigma_H^2}\right], I_H > 0. \quad (1)$$

In Eq. (1), $\mu_H = \sum_{n=1}^N 2\mu_{x_n}$ and $\sigma_H^2 = \sum_{n=1}^N 4\sigma_{x_n}^2$. The attenuation loss due to scattering and absorption is modeled using Beers-Lambert law [10] and is given as $h_d = \exp^{-d\sigma}$ where σ denotes an attenuation coefficient in dB/km. The overall channel gain from satellite to ground via k aerial nodes can be expressed as:

$$h_{\text{total}} = h_{S-A} \prod_{i=1}^k h_{\text{node}_i\text{-ground}} h_d \quad (2)$$

where $h_{\text{node}_i\text{-ground}}$ represents the channel gain for the FSO link between the i -th aerial node and the ground.

III. OPTIMIZATION OF AERIAL NODES PLACEMENT

In this section, we formulate the aerial node placement optimization problem for the deployment configurations discussed above. For serial transmission, the S-G link has $(k + 1)$ consecutive hops through k DF aerial nodes. An outage occurs if any of the hops fails to meet the minimum SNR threshold. Assuming independent lognormal fading on each hop, the end-to-end outage probability is given by [2], [6]:

$$P_{\text{out}}^{\text{serial}} = 1 - \prod_{i=1}^{k+1} \left(1 - Q\left(\frac{\ln\left(\frac{h_{d_i} P_M}{k+1}\right) + 2\mu_H(d_i)}{2\sigma_H(d_i)}\right) \right), \quad (3)$$

where h_{d_i} denotes the deterministic path loss at distance d_i , P_M is the power margin, and $\mu_H(d_i)$, $\sigma_H(d_i)$ are the mean and standard deviation of the log-amplitude fading, respectively. For optimal aerial node location we need to minimize P_{out} with respect to distance between intermediate links i.e., $d_1, d_2, \dots, d_{k+1}$. As given in [2], we define the following functions:

$$h(d_1, d_2, \dots, d_{k+1}) = \prod_{i=1}^{k+1} \varphi(\mathcal{F}(d_i)). \quad (4)$$

$$D(d_1, d_2, \dots, d_{k+1}) = \sum_{i=1}^{k+1} d_i. \quad (5)$$

The optimization problem becomes

$$(P1): \max_{d_1, d_2, \dots, d_{k+1}} h(d_1, d_2, \dots, d_{k+1}) \quad (6)$$

s.t., $D(d_1, d_2, \dots, d_{k+1}) = d_{S-G}$.

$P1$ is a concave optimization problem with respect to $\mathcal{F}(d_i)$ which is a monotonically decreasing function and the solution is $d_i = d_k$ [2]. Therefore, P_{out} is minimized when consecutive aerial nodes are placed equidistant inbetween S-G nodes in case of serial transmission configuration. For the parallel

configuration, the satellite simultaneously transmits to k aerial nodes, each forwarding the signal independently to the ground. The outage probability must account for all 2^k decoding combinations at the relay layer, depending on which subset of aerial nodes successfully decode and forward the signal. As described in [10], the total outage probability is given by:

$$P_{\text{out}}^{\text{parallel}} = \sum_{i=1}^{2^k} \left[\prod_{j \in W(i)} (1 - Q(U(d_{S,j}))) \prod_{j \notin W(i)} Q(U(d_{S,j})) \times Q(V(d_{j,G})) \right], \quad (7)$$

where $d_{S,j}$ and $d_{j,G}$ represent the satellite-to-aerial and aerial-to-ground link distances, respectively. The functions $U(\cdot)$ and $V(\cdot)$ are defined as:

$$U(d_{S,j}) = \frac{\ln \left(\frac{h(d_{S,j}) P_M}{2N} \right) + 2\mu_{x_n}(d_{S,j})}{2\sigma_{x_n}(d_{S,j})}, \quad (8)$$

$$V(\bar{d}_{S(i)}) = \frac{\ln \left(\frac{P_M e^{\mu_\xi}}{2N} \right)}{\sigma_\xi(\bar{d}_{S(i)})}, \quad (9)$$

where μ_ξ and σ_ξ^2 are the equivalent mean and variance of the log-amplitude fading at the ground node and are given by:

$$\mu_\xi(\bar{d}_{S(i)}) = \ln \left(\sum_{j \in S(i)} h(d_{j,G}) \right) - \frac{\sigma_\xi^2}{2}, \quad (10)$$

$$\sigma_\xi^2(\bar{d}_{S(i)}) = \ln \left(1 + \frac{\sum_{j \in S(i)} h^2(d_{j,G}) (e^{4\sigma_{x_n}^2} - 1)}{\left(\sum_{j \in S(i)} h(d_{j,G}) \right)^2} \right). \quad (11)$$

The corresponding optimization problem becomes:

$$(P2) : \min_{\{d_{S,j}, d_{j,G}\}} Z(\{d_{S,j}, d_{j,G}\}), \quad (12)$$

$$\text{s.t. } d_{S,j} + d_{j,G} = D_{S,G}, \quad \forall j = 1, 2, \dots, k.$$

To tackle this non-convex problem, a genetic algorithm is employed [10], [11], with the optimal solution theoretically occurring when all aerial nodes are positioned at the exact same point.

A. Problem Formulation for Proposed OAP Scheme

For multi-hop parallel transmission shown in Fig. 2(c) the aerial nodes are grouped into N layers. Each layer contains k_i nodes positioned at $p_{i,j} = (x_{i,j}, y_{i,j}, z_i)$, where $i = 1, \dots, N$ and $j = 1, \dots, k_i$. The transmission from satellite to ground node takes place in $N + 1$ phases. Let $p_{0,1}$ and $p_{N+1,1}$ represent the satellite and ground station positions respectively. The hop distance between nodes $(i-1, j)$ and (i, m) is:

$$d_{(i-1,j) \rightarrow (i,m)} = \|p_{i-1,j} - p_{i,m}\|_2.$$

Let a hop fails with probability $\varphi(F(\cdot))$. Each phase fails only if all its constituent hops fail. Therefore, the outage probability for phase i is:

$$P_{\text{out},i} = \prod_{j=1}^{k_{i-1}} \prod_{m=1}^{k_i} \varphi(F(d_{(i-1,j) \rightarrow (i,m)})). \quad (13)$$

Let all the phases are independent and the total outage probability is:

$$P_{\text{out}}^{\text{OAP}} = 1 - \prod_{i=1}^{N+1} (1 - P_{\text{out},i}). \quad (14)$$

Algorithm 1 Placement Optimization for OAP Scheme (P3)

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1: Result:  $\{p_{i,j}^*\}$ 
2: Input:  $N, \{k_i\}, P_M, z_{\min}, z_{\max}, \mathcal{D}_i, s_{\min}, M, G, \mu$ 
3: Initialize:  $\mathcal{P}_g = \{P_1, P_2, \dots, P_M\}, g = 1$ 
4: for  $g = 1, \dots, G$  do
5:   for  $m = 1, \dots, M$  do
6:     Evaluate fitness of individual  $P_m$ :
        $J_m = 1 - \prod_{i=1}^{N+1} \left( 1 - \prod_{j=1}^{k_{i-1}} \prod_{l=1}^{k_i} \varphi(F(d_{(i-1,j) \rightarrow (i,l)})) \right)$ 
7:     Add penalty if any constraint is violated:
8:        $z_S > z_1 > \dots > z_G$ 
9:        $\|p_{i,j} - p_{i,\ell}\| < s_{\min}, \forall j \neq \ell$ 
10:       $z_i \notin [z_{\min}, z_{\max}]$ 
11:   end for
12:    $\mathcal{P}_{g+1} = \text{Variation}(\mathcal{P}_g, \mu)$ 
13: end for
14: return  $P^* = \arg \min J_m$ 

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The optimization problem for proposed OAP scheme is:

$$(P3) : \min_{\{p_{i,j}\}} 1 - \prod_{i=1}^{N+1} \left(1 - \prod_{j=1}^{k_{i-1}} \prod_{m=1}^{k_i} \varphi(F_{ijm}) \right) \quad (15)$$

$$\text{s.t. } z_S > z_1 > z_2 > \dots > z_N > z_G, \quad (15)$$

$$(x_{i,j}, y_{i,j}) \in \mathcal{D}_i, \quad z_{\min} \leq z_i \leq z_{\max}, \quad (16)$$

$$\|p_{i,j} - p_{i,\ell}\|_2 \geq s_{\min}, \quad \forall i, j \neq \ell. \quad (17)$$

Here, $F_{ijm} = F(d_{(i-1,j) \rightarrow (i,m)})$ and in the constraints $\mathcal{D}_i$ represents the allowed horizontal region for layer i , $z_{\min}, z_{\max}$ is the altitude bounds (platform limits) and $s_{\min}$ is the minimum intra-layer separation to ensure spatial diversity.

B. Solution of Problem (P3)

The optimization in (P3) is carried out over the 3D locations of all aerial nodes, considering constraints on altitude order, minimum spacing between nodes, and height limits. The outage probability expression includes products across all FSO links, which depend on the positions of multiple nodes. This makes the problem non-convex. We use a Genetic Algorithm (GA) to obtain an approximate solution. Each individual in the GA population encodes a complete set of aerial node positions. The fitness function is based on the total outage probability defined in (P3), with a penalty term added for constraint violations. The GA evolves the population over G generations with a population size of M , using tournament selection, one-point crossover, and Gaussian mutation. Elitism is used to retain the best-performing solutions across generations. The overall optimization procedure is summarized in Algorithm 1.

IV. NUMERICAL SIMULATIONS AND OUTAGE PERFORMANCE RESULTS

This section presents simulation results for the outage performance of a multi-hop parallel configuration utilizing various aerial nodes, alongside a comparative analysis of serial and parallel transmission configurations. Table I summarizes the key parameters used in our simulations. The FSO link is simulated under clear weather conditions with a visibility of

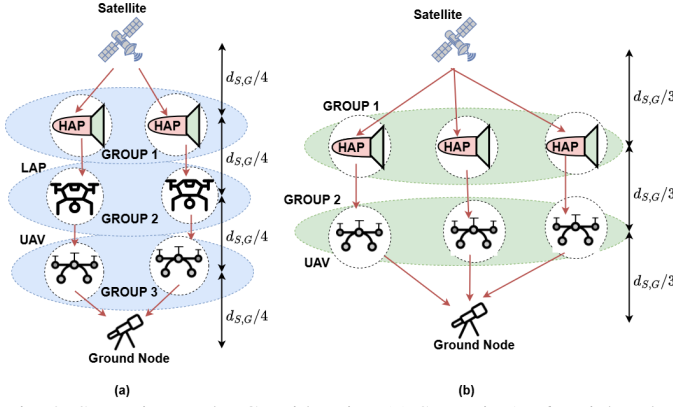


Fig. 3: Scenarios Under Consideration (a) Scenario 1 : 6 aerial nodes in 3 groups ($N = 3$) and each group has 2 aerial nodes ($k = 2$) (b) 6 aerial nodes in 2 groups ($N = 2$) and each group has 3 aerial nodes ($k = 3$).

TABLE I: Simulation Parameters

Satellite Parameters	
LEO Altitude (H_{sat})	500 km [6]
Zenith Angle (θ_{sat})	15 μ rad [6]
Beam Divergence (ξ_{sat})	10 $^\circ$ [6]
HAP Parameters	
Altitude (H_{HAP})	25 km [1]
Aperture Radius (R_{HAP})	0.1 m [1]
Zenith Angle (HAP-UAV, θ_{HU})	4 mrad [1]
Zenith Angle (HAP-Ground, θ_{HG})	3 mrad [1]
UAV Parameters	
Altitude Range (H_{UAV})	1–20 km [3]
Zenith Angle (θ_{UAV})	60 $^\circ$ [3]
Ground Terminal Parameters	
Altitude (H_{ground})	50 m [2]
Aperture Radius (R_{ground})	0.1 m [2]

10 km. The operating wavelength is $\lambda = 1550$ nm. The atmospheric attenuation coefficient is assumed to be 0.43 dB/km. The refractive index structure parameter C_n^2 is modeled using the Hufnagel–Valley (HV) profile [1].

For proposed OAP scheme, we consider a satellite-ground FSO link based on the mix of serial and parallel transmission between aerial nodes. We investigate the following two aerial node placement configurations:

- Scenario 1 (S1) : In this scenario, we consider six aerial nodes (2 HAPs, 2 LAPs, 2 UAVs) and club them in three groups ($N = 3$) with each group consisting of two aerial nodes ($k = 2$) as shown in Fig. 3(a).
- Scenario 2 (S2) : In this scenario, we consider six aerial nodes (3 HAPs, 3 UAVs) and club them in two groups ($N = 2$) and each group has three aerial nodes ($k = 3$) as shown in Fig. 3(b).

As benchmarks, we also examine purely serial and parallel configurations for comparison. Specifically, we consider all six aerial nodes are aligned vertically on a single line between S-G link in serial configuration. For parallel configuration benchmark, we consider all aerial nodes are placed at same height, midway between S-G link on a horizontal line. In Fig. 4(a) and (b), we present outage performance of proposed OAP scheme for scenarios 1 and 2 (S1 AND S2) along with serial and parallel transmission cases for comparison. As evident from the results, combining parallel and serial transmission between aerial nodes significantly enhances performance compared to

stand-alone serial or parallel transmission schemes. For an outage probability of 10^{-3} , performance gains of about 10 dB and 15 dB are observed for S1 ($N = 3$ and $k = 2$) over stand-alone serial and parallel transmission. At a target outage probability of 10^{-3} , S2 configuration ($N = 2$ and $k = 3$) shows 3 dB and 11 dB performance improvement compared to serial and parallel transmission.

Remark 1. Gains in the proposed OAP scheme arise from the multi-hop parallel transmission strategic utilization of distance-dependent log-amplitude variance ($\sigma_H^2 = \sum_{n=1}^N 4\sigma_{x_n}^2$) of the turbulent channel and hence is more effective than independent serial or parallel transmission setups.

Fig. 4 (c) compares the outage performance of proposed OAP transmission scheme by examining the impact of varying the no. of groups (N) while keeping the no. of aerial nodes ($k = 2$) fixed in each group. The results reveal that increasing the no. of groups enhances performance. Specifically, at an outage probability of 10^{-2} , performance gains of about 26 dB, 15 dB and 6 dB are observed for $N = 4$ over $N = 1$, $N = 2$ and $N = 3$. This improvement is attributed to the increased no. of hops with increasing the number of groups, which leverages the distance-dependency of the log-amplitude variance (σ_H^2) of turbulent channel more effectively.

Remark 2. It is evident from Fig. 4 that optimized aerial node placements (based on geometric separation and atmospheric turbulent channel modeling) play a critical role in FSO link performance. The outage curves proves that a close attention to these parameters is yielding significant SNR benefits, especially when atmospheric turbulence is a factor.

Fig. 5(a) and (b) compare the performance of amplify-and-forward (AF) and decode-and-forward (DF) transmissions for the serial, parallel and proposed OAP scheme. For serial and parallel transmission we consider two, three and four aerial nodes placed between S-G node. Fig. 5(c) shows the outage performance for OAP scheme where we place the aerial nodes in two ($N = 2$), three ($N = 3$) and four ($N = 4$) groups with each group having two ($k = 2$) aerial nodes. Results indicate that DF transmission consistently outperforms AF transmission due to its signal regeneration capability, which enhances reliability across nodes. However, AF transmission offer lower complexity since they bypass the decoding process. The trade-off is particularly noticeable at higher target outage levels (e.g., 10^{-4}), where DF achieves performance gains of up to 14 dB for serial transmission configurations having four aerial nodes. For parallel transmission the performance gain is little less compared to serial transmission case. However, here also DF transmission shows a performance gain of about 14 dB over AF transmission with four aerial nodes. Finally, in Fig. 5(c) we see that outage performance of proposed OAP transmission using DF and AF protocols outperforms the serial and parallel transmission schemes. Fig. 5(c) also shows that increasing the no. of groups of aerial nodes significantly lowers the outage probability. With $N = 4$, performance gains of 3 dB and 7 dB are observed compared to setups with $N = 3$ and $N = 2$, respectively, at a target outage of 10^{-4} for DF protocol. For AF protocol, performance gain of 6 dB and 8

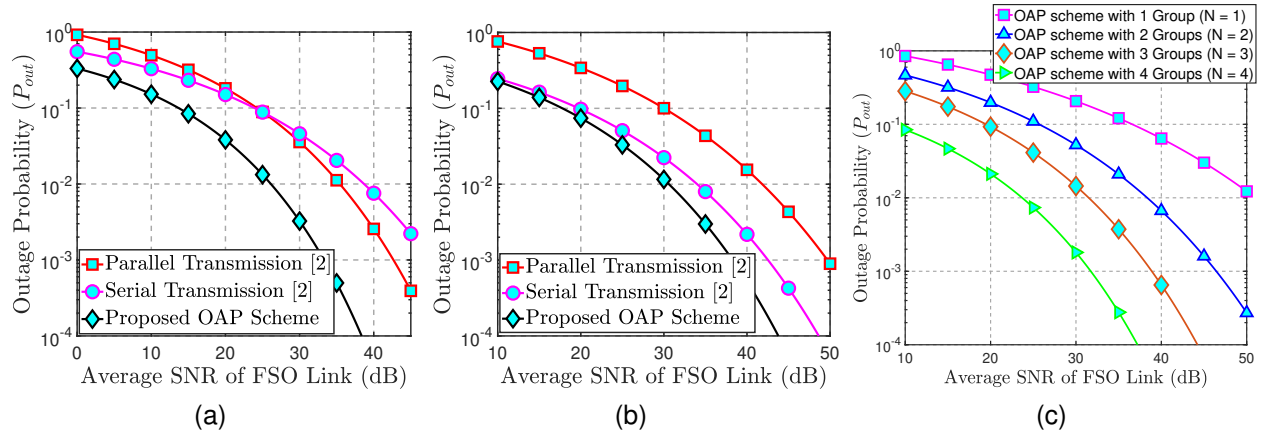


Fig. 4: Outage Performance Comparison Between Parallel, Serial and Multi-Hop Transmission for S-G FSO Link (a) For Scenario 1 (b) For Scenario 2 (c) Effect of Different Number of Aerial Groups on Outage Performance.

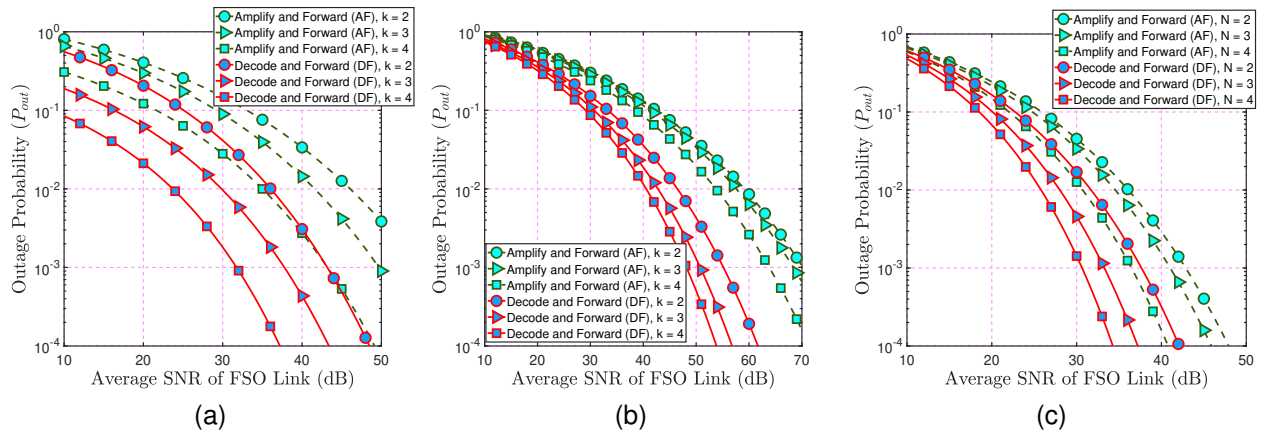


Fig. 5: Performance Comparison of Decode-and-Forward (DF) and Amplify-and-Forward (AF) with Different Number of Aerial Nodes in S-G FSO Link (a) Serial Transmission (b) Parallel Transmission (c) OAP Transmission.

dB are observed with $N = 4$, compared to $N = 3$ and $N = 2$, respectively. Overall, OAP scheme shows performance gain of 6 dB and 20 dB for $N = 4$ compared to $k = 4$ in serial and parallel transmission using DF protocol respectively.

V. CONCLUSION

This paper presented a comprehensive analysis of enhancing satellite-to-ground FSO communication by optimally positioning aerial nodes, integrating serial, parallel, and mesh configurations. Through our proposed OAP framework, we leveraged the unique benefits of strategically positioned aerial nodes to improve FSO link reliability in the face of atmospheric turbulence. Our analysis showed that the proposed OAP configurations outperform standalone serial and parallel systems. We also presented the comparative advantages of DF over AF in terms of outage performance of S-G FSO link. By examining scenarios with different numbers of aerial nodes placed at optimized locations, our findings emphasize that optimal node separation distances are critical in minimizing outage probability, a factor often underutilized in traditional SAGIN FSO systems.

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