Evaluating FSO-HAPS Model in Communication Network

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***Abstract*—In this study, the error performance and the capacity analysis is performed for the decode-and-forward based dual-hop asymmetric free space optical communication (FSO) system. The FSO link is characterized by path loss, Gamma–Gamma distributed turbulence and pointing error. For this mixed FSO cooperative system, novel closed-form mathematical expressions are derived for cumulative distribution function, probability density function and moment generating function of the equivalent signal-to-noise ratio in terms of Meijer-G function. Using these channel statistics, new finite power series based analytical expressions are obtained for the outage probability, the average bit error rate for various binary and M-ary modulation techniques and the average channel capacity of the considered system in terms of Meijer-G function. As a special case, the analytical framework can also be obtained for channel statistics and performance metrics of dual-hop mixed Rayleigh–Gamma–Gamma system. Simulation results validate the proposed mathematical analysis. The effects of fading, turbulence and pointing error are studied on the outage probability, average bit error rate and channel capacity of the asymmetric FSO system.**

I. Introduction

Free space optical (FSO) communication systems offer numerous advantages, including low power requirements, cost-effective installation and operation, license-free spectrum usage, immunity to interference, and high bandwidth capacity (up to 10 Gbps). These characteristics make FSO systems attractive for various terrestrial and satellite communication applications, such as last mile access, backhauling services, data recovery, and high-definition transmission. However, the performance of FSO systems is heavily influenced by atmospheric conditions, path loss, and pointing errors. Vibrations in transmitted laser beams, caused by factors like wind, earthquakes, and thermal expansion of tall buildings, often lead to misalignment between the transmitter and receiver, resulting in pointing errors. The increasing demand for high-speed and reliable communication has spurred the exploration of innovative technologies, with one promising avenue being the integration of FSO with radio frequency (RF) communication. The decode-and-forward dual-hop asymmetric FSO communication system represents a significant advancement, combining the robustness of RF with the high bandwidth capabilities of FSO. This system involves relaying information through an intermediary node using the decode-and-forward protocol. Evaluating the performance of this dual-hop asymmetric system is crucial for understanding its behavior under different conditions. The asymmetry in the FSO and RF links introduces complexities related to fading, turbulence, path loss, and pointing errors. Performance assessment involves analyzing key metrics such as outage probability, bit error rate (BER), and channel capacity. Researchers aim to unravel the intricate interplay of FSO components, providing insights into the system's reliability, robustness, and overall efficiency. This research contributes to the evolving landscape of FSO communication systems by conducting a detailed performance evaluation of the decode-and-forward dual-hop asymmetric configuration. Through analytical modeling and simulations, the study seeks to derive mathematical expressions and finite power series-based formulations for outage probability, BER, and channel capacity. Factors considered include atmospheric turbulence, path loss, and pointing errors, creating a comprehensive assessment framework. In summary, this performance evaluation aims to illuminate the strengths and limitations of the decode-and-forward dual-hop asymmetric FSO communication system. The outcomes of this study can guide the optimization of such systems, leading to advancements in hybrid communication technologies and their application in diverse scenarios.

II. System Model

Consider an asymmetric dual-hop cooperative communication system divided into two parts; one is a terrestrial communication system, and the other is an aerial communication system. In the terrestrial communication system, a source (S) communicates with a destination (D) via a relay node (R), as shown in figure. A scenario of FSO wireless communication is assumed that is, the S-R link and the R-D link, both of which are FSO links characterized by path loss, Gamma-Gamma distributed turbulence, and pointing errors.

In the Fig. 1, $\gamma_{s,r}$ and $\gamma_{r,d}$ are the instantaneous signal-to-

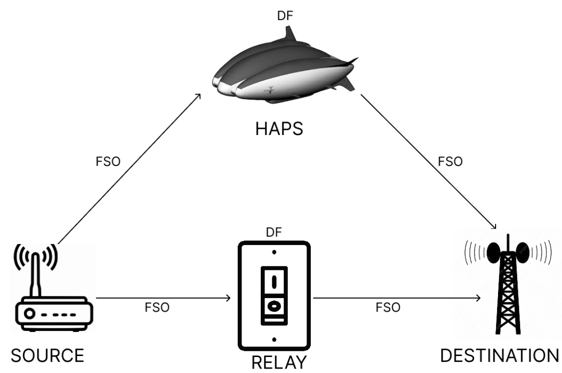

Fig. 1. System Model

noise ratios (SNRs) of the S-R and the R-D links, respectively, $\sigma_{s,r}^2$ and $\sigma_{r,d}^2$ are the AWGN variances of the S-R and the R-D links; a and b are the atmospheric turbulence parameters that depend upon the FSO link length, L, operating wavelength, and the refractive-index structure parameter, C_n^2, as $a = \left[\exp\left(0.49\sigma_l^2/\left(1+1.11\sigma_l^{12/5}\right)^{7/6}\right)-1\right]^{-1}$ and $b = \left[\exp\left(0.51\sigma_l^2/\left(1+0.69\sigma_l^{12/5}\right)^{5/6}\right)-1\right]^{-1}$, where the Rytov variance of $\sigma_l^2 = 1.23C_n^2 k^{7/6} L^{11/6}$, in which wave number $k = 2\pi/\lambda$ $[12, 13]$. The relay contains hybrid capabilities; it decodes the data transmitted by S and transmits the newly encoded data over the FSO link to D, by using a SIM scheme. Now, in the aerial communication system, a source (S) communicates with a destination (D) via a HAPS node (H), as shown in Fig. A scenario of FSO wireless communication is assumed, that is, the S-H link and the H-D link, both of which are FSO links characterized by path loss, Gamma—Gamma distributed turbulence, and pointing errors. In Fig. 1, $\gamma_{s,h}$ and $\gamma_{h,d}$ are the instantaneous signal-to-noise ratios (SNRs) of the S-H and the H-D links, respectively, $\sigma_{s,h}^2$ and $\sigma_{h,d}^2$ are the AWGN variances of the S-H and the H-D links; a and b are the atmospheric turbulence parameters, which depend upon the FSO link length, L, operating wavelength, and the refractive-index structure parameter, C_n^2, as $a = \left[\exp\left(0.49\sigma_l^2/\left(1+1.11\sigma_l^{12/5}\right)^{7/6}\right)-1\right]^{-1}$ and $b = \left[\exp\left(0.51\sigma_l^2/\left(1+0.69\sigma_l^{12/5}\right)^{5/6}\right)-1\right]^{-1}$, where the Rytov variance of $\sigma_l^2 = 1.23C_n^2 k^{7/6} L^{11/6}$, in which wave number $k = 2\pi/\lambda$ $[12, 13]$. HAPS works as a relay in DF mode between Source and Destination nodes. The FSO systems incorporate the SC technique, which selects the signal with the best SNR at both HAPS and Destination. As HAPS works in DF mode, the signal with higher SNR in the Source-HAPS link is first decoded, then re-encoded and forwarded to the Destination using the FSO system. Like, HAPS node, Destination selects the signal with a higher SNR in the HAPS-Destination link and decodes the signal. The FSO link is characterized by atmospheric attenuation, Gamma-Gamma distributed turbulence, Rayleigh distributed pointing errors, and the impacts of hovering fluctuations of the considered HAPS. It is worth mentioning that the position vibrations of the optical receiver as well as the AOA fluctuations of the received optical beam are lumped together in hovering fluctuations. The received signal at HAPS transmitted by Source via the FSO link is given by,

$$y_{H,f} = \eta_1 g_1 x_S + e_H,$$

where η_1 is the photo-electronic conversion ratio of the considered photodetector (PD) at HAPS, g_1 is the FSO channel coefficient, and e_H is the complex-valued AWGN with zero mean and variance $\sigma_{e,H}^2$. The instantaneous and average optical-equivalent electrical SNRs of the source-HAPS FSO link can be represented as, $\gamma_{fso_1} = \frac{\eta_1^1 P_{t_1}|g_1|^1}{\sigma_{s,H}^1}$ and $\mu_{fso_1} = \frac{\eta_2^2 P_{t_1} E\left[|g_1|^1\right]}{\sigma_{s,H}^1}$, respectively, where P_{t_1} denotes the equivalent transmit power of the SGS node for FSO node transmission. The signal received at the destination through the HAPS-D FSO link is given by

$$y_{D,f} = \eta_2 g_2 \hat{x}_S + e_D,$$

, where, η_2 is the photo-electronic conversion ratio of the considered PD at DGS, g_2 is the FSO channel coefficient, and e_D is the AWGN with zero mean and variance $\sigma_{e,D}^2$. The instantaneous and average optical-equivalent electrical SNRs of the (HAPS-DGS) FSO link are, $\gamma_{fso_2} = \frac{\eta_2^2 P_{t_2}|g_2|^2}{\sigma_{s,D}^2}$ and $\mu_{fso_2} = \frac{\eta_2^2 P_{t_2} E\left[|g_2|^2\right]}{\sigma_{s,D}^2}$ where, P_{t_2} represents the electrical equivalent transmit power of HAPS for the FSO mode of data transmission. Finally, at destination, SC is performed and detects the signal transmitted from the HAPS. Now, let's assume that the instantaneous signal-to-noise ratio from source to relay is said to be γ_1, γ_2 from relay to destination. Furthermore, the whole SNR for the terrestrial system will be γ_t and γ_a for the aerial system. γ_t = min (γ_1, γ_2) and γ_a = min (γ_3, γ_4).

III. CHANNEL MODELLING

The mathematical expressions of CDF and PDF of the DF-based dual-hop asymmetric FSO systems are derived for the following two scenarios, considering only turbulence in the FSO link in the first scenario and the combined effect of turbulence, path loss, and pointing error in the FSO link in the second scenario.

UNDER ATMOSPHERIC TURBULENCE

The FSO link experiences Gamma-Gamma distributed turbulence; the statistical characteristics are obtained as follows: If the FSO link is assumed to undergo Gamma-Gamma turbulence only, then the PDF of $\gamma_{r,d}$ is given by,

$$f_{\gamma_{rd}}(\gamma)=\frac{\xi^2}{2\gamma\Gamma(a)\Gamma(b)}G_{1,3}^{3,0}\left(pab\sqrt{\frac{\gamma}{\bar{\gamma}_{r,d}}}\middle|\begin{array}{c}\xi^2+1\\ \xi^2,a,b\end{array}\right)$$

where $\gamma=\bar{\gamma}_{r,d}/h_lA_0p$, $p=\xi^2/\left(\xi^2+1\right)$, $\mathcal{A}_0=\left[\operatorname{erf}\left(v_{p,q}\right)\right]^2$, $v=\sqrt{\pi/2}R/w_b,\xi=w_e/(2\sigma_s)$, $\operatorname{erf}(\cdot)$ denotes the error function, R is the radius of the receiver aperture, w_b is the normalised beamwaist, w_e is the equivalent beamwaist and σ_s is the pointing error displacement standard deviation at the receiver.Similarly, PDF of $\gamma_{s,r}$ can also be given like this. Using this, the CDF of $\gamma_{r,d}$ can be derived as,

$$F_{\gamma_{r,d}}(\gamma)=\frac{2^{z_1-2}\xi^2}{2\pi\Gamma(a)\Gamma(b)}G_{3,7}^{6,1}\times\left(\frac{(pab)^2\gamma}{16\bar{\gamma}_{r,d}}\middle|\begin{array}{c}1,\frac{\xi^2+1}{2},\frac{\xi^2+2}{2}\\ \frac{\xi^2}{2},\frac{\xi^2+1}{2},\frac{a}{2},\frac{a+1}{2},\frac{b}{2},\frac{b+1}{2},0\end{array}\right)$$

where $z_1=a+b,z_2=a-b$ and $G(\cdot)$ is the Meijer- G function.
The PDF of γ_3 can be derived as,

$$f_{\gamma fso_i}\left(\gamma_{fso_i}\right)=\frac{R_i^{C_{3_i}+1}\gamma_{fso_i}^{\frac{C_{3_i}-2}{2}}}{2\left(C_{3_i}+1\right)^{C_{3_i}}\mu_i^{\frac{C_{3_i}}{2}}}+\frac{R_iS_i\delta\left(\frac{R_i}{C_{3_i}+1}\left(\frac{\gamma_{fs_i}}{\mu_i}\right)^{\frac{1}{2}}\right)}{2\left(C_{3_i}+1\right)\left(\mu_i\gamma_{fss_i}\right)^{\frac{1}{2}}}$$

$$\text{and } F_{\gamma_{fso_i}}\left(\gamma_{fss_i}\right)=\frac{{R_i}^{C_{3_i}+1}\gamma_{fso_i}^{C_{3_i}/2}}{\left(C_{3_i}+1\right)^{C_{3_i}}C_{3_i}\mu_i^{C_{3_i}/2}}+S_i$$

respectively. Here, $R_i=\frac{2^{2C_{5_i}+1}C_{1_i}{}^{-C_{3_i}}C_{4_i}}{(4\alpha_i\beta_i)_{5_i}{}^{2}}\Gamma\left(\frac{2C_{5_i}+2+\alpha_i-\beta_i}{2}\right)\times\Gamma\left(\frac{2C_{S_i}+2+\beta_i-\alpha_i}{2}\right)\left(1-e^{\frac{-\theta_{FOV_i}^2}{2\sigma_O^2}}\right)$ and $S_i=e^{\frac{-\theta_{FOV_i}^2}{2\sigma_o^2}}$ for $i\in\{1,2\}$.

STATISTICAL CHARACTERISTICS OF DUAL-HOP DF BASED FSO SYSTEM

The mathematical expressions of CDF, PDF of the DF based dual-hop asymmetric FSO-FSO systems are derived for the following two scenarios, considering only turbulence in the FSO link in the first scenario and combined effect of turbulence, path loss and pointing error in the FSO link in the second scenario.

UNDER ATMOSPHERIC TURBULENCE

When the FSO link experiences Gamma-Gamma distributed turbulence, the statistical characteristics are obtained as follows.

CUMULATIVE DISTRIBUTION FUNCTION(CDF)

Using γ_z = min ($\gamma_{s,r}$, $\gamma_{r,d}$) we can say that the CDF of the equivalent SNR (γ_z) for the considered FSO system is given by,

F(γ_z) (γ) = F$\gamma_{s,r}$ (γ) + F$\gamma_{r,d}$ (γ) - F$\gamma_{s,r}$ (γ)F$\gamma_{r,d}$ (γ)

where F$\gamma_{s,r}$ is the CDF of the instantaneous SNR of the S-R link. Using the relation,

$$\gamma_T=\max\left(\gamma_{rf_i},\gamma_{fso_i}\right)$$

and the CDF of γ_z can be written as,

$$\begin{aligned}F_{\gamma_z}(\gamma)=&1-\left(1-\mathcal{K}_1\gamma\left(m,\frac{m\gamma}{\bar{\gamma}_{s,r}}\right)\right)\\&\times\left(1-\mathcal{K}_2\gamma^{z_1/4}G_{1,3}^{2,1}\left(\mathcal{W}_1\sqrt{\gamma}\middle|\begin{array}{c}1-\frac{z_1}{2}\\ \frac{z_2}{2},-\frac{z_2}{2},-\frac{z_1}{2}\end{array}\right)\right)\end{aligned}$$

where $\gamma(s,x)=\int_0^x t^{s-1}\mathrm{e}^{-t}\,\mathrm{d}t$ represents the lower incomplete Gamma function, $\mathcal{K}_1=1/\Gamma(m)$, $\mathcal{K}_2=(1/\Gamma(a)\Gamma(b))\left(ab/\sqrt{\bar{\gamma}_{r,d}}\right)$ and $\mathcal{W}_1=ab/\sqrt{\bar{\gamma}_{r,d}}$.

PROBABILITY DENSITY FUNCTION(PDF)

The PDF of the equivalent SNR for the DF based dual hop system is given by,

$$f_{\gamma_z}(\gamma)=f_{\gamma_{s,r}}(\gamma)+f_{\gamma_{r,d}}(\gamma)-f_{\gamma_{s,r}}(\gamma)F_{\gamma_{r,d}}(\gamma)-F_{\gamma_{s,r}}(\gamma)f_{\gamma_{r,d}}(\gamma)$$

the PDF can be obtained as,

$$\begin{aligned}f_{\gamma_z}(\gamma)=&\left(\mathcal{K}_1\left(\frac{m}{\bar{\gamma}_{s,r}}\right)^m\gamma^{m-1}\exp\left(\frac{-m\gamma}{\bar{\gamma}_{s,r}}\right)\right)\\&\times\left(1-\mathcal{K}_2\gamma^{z_1/4}G_{1,3}^{2,1}\left(\mathcal{W}_1\sqrt{\gamma}\middle|\begin{array}{c}1-\frac{z_1}{2}\\ \frac{z_2}{2},-\frac{z_2}{2},-\frac{z_1}{2}\end{array}\right)\right)\\&+\left(1-\mathcal{K}_1\gamma\left(m,\frac{m\gamma}{\bar{\gamma}_{s,r}}\right)\right)\left(\mathcal{K}_2\gamma^{(z_1/4)-1}K_{a-b}\left(2\sqrt{\mathcal{W}_1\sqrt{\gamma}}\right)\right)\end{aligned}$$

UNDER THE COMBINED EFFECT OF PATH LOSS, ATMOSPHERIC TURBULENCE AND POINTING ERROR

When the FSO link is characterized by the path loss, Gamma-Gamma distributed turbulence and pointing error, the statistical characteristics are obtained as follows,

$$F_{\gamma_z}(\gamma)=1-\left(1-\mathcal{K}_1\gamma\left(m,\frac{m\gamma}{\bar{\gamma}_{s,r}}\right)\right)\times\left(1-\mathcal{K}_4G_{3,7}^{6,1}\left(\mathcal{W}_4\gamma|_{\mathcal{P}_4,0}^{1,\mathcal{P}_3}\right)\right)$$

where $\mathcal{K}_4=2^{z_1-2}\xi^2/(2\pi\Gamma(a)\Gamma(b))$, $\mathcal{W}_4=(pab)^2/\left(16\gamma_{r,d}\right)$, $\mathcal{P}_3=\left(\xi^2+1\right)/2,\left(\xi^2+2\right)/2$ and $\mathcal{P}_4=\xi^2/2,\left(\xi^2+1\right)/2,a/2,(a+1)/2,b/2,(b+1)/2$.

The PDF can be obtained by,

$$\begin{aligned}f_{\gamma_z}(\gamma)=&\left(\mathcal{K}_1\left(\frac{m}{\bar{\gamma}_{s,r}}\right)^m\gamma^{m-1}\exp\left(\frac{-m\gamma}{\bar{\gamma}_{s,r}}\right)\right)\\&\times\left(1-\mathcal{K}_4G_{3,7}^{6,1}\left(\mathcal{W}_4\gamma\middle|\begin{array}{c}1,\mathcal{P}_3\\ \mathcal{P}_4,0\end{array}\right)\right)\\&+\mathcal{K}_4\gamma^{-1}\left(1-\mathcal{K}_1\gamma\left(m,\frac{m\gamma}{\bar{\gamma}_{s,r}}\right)\right)G_{2,6}^{6,0}\left(\mathcal{W}_4\gamma|_{\mathcal{P}_4}^{\mathcal{P}_3}\right)\end{aligned}$$

PERFORMANCE OF THE DUAL-HOP ASYMMETRIC FSO COOPERATIVE SYSTEM

Outage Probability: Outage probability is defined as the probability at which the equivalent SNR, γ_z, falls below a predetermined threshold value γ_{th}. The outage probability for the DF based dual hop FSO cooperative system under no pointing error can be derived by using as,

$$P_{\text{out}}\left(\gamma_{\text{th}}\right)=1-\left(1-\mathcal{K}_1\gamma\left(m,\frac{m\gamma_{\text{th}}}{\bar{\gamma}_{s,r}}\right)\right)\times\left(1-\mathcal{K}_2\gamma_{\text{th}}^{z_1/4}G_{1,3}^{2,1}\left(\mathcal{W}_1\sqrt{\gamma_{\text{th}}}\,\middle|\,\begin{array}{c}1-\frac{z_1}{2}\\ \frac{z_2}{2},-\frac{z_2}{2},-\frac{z_1}{2}\end{array}\right)\right)$$

Average Bit Error Rate: In this section, the BER of the DF based mixed FSO system is derived for various binary modulation techniques under no pointing errors. *Binary Modulation Techniques*: The average BER for the considered cooperative system is expressed by,

$$P_{e_b}=\frac{y^x}{2\Gamma(x)}\int_0^\infty\gamma^{x-1}\exp(-y\gamma)F_{\gamma_z}(\gamma)\mathrm{d}\gamma$$

where x and y are the BER parameters describing various binary modulation techniques, the mathematical expression for the BER for binary modulation techniques is given by,

$$P_{e_b}=\frac{\mathcal{K}_1}{2\Gamma(x)}G_{2,2}^{1,2}\left(\frac{m}{y\bar{\gamma}_{s,r}}\,\middle|\,\begin{array}{c}1-x,1\\ m,0\end{array}\right)+\sum_{k=0}^{m-1}\frac{y^x\mathcal{K}_3}{2\Gamma(x)}\left(y+\frac{m}{\bar{\gamma}_{s,r}}\right)^{(-z_1/4)-x-k}$$

NUMERICAL RESULTS

In this section, the numerical results for the outage probability and the average BER are discussed for the considered DF based dual hop asymmetric FSO communication system. The FSO link experiences Gamma–Gamma turbulence, characterizing weak to strong turbulence along with path loss and pointing error. We know that almost all the commercially available FSO systems operate in the wavelength range of $0.60\mu\mathrm{m}<\lambda<1.55\mu\mathrm{m}$ and that the attenuation inversely depends on the wavelength. Thus, in our paper, $1.55\mu\mathrm{m}$ wavelength is assumed because it undergoes least smoke and fog attenuation, making it favorable for varied atmospheric conditions. It is assumed that the average SNRs of both the links are equal. Fig. 5 presents the outage performance of the considered system for various fading and turbulence parameters; no and significant $(\xi=1.8)$ pointing error; and γ_{th} is set to 10 dB. It is seen that stronger the effect of fading and turbulence, poorer is the outage performance of the system. Moreover, the degradation in the outage performance increases with the unified effect of turbulence and the pointing error. This can be explained by the fact that in case of significant pointing errors, the total impairment of the FSO link is the product of the impairments caused by the turbulence and the pointing errors. For example, at $\mathrm{SNR}=40$ dB, for $m=4$, $a=4, b=4, \xi=2.3$, the outage probability is $P_{\text{out}}=6.308\times10^{-4}$ which increases to $P_{\text{out}}=2.08\times10^{-2}$ and 1.921×10^{-1} for $m=2$, $a=4.2$, $b=1.4$, $\xi=2.3$ and $m=3$, $a=2$, $b=0.5$, $\xi=2.3$, respectively. An interesting observation is made here that the for moderate turbulence scenario, the effect of pointing error is quite significant. However, under severe turbulence case, the effect of pointing error is negligible as the system is already in highly degraded state. In Fig. 3, the average BER against the average SNR plots are analyzed for various modulation techniques, that is, CBPSK, CBFSK, NBFSK and DBPSK with fixed fading statistics and pointing error parameter, $a=4.2, b=1.4$ and $\xi=1.3$. From Fig. 3, it can be observed that CBPSK outperforms the other modulation techniques because it is the most power-efficient modulation technique. Coherent techniques perform better than their corresponding non-coherent techniques because they have the knowledge of the phase of the carrier at the receiver which can be exploited to recover the message signal correctly. Fig. 4 presents the average BER performance of the asymmetric FSO system using CBFSK modulation technique, for different values of fading statistics but fixed pointing error parameter $\xi=1.2$. It can be seen from the figure that severe the effect of fading and turbulence more is the degradation in the BER performance of the system. For example, at $\mathrm{SNR}=40$ dB and $\xi=1.2$, for $a=4, b=1.9$, the BER is $P_e=1.856\times10^{-3}$ and it increases to $P_e=3.598\times10^{-3}$ and $P_e=1.177\times10^{-2}$, for $a=4.2, b=1.4$ and $a=2, b=1$, respectively. It can also be seen that the FSO link acts as the dominant link among both of them, as the BER under the strong fading and moderate turbulence is less than the BER under moderate fading and strong turbulence. Similar to Fig. 5. it is observed that the impact of pointing error increases as the severity in the turbulence decreases. In Fig. 5, the average BER against average SNR plots are analyzed under CBPSK and for various values of pointing error parameter, that is, $\xi=1.1,1.3,1.5,1.9$. The fading parameters are fixed to $a=4, b=4$. From the figure, it can be noted that stronger the effect of pointing errors, that is, smaller the value of pointing error parameter ξ, higher is the average BER. This behavior can be easily understood from the definition of ξ which explains that higher the pointing error displacement standard deviation at the destination, lower is the value of ξ and degraded is the average BER performance of the system. For example, at $\mathrm{SNR}=40$ dB, the BER, $P_e=1.84\times10^{-6}$, $5.346\times10^{-6}, 4.113\times10^{-5}$ and 1.079×10^{-3} for no pointing error scenario, $\xi=1.9,1.5$ and 1.1 , respectively. It can be observed from Figs. 2 and 4, that the simulation results for the outage probability and the average BER of the asymmetric FSO system match well with their corresponding analytical results. Moreover, it requires only 200 terms in case of turbulence only scenario and 250 terms in case of unified effect scenario, for the analytical results of the capacity of the considered system to match well with the simulated capacity.

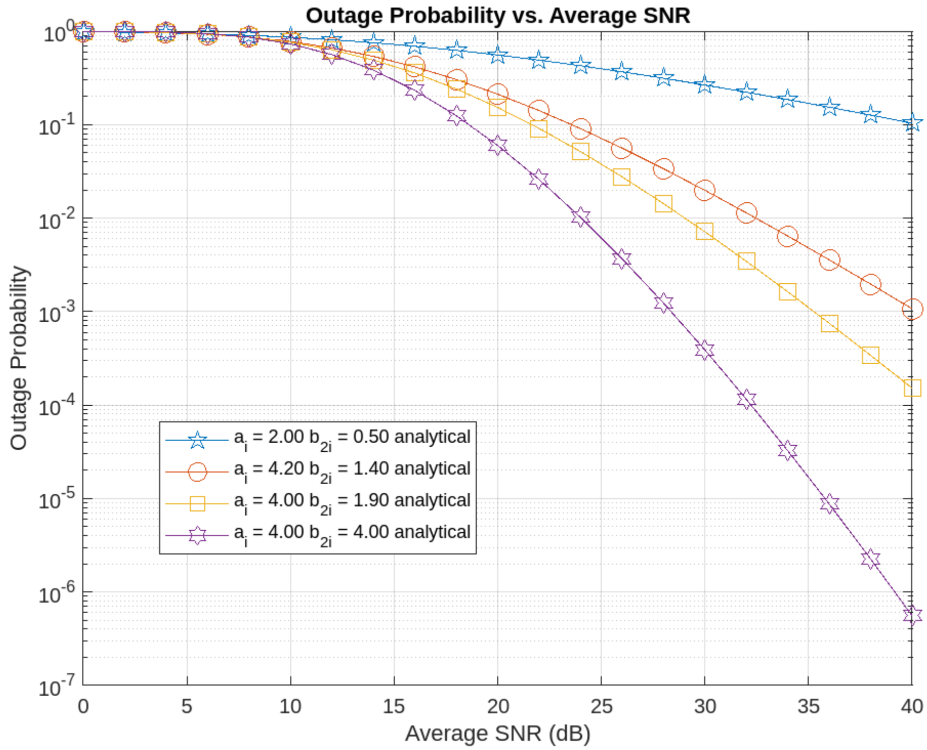

Fig. 2. Outage probability against average SNR per hop for different values of fading and turbulence parameters, and $\xi = 2.3$

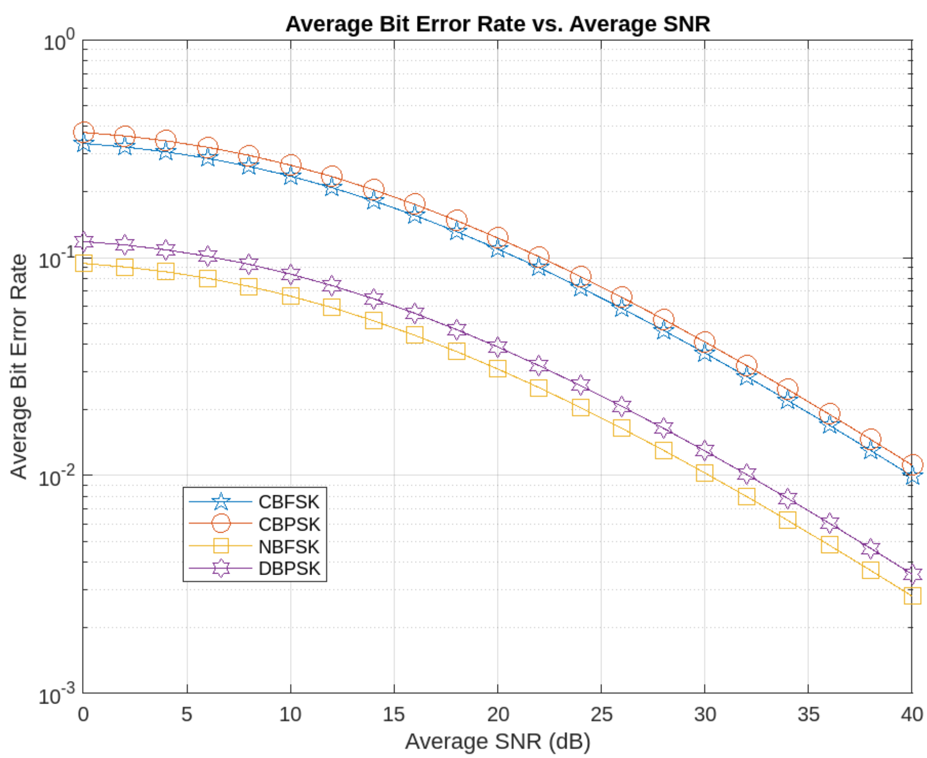

Fig. 3. Average BER against average SNR per hop for different modulation techniques, when $m = 4, a = 4.2, b = 1.4, \xi = 1.3$

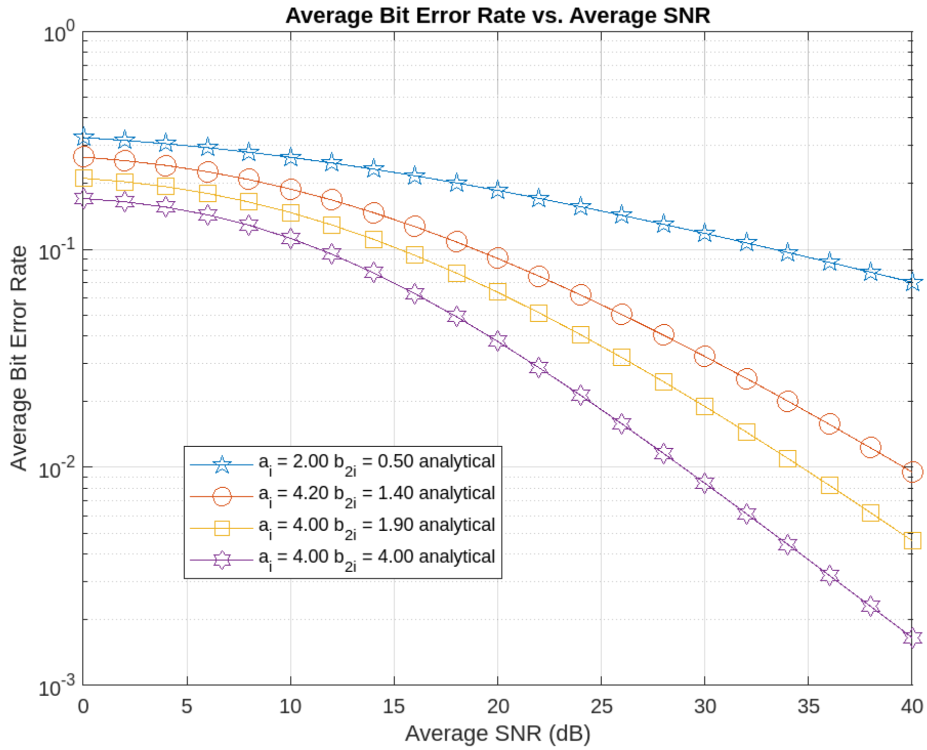

Fig. 4. Average BER against average SNR per hop for different fading and turbulence conditions in case of CBFSK with $\xi = 1.2$

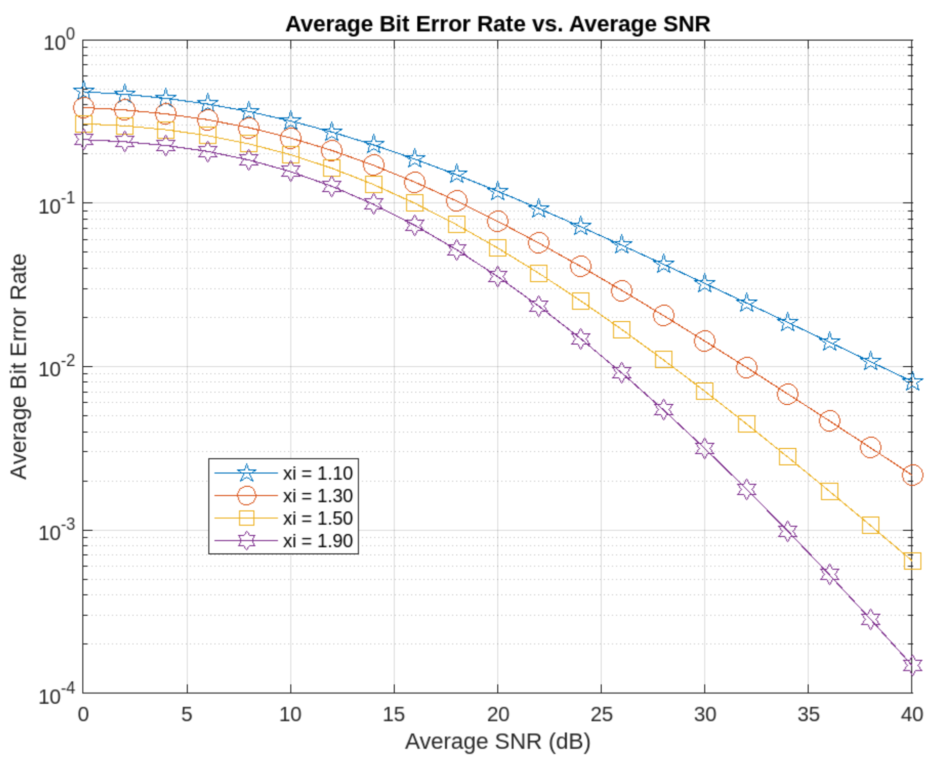

Fig. 5. Average BER against average SNR per hop for different values of pointing error parameter ξ, in case of CBPSK and $a = 4$ and $b = 4$

CONCLUSION

In conclusion, this presents a comprehensive analysis of a dual-hop mixed FSO cooperative communication system assisted by High Altitude Platform Stations (HAPS). The study contributes to the understanding of system performance and optimization in two main aspects.

Firstly, mathematical expressions have been derived to characterize the statistical properties of the equivalent signal-to-noise ratio (SNR) in the considered DF-based dual-hop FSO system. These expressions enable the calculation of outage probability, Bit Error Rate (BER), and average capacity, considering the impact of fading, turbulence, and pointing errors on system performance. The analysis reveals that pointing error has a dominant effect under moderate turbulence, while the FSO link acts as the dominant link in the FSO system, particularly evident in BER plots.

Secondly, the study focuses on the role of HAPS in improving connectivity services in terrestrial networks. The proposed dual-hop hybrid FSO communication network, with HAPS operating in DF mode, is analyzed for OP and BER performance. Optimal power allocation schemes are investigated, considering factors such as fading parameters, turbulence conditions, HAPS position fluctuation, and transmitter beam width. Simulation results validate the accuracy of the analytical findings, indicating significant SNR improvement with the derived optimal power allocation scheme.

Overall, the study underscores the importance of HAPS-assisted communication systems in enhancing network coverage and performance. By integrating HAPS with terrestrial networks and leveraging hybrid FSO communication, the proposed approach offers insights into system design, optimization, and resilience against environmental challenges. These findings contribute to the advancement of optical-wireless communication systems, paving the way for future integrated aerial-terrestrial networks and improved connectivity services.

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