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Performance Analysis of HAPS-Based Relaying for Hybrid FSO/RF Downlink Satellite Communication

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Abstract—Free space optics (FSO) communication has garnered significant importance to provide gigabit capacity links owing to its unique features. However, its performance is limited by the adverse effects of transmission medium such as atmospheric turbulence induced fading, wind, etc. Therefore, it is wise to backup with reliable radio frequency (RF) links to improve the performance of FSO communication. The fusion of FSO and RF technologies is a suitable candidate for future satellite communication (SATCOM) systems. In this context, the present paper proposes a novel system model for High-Altitude Pseudo-Satellite (HAPS)-based relaying for downlink scenario utilizing both FSO and RF links. The performance of the proposed hybrid FSO/RF SATCOM system is investigated through average and asymptotic symbol error probability (SEP) analyses. Further, the obtained closed-form expressions for average SEP are validated using Monte-Carlo simulation results.

Index Terms—Free space optics, high-altitude pseudo-satellite, hybrid FSO/RF, performance analysis, and satellite communication.

I. INTRODUCTION

High-Altitude Platform Station or High-Altitude Pseudo-Satellite (HAPS) is an aerial vehicle situated well above the clouds at typical heights of 17 to 25 km, where the atmospheric impact on an optical beam is less severe than directly above ground. The main advantages of HAPS are easier and faster deployment than satellite, medium operational costs, easy maintenance, etc. [1]. HAPS can act as a relay station between satellite and ground station (GS) and improve the performance of the satellite-to-GS and GS-to-satellite communication links. Currently, most of the satellite communication (SATCOM) systems are based on radio frequency (RF) links, where the data rate is limited to a few hundred megabits per second (Mbps). In recent years, a growing interest is witnessed in the research and development of establishing free space optics (FSO) links between GS and satellite, which can offer much larger data rates even up to terabits per second [2].

It is to be noted that FSO supports high data rate only for short-range transmission and thus the performance of GS-to-satellite FSO link is limited by the adverse effects of the atmospheric turbulence induced fading. FSO system uses the concept of relaying technique to counteract atmospheric turbulence, thereby achieving some improvement in the system performance [3]-[4]. By deploying HAPS as a relay terminal, the satellite-to-GS downlink is split into two parts: (i) satellite-to-HAPS and (ii) HAPS-to-GS. Among the two links, HAPS-to-GS link is more sensitive to atmospheric turbulence and

hence, it is mandatory to backup high capacity FSO link with a reliable RF link to establish a seamless hybrid FSO/RF communication. HAPS are located in a cloud-free atmospheric altitude and reliability is not a major concern for satellite-to-HAPS link. Thus, we can restrict satellite-to-HAPS link to FSO communication alone as shown in Fig. 1

In prior works, the performance of dual-hop (DH) relay-assisted FSO and hybrid FSO/RF communication was investigated in [3] and [4] for terrestrial communication, respectively. In [5], performance analysis of a hybrid satellite-terrestrial FSO cooperative link was carried out using satellite RF link and terrestrial FSO link. However, only very few works are available in SATCOM scenario considering single-hop (SH) FSO communication between satellite and GS. In [2], performance analysis of FSO-based downlink SATCOM system with spatial diversity was carried out over Gamma-Gamma turbulence induced fading channels. However, closed-form expressions were obtained only for outage probability but not for average bit error rate (BER). Moreover, in [6], BER evaluation of various modulation schemes was performed for SH FSO-based uplink and downlink SATCOM systems. Thus, DH HAPS-based SATCOM system considering both FSO and RF links to counteract atmospheric channel distortions has not been proposed and its performance has not been investigated in the literature to the best of our knowledge.

The major contributions of our work are as follows:

- A novel system model for decode-and-forward (DF) relaying scenario using HAPS utilizing both FSO and RF links is proposed for downlink SATCOM system.
- End-to-end average symbol error probability (SEP) analysis of the DH hybrid system is carried out with Gamma-Gamma turbulence induced fading for FSO communication and Rician fading for RF communication.
- Average and asymptotic SEP expressions to evaluate the diversity order of the proposed system are derived in closed-form and the derived expressions are validated using Monte-Carlo simulation results.

It is to be noted that the effect of beam wander induced pointing errors is negligible in case of downlink signals from satellite, as the beam size when reaches the atmosphere is much larger than the turbulent eddy size [7]. Thus, we have neglected the effect of pointing errors in our analysis.

Fig. 1. Dual-hop relaying using high altitude platform station

II. SYSTEM AND CHANNEL MODELS

We consider a SATCOM system comprising of a GS, a HAPS-based relay node, and a low-earth orbit (LEO) satellite as shown in Fig. 1. Both FSO and RF transmission are considered over HAPS-to-GS link with higher priority to FSO link and only FSO transmission is considered over LEO-satellite-to-HAPS link. An erroneous DF-relaying-based SATCOM system, where HAPS-based relay node forwards the information to GS irrespective of decoding errors, is assumed in our work. It is to be noted that in the downlink scenario, LEO satellite and GS will act as a source (S) node and a destination (D) node, respectively, and HAPS will act as a relay (R) node. The atmospheric turbulence induced fading over S-R and R-D FSO links, which are denoted as I_{SR} and I_{RD} , respectively, are modeled using Gamma-Gamma distribution. Moreover, the flat fading channel gain over R-D link is denoted as h_{RD} and the norm of the flat fading channel gain is modeled using Rician distribution. It is assumed that there exist a strong line-of-sight (LOS) RF component with weak scattered components between GS and HAPS.

The proposed system model adopts two-phase orthogonal transmission. In case of downlink scenario, S (i.e. LEO satellite) transmits the information signal to R (i.e. HAPS) over FSO link during the first phase. During the second or orthogonal phase transmission, R transmits the decoded information signal to D (i.e. GS) over FSO or RF link depending on the channel conditions. If the instantaneous signal-to-noise ratio (SNR) of FSO link at D, which is denoted as γ_{RD}^f , where f denotes FSO transmission, is above a particular threshold value γ_t , then FSO link will be used for transmission. However, if γ_{RD}^f drops below γ_t , then the receiver sends a 1-bit feedback signal to activate the RF sub-system and the information signal will be transmitted over RF link. Meanwhile, the FSO sub-system will be put on a standby mode. As the FSO channel varies on the order of millions of symbol intervals [8], it is not required to monitor the SNR of FSO link at regular intervals unlike RF system to send the feedback signal. In addition, sub-carrier intensity modulation based M -ary phase-shift-keying (SIM-MPSK) scheme is assumed for FSO subsystem and MPSK scheme for RF subsystem. The instantaneous SNR expression for FSO link is given by $\gamma_{ii}^f = \Gamma_{ii}^f I_{ii}^2$, where

$ii \in \{SR, RD\}$ and Γ_{ii}^f is the average SNR of FSO link. Similarly, the instantaneous SNR expression for RF link is given by $\gamma_{RD}^r = \Gamma_{RD}^r |h_{RD}|^2$, where Γ_{RD}^r is the average SNR of RF link.

The atmospheric turbulence-induced fading I_{ii} in case of FSO link is modeled using Gamma-Gamma (GG) distribution [4, eq.(1)], which is used to characterize moderate to strong atmospheric turbulence condition. The probability density function (PDF) of the instantaneous SNR of FSO links can be obtained from GG distribution using the power transformation of random variable. The resultant PDF expression can be written in terms of Meijer G-function $G_{m,n}^{p,q}(\cdot)$ using [9, eq.07.34.03.0605.01] and is given by

$$f_{\gamma_{ii}^f}(\gamma_{ii}) = \mathcal{A}_1^{ii} (\gamma_{ii})^{-1} G_{0,2}^{2,0} \left(D_{ii} (\gamma_{ii})^{\frac{1}{2}} \mid \begin{matrix} - \\ \alpha_{ii}, \beta_{ii} \end{matrix} \right), \quad (1)$$

where $\mathcal{A}_1^{ii} = \frac{1}{2\Gamma(\alpha_{ii})\Gamma(\beta_{ii})}$, $D_{ii} = \frac{\alpha_{ii}\beta_{ii}}{\sqrt{\Gamma_{ii}^f}}$, $\Gamma(\cdot)$ is the gamma function, α_{ii} and β_{ii} are the small scale and large scale turbulence parameters of the scattering environment, respectively. The expressions to calculate α_{ii} and β_{ii} for SATCOM links are different from that of terrestrial links and are given in [6] and [7]. It is observed that the turbulence parameters of HAPS-to-GS link (i.e. α_{RD} and β_{RD}) depend on Rytov variance [6], [7] for the slant optical path from HAPS to GS, wave number k_1 , zenith angle θ_p , GS aperture height H_0 , HAPS altitude H_p , wind velocity w , and turbulence strength C_n^2 . Similarly, the turbulence parameters of satellite-to-HAPS link depend on Rytov variance parameter from LEO satellite to HAPS, k_1 , θ_p , H_p , C_n^2 , and LEO satellite altitude H_s . The cumulative distribution function (CDF) of γ_{ii}^f is given by

$$F_{\gamma_{ii}^f}(\gamma_{ii}) = \mathcal{A}_2^{ii} G_{1,5}^{4,1} \left(\frac{D_{ii}^2 \gamma_{ii}}{16} \mid \begin{matrix} 1 \\ \mathcal{E}_{ii} \end{matrix} \right), \quad (2)$$

where $\mathcal{A}_2^{ii} = \frac{2^{\alpha_{ii}+\beta_{ii}-2}}{\pi\Gamma(\alpha_{ii})\Gamma(\beta_{ii})}$ and $\mathcal{E}_{ii} = \left\{ \frac{\alpha_{ii}}{2}, \frac{\alpha_{ii}+1}{2}, \frac{\beta_{ii}}{2}, \frac{\beta_{ii}+1}{2}, 0 \right\}$.

The small scale fading of RF channel is modeled using Rician distribution [10, eq.(2.16)]. Applying the power transformation of random variable on the PDF of Rician distribution, we obtain the PDF of instantaneous SNR of RF link, which is given by

$$f_{\gamma_{RD}^r}(\gamma_{RD}^r) = \frac{K+1}{\Gamma_{RD}^r} \exp \left(-K - (K+1) \frac{\gamma_{RD}^r}{\Gamma_{RD}^r} \right) \times \left\{ I_0 \left(2 \sqrt{K(K+1) \frac{\gamma_{RD}^r}{\Gamma_{RD}^r}} \right) \right\}, \quad (3)$$

where $I_0(\cdot)$ indicates zeroth order modified Bessel function of the first kind and K denotes the shape (Rice) parameter, which is the ratio of the power in the direct path to the power in other scattered paths.

III. PERFORMANCE ANALYSIS

The conditional SEP of MPSK signaling conditioned on the instantaneous SNR of a given link is given by [4, eq.(14)]

$$p(e/\gamma_{ii}) = \frac{A}{2} \operatorname{erfc}(\sqrt{\gamma_{ii}}B), \quad (4)$$

where $A=1$ when modulation order $M=2$ i.e. binary phase-shift keying (BPSK), $A=2$ when $M > 2$, $B = \sin(\pi/M)$, and $\text{erfc}(\cdot)$ denotes the complementary error function. Using the relation between $\text{erfc}(\cdot)$ and Meijer G-function [9, eq.(07.34.03.0619.01)], the conditional SEP can also be written in terms of Meijer G-function and is given by

$$p(e/\gamma_{ii}) = \frac{A}{2\sqrt{\pi}} G_{1,2}^{2,0} \left(B^2 \gamma_{ii} \mid \begin{matrix} 1 \\ \alpha, \beta \end{matrix} \right). \quad (5)$$

The conditional SEP can also be expressed in terms of Maclaurin series expansion [11, eq.(3.321)] and is given by

$$p(e/\gamma_{ii}) = \frac{A}{2} \left\{ 1 - \frac{2}{\sqrt{\pi}} \sum_{k=0}^{\infty} \frac{(-1)^k (\gamma_{ii})^{\frac{2k+1}{2}} B^{2k+1}}{k!(2k+1)} \right\}. \quad (6)$$

The conditional SEP of S-R-D link considering M -ary signalling during downlink can be written as

$$P_{eSRD}(\gamma_{SR}, \gamma_{RD}) = P_e(\gamma_{SR}) + P_e(\gamma_{RD}) - P_e(\gamma_{SR})P_e(\gamma_{RD}). \quad (7)$$

After averaging (7) over the PDFs of the instantaneous SNR values of FSO and RF links, the average SEP is given by

$$P_{eSRD}(\Gamma_{SR}, \Gamma_{RD}) = P_e(\Gamma_{SR}) + P_e(\Gamma_{RD}) - P_e(\Gamma_{SR})P_e(\Gamma_{RD}). \quad (8)$$

Note that $P_e(\Gamma_{RD})$ in (8) is the average SEP of hybrid FSO/RF link and the same can be written as

$$P_e(\Gamma_{RD}) = B_f(\gamma_t) + P_f^{out} B_r, \quad (9)$$

where $B_f(\gamma_t)$ denotes the average SEP of FSO link when $\gamma_{RD}^f > \gamma_t$, P_f^{out} indicates the outage probability of FSO link, and B_r denotes the average SEP of RF link. Now $B_f(\gamma_t)$ can be derived as follows:

$$B_f(\gamma_t) = \underbrace{\int_0^{\infty} p(e/\gamma_{RD}) f_{\gamma_{RD}^f}(\gamma_{RD}) d\gamma_{RD}}_{I_1} - \underbrace{\int_0^{\gamma_t} p(e/\gamma_{RD}) f_{\gamma_{RD}^f}(\gamma_{RD}) d\gamma_{RD}}_{I_2(\gamma_t)} \quad (10)$$

Now (10) is divided into two terms I_1 and $I_2(\gamma_t)$. After substituting (1) and (5) in I_1 and simplifying the resultant expression using [9, eq.(07.34.21.0013.01)], the final expression in closed-form is given by

$$I_1 = A A_2^{RD} G_{2,5}^{4,2} \left(\left\{ \frac{D_{RD}}{4B} \right\}^2 \mid \begin{matrix} 1, 1/2 \\ \mathcal{E}_{RD} \end{matrix} \right), \quad (11)$$

In (10), the expression for $I_2(\gamma_t)$ can be derived as follows: After substituting (1) and (6) in $I_2(\gamma_t)$, the final expression can be obtained by simplifying using [9, eq.(07.34.21.0084.01)] and is given by

$$I_2(\gamma_t) = \frac{A A_2^{RD}}{2} \left[G_{1,5}^{4,1} \left(\left\{ \frac{D_{RD}^2}{16} \right\} \mid \begin{matrix} 1 \\ \mathcal{E}_{RD} \end{matrix} \right) - \frac{2}{\sqrt{\pi}} \sum_{k=0}^{\infty} \frac{(-1)^k B^{2k+1}}{k! 2k+1} G_{1,5}^{4,1} \left(\left\{ \frac{D_{RD}^2 \gamma_t}{16} \right\} \mid \begin{matrix} 1 - (k+0.5) \\ B_2 \end{matrix} \right) \right], \quad (12)$$

where $B_2 = \left\{ \frac{\alpha_{RD}}{2}, \frac{\alpha_{RD}+1}{2}, \frac{\beta_{RD}}{2}, \frac{\beta_{RD}+1}{2}, -(k+0.5) \right\}$.

The outage probability of FSO subsystem over R-D link can be obtained from (2) and is given by $P_f^{out} = F_{\gamma_{RD}^f}(\gamma_{RD})$.

The average SEP of RF link is given by

$$B_r = \int_0^{\infty} p(e/\gamma_{RD}) f_{\gamma_{RD}}(\gamma_{RD}) d\gamma_{RD}. \quad (13)$$

After substituting (3) and (4) in (13), $I_0(\cdot)$ in (3) is expanded in terms of infinite series [11, eq.(8.445)] and then using integration by parts, the integral in (13) is simplified to obtain the final expression as

$$B_r = \sum_{n=0}^{\infty} \frac{A(K+1)e^{-K}(K(K+1))^n}{2(\Gamma_{RD}^r)^{n+1}(n!)^2} \left[\frac{\Gamma(n+1)}{C^{n+1}} - \frac{Bn!}{\sqrt{\pi}} \times \sum_{m=0}^n \frac{\Gamma(m+0.5)}{m! C^{n+1-m}(B^2+C)^{m+0.5}} \right], \quad (14)$$

where $C = \frac{K+1}{\Gamma_{RD}^r}$. Since FSO transmission is taking place over S-R link, the average SEP expression can be written as

$$P_e(\Gamma_{SR}) = \int_0^{\infty} p(e/\gamma_{SR}) f_{\gamma_{SR}^f}(\gamma_{SR}) d\gamma_{SR}. \quad (15)$$

After substituting (1) and (5) in (15), the final expression is obtained from (11) by replacing $\mathcal{A}_2^{RD}$, D_{RD} and $\mathcal{E}_{RD}$ with $\mathcal{A}_2^{SR}$, D_{SR} and $\mathcal{E}_{SR}$, respectively. Finally, the average SEP expression, which is given by $P_{eSRD}(\Gamma_{SR}, \Gamma_{RD})$, is obtained in closed-form by substituting (9) and (15) in (8).

The asymptotic expression is also derived in closed-form to obtain the diversity gain of the proposed system. Using [9, eq.(07.34.06.0040.01)], the asymptotic expression for $P_e(\Gamma_{SR})$ when $\Gamma_{SR}^f \rightarrow \infty$ is obtained and the same is given by

$$P_e^a(\Gamma_{SR}) = \frac{A A_2^{SR}}{2\sqrt{\pi}} \sum_{l=1}^4 \prod_{\substack{j=1 \\ j \neq l}}^4 \Gamma(b_j - b_l) \times \frac{\prod_{j=1}^2 \Gamma(1 - a_j + b_l)}{\Gamma(1 - b_5 + b_l)} \left(\frac{D_{SR}}{4B} \right)^{2b_l}, \quad (16)$$

where $a_1 = 1, a_2 = 2, b_1 = \frac{\alpha_{SR}}{2}, b_2 = \frac{\alpha_{SR}+1}{2}, b_3 = \frac{\beta_{SR}}{2}, b_4 = \frac{\beta_{SR}+1}{2}$, and $b_5 = 0$. Similarly, the asymptotic expression for $P_e(\Gamma_{RD})$ when $\Gamma_{RD}^f \rightarrow \infty$ is given by

$$P_e^a(\Gamma_{RD}) = B_f^a(\gamma_t) + P_f^{out/asy} B_r, \quad (17)$$

Using [9, eq.(07.34.06.0040.01)], the expression for $B_f^a(\gamma_t)$ is obtained as follows:

$$B_f^a(\gamma_t) = I_1^a + I_2^a(\gamma_t), \quad (18)$$

where I_1^a is given by (16) by replacing $\mathcal{A}_2^{SR}$, α_{SR} , β_{SR} , D_{SR} , and Γ_{SR}^f with $\mathcal{A}_2^{RD}$, α_{RD} , β_{RD} , D_{RD} , and Γ_{RD}^f , respectively.

TABLE I
SIMULATION PARAMETERS

Wave number k_1	1550 nm
HAPS altitude H_p	20 Km
LEO satellite altitude H_s	620 Km
GS aperture height H_0	1 m
Shape (Rice) parameter K	(a) 3 (b) 5
Zenith angle θ_p	(a) 80° (b) 50° (c) 40°
Wind velocity w	(a) 31 m/s (b) 21 m/s (c) 11 m/s

Now $I_2^a(\gamma_t)$ can be written as

$$I_2^a(\gamma_t) = \frac{A}{4\sqrt{\pi}\Gamma(\alpha_{RD})\Gamma(\beta_{RD})} \left\{ \Gamma(\beta_{RD} - \alpha_{RD}) D_{RD}^{\alpha_{RD}} \gamma_t^{\frac{\alpha_{RD}}{2}} G_{2,3}^{3,0} \left(B^2 \gamma_t \mid \begin{matrix} 1, 1 - \frac{\alpha_{RD}}{2} \\ -\frac{\alpha_{RD}}{2}, 0, \frac{1}{2} \end{matrix} \right) + \Gamma(\alpha_{RD} - \beta_{RD}) D_{RD}^{\beta_{RD}} \gamma_t^{\frac{\beta_{RD}}{2}} G_{2,3}^{3,0} \left(B^2 \gamma_t \mid \begin{matrix} 1, 1 - \frac{\beta_{RD}}{2} \\ -\frac{\beta_{RD}}{2}, 0, \frac{1}{2} \end{matrix} \right) \right\}. \quad (19)$$

The asymptotic expression for $P_f^{out/asy}$ is given by

$$P_f^{out/asy} = \mathcal{A}_2^{RD} \sum_{l=1}^4 \frac{\prod_{j=1}^4 \Gamma(b_j - b_l) \Gamma(1 - a_1 + b_l) (V \gamma_t)^{b_l}}{1 - b_5 + b_l}, \quad (20)$$

where $V = \frac{\alpha_{RD} \beta_{RD}}{16 \Gamma_{RD}^f}$. Therefore, the end-to-end asymptotic expression for S-R-D link from (16) and (17) is given by

$$P_{eSRD}^a(\Gamma_{SR}, \Gamma_{RD}) = P_e^a(\Gamma_{SR}) + P_e^a(\Gamma_{RD}) - P_e^a(\Gamma_{SR}) P_e^a(\Gamma_{RD}). \quad (21)$$

From the derived expression, it is observed that $P_{eSRD}^a(\Gamma_{SR}, \Gamma_{RD}) \propto (\Gamma_{RD}^f)^{-v_{RD}}$, where $v_{RD} = \min\left(\frac{\alpha_{RD}}{2}, \frac{\beta_{RD}}{2}\right)$. Thus, the diversity gain G of the proposed system is given by $G = v_{RD}$.

IV. NUMERICAL RESULTS AND DISCUSSIONS

The parameters assumed in our simulation studies are shown in Table I. For simplicity, we assume $\Gamma_{SR}^f = \Gamma_{RD}^f$ and $\theta_p = \theta_S = \theta_H$, where θ_S and θ_H are the zenith angles that indicate the angle between the zenith and the propagation orientation from satellite-to-HAPS and HAPS-to-GS links, respectively. The summation limits in (12) and (14) are truncated to $k = 50$ and $n = 10$, as $k > 50$ and $n > 10$ do not have an impact on the fifth decimal figure of the average SEP values. In Fig. 2, the average SEP performance comparison of SH FSO system, DH FSO system, and DH hybrid FSO/RF system with respect to average SNR of FSO links is shown assuming zenith angle $\theta_p = 80^\circ$, wind velocity $w = 21$ m/s, shape (Rice) parameter $K = 5$, and $\gamma_t = \gamma_t^{opt}$, where γ_t^{opt} denotes the optimum threshold SNR value. It is observed from the plots that the theoretical SEP values exactly match with the SEP values obtained from Monte-Carlo simulations. The performance of hybrid FSO/RF system is shown for different values of modulation order M and average SNR of RF links Γ_{RD}^r . It is noticed that the SEP performance degrades with increase in M as expected. Further, the performance of hybrid FSO/RF system improves with increase in Γ_{RD}^r from 5 dB to

Fig. 2. SEP performance comparison of SH FSO, DH FSO, and proposed DH HAPS-based hybrid FSO/RF systems

Fig. 3. SEP performance of HAPS-based hybrid FSO/RF system for different zenith angle values

10 dB. Most importantly, it is inferred that the hybrid FSO/RF system performs better than the SH FSO and DH FSO systems with a coding gain of around 10 dB at an SEP value of 10^{-2} for the case when $\Gamma_{RD}^r = 5$ dB.

In Fig. 3, the SEP performance of DH hybrid FSO/RF system is shown for different values of zenith angle θ_p assuming $\Gamma_{RD}^r = 10$ dB, $w = 21$ m/s, $\gamma_t = \gamma_t^{opt}$, and $K = 5$. It is observed from the performance that decrease in the zenith angle improves the SEP performance. Note that with decrease in zenith angle, the Rytov variance decreases and the small and large scale turbulence parameters increases. Since the diversity order depends on the turbulence parameters, the performance improves with decrease in zenith angle. However, the coding gain of DH hybrid FSO/RF system compared to DH FSO system deteriorates with decrease in zenith angle. As shown in Fig. 2, coding gain value of 10 dB is obtained compared to DH FSO system. But the SEP performances of FSO and hybrid FSO/RF systems are almost equal for $\theta_p = 50^\circ$ as shown in Fig. 3. It is also noticed in the figure that the asymptotic SEP performance matches with the exact SEP performance in the

Fig. 4. SEP performance of HAPS-based hybrid FSO/RF system for different values of wind velocity and shape parameter

Fig. 5. Average SEP versus threshold SNR for different values of average SNR of RF link

high-SNR region, which validates the fact that the diversity order of the proposed system is $\min\left(\frac{\alpha_{RD}}{2}, \frac{\beta_{RD}}{2}\right)$.

In Fig. 4, the SEP performances of the DH FSO and hybrid FSO/RF systems are compared for different values of w and K assuming $\Gamma_{RD}^r = 5$ dB, $\theta_p = 80^\circ$, $\gamma_t = \gamma_t^{opt}$, and $M = 2$. It is inferred from the figure that the SEP performance improves with increase in the value of K . This is due to the fact that increase in K results in increase in the power of the direct path compared to scattered paths. It is also observed that increase in wind velocity w deteriorates the performance of both FSO and hybrid FSO/RF systems. Most importantly, it is inferred from the performance curves that the wind velocity impacts the performance of FSO system to a larger extent compared to hybrid FSO/RF system. Thus, the impact of wind velocity on the system performance has been reduced by using reliable RF link as a backup to FSO link.

In Fig. 5, the average SEP of hybrid FSO/RF system is plotted against the threshold SNR γ_t for different values of average SNR of RF links Γ_{RD}^r assuming $K = 5$, $w = 21$ m/s, $\theta_p = 80^\circ$, and $M = 4$. From the plots, it is inferred that

the SEP reaches minimum at $\gamma_t = [0 \ 4 \ 8 \ 10 \ 10 \ 12]$ dB for $\Gamma_{RD}^r = [0 \ 5 \ 10 \ 15 \ 20 \ 25]$ dB. The corresponding γ_t values for which the average SEP performance curves reach minimum are called optimum threshold SNR values γ_t^{opt} and they remain same irrespective of the average SNR of FSO links. The average SEP increases with increase in γ_t above γ_t^{opt} due to frequent usage of FSO link compared to RF link. This will lead to degradation in the performance, as FSO link is more prone to atmospheric channel distortions.

V. CONCLUSIONS

We proposed a novel system model for downlink SATCOM using HAPS-based relay station with hybrid FSO/RF links and derived the exact expression for the average SEP in closed-form assuming Gamma-Gamma and Rician distributions for FSO and RF links, respectively. In addition, closed-form asymptotic expression with less computational complexity was also derived and the diversity gain was obtained. From the performance plots, we inferred that the DH hybrid FSO/RF system achieves a coding gain of about 10 dB at the SEP value of 10^{-2} compared to DH and SH FSO systems for zenith angle $\theta_p = 80^\circ$. However, when θ_p decreases, the coding gain deteriorates. Most importantly, we also identified that the impact of wind velocity on the system performance has been drastically reduced due to reliable RF links.

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