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Switching-Based Cooperative Decode-and-Forward Relaying for Hybrid FSO/RF Networks

Shubha Sharma, AS Madhukumar, and Swaminathan R

Abstract—In this paper, we propose a novel switching scheme for hybrid free-space optical (FSO)/radio frequency (RF) system with selective decode-and-forward (DF) relay network. Specifically, the system transmits over FSO channels when the instantaneous signal-to-noise ratio (SNR) at the FSO receiver is greater than the threshold SNR. If the SNR drops below the threshold, the system switches its transmission over RF channels. The exact outage probability and average symbol error rate (SER) expressions are derived for selective DF relay network with maximal ratio combining (MRC) assumed at the destination. In addition, the asymptotic outage and SER expressions with lower computational complexity are derived and the diversity order is determined. The optimum value of threshold SNR, which satisfies target SER, has been calculated numerically for the proposed switching scheme. The theoretical results, which are validated by Monte-carlo simulations, show that the proposed switching scheme for cooperative hybrid FSO/RF system drastically improves the performance compared to that of single hop (SH) switching-based hybrid FSO/RF and cooperative FSO systems.

Index Terms—Gamma-Gamma distribution, hybrid FSO/RF, maximal ratio combining, switching scheme.

I. INTRODUCTION

FREE space optics (FSO) and millimeter wave (MMW) RF transmissions support high data rate (up to GBPS) for short range transmission up to few kilometers [1]. However, the FSO link is highly susceptible to atmospheric effects like pressure and temperature, which cause atmospheric turbulence along the propagation path [1]. These factors lead to variation in laser beam strength at the receiver that affects the link range and the system reliability [1]. The major challenge for FSO link is the attenuation due to fog but it is not affected by O_2 absorption and rain. However, MMW RF link is not affected by fog but is affected by O_2 absorption and rain [2], [3]. Thus, both FSO and MMW RF exhibit complementary characteristics. In this perspective, the combination of FSO and MMW RF is considered as a powerful candidate for high data rate reliable communication for wireless back-haul networks [3], [4].

In hybrid FSO/RF systems, to guarantee reliability, various schemes are proposed in the literature, which can be divided into three categories. The first category is simultaneous or parallel transmission, where both FSO and RF link transmit identical information at the cost of reduced data rate of the FSO links [3], [5]. It is important to note that this leads to wastage of power and unnecessary interference. The second category is hard switching, where either the FSO or RF link is selected based on the channel conditions [6]–[9]. A

feedback signal is required from the destination to the source. Though this scheme provides an efficient transmission and higher data rate compared to simultaneous transmission, this method is more complex than the simultaneous transmission. And the third category is soft switching, which is the most complex scheme, where joint coding is done for FSO and RF links based on the channel conditions [4], [10]. Among the mentioned schemes, hard switching scheme offers a trade-off among reliability, data rate and system complexity. It is important to note that the aforementioned schemes are restricted to a single-hop (SH) system.

Fig. 1. System Architecture

It is to be noted that FSO and MMW RF transmissions are confined to short distances [6]–[9]. Consequently for a backhaul network, a distributed architecture is required, where the back-haul traffic is relayed from the small cell base station (BS) to adjacent BS and then finally forwarded to the macro-cell BS as shown in Fig.1. Mixed RF-FSO relaying systems have been extensively discussed in literature, where FSO transmission is mostly used as a last mile access link. For instance, [11]–[16] investigate mixed dual-hop (DH) systems using amplify-and-forward (AF) based relaying scheme with an RF source-to-relay link and an FSO relay-to-destination link. Further in [16], the closed-form expressions for outage probability and average bit error rate are derived using *Malaga* distribution which is considered as a generalized fading model for the FSO link. In case of AF relaying, the relay node amplifies the received message signal and then forwards the amplified version to the destination node. However, the noise together with the signal is also amplified, which is the main disadvantage of AF relaying scheme.

In [17], similar mixed RF-FSO DH system using decode-and-forward (DF) based relaying scheme has been investigated. It is to be noticed that all the aforementioned mixed RF-FSO systems do not consider the presence of direct source-to-destination link except [18], which considers an RF source-to-destination link. In [19] and [20], DF-relaying-

based FSO system with a source-to-destination link is investigated. In [21], DF-based mixed RF-FSO system is considered with single-input-multiple-output (SIMO) RF source-to-relay links and single-input-single-output (SISO) FSO relay-to-destination link. In all the aforementioned mixed RF-FSO systems, the FSO is considered only as a last mile access link. Further in [22], the closed-form expressions of outage probability and ergodic achievable rates for the DF-relaying-based RF-FSO multi-hop and mesh networks are investigated. In [6], the performance of switching-based hybrid FSO/RF system is investigated for SH scenario, which is restricted to log-normal fading for FSO link. In [8], the switching scheme is considered for a direct source-to-destination FSO link and a DH mixed RF-FSO backup link with source-to-relay RF link and relay-to-destination FSO link. Further in [6] and [8], two different link switching strategies are examined such as a single FSO threshold scheme which offers simplicity in transceiver design, and a dual FSO threshold scheme that prevents unnecessary switching between primary FSO link and backup RF link or backup mixed RF-FSO link. In [9], we have analyzed the performance of switching-based hybrid FSO/RF transmission in DH scenario with selection combining (SC). But the derived exact expressions are too complex and therefore, simpler asymptotic expressions are required. It is noted that the conventional DF scheme significantly degrades the system performance due to decoding errors at the relay.

In this paper, we propose a switching scheme for a DF-relaying-based hybrid FSO/RF system using MRC at the destination. To overcome the shortcomings of conventional DF relaying, we use selective DF-relaying protocol, where the transmission is conditioned on successful decoding at the relay [23]. The system comprises of DF-relaying-based FSO and RF sub-systems, which are activated using a switching mechanism with the priority to FSO sub-system. The FSO sub-system initiates the transmission as long as the instantaneous signal-to-noise ratio (SNR) at the optical receiver is above a certain threshold, γ_{th} . When the SNR falls below γ_{th} , the system switches to the RF sub-system, while putting the FSO sub-system on a standby mode.

In contrast to [11]–[21], the present work does not restrict FSO transmission to last mile access alone. Please note that in the proposed scheme, we consider switching of the entire sub-system and not at individual link level. FSO transmission achieves higher data rate than MMW RF transmission. When the system is switched to FSO or RF sub-system, then source and relay transmit using corresponding FSO or RF links, respectively, and MRC is used to combine the received signal at destination. In this manner, the hybrid FSO/RF system supports the transmission rates of FSO and MMW RF sub-systems separately. Therefore, the presented scheme achieves higher data rate in average compared to [3] and [11]–[22], where the data rate is always restricted to the data rate of RF links. The FSO links are characterized by Gamma-Gamma turbulence with weather attenuation factors. In [6], [7], [9] and [36], Nakagami- m distribution is used to model the MMW RF channel. Therefore, in this work, the MMW RF links are characterized using Nakagami- m distribution, as it can model wide variety of line-of-sight (LOS) and non-LOS channel

scenarios by varying the values of m together with different path loss factors. The motivations and contributions of our work are summarized as follows:

A. Motivations

- In prior work, switching-based hybrid FSO/RF transmission has been investigated for SH scenario, which is restricted to log-normal fading for FSO link. Since FSO or MMW RF transmission is restricted to short range communication, the performance analysis of DH cooperative relaying scenario is required to improve the coverage and reliability. Moreover, in the context of 5G cellular networks, cooperative relaying is necessary for efficient transmission.
- In prior works, conventional DF-relaying-based system, where the relay transmits the information to destination irrespective of the decoding errors, has been investigated. But the performance of DF relaying can be improved by letting the relay forward the information, only if it is successfully decoded (i.e. selective DF relaying). Hence, a selective DF-relaying-based hybrid FSO/RF system is required to be investigated.
- Switching-based system was also proposed for DH scenario with SC at the destination. The derived expressions were too complex to comprehend. Therefore, simpler asymptotic expressions are required to understand the system behavior. It is also mandatory to investigate the performance of switching-based hybrid FSO/RF system using MRC, which is an optimal combining scheme, at the destination.
- It is also noticed that the performance of switching-based hybrid FSO/RF system has not been investigated for different weather conditions.
- The optimum threshold SNR value for switching-based system has not been investigated in the past and the same is mandatory to achieve optimal performance.

B. Contributions

- We propose a novel switching scheme for a DF-relaying-based hybrid FSO/RF system with MRC. The proposed scheme provides high data rate in average due to the default usage of FSO sub-system and switching between FSO and RF sub-systems, when the FSO link is in outage.
- To overcome the shortcomings of DF transmission, we use selective DF-relaying protocol, where the transmission from relay-to-destination is conditioned on the successful decoding at relay.
- The performance analysis of the proposed system has been carried out by deriving exact closed-form expressions for outage probability and average symbol error rate (SER). The average SER analysis is investigated for sub-carrier-intensity-based M -ary phase-shift keying (MPSK) signaling.
- In addition, the asymptotic outage and SER expressions with lower computational complexity are derived in closed-form and the diversity order is determined. Note that all the exact and asymptotic expressions are verified using Monte-Carlo simulation results.

- The performance of DF-relaying-based hybrid FSO/RF system is reported for various weather conditions.
- The optimum switching threshold SNR value γ_{th}^{opt} for the proposed switching scheme is obtained numerically by plotting the average SER with respect to threshold SNR values γ_{th} . The optimum value of γ_{th} is chosen to satisfy a target average SER value and to achieve high capacity.

The rest of the paper is organized as follows: The system and channel models of the proposed scheme are given in section II. Statistical characteristics of FSO and RF systems are also discussed in section II. In section III and IV, outage and average SER analyses are presented, respectively. The asymptotic analyses are given in section V. Section VI discusses the results and the paper concludes at Section VII.

II. SYSTEM AND CHANNEL MODEL

A switching-based hybrid FSO/RF system comprises of a DF-relaying-based FSO sub-system and a DF-relaying-based RF sub-system as shown in Fig. 2. The sub-systems employ MRC to combine the data of the two phase transmission at the destination. For MMW RF transceivers, the pointing precision

Fig. 2. Hybrid FSO/RF system model

can be achieved using a mechanical positioning platform, which is known as gimbal [24]. In FSO, the pointing precision can be achieved using a fast scanning mirror as mentioned in [24]. In [25], different mechanisms (such as 1. Gimbal-based technique, 2. Mirror-based technique, 3. Liquid-crystal-based mechanism, and 4. Adaptive optics) are presented for acquisition, pointing and tracking of optical beam. In adaptive optics, there are three techniques in which the transceivers use feedback messages to correct the pointing errors. In [26], the performance of FSO MIMO links with pointing errors has been investigated with greater details. The results available in [26] will be used in future for analyzing the performance of the proposed hybrid system in the presence of misalignment or pointing errors.

The proposed system comprises of a source (S), relay (R), and destination (D). The atmospheric turbulence induced fading channels over FSO links S-D, S-R and R-D (I_{SD} , I_{SR} , and I_{RD}) are modeled using Gamma-Gamma distribution. The corresponding norm of the flat faded RF channel gains (h_{SD} , h_{SR} , and h_{RD}) are modeled using Nakagami- m distribution. We also consider path loss attenuation in different weather conditions for both FSO and MMW RF channels. It is assumed that the channel gains of FSO and MMW RF links are mutually independent. For the case of FSO, the received base-band signals for the k -th symbol interval at R and D are, respectively, given by

$$\begin{aligned} y_{SR}^f[k] &= \eta \sqrt{E_g/2P_{SR}^f I_{SR} g_{SR}^f} x_f[k] + n_{SR}^f[k], \\ y_{SD}^f[k] &= \eta \sqrt{E_g/2P_{SD}^f I_{SD} g_{SD}^f} x_f[k] + n_{SD}^f[k]. \end{aligned} \quad (1)$$

During second phase, the decoded data $\hat{x}_f[k]$ at R is forwarded to D and the received base-band signal at D is given by

$$y_{RD}^f = \eta \sqrt{E_g/2P_{RD}^f I_{RD} g_{RD}^f} \hat{x}_f[k] + n_{RD}^f, \quad (2)$$

where P_j^f is the transmitted optical power, I_j is the FSO channel fading coefficient with $E[I_j] = 1$, where $E[\cdot]$ is the expectation operator, $n_j^f[k]$ is the additive white Gaussian noise component with zero mean and variance $\sigma_{fj}^2 = 2\sigma_1^2 = E[n_j^f[k]n_j^{f*}[k]]$, where $j \in \{SR, RD, SD\}$. Note that $x_f[k]$ is the transmitted symbol, which is one of the M constellation points in the MPSK signal space, E_g is the energy of the shaping pulse, and η is the optical-to-electrical conversion coefficient. The average gain of the FSO link or the attenuation factor is given by $g_j^f = \exp(-\alpha_1 L)$, where α_1 is a weather dependent attenuation coefficient (in 1/km) and L is the link distance. Similarly, for RF, the received base-band signals in the k -th symbol interval at R and D are, respectively, given by

$$\begin{aligned} y_{SR}^r[k] &= \sqrt{E_g/2} \sqrt{P_{SR}^r} \sqrt{g_{SR}^r} h_{SR} x_r[k] + n_{SR}^r[k], \\ y_{SD}^r[k] &= \sqrt{E_g/2} \sqrt{P_{SD}^r} \sqrt{g_{SD}^r} h_{SD} x_r[k] + n_{SD}^r[k]. \end{aligned} \quad (3)$$

During second phase, the decoded data $\hat{x}_r[k]$ at R is forwarded to D and the received baseband signal at D is given by

$$y_{RD}^r = \sqrt{E_g/2} \sqrt{P_{RD}^r} \sqrt{g_{RD}^r} h_{RD} \hat{x}_r[k] + n_{RD}^r, \quad (4)$$

where P_j^r is the transmitted power, h_j is the RF channel fading with $E[h_j^2] = 1$, $n_j^r[k]$ is the additive white Gaussian noise component with zero mean and variance $\sigma_{rj}^2 = E[n_j^r[k]n_j^{r*}[k]]$, $x_r[k]$ is the transmitted symbol which is one of the M constellation points in the MPSK signal space. Assuming the RF carrier frequency of 60 GHz, the average power gain of the RF link is given by

$$g_j^r[\text{dB}] = G_t + G_r - 20\log_{10}(4\pi L/\lambda_r) - (\alpha_{oxy} + \alpha_{rain})L, \quad (5)$$

where G_t and G_r denote the transmit and receive antenna gains, respectively, λ_r is the wavelength of the RF system, and α_{oxy} and α_{rain} are the attenuation caused by oxygen absorption and rain, respectively. The noise variance in the RF link is given by $\sigma_{rj}^2[\text{dBm}] = B + N_o + N_F$ [4], where B is the RF bandwidth (in dBMHz), N_o is the noise power spectral density (in dBm/MHz), and N_F is the noise figure of the receiver.

A. FSO Channel Model

We adopt sub-carrier intensity modulation/direct detection for the FSO links [7] assuming perfect alignment between FSO transmitter and receiver apertures. The intensity of the laser beam is modulated using PSK signal. However, a DC bias must be added to ensure non-negative input constraint for PSK waveform. The instantaneous SNR (γ_j^f) and the average SNR ($\bar{\gamma}_j^f$) at the output of the FSO receiver are, respectively, given by

$$\gamma_j^f = \bar{\gamma}_j^f |I_j|^2, \quad \bar{\gamma}_j^f = \frac{(P_j^f)^2 \eta^2 E_g (g_j^f)^2}{\sigma_{fj}^2 2}. \quad (6)$$

TABLE I
NOTATIONS USED THROUGH OUT THE PAPER

$\mathcal{A}^j \triangleq \frac{1}{2\Gamma(\alpha_j)\Gamma(\beta_j)}$	$\mathfrak{R}^j \triangleq \alpha_j, \beta_j$	$\mathcal{A}_{n_1} \triangleq \mathcal{A}_1^{SD} \mathcal{A}_1^{RD} \Gamma\left(\frac{\alpha_{RD}}{2} + 1\right) \frac{1}{n_1!}$	$\mathcal{J}_j \triangleq \frac{1}{\Gamma(\alpha_j)\Gamma(\beta_j)} \frac{\pi}{2\sin(\pi(\alpha_j - \beta_j))} (\alpha_j \beta_j / \sqrt{\gamma_j})^{(\frac{\alpha_j + \beta_j}{2})}$
$\mathcal{A}_1^j \triangleq \frac{2^{\alpha_j + \beta_j}}{4\pi\Gamma(\alpha_j)\Gamma(\beta_j)}$	$v_j^f \triangleq \frac{(\alpha_j \beta_j)^2}{16\gamma_j^f}$	$\mathcal{B}_1^j \triangleq \frac{\alpha_j}{2}, \frac{\alpha_j + 1}{2}, \frac{\beta_j}{2}, \frac{\beta_j + 1}{2}$	$\mathcal{J}_{1n}^j \triangleq \frac{1}{\Gamma(n - (\alpha_j - \beta_j) + 1)n!} (\alpha_j \beta_j / \sqrt{\gamma_j})^{(2n - (\alpha_j - \beta_j))/2}$
$A_{n_4} \triangleq \frac{(-1)^{n_4} D^{2n_4 + 1}}{n_4! (2n_4 + 1)}$	$w_j \triangleq \frac{m_j}{\gamma_j^f}$	$\mathcal{B}_{2,n_1}^j \triangleq \frac{\alpha_j}{2} + n_1, \frac{\alpha_j + 1}{2}, \frac{\beta_j}{2}, \frac{\beta_j + 1}{2}$	$\mathcal{J}_{2n}^j \triangleq \frac{1}{\Gamma(n + (\alpha_j - \beta_j) + 1)n!} (\alpha_j \beta_j / \sqrt{\gamma_j})^{(2n + (\alpha_j - \beta_j))/2}$
$C_{k_1}^m \triangleq m_{SD} + k_1$	$c \triangleq \frac{\alpha_{RD}}{2} + 1$	$\mu_{1n}^j \triangleq \frac{2n - (\alpha_j - \beta_j)}{4} + \frac{\alpha_j + \beta_j}{4}$	$C_{n_2}^{k_1} \triangleq \frac{w_{SD}^{-k_1} w_{RD}^{m_{RD} + n_2}}{\Gamma(m_{SD})\Gamma(m_{RD})} \frac{(-1)^{n_2 + k_1}}{n_2! (m_{RD} + n_2)} \binom{m_{RD} + n_2}{k_1}$
$C_{n_2, k_1}^m \triangleq m_{RD} + n_2 - k_1$	$c_{n_1} \triangleq \mu_{g,n}^{SD} + n_1$	$\mu_{2n}^j \triangleq \frac{2n + (\alpha_j - \beta_j)}{4} + \frac{\alpha_j + \beta_j}{4}$	$C_{n_2, k_1}^{m, p_1} = (C_{n_2, k_1}^m + p_1), \ell_{11} = 1, \ell_{12} = -1$

The PDF of instantaneous SNR of FSO link is given by

$$f_{\gamma_j^f}(\gamma) = \frac{\left(\frac{\alpha_j \beta_j}{\sqrt{\gamma_j^f}}\right)^{\frac{\alpha_j + \beta_j}{2}} (\gamma)^{\frac{\alpha_j + \beta_j}{4} - 1}}{\Gamma(\alpha_j)\Gamma(\beta_j)} K_{\alpha_j - \beta_j} \left(2\sqrt{\frac{\alpha_j \beta_j \gamma}{\sqrt{\gamma_j^f}}}\right), \quad (7)$$

where $\Gamma(\cdot)$ is the gamma integral function [29, Eq. (8.310.1)] and $K_a(\cdot)$ is the modified Bessel function of the second kind of order a [29]. Here, α_j and β_j are the small scale and large scale parameters of the scattering environment of j^{th} link. Assuming spherical wave propagation, these parameters can be directly related to atmospheric conditions as [30, Eq. (2,3)]

$$\alpha_j = \left[e^{\frac{0.49\chi_j^2}{(1+0.18d_j^2+0.56\chi_j^{12/5})^{7/6}} - 1} \right]^{-1},$$

$$\beta_j = \left[e^{\frac{0.51\chi_j^2(1+0.69\chi_j^{12/5})^{-5/6}}{(1+0.9d_j^2+0.62d_j^2\chi_j^{12/5})^{5/6}} - 1} \right]^{-1}, \quad (8)$$

where $\chi_j^2 = 0.5C_n^2 k^{7/6} L_j^{11/6}$ is the Rytov variance and $d_j = (kD^2/4L_j)^{1/2}$. Here, $k = 2\pi/\lambda$ is the optical wave number, λ is the wavelength, D is the diameter of the receiver aperture, and L_j is the link distance in meters. It is to be noted that C_n^2 stands for the refractive index structure parameter and is altitude-dependent. In general, C_n^2 varies from $10^{-13}(\text{m}^{-2/3})$ (for strong turbulence) to $10^{-16}(\text{m}^{-2/3})$ (for weak turbulence). Equation (7) can be expressed in terms of Meijer G-function as follows

$$f_{\gamma_j^f}(\gamma) = \mathcal{A}^j \gamma^{-1} G_{0,2}^{2,0} \left(\alpha_j \beta_j \sqrt{\gamma/\gamma_j^f} \middle| \begin{matrix} - \\ \mathfrak{R}^j \end{matrix} \right), \quad (9)$$

where $\mathcal{A}^j, \mathfrak{R}^j$ are given in Table I, and $G_{p,q}^{m,n}(\cdot)$ is the Meijer G-function [29, Eq.(9.301)]. It is rather challenging to directly deal with the PDF of the FSO channel. Specially, for the DF-relaying scenarios, it is not easy to obtain analytical results by using the PDF given in (7) and (9). Therefore, we need an alternative representation of the PDF of the Gamma-Gamma distribution, which can render simplified analysis. Using [31, Eq.(03.04.06.0002.01)], (7) can be written as

$$f_{\gamma_j^f}(\gamma) = \mathcal{J}_j \sum_{g=1}^2 \ell_{1g} \sum_{n=0}^{\infty} \mathcal{J}_{gn}^j \gamma^{\mu_{gn}^j - 1}, \quad (10)$$

where $\mathcal{J}_j, \ell_{1g}, \mathcal{J}_{gn}^j$, and μ_{gn}^j are given in Table I. Using (9) and [32, Eq.(07.34.21.0084.01)], the cumulative distribution function (CDF) of γ_j^f can be expressed as

$$F_{\gamma_j^f}(\gamma) = \mathcal{A}_1^j G_{1,5}^{4,1} \left(v_j^f \gamma \middle| \begin{matrix} 1 \\ \mathcal{B}_{1,0}^j \end{matrix} \right), \quad (11)$$

where $\mathcal{A}_1^j, v_j^f$, and $\mathcal{B}_1^j$ are given in Table I.

B. MMW RF Channel Model

The instantaneous received SNR (γ_j^r) and the average SNR ($\bar{\gamma}_j^r$) of any given MMW RF link are, respectively, given by

$$\gamma_j^r = \bar{\gamma}_j^r |h_j|^2, \quad \bar{\gamma}_j^r = \frac{P_j^r g_j^r E_g}{\sigma_{rj}^2} \frac{1}{2}. \quad (12)$$

The norm of the fading channel gain i.e. $|h_j|$ is modeled as Nakagami- m distribution, where m indicates the fading severity parameter and it represents a wide variety of realistic line-of-sight (LOS) (with high values for m [6] and [7]) and non-LOS fading channels encountered in practice. Now the PDF of γ_j^r , which follows Gamma distribution, is given by

$$f_{\gamma_j^r}(\gamma) = w_j^{m_j} \frac{\gamma^{m_j - 1}}{\Gamma(m_j)} e^{-w_j \gamma}, \quad (13)$$

where w_j is given in Table I. By using [29, Eq. (3.351.1)], the CDF of γ_j^r can be expressed

$$F_{\gamma_j^r}(\gamma) = \gamma(m_j, w_j \gamma) / \Gamma(m_j), \quad (14)$$

where $\gamma(\cdot, \cdot)$ is the lower incomplete gamma function [29, Eq. (8.350.1)].

III. OUTAGE ANALYSIS

An outage of the communication system is encountered when the output instantaneous SNR drops below a predetermined threshold. In this scenario, S and R can transmit over FSO links given that the instantaneous SNR of the FSO links at D after MRC is greater than the threshold SNR of FSO (γ_{th}^f). If the SNR drops below γ_{th}^f , then the system will switch to MMW RF links, if instantaneous SNR is above the threshold SNR of RF links (γ_{th}^r). If the received SNRs of both FSO and MMW RF links are below their respective thresholds, an outage will be declared. A one-bit feedback signal is used to switch or to select between FSO and RF sub-systems [27]. We use one of the following vectors, either $\mathbf{v}_f = [a, 1 - a]^T$ for FSO or $\mathbf{v}_r = [1 - a, a]^T$ for RF transmission. The choice of vector depends upon the one bit feedback received from D. If it is assumed that there is no error in feedback, then the best strategy is to use $\mathbf{v}_f$ if $\gamma_{MRC}^f > \gamma_{th}^f$ and $\mathbf{v}_r$ if $\gamma_{MRC}^f < \gamma_{th}^f$, where $a = 1$ and γ_{MRC}^f is the instantaneous SNRs of FSO sub-system after MRC [27]. The expression for outage probability is given by

$$P_{MRC} = F_{\gamma_{MRC}^f}(\gamma_{th}^f) F_{\gamma_{MRC}^r}(\gamma_{th}^r), \quad (15)$$

where $F_{\gamma_{MRC}^f}(\gamma_{th}^f)$ and $F_{\gamma_{MRC}^r}(\gamma_{th}^r)$ are the CDFs of the instantaneous SNRs of FSO and MMW RF sub-systems, respectively, after MRC. The output SNR at D, conditioned on the successful decoding at R, is given by $\gamma_C^T = \gamma_{SD}^T + \gamma_{RD}^T$,

where γ_{SD}^T and γ_{RD}^T represent the instantaneous SNRs of S-D and R-D links, respectively, and $T \in \{f, r\}$. Since γ_{SD}^T and γ_{RD}^T are independent random variables, the CDF of γ_C^T is given by

$$F_{\gamma_C^T}(\gamma) = \int_0^\gamma \int_0^{\gamma-\gamma^s} f_{\gamma_{RD}^T}(\gamma^k) f_{\gamma_{SD}^T}(\gamma^s) d\gamma^k d\gamma^s. \quad (16)$$

On the other hand, if R fails to decode in first transmission phase, it will remain silent in the second transmission phase. In this case, it is still possible for D to receive and decode the data through the direct S-D link. The CDF of γ_{MRC}^T in case of either FSO or RF transmission can be written as

$$F_{\gamma_{MRC}^T}(\gamma) = F_{\gamma_C^T}(\gamma) (1 - F_{\gamma_{SR}^T}(\gamma)) + F_{\gamma_{SR}^T}(\gamma) F_{\gamma_{SD}^T}(\gamma). \quad (17)$$

In case of FSO transmission, the inner integral in (16) is solved by substituting (9) and using [33, Eq. (2.24.2.2)]. The resultant expression is further simplified using [33, Eq. (6.11.1.1)]. Finally, the integral is solved using [33, Eq. (2.24.2.2)] to get the exact expression as

$$F_{\gamma_C^f}(\gamma) = \sum_{n_1=0}^{\infty} \mathcal{A}_{n_1} G_{1,5}^{4,1} \left(v_{RD} \gamma \middle| \mathcal{B}_{2,n_1}^{RD}, 0 \right) G_{1,5}^{4,1} \left(v_{SD} \gamma \middle| \mathcal{B}_{1,-n_1-\frac{\alpha_{RD}}{2}}^{SD} \right) \quad (18)$$

where $\mathcal{A}_{n_1}$, $\mathcal{B}_{2,n_1}^{RD}$ are given in Table I. In case of RF transmission, we solve (16) as in [28] to get the exact expression as

$$F_{\gamma_C^r}(\gamma) = \sum_{n_2=0}^{\infty} \sum_{k_1=0}^{m_{RD}+n_2} C_{n_2}^{k_1} \gamma^{C_{n_2,k_1}^m} \gamma \left(C_{k_1}^m, w_{SD} \gamma \right), \quad (19)$$

where $C_{n_2}^{k_1}$, C_{n_2,k_1}^m and $C_{k_1}^m$ are given in Table I. By substituting (11) and (18) into (17), we obtain $F_{\gamma_{MRC}^f}(\gamma_{th}^f)$ and by substituting (14) and (19) into (17), we obtain $F_{\gamma_{MRC}^r}(\gamma_{th}^r)$. By substituting $F_{\gamma_{MRC}^f}(\gamma)$ and $F_{\gamma_{MRC}^r}(\gamma)$ into (15), outage probability of the proposed system is obtained.

In order to obtain the PDF $f_{\gamma_C^f}(\gamma)$, we recalculate $F_{\gamma_C^f}(\gamma)$ and the inner integral in (16) is solved using [33, Eq. (2.24.2.2)]. The resultant expression is further simplified using [33, Eq. (6.11.1.1)]. Finally, the remaining integral is solved by substituting (10) and using [29, Eq. (3.191)] to get the exact expression as

$$F_{\gamma_C^f}(\gamma) = \mathcal{A}_1^{RD} \mathcal{J}_{SD} \sum_{n_1=0}^{\infty} \frac{1}{n_1!} G_{1,5}^{4,1} \left(v_{RD} \gamma \middle| \mathcal{B}_{2,n_1}^{RD}, 0 \right) \times \sum_{g=1}^2 \ell_{1g} \mathcal{J}_{g,n}^{SD} B(c, c_{n_1}) \gamma^{\mu_{g,n}^{SD}}, \quad (20)$$

where $\mathcal{A}_1^j$, $\mathcal{J}_j$, v_j , ℓ_{1g} , $\mathcal{J}_{g,n}^j$, c , c_{n_1} , $\mu_{g,n}^j$ are given in Table I, $j \in \{SD, RD\}$, and $B(\cdot, \cdot)$ is the beta function [29,

Eq. (8.384.1)]. The PDF of γ_C^f , obtained by differentiating (20) with respect to γ , is given by (21). The PDF of γ_C^r , obtained by differentiating (19) with respect to γ using [29, Eq. (8.352.6)], is given by (22).

IV. AVERAGE SER

For SER analysis, we assume that the data is modulated using MPSK signaling. The conditional SER for MPSK signaling conditioned on the instantaneous SNR of any given link γ is given by [6, Eq. 11]

$$p(e/\gamma) = \frac{A}{2} \operatorname{erfc}(\sqrt{\gamma} D), \quad (23)$$

where $A = 1$ for modulation order $M = 2$, $A = 2$ for $M > 2$, $D = \sin(\frac{\pi}{M})$, and $\operatorname{erfc}(\cdot)$ is the complementary error function. The conditional SER can be represented in terms of Meijer G function as [32, Eq. (07.34.03.0619.01)]

$$p(e|\gamma) = \frac{A}{2\sqrt{\pi}} G_{1,2}^{2,0} \left(D^2 \gamma \middle| 0, \frac{1}{2} \right), \quad (24)$$

and it can also be represented using McLaurin series [29, Eq. (3.321)] as

$$p(e|\gamma) = \frac{A}{2} \left[1 - \frac{2}{\sqrt{\pi}} \sum_{n_4=0}^{\infty} A_{n_4} \gamma^{\frac{2n_4+1}{2}} \right]. \quad (25)$$

where A_{n_4} is given in Table I. The average SER during non-outage period can be calculated in terms of the average SER of individual FSO and MMW RF links and is given by

$$\overline{SER}_{MRC} = \frac{B_{MRC}^f(\gamma_{th}^f) + F_{\gamma_{MRC}^f}(\gamma_{th}^f) B_{MRC}^r(\gamma_{th}^r)}{1 - P_{MRC}}, \quad (26)$$

where P_{MRC} is given by (15) and $F_{\gamma_{MRC}^f}(\gamma_{th}^f)$ is given by (17). The PDF of both FSO and RF sub-systems, obtained by differentiating (17) with respect to γ , is given by

$$f_{\gamma_{MRC}^T}(\gamma) = f_{\gamma_C^T}(\gamma) - f_{\gamma_C^T}(\gamma) F_{\gamma_{SR}^T}(\gamma) - F_{\gamma_C^T}(\gamma) f_{\gamma_{SR}^T}(\gamma) + f_{\gamma_{SR}^T}(\gamma) F_{\gamma_{SD}^T}(\gamma) + f_{\gamma_{SD}^T}(\gamma) F_{\gamma_{SR}^T}(\gamma). \quad (27)$$

Using (27), the average SER of FSO and RF sub-systems, when $\gamma_{MRC}^T > \gamma_{th}^T$, is given by (28).

V. ASYMPTOTIC ANALYSIS

The closed-form expressions for outage probability and average SER are very complex to study the effect of various system parameters. Hence, it is important to derive asymptotic expressions to get more insights about the system performance and also to derive diversity order of the system. Generally, at high SNR values, the outage probability and average SER of a certain transmission link can be expressed as $P_{MRC} \approx (G_c \bar{\gamma}^f)^{-G_d}$ and $\overline{SER}_{MRC} \approx (G_c \bar{\gamma}^f)^{-G_d}$

$$f_{\gamma_C^f}(\gamma) = \mathcal{A}_1^{RD} \mathcal{J}_{SD} \sum_{n_1=0}^{\infty} \frac{1}{n_1!} \sum_{g=1}^2 \ell_{1g} \sum_{n=0}^{\infty} \mathcal{J}_{gn}^{SD} B(c, c_{n_1}) \left[\gamma^{\mu_{gn}^{SD}} G_{2,6}^{4,2} \left(v_{RD} \gamma \middle| \mathcal{B}_{2,n_1}^{RD}, 0, -1 \right) + \mu_{gn}^{SD} \gamma^{\mu_{gn}^{SD}-1} G_{1,5}^{4,1} \left(v_{RD} \gamma \middle| \mathcal{B}_{2,n_1}^{RD}, 0 \right) \right] \quad (21)$$

$$f_{\gamma_C^r}(\gamma) = \sum_{n_2=0}^{\infty} \sum_{k_1=0}^{m_{RD}+n_2} C_{n_2}^{k_1} (C_{k_1}^m - 1)! \left[C_{n_2,k_1}^m \gamma^{C_{n_2,k_1}^m} - \sum_{p_1=0}^{C_{k_1}^m-1} \frac{w_{SD}^{p_1}}{p_1!} C_{n_2,k_1}^{m,p_1} \gamma^{C_{n_2,k_1}^m-p_1-1} e^{-w_{SD} \gamma} + \sum_{p_1=0}^{C_{k_1}^m-1} \frac{w_{SD}^{p_1+1}}{p_1!} \gamma^{C_{n_2,k_1}^m-p_1} e^{-w_{SD} \gamma} \right] \quad (22)$$

$$\begin{aligned}
B_{MRC}^T(\gamma_{th}^T) &= \int_{\gamma_{th}^T}^{\infty} p(e|\gamma) f_{\gamma_{MRC}}(\gamma) d\gamma = \underbrace{\int_{\gamma_{th}^T}^{\infty} p(e|\gamma) f_{\gamma_C^T}(\gamma) d\gamma}_{B_{C,MRC}^T(\gamma_{th}^T)} - \underbrace{\int_{\gamma_{th}^T}^{\infty} p(e|\gamma) f_{\gamma_C^T}(\gamma) F_{\gamma_{SR}^T}(\gamma) d\gamma}_{B_{C,SR}^T(\gamma_{th}^T)} \\
&\quad - \underbrace{\int_{\gamma_{th}^T}^{\infty} p(e|\gamma) f_{\gamma_{SR}^T}(\gamma) F_{\gamma_C^T}(\gamma) d\gamma}_{B_{SR,C}^T(\gamma_{th}^T)} + \underbrace{\int_{\gamma_{th}^T}^{\infty} p(e|\gamma) f_{\gamma_{SR}^T}(\gamma) F_{\gamma_{SD}^T}(\gamma) d\gamma}_{B_{SR,SD}^T(\gamma_{th}^T)} + \underbrace{\int_{\gamma_{th}^T}^{\infty} p(e|\gamma) f_{\gamma_{SD}^T}(\gamma) F_{\gamma_{SR}^T}(\gamma) d\gamma}_{B_{SD,SR}^T(\gamma_{th}^T)}. \quad (28)
\end{aligned}$$

The detailed derivations of each term in (28) for $B_{MRC}^f(\gamma_{th}^f)$ and $B_{MRC}^r(\gamma_{th}^r)$ are given in Appendix A and B, respectively.

respectively, where G_c is the coding gain of the system and G_d is the diversity order of the system. Mathematically, the diversity order is defined as

$$G_{op} = -\lim_{\bar{\gamma}^f \rightarrow \infty} \frac{\log(P_{MRC})}{\log(\bar{\gamma}^f)}, \quad G_{SER} = -\lim_{\bar{\gamma}^f \rightarrow \infty} \frac{\log(\overline{SER}_{MRC})}{\log(\bar{\gamma}^f)}.$$

A. Outage Probability

We assume that the average electrical SNR of any given FSO link ($\bar{\gamma}^f$) goes to infinity for a fixed value of average SNR of RF links. The asymptotic outage probability is given by

$$P_{MRC}^{f\infty} = F_{\gamma_{MRC}^f}^{\infty}(\gamma_{th}^f) F_{\gamma_{MRC}^r}^{\infty}(\gamma_{th}^r), \quad (29)$$

where $F_{\gamma_{MRC}^r}^{\infty}(\gamma_{th}^r)$ is given by (17) and $F_{\gamma_{MRC}^f}^{\infty}(\gamma_{th}^f)$ is given by

$$F_{\gamma_{MRC}^f}^{\infty}(\gamma_{th}^f) = F_{\gamma_C^f}^{\infty}(\gamma) (1 - F_{\gamma_{SR}^f}^{\infty}(\gamma)) + F_{\gamma_{SR}^f}^{\infty}(\gamma) F_{\gamma_{SD}^f}^{\infty}(\gamma). \quad (30)$$

Applying [29, Eq. (07.34.06.0040.01)] in (11), the CDF of the end-to-end SNR in the asymptotic regime is given as

$$F_{\gamma_j^f}^{\infty}(\gamma_{th}^f) \simeq \sum_{k=1}^4 \mathcal{A}_1^j \Lambda_{1,k}^j [\bar{\gamma}_j^f]^{-\mathcal{B}_{1,k}^j}, \quad (31)$$

where $\Lambda_{1,k}^j$ is given in Table II and $j \in \{SD, SR\}$. The series in (31) can be further simplified by taking only the k^{th} term that is related to the minimum value of $\mathcal{B}_{1,k}^j$. Such an assumption is justified by the fact that at $\bar{\gamma}_j^f \rightarrow \infty$,

we have term $\left[(\alpha\beta)^2 \gamma_{th}^f / 16 \bar{\gamma}_j^f\right]^{\mathcal{B}_{1,k}^j} \rightarrow 0$ for large $\mathcal{B}_{1,k}^j$ values. Accordingly, we get

$$F_{\gamma_j^f}^{\infty}(\gamma_{th}^f) \simeq \sum_{k=1}^4 \mathcal{A}_1^j \Lambda_{1,k}^j [\bar{\gamma}_j^f]^{-v_j}, \quad (32)$$

where $v_j = \min\{\frac{\alpha_i}{2}, \frac{\beta_j}{2}\}$. By applying [32, Eq.

TABLE II
NOTATIONS USED IN ASYMPTOTIC OUTAGE ANALYSIS

$\Lambda_{1,k}^j = \frac{\prod_{q=1, q \neq k}^4 \Gamma(\mathcal{B}_{1,q}^j - \mathcal{B}_{1,k}^j) \Gamma(\mathcal{B}_{1,k}^j)}{\Gamma(1 + \mathcal{B}_{1,k}^j)} \left[\frac{(\alpha_j \beta_j)^2 \gamma_{th}^f}{16} \right]^{\mathcal{B}_{1,k}^j}$
$\Lambda_{2,k}^{j,n_1} = \frac{\prod_{q=1, q \neq k}^4 \Gamma(\mathcal{B}_{1,q}^j - \mathcal{B}_{1,k}^j) \Gamma(n_1 + \mathcal{B}_{1,k}^j)}{\Gamma(1 + n_1 + \frac{\alpha_j}{2} + \mathcal{B}_{1,k}^j)} \left[\frac{(\alpha_j \beta_j)^2 \gamma_{th}^f}{16} \right]^{\mathcal{B}_{1,k}^j}$
$\Lambda_{3,k}^{j,n_1} = \frac{\prod_{q=1, q \neq k}^4 \Gamma(\mathcal{B}_{2,q}^{j,n_1} - \mathcal{B}_{2,k}^{j,n_1}) \Gamma(\mathcal{B}_{2,k}^{j,n_1})}{\Gamma(1 + \mathcal{B}_{2,k}^{j,n_1})} \left[\frac{(\alpha_j \beta_j)^2 \gamma_{th}^f}{16} \right]^{\mathcal{B}_{2,k}^{j,n_1}}$

(07.34.06.0040.01)] in (18), $F_{\gamma_C^f}^{\infty}(\gamma_{th}^f)$ in the asymptotic regime is given as

$$F_{\gamma_C^f}^{\infty}(\gamma_{th}^f) \simeq \sum_{n_1=0}^{\infty} \sum_{k=1}^4 \mathcal{A}_{n_1} \Lambda_{2,k}^{SD,n_1} \Lambda_{3,k}^{RD,n_1} [\bar{\gamma}_{SD}^f]^{-v_{SD}} [\bar{\gamma}_{RD}^f]^{-v_{RD}}, \quad (33)$$

where $\Lambda_{2,k}^{SD,n_1}$ and $\Lambda_{3,k}^{RD,n_1}$ are given in Table II. By substituting (32) and (33) into (30), we obtain $F_{\gamma_{MRC}^f}^{\infty}(\gamma_{th}^f)$. It is inferred from (34), given on the top of next page, that the diversity order depends on $F_{\gamma_C^f}^{\infty}(\gamma_{th}^f)$ or $F_{\gamma_{SR}^f}^{\infty}(\gamma_{th}^f) F_{\gamma_{SD}^f}^{\infty}(\gamma_{th}^f)$. To calculate the diversity order, we assume $\bar{\gamma}_{SD}^f = \bar{\gamma}_{SR}^f = \bar{\gamma}_{RD}^f = \bar{\gamma}^f$. Therefore, the diversity order is given by $G_{op} = v_i + v_j$, where $i \in \{SR, RD\}$ and $j = SD$. It can be written as $G_{op} = \min\{\frac{\alpha_i}{2}, \frac{\beta_j}{2}\} + \min\{\frac{\alpha_j}{2}, \frac{\beta_j}{2}\}$. Since $\alpha > \beta$ in (8), the diversity order can be simplified as $G_{op} = \frac{\beta_i}{2} + \frac{\beta_j}{2}$. If $\beta = \beta_j = \beta_i$, then the diversity order is given by $G_{op} = \beta$.

B. SER Analysis

The asymptotic SER during non-outage period can be calculated in terms of the average SER of individual FSO and MMW RF links and is given by

$$\overline{SER}_{MRC}^{\infty} = \frac{B_{MRC}^f(\gamma_{th}^f) + F_{\gamma_{MRC}^f}^{\infty}(\gamma_{th}^f) B_{MRC}^r(\gamma_{th}^r)}{1 - P_{MRC}^{\infty}}, \quad (35)$$

where $B_{MRC}^r(\gamma_{th}^r)$, P_{MRC}^{∞} and $F_{\gamma_{MRC}^f}^{\infty}$ are given by (28), (29) and (30) respectively. Using $f_{\gamma_{MRC}^f}^{\infty}(\gamma)$ in (27) in the asymptotic regime, the asymptotic average SER of FSO sub-system, when $\gamma_{MRC}^f > \gamma_{th}^f$, is given by (36). It is inferred from (37) that the diversity order depends on $B_{C^f}^{\infty}(\gamma_{th}^f)$ or $B_{SR,SD}^{\infty}(\gamma_{th}^f)$ or $B_{SD,SR}^{\infty}(\gamma_{th}^f)$. Using similar arguments while calculating G_{op} , the diversity order is given by $G_{SER} = \frac{\beta_i}{2} + \frac{\beta_j}{2}$ or $G_{SER} = \beta$.

VI. NUMERICAL RESULTS AND DISCUSSIONS

In the simulations, the FSO link parameter values (i.e. α and β) are calculated from (8), where a point receiver is used i.e. $D \ll L_j$ leading to $d = 0$ [30]. In this case, α and β are functions of χ^2 , which is further dependent on C_n^2 and L_j as reflected by (8). We consider $L_{SD} = L_{SR} + L_{RD}$ and $L_{SR} = L_{RD} = 0.5 L_{SD}$. We assume $m_{SD} = m_{SR} = m_{RD} = m = 5$ for which Nakagami- m distribution perfectly models fading over MMW RF channel [6], [7] and [9]. The values of FSO and RF parameters used in the simulations are given in Table III. For all the plots, we assume weather condition as clear air unless otherwise stated, however the turbulence

$$F_{\gamma_{MRC}}^{\infty}(\gamma_{th}^f) \propto \underbrace{[\tilde{\gamma}_{SD}^f]^{-v_{SD}} [\tilde{\gamma}_{RD}^f]^{-v_{RD}}}_{\text{terms of } F_{\gamma_C}^{\infty}(\gamma_{th}^f)} - \underbrace{[\tilde{\gamma}_{SD}^f]^{-v_{SD}} [\tilde{\gamma}_{RD}^f]^{-v_{RD}} [\tilde{\gamma}_{SR}^f]^{-v_{SR}}}_{\text{terms of } F_{\gamma_C}^{\infty}(\gamma) F_{\gamma_{SR}}^{\infty}(\gamma)} + \underbrace{[\tilde{\gamma}_{SR}^f]^{-v_{SR}} [\tilde{\gamma}_{SD}^f]^{-v_{SD}}}_{\text{terms of } F_{\gamma_{SR}}^{\infty}(\gamma) F_{\gamma_{SD}}^{\infty}(\gamma)}. \quad (34)$$

$$\begin{aligned} B_{MRC}^f(\gamma_{th}^f) &= \int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_{MRC}}^{\infty}(\gamma) d\gamma = \underbrace{\int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_C}^{\infty}(\gamma) d\gamma}_{B_C^f(\gamma_{th}^f)} - \underbrace{\int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_C}^{\infty}(\gamma) F_{\gamma_{SR}}^{\infty}(\gamma) d\gamma}_{B_{C,SR}^f(\gamma_{th}^f)} \\ &\quad - \underbrace{\int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_{SR}}^{\infty}(\gamma) F_{\gamma_C}^{\infty}(\gamma) d\gamma}_{B_{SR,C}^f(\gamma_{th}^f)} + \underbrace{\int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_{SR}}^{\infty}(\gamma) F_{\gamma_{SD}}^{\infty}(\gamma) d\gamma}_{B_{SR,SD}^f(\gamma_{th}^f)} + \underbrace{\int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_{SD}}^{\infty}(\gamma) F_{\gamma_{SR}}^{\infty}(\gamma) d\gamma}_{B_{SD,SR}^f(\gamma_{th}^f)}. \quad (36) \end{aligned}$$

The detailed derivation of (36) is given in Appendix C.

$$\begin{aligned} B_{MRC}^f(\gamma_{th}^f) &\propto \underbrace{[\tilde{\gamma}_{SD}^f]^{-v_{SD}} [\tilde{\gamma}_{RD}^f]^{-v_{RD}}}_{\text{terms of } B_C^f(\gamma_{th}^f)} - \underbrace{[\tilde{\gamma}_{SR}^f]^{-v_{SR}} [\tilde{\gamma}_{RD}^f]^{-v_{RD}} [\tilde{\gamma}_{SD}^f]^{-v_{SD}}}_{\text{terms of } B_{C,SR}^f(\gamma_{th}^f)} \\ &\quad - \underbrace{[\tilde{\gamma}_{SR}^f]^{-v_{SR}} [\tilde{\gamma}_{RD}^f]^{-v_{RD}} [\tilde{\gamma}_{SD}^f]^{-v_{SD}}}_{\text{terms of } B_{SR,C}^f(\gamma_{th}^f)} + \underbrace{[\tilde{\gamma}_{SR}^f]^{-v_{SR}} [\tilde{\gamma}_{SD}^f]^{-v_{SD}}}_{\text{terms of } B_{SR,SD}^f(\gamma_{th}^f)} + \underbrace{[\tilde{\gamma}_{SD}^f]^{-v_{SD}} [\tilde{\gamma}_{SR}^f]^{-v_{SR}}}_{\text{terms of } B_{SD,SR}^f(\gamma_{th}^f)}. \quad (37) \end{aligned}$$

TABLE III
PARAMETER OF FSO AND RF SUB-SYSTEMS[3], [4]

FSO Parameter	Symbol	Value	
Wavelength	λ_1	1.55 μm	
Transmit Power	P_j^f	50 mW	
Responsivity	η	0.5 $\frac{\text{A}}{\text{W}}$	
Noise variance	σ_1^2	10^{-14}	
RF Parameter			
RF Parameter	Symbol	Value	
Carrier Frequency	f_c	60 GHz	
Transmit Power	P_j^r	10 mW	
Transmit Antenna Gain	G_t	44 dBi	
Receive Antenna Gain	G_r	44 dBi	
Attenuation (oxygen)	α_{oxy}	15.1 dB/km	
Fading severity parameter	m	5	
Noise Power Spectral Density	N_o	-114 dBm/MHz	
Receiver Noise Figure	N_f	5 dB	
Weather dependent parameters of FSO and RF channels			
Weather Conditions	α_1 (dB/km)	α_{rain} (dB/km)	C_n^2 ($\text{m}^{-\frac{2}{3}}$)
Clear air	0.43	0	5×10^{-14}
Haze	4.2	0	1.7×10^{-14}
Moderate rain	5.8	5.6	5×10^{-15}

conditions are varied by varying C_n^2 . For simplicity, all the results are plotted for independent and identically distributed (i.i.d) scenario. However, the results can also be extended to non-i.i.d scenario as well. It is found that the summation limits in (10), (18), (19), (25) and the obtained equations using these limits for computing the exact outage probability and average SER values can be truncated to $n = 50$, $n_1 = 50$, $n_2 = 100$, and $n_4 = 50$. Because, $n > 50$, $n_1 > 50$, $n_2 > 100$, and $n_4 > 50$ do not have an impact on the fifth decimal figure of the outage probability and average SER values.

A. Threshold SNR

To obtain the optimum threshold SNR value for the proposed switching based hybrid FSO/RF system, we have an-

alyzed the average SER performances of FSO and RF sub-systems with extensive simulation studies. Fig. 3a shows the average SER performance curves for the FSO and RF systems, without switching scheme, with respect to the threshold SNR (γ_{th}) for different values of average SNR of the FSO and RF links ($\bar{\gamma}^f$ and $\bar{\gamma}^r$), respectively. From Fig. 3a, the threshold SNR values for the FSO and RF systems to satisfy the target SER of 10^{-3} are observed to be different and are given by 4.8 dB and 9 dB, respectively. These values are obtained by considering the average SNR values corresponding to the worst case performances of FSO and RF systems, which are noticed at $\bar{\gamma}^f = 0$ dB and $\bar{\gamma}^r = 0$ dB. In case of switching based hybrid FSO/RF system, Fig. 3b and Fig. 3c show the average SER performance curves with respect to the threshold SNR for different values of average SNR of RF and FSO links, respectively. To satisfy the target SER value of 10^{-3} , the threshold SNR value is obtained by considering the worst case performance of hybrid FSO/RF system, which is noticed at $\bar{\gamma}^f = 0$ dB and $\bar{\gamma}^r = 4$ dB. The threshold SNR value for the hybrid FSO/RF system is observed to be a common value of $\gamma_{th} = 6.5$ dB.

To choose between the different or a common values of the threshold SNR, we have plotted the average SER curves with respect to the average SNR of FSO links in Fig 4 and compared the performance for different values of average SNR of RF links. It can be observed that the hybrid FSO/RF system with common threshold value i.e. ($\gamma_{th} = 6.5$ dB) performs better than the system with different threshold i.e. ($\gamma_{th}^f = 4.8$ dB and $\gamma_{th}^r = 9$ dB). Therefore, we have used common threshold values for further analysis of hybrid FSO/RF system. However, for plotting the results of the individual FSO system or RF system, we have used the different values of threshold SNR. Here, the target SER is considered as a trade off parameter across the performance and overall capacity of the

Fig. 3. Average SER vs γ_{th} for optimum threshold decision for hybrid FSO/RF system with MRC

Fig. 4. Average SER vs average SNR of FSO ($\bar{\gamma}^f$) for different values of threshold SNR (γ_{th}) and average SNR of RF ($\bar{\gamma}^r$) links

systems under consideration. Note that a very low value of target SER can be achieved only at very high value of γ_{th} , but the performance degrades in terms of capacity, as the system will be in outage more frequently.

B. Results

Fig 4 also shows the variation of average SER with respect to average SNR of FSO links for different values of $\bar{\gamma}^r$ assuming strong turbulence condition. The effect of the RF sub-system in a switching-based hybrid FSO/RF system is observed by fixing the value of $L_{SD} = 3000$ m, $\gamma_{th} = 6.5$ dB, and varying the value of average SNR of RF links ($\bar{\gamma}^r$). It is observed that as we increase the value of $\bar{\gamma}^r$, there is a significant improvement in the performance of the hybrid FSO/RF system. It is noticed that the hybrid FSO/RF system with MRC offers the SNR gain value of 7 dB and 4dB for $\bar{\gamma}^r = 10$ dB and $\bar{\gamma}^r = 5$ dB, respectively, to achieve the average SER value of 10^{-5} , compared to the FSO system. When the quality of RF link is high (i.e. $\bar{\gamma}^r = 10$ dB), considerable

performance improvement is observed, especially in the low-SNR region. This is because at a very low value of $\bar{\gamma}^f$, the high-quality RF link is being used frequently. Further, as the average SNR of FSO link ($\bar{\gamma}^f$) slightly increases, the FSO link is used more often, which is weaker than the RF link and hence, degradation in the SER performance is initially observed. When $\bar{\gamma}^f$ increases further, the FSO links become stronger and improvement in the SER performance is obtained.

Fig. 5a and Fig. 5b show the outage performance and average SER curves with respect to the average SNR of FSO links ($\bar{\gamma}^f$), respectively, where average SNR of MMW RF links are given by $\bar{\gamma}^r = 10$ dB. For Fig. 5a, $C_n^2 = 3 \times 10^{-14} \text{ m}^{-\frac{2}{3}}$ and for Fig. 5b, $C_n^2 = 1 \times 10^{-13} \text{ m}^{-\frac{2}{3}}$, which are the values of refractive index of FSO links at moderate and strong turbulence conditions, respectively. The simulated outage probability and average SER values closely match with the analytical results for all the SNR values as seen from the figures. This observation justifies the correctness of the proposed analysis. The derived asymptotic outage and SER values is sufficiently tight with the analytical outage and SER values at high SNR, as seen in the figures. Further, it is noticed that the diversity gain is affected by the atmospheric turbulence parameters. From the plots, it is observed that the proposed cooperative hybrid FSO/RF system outperforms the individual cooperative FSO system due to switching benefits. It is also observed from the figures that the proposed hybrid FSO/RF with MRC achieves the outage and SER value of 10^{-5} with the SNR gain of more than 6 dB compared to the FSO system with MRC. The hybrid FSO/RF system with MRC achieve an outage and SER value of 10^{-5} with the SNR gain of more than 10 dB compared to SH hybrid FSO/RF system. Moreover, this phenomenon confirms that by exploiting the diversity benefit of DH scenario with MRC, we can achieve outage and SER

Fig. 5. Analytical, asymptotic, and simulated outage and SER performance plots

(a) Outage probability vs transmit power of FSO links (P^f) (b) Average SER vs transmit power of FSO links (P^f)

Fig. 6. Performance in different attenuation conditions

performance improvement. In Fig.5b, we have also plotted the average SER performance of the hybrid FSO/RF system with conventional DF relaying. It is noticed that the hybrid FSO/RF system offers the SNR gain value of 6.5 dB for both conventional and selective DF relaying when compared to the respective FSO systems, to achieve the average SER value of 10^{-5} . Thus, the error propagation in case of conventional DF relaying does not affect the SNR gain offered by hybrid FSO/RF system compared to FSO system. It is to be noted that the SNR gain of 2.5 dB is attained for selective DF relaying over conventional DF relaying due to the probability of error propagation in conventional DF relaying scenario. Further, the use of the error correcting codes can be used to improve the performance of conventional DF relaying scheme.

Fig. 6a and Fig. 6b show the outage probability and average SER of the proposed system with respect to the FSO transmit power for different weather attenuation conditions (Table III). From the plots, it is observed that the hybrid FSO/RF system in clear air conditions outperforms the haze and rain conditions due to less severe weather attenuation. However, it is also observed that the system in rainy conditions outperforms clear air and haze conditions in high SNR region even though the attenuation rain conditions is high. This is due to the fact that the atmospheric turbulence is low for the high attenuation weather condition (refer Table III). Therefore, it observed that the atmospheric turbulence has severe effect on the performance of the hybrid FSO/RF system than the weather attenuation.

Fig. 7. Average SER vs average SNR of FSO and RF links ($\bar{\gamma}^f = \bar{\gamma}^r$)

In Fig. 7, we have plotted the average SER with respect to the average SNR of FSO and RF links ($\bar{\gamma}^f = \bar{\gamma}^r$), where the values of $\bar{\gamma}^f$ and $\bar{\gamma}^r$ are varied simultaneously. We have also plotted the average SER with respect to $\bar{\gamma}^f$ for the hybrid

FSO/RF system (with $\bar{\gamma}^r = 10$ dB) and for the FSO system. It is observed that at high SNR, the average SER curves for hybrid FSO/RF system merge with the SER curve of FSO system while attaining the same slope. This shows that at high SNR, the hybrid FSO/RF system completely depends on the FSO sub-system regardless of the SNR of the RF sub-system due to priority given for FSO transmission. Therefore, this shows that the RF sub-system does not contribute in improving the diversity gain of the overall system. However, RF sub-system helps in improving the coding gain of the system.

Fig. 8. Average SER vs average SNR of FSO links ($\bar{\gamma}^f$) for different modulation order and turbulence

Fig. 8 shows the average SER versus average SNR of FSO for binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), and 8-PSK modulation schemes assuming strong atmospheric turbulence condition, $\bar{\gamma}^r = 10$ dB and $L_{SD} = 3000$ m. The SER performance of the BPSK modulation scheme is better than QPSK and 8-PSK modulation schemes, as expected. We have also plotted the average SER performance curves for strong and weak turbulence conditions assuming $C_n^2 = 1 \times 10^{-13}$ and $4 \times 10^{-15} \text{ m}^{-2/3}$, respectively [27]. We can observe that the proposed system performs better under weak turbulence conditions. For example, the proposed system achieves an average SER value of 10^{-2} with the SNR gain of more than 11 dB compared to strong turbulence condition.

Fig. 9 shows the performance of the proposed system for different link distance values and fading severity parameter m_j under strong turbulence condition. From (8), the values of α_{SD} and β_{SD} considering $L_{SD} = 3000$ m are given by 2.184 and 1.187, respectively. And, the value of $\alpha_{SR} = \alpha_{RD}$ and $\beta_{SR} = \beta_{RD}$ considering $L_{SR} = L_{RD} = 1500$ m are given by 2.316 and 1.847, respectively. Similarly, they are calculated for the case when $L_{SD} = 1000$ m. It is observed that the hybrid

Fig. 9. Average SER vs average SNR of FSO links ($\bar{\gamma}^f$) for different values of link distance L

FSO/RF system with a shorter link distance greatly improves the SER performance. This is because, as the value of L_{SD} increases, the values of α_{SD} and β_{SD} decreases and the system is more prone to atmospheric turbulence, which affects the performance to a greater extent. For plotting the non-identical values of MMW RF links, we assume: a) $m_{SD} = 1$, $m_{SR} = 2$, and $m_{RD} = 2$ and b) $m_{SD} = 0.5$, $m_{SR} = 0.5$, and $m_{RD} = 1$ and for the identical case, we assume $m_{SD} = m_{SR} = m_{RD} = m = 5$. It is noticed that the hybrid FSO/RF system offers the SNR gain value of 9 dB and 7dB for identical and non-identical scenarios, respectively, to achieve the average SER value of 3×10^{-5} , compared to the FSO system. Thus, due to high fading severity, there is a decrease in the SNR gain of around 2 dB for non-identical scenario. We have also verified the theoretical analysis performed for identical and non-identical scenarios using simulations. The trends of the plots suggest that the proposed hybrid FSO/RF system performs well for both the scenarios compared to the existing FSO system.

VII. CONCLUSIONS

In this paper, we proposed a novel switching scheme for a selective DF-relaying-based hybrid FSO/RF system with MRC. We investigated the performance of the proposed scheme by obtaining the exact and asymptotic outage probability and average SER expressions in closed-form. It is inferred from the asymptotic expression that the diversity order of the proposed system is equal to β . It is observed from the simulation results that the proposed hybrid system with MRC performs better than the SH hybrid system and cooperative FSO system with MRC due to diversity and switching benefits, respectively.

APPENDIX A

AVERAGE SER OF FSO SUB-SYSTEM

In this appendix, we define all the terms in (28) to derive the average SER of the FSO sub-system. $B_{MRC}^f(\gamma_{th}^f)$ can be expressed as

$$B_{MRC}^f(\gamma_{th}^f) = \int_{\gamma_{th}^f}^{\infty} p(e|\gamma) f_{\gamma_{MRC}^f}(\gamma) d\gamma = B_{MRC}^f - B_{MRC}^{f,out}(\gamma_{th}^f), \quad (38)$$

where B_{MRC}^f , the average SER of FSO system, is given by

$$B_{MRC}^f = \int_0^{\infty} p(e|\gamma) f_{\gamma_{MRC}^f}(\gamma) d\gamma. \quad (39)$$

Now the average SER of FSO sub-system during the outage period (i.e. $\gamma_{MRC}^f < \gamma_{th}^f$) is given by

$$B_{MRC}^{f,out}(\gamma_{th}^f) = \int_0^{\gamma_{th}^f} p(e|\gamma) f_{\gamma_{MRC}^f}(\gamma) d\gamma. \quad (40)$$

Each term in (28) is solved using (39) and (40). $B_{j,i}^f(\gamma_{th}^f)$ in (28), where $j \in \{SR, SD\}$ and $i \in \{SD, SR\}$ is solved using (38). We substitute (10), (11) and (24) in (39) and using [32, Eq. (07.34.21.0013.01)], $B_{j,i}^f$ is given by

$$B_{j,i}^f = \frac{A}{2\sqrt{\pi}} \mathcal{A}_1^j \mathcal{J}_i \sum_{g=1}^2 \sum_{n=0}^{\infty} \frac{\ell_{1,g}}{D^{2\mu_{g,n}^i}} \mathcal{J}_{g,n}^i G_{3,6}^{4,3} \left(\frac{v_j}{D^2} \middle| \frac{\mathcal{B}_{3,g,n}^i}{\mathcal{B}_{4,g,n}^i} \right), \quad (41)$$

where $\mathcal{A}_1^j$, $\mathcal{J}_i$, $\ell_{1,g}$, $\mathcal{J}_{g,n}^i$ and v_j are given in Table I and $\mathcal{B}_{3,g,n}^i$, $\mathcal{B}_{4,g,n}^i$ are given in Table IV. Substituting (10), (11) and (25) into (40) and using [32, Eq. (07.34.21.0084.01)], the exact expression for $B_{j,i}^{f,out}(\gamma_{th}^f)$ is given by

$$B_{j,i}^{f,out}(\gamma_{th}^f) = \frac{A \mathcal{A}_1^j \mathcal{J}_i}{2} \sum_{g=1}^2 \sum_{n=0}^{\infty} l_{3,g,n}^i G_{2,6}^{4,2} \left(v_j \gamma_{th}^f \middle| \frac{\mathcal{B}_{5,g,n}^i}{\mathcal{B}_{6,g,n}^i} \right), \quad (42)$$

where $l_{3,g,n}^i$, $\mathcal{B}_{5,g,n}^i$ and $\mathcal{B}_{6,g,n}^i$ are given in Table IV. $B_C^f(\gamma_{th}^f)$ in (28) is solved using (38). We substitute (21) and (24) in (39) and by using [32, Eq. (07.34.21.0013.01)], B_C^f is given by (43), on the top of the next page, where $\mu_{g,n}^j$, c , and c_{n_1} are given in Table I. Substituting (21) into (40) and by using similar approach as in (42), the exact expression for $B_{C,SR}^{f,out}(\gamma_{th}^f)$ is given by (44), on the top of the next page, where $\mathcal{B}_{7,g,n}^{SD,n_4}$ and $\mathcal{B}_{8g,n}^{RD,n_4}$ are given in Table IV. $B_{C,SR}^f(\gamma_{th}^f)$ in (28) is solved using (38). We substitute (11), (21) and (23) in (40). We use [29, Eq.(9.301)] to expand the Meijer G functions and the integral is solved using [35, Eq. (4.1.11)]. Using [34], we obtain a generalized Meijer G function of two variables and the final expression for $B_{C,SR}^f$ is given by

$$B_{C,SR}^f = \frac{A \mathcal{A}_1^{SR} \mathcal{A}_1^{RD} \mathcal{J}_{SD}}{2\sqrt{\pi}} \sum_{n_1=0}^{\infty} \frac{1}{n_1!} \sum_{g=1}^2 \ell_{1,g} \sum_{n=0}^{\infty} \mathcal{J}_{g,n}^{SD} B(c, c_{n_1}) \times \left[\frac{G_{2,1:1,5;2,6}^{2,0:4,1;4,2} \left(\mu_{g,n}^{SD} + \frac{3}{2}, \mu_{g,n}^{SD} + 1 \middle| \frac{1}{\mu_{g,n}^{SD} + 2} \middle| \frac{\mathcal{B}_{1,n}^{SR}}{\mathcal{B}_{2,n_1}^{RD}} - 1, 0 \middle| \frac{v_{SR}}{D^2}, \frac{v_{RD}}{D^2} \right)}{D^{2(\mu_{g,n}^{SD} + 1)}} + \frac{\mu_{g,n}^{SD} G_{2,1:1,5;1,5}^{2,0:4,1;4,1} \left(\mu_{g,n}^{SD} + 1, \mu_{g,n}^{SD} + \frac{1}{2} \middle| \frac{1}{\mu_{g,n}^{SD} + \frac{3}{2}} \middle| \frac{1}{\mathcal{B}_{1,n}^{SR}} \middle| \frac{1}{\mathcal{B}_{2,n_1}^{RD}} \middle| \frac{v_{SR}}{D^2}, \frac{v_{RD}}{D^2} \right)}{D^{2\mu_{g,n}^{SD}}} \right] \quad (45)$$

Substituting (11), (21) and (25) into (40). We use [29, Eq.(9.301)] to expand the Meijer G functions and the integral is solved using [29, Eq.(3.191.1)]. Using [34], we obtain a generalized Meijer G function of two variables and the final expression for $B_{C,SR}^{f,out}(\gamma_{th}^f)$ is given by

TABLE IV
NOTATIONS USED IN (41), (42), (44), (46), AND (48)

$l_{3,1,n}^i \triangleq \mathcal{J}_{1,n}^i(\gamma_{th}^f)^{\mu_{1,n}^i}$	$\mathcal{B}_{4,1,n}^{j,i} \triangleq \mathcal{B}_1^j, -\mu_{1,n}^i$	$\mathcal{B}_{5,3,n}^i \triangleq 1 - \mu_{1,n}^i - (n_4 + \frac{1}{2}), 1$	$\mathcal{B}_{7,3,n}^j \triangleq -\mu_{1,n}^j - n_4 - \frac{1}{2}, -1, 0$
$l_{3,2,n}^i \triangleq -\mathcal{J}_{2,n}^i(\gamma_{th}^f)^{\mu_{2,n}^i}$	$\mathcal{B}_{4,2,n}^{j,i} \triangleq \mathcal{B}_1^j, -\mu_{2,n}^i$	$\mathcal{B}_{5,4,n}^i \triangleq 1 - \mu_{2,n}^i - (n_4 + \frac{1}{2}), 1$	$\mathcal{B}_{7,4,n}^j \triangleq -\mu_{2,n}^j - n_4 - \frac{1}{2}, -1, 0$
$l_{3,3,n}^i \triangleq -\sum_{n_4=0}^{\infty} \frac{2A_{n_4}}{\sqrt{\pi}} \mathcal{J}_{1,n}^i(\gamma_{th}^f)^{\mu_{1,n}^i + n_4 + \frac{1}{2}}$	$\mathcal{B}_{5,1,n}^i \triangleq 1 - \mu_{1,n}^i, 1$	$\mathcal{B}_{6,3,n}^{j,i} \triangleq \mathcal{B}_1^j, 0, -(\mu_{1,n}^i - n_4 - \frac{1}{2})$	$\mathcal{B}_{8,1,n}^{j,i} \triangleq \mathcal{B}_2^j - 1, 0, -1, -\mu_{1,n}^i - 1$
$l_{3,4,n}^i \triangleq \sum_{n_4=0}^{\infty} \frac{2A_{n_4}}{\sqrt{\pi}} \mathcal{J}_{2,n}^i(\gamma_{th}^f)^{\mu_{2,n}^i + n_4 + \frac{1}{2}}$	$\mathcal{B}_{5,2,n}^i \triangleq 1 - \mu_{2,n}^i, 1$	$\mathcal{B}_{6,4,n}^{j,i} \triangleq \mathcal{B}_1^j, 0, -(\mu_{2,n}^i + n_4 + \frac{1}{2})$	$\mathcal{B}_{8,2,n}^{j,i} \triangleq \mathcal{B}_2^j - 1, 0, -1, -\mu_{2,n}^i - 1$
$\mathcal{B}_{3,1,n}^i \triangleq 1, 1 - \mu_{1,n}^i, -\mu_{1,n}^i + \frac{1}{2}$	$\mathcal{B}_{6,1,n}^{j,i} \triangleq \mathcal{B}_1^j, 0, -\mu_{1,n}^i$	$\mathcal{B}_{7,1,n}^{SD} \triangleq -\mu_{1,n}^{SD}, -1, 0$	$\mathcal{B}_{8,3,n}^{RD,SD} \triangleq \mathcal{B}_2^{RD} - 1, 0, -1, -\mu_{1,n}^{SD} - n_4 - \frac{3}{2}$
$\mathcal{B}_{3,2,n}^i \triangleq 1, 1 - \mu_{2,n}^i, -\mu_{2,n}^i + \frac{1}{2}$	$\mathcal{B}_{6,2,n}^{j,i} \triangleq \mathcal{B}_1^j, 0, -\mu_{2,n}^i$	$\mathcal{B}_{7,2,n}^{SD} \triangleq -\mu_{2,n}^{SD}, -1, 0$	$\mathcal{B}_{8,4,n}^{RD,SD} \triangleq \mathcal{B}_2^{RD} - 1, 0, -1, -\mu_{2,n}^{SD} - n_4 - \frac{3}{2}$

$$B_C^f = \frac{AA_1^{RD} \mathcal{J}_{SD}}{2\sqrt{\pi}} \sum_{n=0}^{\infty} \sum_{n_1=0}^{\infty} \sum_{g=1}^2 \frac{\ell_{1,g} \mathcal{J}_{g,n}^{SD} B(c, c_{n_1})}{n_1! D^{2\mu_{g,n}^{SD}}} \left[\frac{1}{D^2} G_{4,7}^{4,4} \left(\frac{v_{RD}}{D^2} \left| \begin{matrix} -1, 0, \mu_{g,n}^{SD}, \mu_{g,n}^{SD} - \frac{1}{2} \end{matrix} \right. \right) + \mu_{g,n}^{SD} G_{3,6}^{4,3} \left(\frac{v_{RD}}{D^2} \left| \begin{matrix} 1, 1 - \mu_{g,n}^{SD}, \frac{1}{2} - \mu_{g,n}^{SD} \end{matrix} \right. \right) \right] \quad (43)$$

$$B_C^{f_{out}}(\gamma_{th}^f) = \frac{AA_1^{RD} \mathcal{J}_{SD}}{2} \sum_{n_1=0}^{\infty} \frac{1}{n_1!} \sum_{g=1}^4 \sum_{n=0}^{\infty} l_{3,g,n}^{SD} B(c, c_{n_1}) \left[\gamma_{th}^f G_{3,7}^{4,3} \left(v_{RD} \gamma_{th}^f \left| \begin{matrix} \mathcal{B}_{7,g,n}^{SD} \\ \mathcal{B}_{8,g,n}^{RD,SD} \end{matrix} \right. \right) + \mu_{g,n}^{SD} G_{2,6}^{4,2} \left(v_{RD} \gamma_{th}^f \left| \begin{matrix} \mathcal{B}_{5,g,n}^{SD} \\ \mathcal{B}_{6,g,n}^{RD,SD} \end{matrix} \right. \right) \right] \quad (44)$$

$$B_{C,SR}^{f_{out}}(\gamma_{th}^f) = \frac{AA_1^{SR} A_1^{RD} \mathcal{J}_{SD}}{2} \sum_{n_1=0}^{\infty} \frac{1}{n_1!} \sum_{g=1}^4 \sum_{n=0}^{\infty} l_{3,g,n}^{SD} B(c, c_{n_1}) \quad N(\lambda, \Omega, \phi, a) = \int_{\phi}^{\infty} \text{erfc}(a\sqrt{Y}) Y^{\lambda-1} e^{-\Omega Y} dY$$

$$= \text{erfc}(a\sqrt{\phi}) \frac{\Gamma(\lambda, \Omega\phi)}{\Omega^{\lambda}} - \frac{a}{\sqrt{\pi}} \sum_{r=0}^{\lambda-1} \frac{\Omega^r \Gamma(r + \frac{1}{2}, (a^2 + \Omega)\phi)}{(a^2 + \Omega)^{r + \frac{1}{2}}}, \quad (49)$$

$$\left[\gamma_{th}^f G_{1,1:1,5:2,6}^{1,0:4,1:4,2} \left(\begin{matrix} \mathcal{B}_{7,g,n}^{SD} + 1 \\ \mathcal{B}_{7,g,n}^{SD} + 2 \end{matrix} \left| \begin{matrix} 1 \\ \mathcal{B}_1^{SR}, 0 \end{matrix} \right| \begin{matrix} -1, 0 \\ \mathcal{B}_{2,n_1}^{RD} - 1, 0, -1 \end{matrix} \right| v_{SR} \gamma_{th}^f, v_{RD} \gamma_{th}^f \right) \right. \\ \left. + G_{1,1:1,5:1,5}^{1,0:4,1:4,1} \left(\begin{matrix} \mathcal{B}_{7,g,n}^{SD} \\ \mathcal{B}_{7,g,n}^{SD} + 1 \end{matrix} \left| \begin{matrix} 1 \\ \mathcal{B}_1^{SR}, 0 \end{matrix} \right| \begin{matrix} 1 \\ \mathcal{B}_{2,n_1}^{RD} \end{matrix} \right| v_{SR} \gamma_{th}^f, v_{RD} \gamma_{th}^f \right) \right] \quad (46)$$

$B_{SR,C}^f(\gamma_{th}^f)$ in (28) is solved using (38). We substitute (10), (18) and (23) in (39). The remaining expression is solved using similar approach as in (45). The final expression for $B_{SR,C}^f$ is given by

$$B_{SR,C}^f = \frac{A \mathcal{J}_{SR}}{2\sqrt{\pi}} \sum_{n_1=0}^{\infty} \mathcal{A}_{n_1} \sum_{g=1}^2 \ell_{1,g} \sum_{n=0}^{\infty} \frac{\mathcal{J}_{g,n}^{SR}}{D^{2\mu_{g,n}^{SR}}} \times G_{2,1:1,5:1,5}^{2,0:4,1:4,1} \left(\begin{matrix} \mu_{g,n}^{SR} + \frac{1}{2}, \mu_{g,n}^{SR} \\ \mu_{g,n}^{SR} + 1 \end{matrix} \left| \begin{matrix} 1 - n_1 \\ \mathcal{B}_1^{SD} \end{matrix} \right| \begin{matrix} 1 \\ \mathcal{B}_{2,n_1}^{RD} \end{matrix} \right| \frac{v_{SD}}{D^2}, \frac{v_{RD}}{D^2} \right) \quad (47)$$

Substituting (10), (18) and (25) into (40) and similar approach is used as in (46) to solve the remaining expression. The final expression for $B_{SR,C}^{f_{out}}(\gamma_{th}^f)$ is given by

$$B_{SR,C}^{f_{out}}(\gamma_{th}^f) = \frac{A \mathcal{J}_{SR}}{2} \sum_{n_1=0}^{\infty} \mathcal{A}_{n_1} \sum_{g=1}^4 \sum_{n=0}^{\infty} l_{3,g,n}^{SR} \times G_{1,1:1,5:1,5}^{1,0:4,1:4,1} \left(\begin{matrix} \mathcal{B}_{7g}^{SR} \\ \mathcal{B}_{7g}^{SR} + 1 \end{matrix} \left| \begin{matrix} 1 - n_1 \\ \mathcal{B}_1^{SD} \end{matrix} \right| \begin{matrix} 1 \\ \mathcal{B}_{2,n_1}^{RD} \end{matrix} \right| v_{SD} \gamma_{th}^f, v_{RD} \gamma_{th}^f \right). \quad (48)$$

APPENDIX B

AVERAGE SER OF RF SUB-SYSTEM

In this appendix, we define all the terms in (28) to derive the average SER of the RF sub-system. In order to derive (28), we define the following functions, as given by

where the expression in (49) is solved using integration by parts as in [6, Eq.(18)] using [29, Eq. (2.33.10) and (2.33.11)], $\Gamma(\cdot, \cdot)$ is the upper incomplete gamma function [29, Eq. (8.350.2)] and

$$P(\lambda, \phi, a) = \int_{\phi}^{\infty} \text{erfc}(a\sqrt{Y}) Y^{\lambda-1} dY \\ = \frac{(-\phi)^{\lambda}}{\lambda} \text{erfc}(a\sqrt{\phi}) + \frac{a^{-2\lambda}}{\lambda \sqrt{\pi}} \Gamma\left(\lambda + \frac{1}{2}, a^2 \phi\right) \quad (50)$$

The integral in (50) is solved using MATHEMATICA. To solve $B_{j,i}^r(\gamma_{th}^r)$, where $j \in \{SD, SR\}$ and $i \in \{SR, SD\}$, we substitute (13), (14), and (23) in (28). Using [29, Eq.(8.352.6)] and (49), $B_{j,i}^r(\gamma_{th}^r)$ is given by

$$B_{j,i}^r(\gamma_{th}^r) = \frac{Aw_j^{m_j}}{2\Gamma(m_j)} \left[N(m_j, w_j, \gamma_{th}^r, D) - \sum_{k_2=0}^{m_i-1} \frac{w_i^{k_2}}{k_2!} N(m_j + k_2, w_{j,i}, \gamma_{th}^r, D) \right] \quad (51)$$

where $w_{j,i} \triangleq w_j + w_i$. To solve $B_C^r(\gamma_{th}^r)$, we substitute (22) and (23) in (28). Using (49) and (50), $B_C^r(\gamma_{th}^r)$ is given by

$$B_C^r(\gamma_{th}^r) = \frac{A}{2} \sum_{n_2=0}^{\infty} \sum_{k_1=0}^{m_{RD}+n_2} C_{n_2}^{k_1} (C_{k_1}^m - 1)! \left[P(C_{n_2, k_1}^m, \gamma_{th}^r, D) \times C_{n_2, k_1}^m - \sum_{p_1=0}^{C_{k_1}^m-1} \frac{w_{SD}^{p_1}}{p_1!} C_{n_2, k_1}^{m, p_1} N(C_{n_2, k_1}^{m, p_1}, w_{SD}, \gamma_{th}^r, D) \right. \\ \left. + \sum_{p_1=0}^{C_{k_1}^m-1} \frac{w_{SD}^{p_1+1}}{p_1!} N(C_{n_2, k_1}^{m, p_1} + 1, w_{SD}, \gamma_{th}^r, D) \right], \quad (52)$$

$$\begin{aligned}
B_{C,SR}^r(\gamma_{th}^r) = & \frac{A}{2} \sum_{n_2=0}^{\infty} \sum_{k_1=0}^{m_{RD}+n_2} C_{n_2}^{k_1} (C_{k_1}^m - 1)! \left[C_{n_2,k_1}^m \left\{ P(C_{n_2,k_1}^m, \gamma_{th}^r, D) - \sum_{k_2=0}^{m_{SR}-1} \frac{w_{SR}^{k_2}}{k_2!} N(C_{n_2,k_1}^m + k_2 + 1, w_{SD}, \gamma_{th}^r, D) \right\} \right. \\
& - \sum_{p_1=0}^{C_{k_1}^m-1} \frac{w_{SD}^{p_1}}{p_1!} (C_{n_2,k_1}^m + p_1) \left\{ N(C_{n_2,k_1}^{m,p_1}, w_{SD}, \gamma_{th}^r, D) - \sum_{k_2=0}^{m_{SR}-1} \frac{w_{SD}^{k_2}}{k_2!} N(C_{n_2,k_1}^{m,p_1} + k_2, w_{SD,SR}, \gamma_{th}^r, D) \right\} \\
& \left. + \sum_{p_1=0}^{C_{k_1}^m-1} \frac{w_{SD}^{p_1+1}}{p_1!} \left\{ N(C_{n_2,k_1}^{m,p_1} + 1, w_{SD}, \gamma_{th}^r, D) - \sum_{k_2=0}^{m_{SR}-1} \frac{w_{SD}^{k_2}}{k_2!} N(C_{n_2,k_1}^{m,p_1} + k_2 + 1, w_{SD,SR}, \gamma_{th}^r, D) \right\} \right]. \quad (53)
\end{aligned}$$

$$B_{SR,C}^r(\gamma_{th}^r) = \frac{A}{2} \sum_{n_2=0}^{\infty} \sum_{k_1=0}^{m_{RD}+n_2} C_{n_2}^{k_1} \frac{w_{SR}^{m_{SR}}}{\Gamma(m_{SR})} (C_{k_1}^m - 1)! N(C_{n_2,k_1}^m + m_{SR}, w_{SR}, \gamma_{th}^r, D) - \sum_{k_2=0}^{m_{SD}-1} \frac{w_{SD}^{k_2}}{k_2!} N(C_{n_2,k_1}^m + m_{SR} + k_2, w_{SD,SR}, \gamma_{th}^r, D). \quad (54)$$

$$f_{\gamma_C^f}(\gamma) = \sum_{n_1=0}^{\infty} \frac{\mathcal{A}_{n_1}}{\gamma} \left[G_{2,6}^{4,2} \left(v_{RD} \gamma \middle| \begin{smallmatrix} 0, 1 \\ \mathcal{B}_{2,n_1}^{RD} 1, 0 \end{smallmatrix} \right) G_{1,5}^{4,1} \left(v_{SD} \gamma \middle| \begin{smallmatrix} 1 - n_1 \\ \mathcal{B}_1^{SD}, -n_1 - \frac{\alpha_{RD}}{2} \end{smallmatrix} \right) + G_{1,5}^{4,1} \left(v_{RD} \gamma \middle| \begin{smallmatrix} 1 \\ \mathcal{B}_{2,n_1}^{RD} 0 \end{smallmatrix} \right) G_{2,6}^{4,2} \left(v_{SD} \gamma \middle| \begin{smallmatrix} 0, 1 - n_1 \\ \mathcal{B}_1^{SD}, -n_1 - \frac{\alpha_{RD}}{2} \end{smallmatrix} \right) \right] \quad (56)$$

To solve $B_{C,SR}^r(\gamma_{th}^r)$, we substitute (22) and (14) in (28). Using [26, Eq.(8.352.6)], (49) and (50), $B_{C,SR}^r(\gamma_{th}^r)$ is given by (53). To solve $B_{SR,C}^r(\gamma_{th}^r)$, we substitute (19) and (13) in (28). Using [26, Eq.(8.352.6)], (49) and (50), $B_{SR,C}^r(\gamma_{th}^r)$ is given by (54).

APPENDIX C

ASYMPTOTIC SER ANALYSIS OF FSO SUB-SYSTEM

In this appendix, we define the terms in (36) to derive the asymptotic average SER of the hybrid system. By applying [32, Eq. (07.34.06.0040.01)] in (9) and (11), the resultant expression along with (24) are substituted into (36). The remaining integral is solved using [32, Eq. (07.34.21.0085.01)]. Finally, the closed-form expression of $B_{j,i}^{\infty f}(\gamma_{th}^f)$, where $j \in \{SR, SD\}$ and $i \in \{SD, SR\}$, is given by

$$\begin{aligned}
B_{j,i}^{\infty f}(\gamma_{th}^f) = & \sum_{k=1}^4 \sum_{k_3=1}^2 \frac{A \mathcal{A}_1^j \mathcal{A}_1^i}{2\sqrt{\pi}} \Lambda_{4,k_3}^j \Lambda_{1,k}^i \Lambda_{x_{1,k_3,k}} \\
& \times [\bar{\gamma}_j^f]^{-v_j} [\bar{\gamma}_i^f]^{-v_i}, \quad (55)
\end{aligned}$$

where $\Lambda_{1,k}^i$ is given in Table II, Λ_{4,k_3}^j , $\Lambda_{x_{1,k_3,k}}$, and $x_{1,k_3,k}$ are given in Table V. In order to obtain simple expressions

TABLE V
NOTATIONS USED IN ASYMPTOTIC SER ANALYSIS

$\Lambda_{4,k_3}^j \triangleq \prod_{q=1, q \neq k_3}^2 \Gamma(\Re_q^j - \Re_{k_3}^j) (\alpha\beta)^{\Re_{k_3}^j}$
$\Lambda_{5,n_1,k}^j \triangleq \prod_{q=1, q \neq k}^4 \Gamma(\mathcal{B}_{2,n_1,q}^j - \mathcal{B}_{2,n_1,k}^j) \left[\frac{(\alpha_j \beta_j)^2}{16} \right]^{\mathcal{B}_{2,n_1,k}^j}$
$\Lambda_{6,k}^j \triangleq \left(\Lambda_2^{SD} \frac{\Gamma(1+\mathcal{B}_{1,k}^{SD})}{\Gamma(\mathcal{B}_{1,k}^{SD})} \right), \Lambda_{x_g} \triangleq \left(\gamma_{th}^f \right)^{x_g} G_{2,3}^{3,0} \left(D^2 \gamma_{th}^f \middle \begin{smallmatrix} 1, 1 - x_g \\ -x_g, 0, \frac{1}{2} \end{smallmatrix} \right)$
$x_{1,k_3,k} \triangleq \left(\frac{\Re_{k_3}^j}{2} + \mathcal{B}_{1,k}^i \right), x_{2,n_1,k} \triangleq \left(\mathcal{B}_{1,k}^{SD} + \mathcal{B}_{2,n_1,k}^{RD} \right)$
$x_{3,n_1,k} \triangleq \left(\mathcal{B}_{1,k}^{SD} + \mathcal{B}_{1,k}^{SR} + \mathcal{B}_{2,n_1,k}^{RD} \right)$
$x_{4,n_1,k,k_3} \triangleq \left(\mathcal{B}_{1,k}^{SD} + \mathcal{B}_{2,n_1,k}^{RD} + \frac{\Re_{k_3}^{SR}}{2} \right)$

for $B_C^{\infty f}(\gamma_{th}^f)$ and $B_{C,SR}^{\infty f}(\gamma_{th}^f)$ we recalculate $f_{\gamma_C^f}(\gamma)$ by differentiating (18) with respect to γ to obtain (56). The

procedure to solve $B_C^{\infty f}(\gamma_{th}^f)$ is similar to that of solving (55). Finally, the closed-form expression of $B_C^{\infty f}(\gamma_{th}^f)$ is given by

$$\begin{aligned}
B_C^{\infty f}(\gamma_{th}^f) = & \frac{A}{2\sqrt{\pi}} \sum_{n_1=0}^{\infty} \sum_{k=1}^4 \mathcal{A}_{n_1} \Lambda_{x_{2,n_1,k}} \left[\Lambda_{2,k}^{SD} \Lambda_{5,n_1,k}^{RD} \right. \\
& \left. + \Lambda_{3,n_1,k}^{RD} \Lambda_{6,k}^{SD} \right] [\bar{\gamma}_{SD}^f]^{-v_{SD}} [\bar{\gamma}_{RD}^f]^{-v_{RD}}, \quad (57)
\end{aligned}$$

where $\Lambda_{2,k}^{SD}$, $\Lambda_{3,n_1,k}^{RD}$ are given in Table II, $\Lambda_{5,n_1,k}^{RD}$, $\Lambda_{6,k}^{SD}$, $\Lambda_{x_{2,n_1,k}}$ and $x_{2,n_1,k}$ are given in Table V. Using a similar approach as in (55), a closed-form expression of $B_{C,SR}^{\infty f}(\gamma_{th}^f)$ is given by

$$\begin{aligned}
B_{C,SR}^{\infty f}(\gamma_{th}^f) = & \frac{A \mathcal{A}_1^{SR}}{2\sqrt{\pi}} \sum_{n_1=0}^{\infty} \sum_{k=1}^4 \mathcal{A}_{n_1} \Lambda_{x_{3,n_1,k}} \left[\Lambda_{2,k}^{SD} \Lambda_{5,n_1,k}^{RD} \Lambda_{1,k}^{SR} \right. \\
& \left. + \Lambda_{3,n_1,k}^{RD} \Lambda_{6,k}^{SD} \Lambda_{1,k}^{SR} \right] [\bar{\gamma}_{SR}^f]^{-v_{SR}} [\bar{\gamma}_{RD}^f]^{-v_{RD}} [\bar{\gamma}_{SD}^f]^{-v_{SD}}, \quad (58)
\end{aligned}$$

where $\Lambda_{x_{3,n_1,k}}$ and $x_{3,n_1,k}$ are given in Table V. The closed-form expression for $B_{SR,C}^{\infty f}(\gamma_{th}^f)$ can be obtained with a similar approach used in (55) and the expression is given by

$$\begin{aligned}
B_{SR,C}^{\infty f}(\gamma_{th}^f) = & \sum_{n_1=0}^{\infty} \sum_{k=1}^4 \sum_{k_3=1}^2 \frac{A \mathcal{A}_1^{SR} \mathcal{A}_{n_1}}{2\sqrt{\pi}} \Lambda_{4,k_3}^{SR} \Lambda_{3,k}^{RD,n_1} \Lambda_{2,k}^{SD} \\
& \times \Lambda_{x_{4,n_1,k,k_3}} [\bar{\gamma}_{SR}^f]^{-v_{SR}} [\bar{\gamma}_{RD}^f]^{-v_{RD}} [\bar{\gamma}_{SD}^f]^{-v_{SD}}, \quad (59)
\end{aligned}$$

where $\Lambda_{x_{4,n_1,k,k_3}}$ and x_{4,n_1,k,k_3} are given in Table V.

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