Performance Analysis of a Decode-and-forward based Mixed RF-FSO-VLC System

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Performance Analysis of a Decode-and-forward based Mixed RF-FSO-VLC System

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Abstract In this paper, the performance analysis of a cooperative radio frequency-free space optical communication-visible-light-communication (RF-FSO-VLC) system using decode-and-forward (DF) relays is presented. In the proposed model, the RF link acts as the core network, the FSO link is used for providing last mile connectivity for the indoor cell users communicating through VLC environment. The RF link is characterized by Nakagami- m -distributed fading, while the FSO link undergoes Double Generalized Gamma (DGG) distributed atmospheric turbulence and pointing errors and the VLC link is characterized by the Lambertian pattern of the LED. The closed-form expressions of the statistical characteristics of signal-to-noise-ratio (SNR) of the DF based triple-hop system are evaluated using which various performance metrics, i.e., outage probability, bit error rate (BER), and capacity of the considered system are obtained. The numerical results show that the system's performance gets severely affected by the RF fading, atmospheric turbulence, and pointing errors. The outage performance of the system decreases as field-of-view (FOV) and the height of the light-emitting-diode (LED) increase. It is also seen from the results that the BER performance of the system is better in case of heterodyne detection as compared to direct-detection. It is also observed that the capacity of the system decreases when the effect of atmospheric turbulence and pointing error is high and it increases when the no. of LEDs increases.

Keywords Free space optics, visible light communication, radio frequency, decode-and-forward, outage probability, bit error rate, capacity

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Fig. 1 Model of DF based triple-hop RF-FSO-VLC system.

1 Introduction

Optical Wireless Communication (OWC) offers wireless connectivity using infra-red (IR), visible or ultra-violet bands and enables features like high bandwidth, low cost, and operation in license free spectrum [1]. The OWC is a promising communication technology which incorporates benefits of both wireless and optical communication. OWC systems can also be installed on those locations where wired communication is not feasible, providing last mile access and backhaul connectivity [2]. Apart from contributing a large and unlicensed band in comparison to radio spectrum, the VLC technology is clustered with numerous other benefits like availability, no electromagnetic interference, high bandwidth, low power consumption etc.

Visible light communication (VLC) carries information by modulating optical signal lying in the visible spectrum (400-700 nm) that is mainly used for illumination. The VLC systems often employ light emitting diodes (LEDs), for both illumination and data communications [3, 4]. In [5], the effect of a rapidly changing driving current, due to data modulation, on the emitted light quality of illumination LEDs is experimentally investigated. In [6], the development of such VLC links for implementation in broadcasting networks featuring advanced modulation formats such as orthogonal frequency division multiplexing (OFDM) or carrier-less amplitude and phase modulation (CAP) in conjunction with equalization techniques are discussed. An adaptive MIMO-OFDM based VLC system is discussed in [7] where, spatial dimension is considered as an adaptation parameter. It discusses a joint MIMO mode selection and bit loading scheme to maximize the spectral efficiency (SE) while satisfying a given bit-error rate (BER) target. The performance analysis of non-orthogonal multiple access (NOMA) in a downlink VLC system is discussed in [8] where analytical expression of the system coverage probability and a closed-form expression of the ergodic sum rate applicable for arbitrary power allocation strategies are derived.

Free space Optical communication (FSO) represents terrestrial point-to-point OWC using lasers and photodetectors to carry out transmission in the IR frequency band. The applications of FSO include short-distance interconnects on integrated circuits, indoor communications, terrestrial outdoor links, and under water optical communication links [9, 10]. The performance of an FSO system is mostly dependent on the weather conditions, path loss, atmospheric turbulence, and pointing errors. In order to investigate the effect of atmospheric turbulence in FSO link, various statistical channel models have been proposed in different research studies. Among them Log-Normal, Gamma-Gamma, and Negative exponential models are in high compliance

with experimental results for weak, moderate to strong, and saturate atmospheric turbulence regime, respectively [11]. However recently proposed Malaga and Double Generalized Gamma (DGG) atmospheric turbulence models have been proposed in [12] and [13] can be used for entire turbulence regime, respectively. The FSO link also suffers from pointing errors, which arise by the misalignment between the transmitter and the receiver, caused by the mechanical vibrations present in the system due to wind, earthquakes, thermal expansion etc. [14].

Some solutions of reducing the effects of atmospheric turbulence and pointing errors proposed in the literature are radio-on-FSO system [15, 16], [17], [18], [19], [20], hybrid RF/FSO communication system [21], [22], [23], [24], [25], [26] multiple-input-multiple-output (MIMO) system [27], [28], and FSO based cooperative communication system [29–32]. By applying different types of relaying techniques, the coverage area of the FSO systems can be increased and also improving the performance and capacity of the system. In [33] and [34], the performance analysis in terms of outage probability, BER, and capacity of a dual-hop asymmetric RF/FSO communication system is performed using amplify and forward (AF) and decode-and-forward (DF) relays, respectively, where, the RF link experiences Nakagami- m fading and FSO link experiences Gamma-Gamma turbulence. Analysis of a secure dual-hop mixed RF-FSO down link for simultaneous wireless information and power transfer system is presented in [35]. A triple-hop DF based mixed RF/FSO/RF system is analyzed in [36], where terrestrial stations communicate with the relays over RF links and the relays communicate with each other over an FSO link. The RF links are characterized by Nakagami- m fading and the FSO link is characterized by path loss, DGG distributed turbulence, and pointing errors. The analysis of indoor relay assisted hybrid RF/VLC system in order to improve the coverage of the wireless system is proposed in [37]. The expressions for the outage probability for a predetermined threshold signal-to-noise-ratio (SNR) and BER performance using pulse position modulation method are obtained. In [38], the outage and the BER performance of the hybrid VLC-RF system under DF and AF schemes are studied. In [39], a cooperative VLC system where an intermediate light source acts as a relay terminal is discussed. The performance evaluations demonstrate the superiority of full-duplex relaying over half-duplex counter part especially for high modulation sizes. A hybrid system with multiple VLC access points (APs) and RF APs is designed and compared in [40]. In indoor environments, VLC APs can provide very high data rates whilst satisfying illumination requirements, and RF APs can offer ubiquitous coverage. It is assumed that the VLC system resources are fixed, and the study quantifies the spectrum and power requirements for a RF system, which after introduction to the VLC system, achieves better per user rate performance.

In this work, the performance analysis of a DF based triple-hop RF-FSO-VLC cooperative system is presented. Since FSO and VLC technologies can be easily integrated with the existing RF technology, this proves as a boon of using the advantages of OWC systems in synergy with existing RF systems. The proposed system provides connectivity between the existing backbone RF network to the end users by the last mile FSO-VLC communication link. VLC uses LEDs for data transmission along with room illumination ensuring safety to human health without extra cost making VLC ideal candidate for indoor communication. The multiple LEDs are mounted on

the ceiling of a room to transmit the data to the end users present in the room. The LEDs are uniformly distributed over the coverage area of the room. However the indoor VLC system must be connected to the outdoor network to establish communication. FSO has garnered significant attention as last mile access solution providing flexibility over optical fibers in terms of deployment and installation specially in topographically challenging locations. For example, in [41], authors have experimentally investigated cascaded FSO/VLC communication link with data aggregation and distribution. In [42], authors have statistically analysed the FSO/VLC link and its outage and BER performance under various channel conditions. In [16], the performance for RF-FSO-VLC system for outage probability and BER for binary modulation technique considering erroneous detection by the relays are discussed. In this study, the relays use the subcarrier-intensity modulation (SIM) technique to transmit the optical signals and the receiving nodes uses either heterodyne or intensity modulation/direct detection (IM/DD) technique. The RF link experiences Nakagami- m fading, the FSO link is modeled by DGG turbulence, path loss, and pointing errors, and VLC links are characterized by Lambertian pattern in the considered cooperative system. Our main contributions are as follows: (1) closed-form mathematical expressions for various statistical characteristics of SNR of the considered system, i.e, cumulative distribution function (CDF) and probability density function (PDF), (2) analytical expressions of the outage probability, BER for different modulation schemes, and the ergodic capacity of the considered system, and (3) study of the effect of the system and channel parameters on the performance metrics of the considered cascaded system.

2 System Model

A DF based triple-hop RF-FSO-VLC cooperative system is considered in this paper. The relay R_1 receives the electrical signal transmitted by source (S) and decodes it as shown in Fig. 1. The signal received at R_1 can be expressed as

$$y_{s,r1} = h_{s,r1}x + e_{s,r1}, \quad (1)$$

where, $h_{s,r1}$ represents Nakagami- m distributed channel gain of the RF link, x denotes the signal transmitted by source S, $e_{s,r1}$ is the complex valued additive white gaussian noise (AWGN) with zero mean and $\sigma_{s,r1}^2$ variance. The SNR of the link is $\gamma_{s,r1} = |h_{s,r1}|^2 \bar{\gamma}_{s,r1}$, where, $\bar{\gamma}_{s,r1} = E_{s,r1} / \sigma_{s,r1}^2$ is the average SNR of the RF link and $E_{s,r1}$ is the transmitted signal power and the path loss is considered to be 1. R_1 re-encodes the signal, then converts it to its corresponding optical signal thereby forwarding it to R_2 over the FSO link by using SIM scheme. In SIM technique, the RF subcarriers are modulated based on the message signal, then with proper DC bias, the intensity of the optical source is altered. That is why optical signal can be modulated by any of the RF modulation schemes. At R_2 , the relay receives the optical signal from the FSO link and decode the corresponding electrical signal and converts it to an optical signal and then transmits it through visible light environment to the end users. The signal received at R_2 is given by

$$y_{r1,r2} = \eta_{r1,r2} I_{r1,r2} \hat{x}_1 + e_{r1,r2}, \quad (2)$$

where, $\hat{x}_1$ denotes the estimated signal at R_2 , $\eta_{r1,r2}$ represents photo electronic conversion ratio of R_1 - R_2 link, $e_{r1,r2}$ is the complex AWGN with zero mean and $\sigma_{r1,r2}^2$ variance, and $I_{r1,r2} = I_l I_t I_p$ denotes the real valued irradiance of R_1 - R_2 links, in which I_l stands for the effect of path loss and is normalized to 1, I_t stands for the turbulence effect modeled by DGG, and I_p stands for the effect caused by pointing error, is considered to be Rayleigh distributed [42]. The instantaneous SNR of the considered link, $\gamma_{r1,r2} = I_{r1,r2}^2 \mu_{r1,r2}$. The average SNR, $\bar{\gamma}_{r1,r2} = \frac{E[I_r]}{E[I_t]} \mu_{r1,r2}$, where, the average electrical SNR is defined as, $\mu_{r1,r2} = \frac{(\eta E[I_t])^r}{N_0}$, r denotes the type of detection method, i.e., for heterodyne detection, $r = 1$ and for IM/DD, $r = 2$. At the destination (D), the photodetector converts the optical signal in to the electrical signal through heterodyne or IM/DD technique. The signal received at destination D is given by

$$y_{r2,d} = \rho h_t P_r \hat{x}_2 + e_{r2,d}, \quad (3)$$

where, h_t is the DC channel gain of the LOS link between LED and t -th user, ρ is electrical to optical conversion ratio of R_2 -D link, $\hat{x}_2$ is the decoded signal at D, P_r is the relay transmit power and $e_{r2,d}$ represents the complex AWGN with zero mean and variance $\sigma_{r2,d}^2$. The instantaneous SNR is given by $\gamma_{r2,d} = h_t^2 \bar{\gamma}_{r2,d}$, in which average electrical SNR is defined as, $\bar{\gamma}_{r2,d} = \rho^2 P_r^2 / \sigma_{r2,d}^2$.

3 Channel Model

In this section, the channel models used for VLC and FSO links along with the various factors affecting them.

3.1 RF Link

The RF link is assumed to undergo Nakagami- m distributed fading, therefore, the instantaneous SNR of the RF link will be Gamma distributed with PDF given by [34]

$$f_{\gamma_R}(\gamma) = \frac{m^m \gamma^{m-1}}{\Gamma(m) \bar{\gamma}^m} e^{-m\gamma/\bar{\gamma}}, \quad (4)$$

where, γ is the instantaneous SNR, $\Gamma(\cdot)$ is a Gamma function, $\bar{\gamma}$ is the average SNR of RF link, and m is the Nakagami parameter. The CDF can be obtained as

$$F_{\gamma_R}(\gamma) = \frac{1}{\Gamma(m)} \gamma \left(m, \frac{m\gamma}{\bar{\gamma}} \right), \quad (5)$$

where, $\gamma(s, x) = \int_0^x t^{s-1} e^{-t} dt$ is the lower incomplete Gamma function.

3.2 FSO Link

As the FSO link is characterized by atmospheric turbulence and pointing errors, the PDF of the instantaneous SNR of FSO link is characterized by DGG turbulence and Rayleigh distributed pointing errors. The unified PDF of SNR of FSO link for both type of detection techniques, heterodyne detection and IM/DD, is written as [42]

$$f_{\gamma_F}(\gamma) = \frac{C_1}{r\gamma} G_{1,\lambda+\sigma+1}^{\lambda+\sigma+1,0} \left(C_2 h \alpha_2 \lambda \left(\frac{\gamma}{\mu_r} \right)^{\frac{\alpha_2 \lambda}{r}} \middle| \begin{matrix} K_2 \\ K_1 \end{matrix} \right), \quad (6)$$

where, $C_1 = \frac{\varepsilon^2 \sigma \beta_1 - 0.5 \lambda \beta_2 - 0.5 (2\pi)^{1 - \frac{(\lambda+\sigma)}{2}}}{\Gamma(\beta_1) \Gamma(\beta_2)}$, $C_2 = \frac{\beta_1^\sigma \beta_2^\lambda}{\lambda^\lambda \sigma^\sigma \Omega_1^\sigma \Omega_2^\lambda}$, λ and σ are positive integers such that $\frac{\lambda}{\sigma} = \frac{\alpha_1}{\alpha_2}$, $K_1 = \frac{\varepsilon^2}{\alpha_2 \lambda}$, $\Delta(\sigma : \beta_1)$, $\Delta(\lambda : \beta_2)$, $K_2 = \frac{\alpha_2 \lambda + \varepsilon^2}{\alpha_2 \lambda}$ and, $h = \frac{C_1 B_1}{(1+\varepsilon^2) C_2^{\frac{1}{\alpha_2 \lambda}}}$, $B_1 = \prod_{i=1}^{\sigma+\lambda} \Gamma(\frac{1}{\alpha_2 \lambda} + K_{0,i})$, $K_{u,v}$ is the v th-term of K_u , $\Delta(x : y) = \frac{y}{x}, \frac{y+1}{x}, \dots, \frac{y+x-1}{x}$. Now, the CDF of the SNR of the FSO link is given by

$$F_{\gamma_F}(\gamma) = \frac{\varepsilon^2 \sigma \beta_1 - 0.5 \lambda \beta_2 - 0.5 (2\pi)^{1 - \frac{r(\lambda+\sigma)}{2}} r^{\beta_1 + \beta_2 - 2}}{\alpha_2 \lambda \Gamma(\beta_1) \Gamma(\beta_2)} \times G_{r+1,u+1}^{u,1} \left(c \left(\frac{\gamma}{\mu_r} \right)^{\alpha_2 \lambda} \middle| \begin{matrix} 1, k_3 \\ k_4, 0 \end{matrix} \right), \quad (7)$$

where, $u = r(\lambda + \sigma + 1)$, $c = (\frac{C_2 h \alpha_2 \lambda}{r^{\lambda+\sigma}})^r$, $k_3 = \Delta(r : K_2)$, and $k_4 = \Delta(r : K_1)$.

3.3 VLC Link

The VLC model is used for indoor cell connectivity, where the LED transmitter is placed at height L , from the m_{th} end user, the angle of incidence Ψ_t , with the angle of irradiance, θ_t , r_e is the maximum radius of a LED cell footprint, ϕ_c is the FOV of the photodiode. The Euclidian distance d_t for the t_{th} user as shown in Fig. 2 is given by $d_t = (r_t^2 + L^2)^{1/2}$ and $\cos(\Psi) = \cos(\phi) = L/d_t$.

The PDF of channel gain can be derived using the change of variable method and is given by [8]

$$f_{h_t}(h) = \frac{2}{r_e^2 (m_l + 3)} (\omega (m_l + 1) L^{m_l + 1})^{2/m_l + 3} h^{-(2/m_l + 3) - 1}, \quad (8)$$

where, $h_t = \frac{\omega (m_l + 1) L^{m_l + 1}}{(r_t^2 + L^2)^{\frac{m_l + 3}{2}}}$, r_t is the radius on the polar coordinate plane, $\omega = \frac{1}{2\pi} A R_p U(\Psi_t) g(\Psi_t)$,

A , is the photodetector area, $R_0(\theta_t)$, is the Lambertian radiant intensity of the transmitting LED and is expressed as $R_0(\theta_t) = \frac{m_l + 1}{2\pi} \cos^m(\theta_t)$, $U(\Psi)$ is the gain of the optical filter, $g(\Psi)$ is the gain of optical concentrator and given as

$$g(\Psi_t) = \begin{cases} \frac{n^2}{\sin^2 \phi_c} & \text{if } 0 \leq \Psi_t \leq \phi_c, \\ 0 & \text{if } \Psi_t > \phi_c. \end{cases}$$

Fig. 2 Geometrical representation of VLC propagation model.

and, n denotes refractive index, m_l is the order of Lambertian emission defined as $m_l = \frac{-\ln 2}{\ln(\cos(\theta_{1/2}))}$, with $\theta_{1/2}$, denoting the transmitter semi-angle at half power. The PDF of the instantaneous SNR, $\gamma_V = \bar{\gamma}_V h_t^2$, is given in [8] as

$$f_{\mathcal{W}}(\gamma) = \frac{\frac{1}{\bar{\gamma}_V^{m_l+3}}}{r_e^2(m_l+3)} (\omega(m_l+1)L^{m_l+1})^{2/m_l+3} \gamma^{-\frac{m_l+4}{m_l+3}}, \quad (9)$$

where, $\bar{\gamma}_V = \frac{\rho P^2}{N_0 B}$, P is transmitted optical power, N_0 being noise spectral density and B is the base-band modulation bandwidth. The CDF is given by

$$F_{\mathcal{W}}(\gamma) = \frac{-1}{r_e^2} (\omega(m_l+1)L^{m_l+1})^{2/m_l+3} \left(\frac{\gamma}{\bar{\gamma}_V} \right) + \left(1 + \frac{L^2}{r_e^2} \right). \quad (10)$$

Now, assuming that all VLC links are independent and identical, the CDF of the SNR for best possible VLC link is given by [8]

$$F_{\mathcal{W}}(\gamma) = \left[\frac{-1}{r_e^2} (\omega(m_l+1)L^{m_l+1})^{2/m_l+3} \left(\frac{\gamma}{\bar{\gamma}_V} \right) + \left(1 + \frac{L^2}{r_e^2} \right) \right]^N. \quad (11)$$

Now, by applying Binomial approximation $(a+b)^n = \sum_0^n \binom{n}{k} a^{n-k} b^k$ in (11) and rearranging the terms, the CDF of the SNR of the VLC link is derived as [8]

$$F_{\mathcal{W}}(\gamma) = v_t^N - N v_t^{N-1} \chi \left(\frac{\gamma}{\bar{\gamma}_V} \right)^{-1/m_l+3}, \quad (12)$$

where, $v_t = \left(1 + \frac{L^2}{r_e^2} \right)$, $\chi = \frac{1}{v_t r_e^2} (\omega(m_l+1)L^{m_l+1})^{2/m_l+3}$, and N is the number of VLC access points.

4 Statistical Characteristics Of Instantaneous SNR of the DF based Triple-hop RF-FSO-VLC system

4.1 Cumulative Distribution Function

For the DF based mixed RF-FSO-VLC cooperative system, the end-to-end SNR is defined as [34],

$$\gamma_{eq} = \min(\gamma_R, \gamma_F, \gamma_V), \quad (13)$$

where, γ_R is the instantaneous SNR of the RF link, γ_F is the instantaneous SNR of the FSO link, and γ_V is the instantaneous SNR of the VLC link. The CDF of the end-to-end system is defined as,

$$F_{\gamma_{eq}}(\gamma) = 1 - [(1 - F_{\gamma_R}(\gamma)) \times (1 - F_{\gamma_F}(\gamma))(1 - F_{\gamma_V}(\gamma))]. \quad (14)$$

By substituting (5), (7), and (12) in (14), the closed-form expression for the CDF of instantaneous SNR of the considered system is obtained as

$$\begin{aligned} F_{\gamma_{eq}}(\gamma) &= 1 - \left(1 - \frac{1}{m} \gamma \left(m, \frac{m\gamma}{\tilde{\gamma}}\right)\right) \\ &\times \left(1 - \frac{\varepsilon^2 \sigma^{\beta_1-0.5} \lambda^{\beta_2-0.5} (2\pi)^{1-\frac{r(\lambda+\sigma)}{2}} r^{\beta_1+\beta_2-2}}{\alpha_2 \lambda \Gamma(\beta_1) \Gamma(\beta_2)}\right) \\ &\times G_{r+1, u+1}^{u, 1} \left(c \left(\frac{\gamma}{\mu_r}\right)^{\alpha_2 \lambda} \middle| 1, k_3 \right) \\ &\times \left(1 - v_t^N + N v_t^{N-1} \chi \left(\frac{\gamma}{\tilde{\gamma}_V}\right)^{-1/m+3}\right). \end{aligned} \quad (15)$$

4.2 Probability Density Function

From (14), the PDF of the instantaneous SNR for the DF based triple-hop system can be obtained by differentiating (14) and then by substituting PDF and CDF of the

instantaneous SNR of the corresponding RF, FSO, and VLC links as

$$\begin{aligned}
f_{\gamma_{eq}}(\gamma) = & \left[1 - \frac{\varepsilon^2 \sigma^{\beta_1-0.5} \lambda^{\beta_2-0.5} (2\pi)^{1-\frac{r(\lambda+\sigma)}{2}} r^{\beta_1+\beta_2-2}}{\alpha_2 \lambda \Gamma(\beta_1) \Gamma(\beta_2)} \right. \\
& \times \frac{m^m \gamma^{m-1}}{\Gamma(m) \bar{\gamma}^m} e^{-m\gamma \bar{\gamma}} G_{r+1, u+1}^{u, 1} \left(c \left(\frac{\gamma}{\mu_r} \right)^{\alpha_2 \lambda} \middle| \begin{matrix} 1, k_3 \\ k_4, 0 \end{matrix} \right) \Bigg] \\
& \left[1 - v_t^N - N v_t^{N-1} \chi \left(\frac{\gamma}{\bar{\gamma}_V} \right)^{-1/m_l+3} \right] \\
& + \left(1 - \frac{1}{\Gamma(m)} \gamma \left(m, \frac{m\gamma}{\bar{\gamma}} \right) \right) \left[\frac{C_1}{r\gamma} G_{1, \lambda+\sigma+1}^{\lambda+\sigma+1, 0} \left(C_2 h^{\alpha_2 \lambda} \left(\frac{\gamma}{\mu_r} \right)^{\frac{\alpha_2 \lambda}{r}} \middle| \begin{matrix} K_2 \\ K_1 \end{matrix} \right) \right. \\
& \left. \left(1 - v_t^N - N v_t^{N-1} \chi \left(\frac{\gamma}{\bar{\gamma}_V} \right)^{-1/m_l+3} \right) + \frac{\bar{\gamma}_V^{\frac{1}{m_l+3}}}{r e^2 (m_l+3)} \right. \\
& \times (\omega(m_l+1) L^{m_l+1})^2 / m_l+3 \gamma^{-\frac{m_l+4}{m_l+3}} \left(1 - \frac{\varepsilon^2 \sigma^{\beta_1-0.5} \lambda^{\beta_2-0.5}}{\alpha_2 \lambda \Gamma(\beta_1) \Gamma(\beta_2)} \right. \\
& \times (2\pi)^{1-\frac{r(\lambda+\sigma)}{2}} r^{\beta_1+\beta_2-2} G_{r+1, u+1}^{u, 1} \left(c \left(\frac{\gamma}{\mu_r} \right)^{\alpha_2 \lambda} \middle| \begin{matrix} 1, k_3 \\ k_4, 0 \end{matrix} \right) \Bigg] \quad (16)
\end{aligned}$$

5 Performance Analysis

In this section, using the expressions of statistical characteristics of the SNR of the considered system discussed in previous section, the performance of the DF based cascaded RF-FSO-VLC communication system is evaluated.

5.1 Outage Probability

The considered RF-FSO-VLC system will be in outage if system's SNR falls below predetermined threshold value " γ_{th} ". The outage probability, P_{out} , of a communication system is defined as follows

$$P_{out} = P_r[\gamma < \gamma_{th}] = F_\gamma(\gamma_{th}). \quad (17)$$

Using (14), the outage probability for the considered cooperative system is obtained.

The outage probability of the considered system depends on the fading parameter of the RF link ' m ', atmospheric turbulence parameters ' β_1' ' and ' β_2' ', and pointing errors of the FSO link, and different VLC parameters like FOV of the photodetector, height of the LED's ' L ', no of LED's ' N '.

Table 1 BER parameters for Various Modulation Techniques [14]

Binary Modulation techniques	p	q
Coherent binary frequency shift keying (CBFSK)	0.5	0.5
Coherent binary phase shift keying (CBPSK)	0.5	1
Non-coherent binary frequency shift keying (NBFSK)	1	0.5
Differential binary phase shift keying (DBPSK)	1	1

5.2 Bit Error Rate

In this subsection, the BER of the DF based triple-hop RF-FSO-VLC system is derived.

5.2.1 Binary modulation techniques

The generalized expression of average BER for various binary digital modulation techniques can be expressed in as [43]

$$P_e = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) F_\gamma(\gamma) d\gamma, \quad (18)$$

where, p and q are the BER modulations parameters describing various binary modulation techniques as shown in Table 1. Substituting $F_{\gamma_{eq}}(\gamma)$ from (14) in (18), the expression for the BER of the RF-FSO-VLC system is given by

$$P_{e,BPSK} = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) \times [1 - [(1 - F_{\gamma_R}(\gamma))(1 - F_{\gamma_F}(\gamma))(1 - F_{\gamma_W}(\gamma))]] d\gamma. \quad (19)$$

By substituting F_{γ_R} , F_{γ_F} , and F_{γ_W} from (5), (7), and (12) in (19) and using the series expansion of the lower incomplete Gamma function, i.e., $\gamma(m, \frac{m\gamma}{\gamma})$ and considering the fact that the finite summation of incomplete gamma function (from 0 to $m-1$) is valid for integer values of m , the expression of BER can be written as

$$P_{e,BPSK} = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) [1 - (R_1 - R_1 F_{\gamma_W}(\gamma) - R_1 F_{\gamma_F}(\gamma) + R_1 F_{\gamma_F}(\gamma) F_{\gamma_W}(\gamma))] d\gamma, \quad (20)$$

where, $R_1 = \exp(-\frac{m\gamma}{\gamma}) \sum_{k=0}^{m-1} \frac{(\frac{m\gamma}{\gamma})^k}{k!}$. By simplifying (20), the BER is given by

$$P_{e,BPSK} = I_1 - I_2 + I_3 + I_4 - I_5, \quad (21)$$

where,

$$\begin{aligned}
I_1 &= \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) d\gamma, \\
I_2 &= \frac{q^p R_1}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) d\gamma, \\
I_3 &= \frac{q^p R_1}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) F_{\mathcal{W}}(\gamma) d\gamma, \\
I_4 &= \frac{q^p R_1}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) F_{\mathcal{F}}(\gamma) d\gamma, \text{ and} \\
I_5 &= \frac{q^p R_1}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) F_{\mathcal{F}}(\gamma) F_{\mathcal{W}}(\gamma) d\gamma.
\end{aligned} \tag{22}$$

I_1 and I_2 are calculated as

$$I_1 = \frac{1}{2}. \tag{23}$$

and

$$I_2 = \sum_{k=0}^{m-1} R_2 \left(\frac{\bar{\gamma}}{m+q\bar{\gamma}} \right)^{(p+k)} \Gamma(p+k), \tag{24}$$

where, $R_2 = \frac{q^p}{2\Gamma(p)} \frac{(\frac{m}{\bar{\gamma}})^k}{k!}$. By substituting (5) and (12) in (22), and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)], I_3 can be derived as

$$\begin{aligned}
I_3 &= \sum_{k=0}^{m-1} R_2 v_t^N \left(\frac{\bar{\gamma}}{q\bar{\gamma}+m} \right)^k \Gamma(p+k) - \sum_{k=0}^{m-1} R_2 R_3 \\
&\times \left(\frac{\bar{\gamma}}{q\bar{\gamma}+m} \right)^{\frac{-1}{m_l+3}} \Gamma\left(p+k - \frac{1}{m_l+3}\right),
\end{aligned} \tag{25}$$

where, $R_3 = N v_t^{N-1} \chi\left(\frac{1}{\bar{\gamma}_v}\right)^{\frac{-1}{m_l+3}}$. The integral of I_4 can be derived by putting (5) and (7) in (22), and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)] as

$$\begin{aligned}
I_4 &= C_1 \sum_{k=0}^{m-1} R_2 W_1^{-(p+k)} \frac{v^{p+k-0.5}}{(2\pi)^{(v-1)0.5}} \\
&\times G_{r+v+1, u+1}^{u, 1+v} \left(c \left(\frac{v}{W_1 \mu_r} \right)^v \middle| 1, \frac{1-(p+k)}{v}, k_3 \right).
\end{aligned} \tag{26}$$

where, $W_1 = -q + \frac{m}{\bar{\gamma}}$. The integral of I_5 can be expressed by putting (5), (7), and (12) in (22), and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)] as

$$\begin{aligned}
I_5 &= C_1 \sum_{k=0}^{m-1} R_2 v_t^N W_1^{-(p+k)} \frac{v^{p+k-0.5}}{(2\pi)^{(v-1)0.5}} \\
&\times G_{r+v+1, u+1}^{u, 1+v} \left(c \left(\frac{v}{W_1 \mu_r} \right)^v \middle| 1, \frac{1-(p+k)}{v}, k_3 \right) \\
&- C_1 R_3 \sum_{k=0}^{m-1} R_2 R_4(k) R_5 G_{r+v+1, u+1}^{u, 1+v} \\
&\times \left(c \left(\frac{v}{W_1 \mu_r} \right)^v \middle| 1, \frac{1-(p+k - \frac{1}{m_l+3})}{v}, k_3 \right),
\end{aligned} \tag{27}$$

$$\begin{aligned}
I_{10} &= v_t^N C_1 \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \sum_{k=0}^{m-1} \frac{\left(\frac{m}{\gamma}\right)^k}{k!} \times \mathcal{P}_1 \times G_{r+v+1, u+1}^{u, 1+v} \left(c(W_2)^v \left| \Delta(v: s_1), 1, k_3 \right. \right)_{k_4, 0} - N v_t^{N-1} \chi \\
&\times \left(\frac{1}{\gamma_v} \right)^{\frac{-1}{m_l+3}} C_1 \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \sum_{k=0}^{m-1} \frac{\left(\frac{m}{\gamma}\right)^k}{k!} \times \mathcal{P}_2 \times G_{r+v+1, u+1}^{u, 1+v} \left(c(W_2)^v \left| \Delta(v: s_2), 1, k_3 \right. \right)_{k_4, 0}, \quad (38)
\end{aligned}$$

where, $R_4 = (-q + \frac{m}{\gamma})^{(p+k-\frac{1}{m_l+3})}$ and $R_5 = \frac{v^{(p+k-\frac{1}{m_l+3})-0.5}}{(2\pi)^{(v-1)0.5}}$. Now, by substituting (23), (24), (25), (26), and (27) in (20), the closed-form expression of BER is obtained as

$$\begin{aligned}
P_{e,BPSK} &= \frac{1}{2} - (1 - v_t^N) \sum_{k=0}^{m-1} R_2 \left(\frac{\bar{\gamma}}{m + q\bar{\gamma}} \right)^{(p+k)} \\
&\times \Gamma(p+k) - R_3 \left(\frac{\bar{\gamma}}{q\bar{\gamma} + m} \right)^{\frac{-1}{m_l+3}} \sum_{k=0}^{m-1} R_2 \left(\frac{\bar{\gamma}}{m + q\bar{\gamma}} \right)^{(p+k)} \\
&\times \Gamma \left(p+k - \frac{1}{m_l+3} \right) + C_1 \left(1 - v_t^N \right) \sum_{k=0}^{m-1} R_2 \\
&\times G_{r+v+1, u+1}^{u, 1+v} \left(c \left(\frac{v}{W_1 \mu_r} \right)^v \left| 1, \frac{1-(p+k)}{v}, k_3 \right. \right)_{k_4, 0} \\
&\times \frac{W_1^{-(p+k)} v^{p+k-0.5}}{(2\pi)^{(v-1)0.5}} + C_1 R_3 \sum_{k=0}^{m-1} R_2 R_4 R_5 \\
&\times G_{r+v+1, u+1}^{u, 1+v} \left(c \left(\frac{v}{W_1 \mu_r} \right)^v \left| 1, \frac{1-(p+k-\frac{1}{m_l+3})}{v}, k_3 \right. \right)_{k_4, 0}. \quad (28)
\end{aligned}$$

5.2.2 MQAM

The generalized expression of the instantaneous BER of the M-QAM modulation scheme can be written as [46]

$$P_e(\gamma) = 4\gamma_M \sum_{j=1}^{\frac{\sqrt{M}}{2}} Q(b_j \sqrt{\gamma}), \quad (29)$$

where, $\gamma_M = \frac{1}{\log_2 M} (1 - \frac{1}{\sqrt{M}})$ and $b_j = (2j-1) \sqrt{\frac{3}{M-1}}$. The average BER is expressed as,

$$P_e = \int_0^\infty P_e(\gamma) f_\gamma(\gamma) d\gamma = \int_0^\infty F_\gamma(\gamma) dP_e(\gamma). \quad (30)$$

By substituting the values of $F_{\gamma_{eq}}(\gamma)$ from (14) and (29) in (30), the expression of BER of the RF-FSO-VLC using M-QAM modulation scheme is given by

$$P_{e,MQAM} = \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \int_0^\infty \gamma^{-0.5} \exp\left(\frac{-b_j^2 \gamma}{2}\right) [1 - (R_1 - R_1 F_{\gamma_W}(\gamma) - R_1 F_{\gamma_F}(\gamma) + R_1 F_{\gamma_F}(\gamma) F_{\gamma_W}(\gamma))] d\gamma. \quad (31)$$

By simplifying the BER can be derived as

$$P_{e,MQAM} = I_6 - I_7 + I_8 + I_9 - I_{10}, \quad (32)$$

where,

$$\begin{aligned} I_6 &= \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \int_0^\infty \gamma^{-0.5} \exp\left(\frac{-b_j^2 \gamma}{2}\right) d\gamma, \\ I_7 &= \frac{4\gamma_M R_1}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \int_0^\infty \gamma^{-0.5} \exp\left(\frac{-b_j^2 \gamma}{2}\right) d\gamma, \\ I_8 &= \frac{4\gamma_M R_1}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \int_0^\infty \gamma^{-0.5} \exp\left(\frac{-b_j^2 \gamma}{2}\right) F_{\gamma_W}(\gamma) d\gamma, \\ I_9 &= \frac{4\gamma_M R_1}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \int_0^\infty \gamma^{-0.5} \exp\left(\frac{-b_j^2 \gamma}{2}\right) F_{\gamma_F}(\gamma) d\gamma, \\ I_{10} &= \frac{4\gamma_M R_1}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \int_0^\infty \gamma^{-0.5} \exp\left(\frac{-b_j^2 \gamma}{2}\right) F_{\gamma_F}(\gamma) F_{\gamma_W}(\gamma) d\gamma. \end{aligned} \quad (33)$$

I_6 and I_7 are calculated as

$$I_6 = 4\gamma_M. \quad (34)$$

and

$$I_7 = \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} \sum_{k=0}^{m-1} \frac{b_j \left(\frac{m}{\gamma}\right)^k}{k!} \left(\frac{2\bar{\gamma}}{2m + \bar{\gamma}b_j^2}\right)^{0.5+k} \Gamma(0.5+k). \quad (35)$$

By substituting (5) and (12) in (33), I_8 can be derived as

$$\begin{aligned} I_8 &= \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \sum_{k=0}^{m-1} \frac{\left(\frac{m}{\gamma}\right)^k}{k!} v_t^N \left(\frac{2\bar{\gamma}}{2m + \bar{\gamma}b_j^2}\right)^{0.5+k} \\ &\quad \Gamma(k+0.5) - \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \sum_{k=0}^{m-1} \frac{\left(\frac{m}{\gamma}\right)^k}{k!} N v_t^{N-1} \chi\left(\frac{1}{\gamma_v}\right)^{\frac{-1}{m_l+3}} \\ &\quad \left(\frac{2\bar{\gamma}}{2m + \bar{\gamma}b_j^2}\right)^{(0.5 - \frac{1}{m-l+3} + k)} \Gamma\left(0.5 - \frac{1}{m_l+3} + k\right). \end{aligned} \quad (36)$$

By substituting (5) and (7) in (33) and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)], I_9 can be derived as

$$I_9 = C_1 \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \sum_{k=0}^{m-1} \frac{\left(\frac{m}{\gamma}\right)^k}{k!} \mathcal{P}_1 \times G_{r+v+1, u+1}^{u, 1+v} \left(cW_2^v \left| \Delta(v : s_1), 1, k_3 \right. \right)_{k_4, 0}, \quad (37)$$

where, $s_1 = 1 - (0.5 + k)$, $\mathcal{P}_1 = \frac{(\alpha_2 \lambda)^k \left(\frac{b_j^2}{2} + \frac{m}{\gamma}\right)^{-(0.5+k)}}{(2\pi)^{(\alpha_2 \lambda - 1)0.5}}$, $j = 0$ to $\frac{\sqrt{M}}{2}$, $k = 0$ to $(m-1)$ and $W_2 = \left(\frac{2\gamma v}{2m + \gamma b_j^2}\right)$. The integral of I_{10} can be expressed by putting (5), (7), and (12) in (33), and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)] and assuming $s_2 = 1 - (0.5 + k - \frac{1}{m_l + 3})$ and $\mathcal{P}_2 = \frac{(\alpha_2 \lambda)^k \left(\frac{b_j^2}{2} + \frac{m}{\gamma}\right)^{-(0.5+k - \frac{1}{m_l + 3})}}{(2\pi)^{(\alpha_2 \lambda - 1)0.5}}$, $j = 0$ to $\frac{\sqrt{M}}{2}$, $k = 0$ to $(m-1)$. Now, by substituting (34), (35), (36), (37), and (38) in (32), the closed-form expression of BER for M-QAM modulation technique is derived as

$$P_{e, MQAM} = 4\gamma_M - \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} \sum_{k=0}^{m-1} \frac{b_j \left(\frac{m}{\gamma}\right)^k}{k!} \times \left(\frac{2\gamma}{2m + \gamma b_j^2}\right)^{0.5+k} \Gamma(0.5 + k) \left[1 - v_t^N + N v_t^{N-1} \times \chi\left(\frac{1}{\gamma_v}\right)^{\frac{-1}{m_l+3}} \left(\frac{2\gamma}{2m + \gamma b_j^2}\right)^{(0.5 - \frac{1}{m_l+3} + k)} \Gamma\left(0.5 - \frac{1}{m_l+3} + k\right) + C_1 \frac{4\gamma_M}{\sqrt{2\pi}} \sum_{j=1}^{\frac{\sqrt{M}}{2}} b_j \sum_{k=0}^{m-1} \frac{\left(\frac{m}{\gamma}\right)^k}{k!} \times \mathcal{P}_1 \left[G_{r+v+1, u+1}^{u, 1+v} \left(c(W_2)^v \left| \Delta(v : s_1), 1, k_3 \right. \right)_{k_4, 0} \right] \times \left(1 - v_t^N\right) - N v_t^{N-1} \chi\left(\frac{1}{\gamma_v}\right)^{\frac{-1}{m_l+3}} \mathcal{P}_2 \times G_{r+v+1, u+1}^{u, 1+v} \left(c(W_2)^v \left| \Delta(v : s_2), 1, k_3 \right. \right)_{k_4, 0} \right]. \quad (39)$$

5.2.3 MPSK

The instantaneous BER of the M-PSK modulation scheme can be written as [46]

$$P_e(\gamma) = \frac{2}{\psi_M} \sum_{j=1}^T Q(a_j \sqrt{2\gamma}), \quad (40)$$

$$\begin{aligned}
I_{15} = & v_t^N \frac{2}{\psi_M \sqrt{\pi}} C_1 \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \times \frac{(\alpha_2 \lambda)^k \left(a_j^2 + \frac{m}{\gamma}\right)^{-(0.5+k)}}{(2\pi)^{(\alpha_2 \lambda - 1)0.5}} \times G_{r+v+1, u+1}^{u, 1+v} \left(c(W_3)^v \middle| \Delta(v: s_1), 1, k_3 \right) \\
& - N v_t^{N-1} \chi \frac{2}{\psi_M \sqrt{\pi}} C_1 \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \frac{(\alpha_2 \lambda)^k \left(a_j^2 + \frac{m}{\gamma}\right)^{-(0.5+k - \frac{1}{m_l+3})}}{(2\pi)^{(\alpha_2 \lambda - 1)0.5}} G_{r+v+1, u+1}^{u, 1+v} \left(c(W_3)^v \middle| \Delta(v: s_2), 1, k_3 \right).
\end{aligned} \tag{48}$$

$$\begin{aligned}
P_{e,MPSK} = & \frac{2}{\psi_M} - \frac{2}{\psi_M \sqrt{\pi}} \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \left(\frac{\gamma}{m + a_j^2 \gamma} \right)^{0.5+k} \Gamma(0.5+k) \left[1 - v_t^N + N v_t^{N-1} \left(\frac{1}{\gamma} \right)^{\frac{-1}{m_l+3}} \right. \\
& \left. \left(\frac{\gamma}{m + a_j^2 \gamma} \right)^{0.5+k + \frac{-1}{m_l+3}} \Gamma(0.5 - \frac{1}{m_l+3} + k) \right] + \frac{2}{\psi_M \sqrt{\pi}} C_1 \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \frac{(\alpha_2 \lambda)^k}{(2\pi)^{(\alpha_2 \lambda - 1)0.5}} \left(a_j^2 + \frac{m}{\gamma} \right)^{-(0.5+k)} \\
& \times \left[G_{r+v+1, u+1}^{u, 1+v} \left(c(W_3)^v \middle| \Delta(v: s_1), 1, k_3 \right) \left(1 - v_t^N \right) - N v_t^{N-1} \chi \left(a_j^2 + \frac{m}{\gamma} \right)^{\left(\frac{-1}{m_l+3}\right)} G_{r+v+1, u+1}^{u, 1+v} \left(c(W_3)^v \middle| \Delta(v: s_2), 1, k_3 \right) \right].
\end{aligned} \tag{49}$$

where, $\psi_M = \max(\log_2 M, 2)$, $T = \max(\frac{M}{4}, 1)$ and $a_j = \sin\left(\frac{(2j-1)\pi}{M}\right)$. By substituting the values of $F_{\gamma_{eq}}(\gamma)$ from (14) and (40) in (30), the expression of BER of the RF-FSO-VLC using M-PSK modulation scheme is given by

$$\begin{aligned}
P_{e,MPSK} = & \frac{2}{\sqrt{\psi_M \pi}} \sum_{j=1}^T a_j \int_0^\infty \gamma^{-0.5} \exp(-a_j^2 \gamma) [1 - (R_1 \\
& - R_1 F_{\gamma_W}(\gamma) - R_1 F_{\gamma_F}(\gamma) + R_1 F_{\gamma_F}(\gamma) F_{\gamma_W}(\gamma))] d\gamma.
\end{aligned} \tag{41}$$

By simplifying the BER can be derived as

$$P_{e,MPSK} = I_{11} - I_{12} + I_{13} + I_{14} - I_{15}, \tag{42}$$

where,

$$\begin{aligned}
I_{11} &= \frac{2}{\psi_M \sqrt{\pi}} \sum_{j=1}^T a_j \int_0^\infty \gamma^{-0.5} \exp(-a_j^2 \gamma) d\gamma, \\
I_{12} &= \frac{2R_1}{\psi_M \sqrt{\pi}} \sum_{j=1}^T a_j \int_0^\infty \gamma^{-0.5} \exp(-a_j^2 \gamma) d\gamma, \\
I_{13} &= \frac{2R_1}{\psi_M \sqrt{\pi}} \sum_{j=1}^T a_j \int_0^\infty \gamma^{-0.5} \exp(-a_j^2 \gamma) F_{\mathcal{W}}(\gamma) d\gamma, \\
I_{14} &= \frac{2R_1}{\psi_M \sqrt{\pi}} \sum_{j=1}^T a_j \int_0^\infty \gamma^{-0.5} \exp(-a_j^2 \gamma) F_{\mathcal{W}}(\gamma) d\gamma, \\
I_{15} &= \frac{2R_1}{\psi_M \sqrt{\pi}} \sum_{j=1}^T a_j \int_0^\infty \gamma^{-0.5} \exp(-a_j^2 \gamma) F_{\mathcal{W}}(\gamma) F_{\mathcal{W}}(\gamma) d\gamma.
\end{aligned} \tag{43}$$

I_{11} and I_{12} can be derived as

$$I_{11} = \frac{2}{\psi_M}. \tag{44}$$

and

$$\begin{aligned}
I_{12} &= \frac{2}{\psi_M \sqrt{\pi}} \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \left(\frac{\bar{\gamma}}{m + a_j^2 \bar{\gamma}}\right)^{0.5+k} \\
&\quad \times \Gamma(0.5 + k).
\end{aligned} \tag{45}$$

By substituting (5) and (12) in (43), I_{13} can be derived as

$$\begin{aligned}
I_{13} &= v_t^N \frac{2}{\psi_M \sqrt{\pi}} \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \left(\frac{\bar{\gamma}}{m + a_j^2 \bar{\gamma}}\right)^{0.5+k} \\
&\quad \times \Gamma(k + 0.5) - N v_t^{N-1} \chi \frac{2}{\psi_M \sqrt{\pi}} \sum_{j=1}^T \sum_{k=0}^{m-1} \left(\frac{1}{\bar{\gamma}_v}\right)^{\frac{-1}{m_l+3}} \\
&\quad \times \frac{a_j \left(\frac{m}{\gamma}\right)^k}{k!} \left(\frac{\bar{\gamma}}{m + a_j^2 \bar{\gamma}}\right)^{0.5+k+\frac{-1}{m_l+3}} \Gamma\left(0.5 - \frac{1}{m_l+3} + k\right).
\end{aligned} \tag{46}$$

By substituting (5) and (7) in (43), and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)], I_{14} can be derived as

$$\begin{aligned}
I_{14} &= \frac{2}{\psi_M \sqrt{\pi}} C_1 \sum_{j=1}^T \sum_{k=0}^{m-1} \frac{a_j \left(\frac{m}{\gamma}\right)^k (\alpha_2 \lambda)^k \left(a_j^2 + \frac{m}{\gamma}\right)^{-(0.5+k)}}{(2\pi)^{(\alpha_2 \lambda - 1)0.5}} \\
&\quad G_{r+v+1, u+1}^{u, 1+v} \left(c(W_3)^v \left| \begin{matrix} \Delta(v : s_1), 1, k_3 \\ k_4, 0 \end{matrix} \right. \right),
\end{aligned} \tag{47}$$

where, $W_3 = \left(\frac{\nu_j^2}{m + a_j^2 \gamma} \right)$. The integral of I_{15} can be expressed by putting (5), (7), and (12) in (43), and using [44, Eq. (8.4.3.1)] and [45, Eq. (07.34.21.0013.01)].

By substituting (44), (45), (46), (47), and (48) in (42), the closed-form expression of BER for M-PSK modulation technique is derived in (49).

5.3 Ergodic Capacity

The ergodic capacity of a system is defined as [47], [48]

$$\begin{aligned} C &= E[\log_2(1 + \delta\gamma)] \\ &= \int_0^\infty \log_2(1 + \delta\gamma) f_{\gamma_{eq}}(\gamma) d\gamma, \end{aligned} \quad (50)$$

where, δ is the free parameter which takes value '1' for heterodyne detection and ' $\frac{e}{2\pi}$ ' for IM/DD detection. The ergodic capacity can be expressed in terms of the complementary CDF as [42]

$$C = \int_0^\infty \frac{1}{\ln(2)} (1 + \delta\gamma)^{-1} F_{\gamma_{eq}}^c(\gamma) d\gamma, \quad (51)$$

where, $F_{\gamma_{eq}}^c(\gamma) = 1 - F_{\gamma_{eq}}(\gamma)$. Putting the values of $F_{\gamma_{eq}}(\gamma)$ from (14) the ergodic capacity of the system can be written as,

$$\begin{aligned} C &= \int_0^\infty (1 + \delta\lambda)^{-1} [(1 - F_{\gamma_R}(\gamma)) \\ &\quad (1 - F_{\gamma_F}(\gamma))(1 - F_{\gamma_W}(\gamma))] d\gamma. \end{aligned} \quad (52)$$

By substituting (5), (7), and (12) in (54), the expression for ergodic capacity can be written as,

$$\begin{aligned} C &= \int_0^\infty \frac{1}{\ln(2)} (1 + \delta\gamma)^{-1} [R_1 - R_1 F_{\gamma_W}(\gamma) \\ &\quad - R_1 F_{\gamma_F}(\gamma) + R_1 F_{\gamma_F}(\gamma) F_{\gamma_W}(\gamma)] d\gamma. \end{aligned} \quad (53)$$

$$= I_{16} - I_{17} - I_{18} + I_{19}, \quad (54)$$

where,

$$\begin{aligned} I_{16} &= \int_0^\infty \frac{R_1}{\ln(2)} (1 + \delta\gamma)^{-1} d\gamma. \\ I_{17} &= \int_0^\infty \frac{R_1}{\ln(2)} (1 + \delta\gamma)^{-1} F_{\gamma_W}(\gamma) d\gamma. \\ I_{18} &= \int_0^\infty \frac{R_1}{\ln(2)} (1 + \delta\gamma)^{-1} F_{\gamma_F}(\gamma) d\gamma. \\ I_{19} &= \int_0^\infty \frac{R_1}{\ln(2)} (1 + \delta\gamma)^{-1} F_{\gamma_F}(\gamma) F_{\gamma_W}(\gamma) d\gamma. \end{aligned} \quad (55)$$

By using the identities [45, Eq. (07.34.03.0271.01) and Eq. (07.34.03.0228.01)] to express $(1 + \delta\gamma)$ and exponential function in terms of Meijer-G and applying formula [45, Eq. (07.34.21.0011.01)] to integrate I_{16} can be calculated as,

$$I_{16} = \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k}{k! \ln(2)} G_{2,1}^{1,2} \left(\left(\frac{\delta\tilde{\gamma}}{m} \right) \middle| \begin{matrix} 0, -k \\ 0 \end{matrix} \right). \quad (56)$$

The integral of I_{17} can be derived by putting (12) in I_{17} . Using [45, Eq. (07.34.03.0271.01) and Eq. (07.34.03.0228.01)] for Meijer-G equivalent conversion of $(1 + \delta\gamma)$ and exponential function, and using [45, Eq. (07.34.21.0011.01)] for integration of two Meijer-G function, I_{17} is derived as,

$$\begin{aligned} I_{17} &= \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m}) v_t^N}{k! \ln(2)} G_{2,1}^{1,2} \left(\left(\frac{\delta\tilde{\gamma}}{m} \right) \middle| \begin{matrix} 0, -k \\ 0 \end{matrix} \right) \\ &\quad - \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^{\frac{1}{m_l+3}-1} N v_t^{N-1} \chi(\frac{1}{\tilde{\gamma}_v})^{\frac{-1}{m_l+3}}}{k! \ln(2)} \\ &\quad G_{2,1}^{1,2} \left(\left(\frac{\delta\tilde{\gamma}}{m} \right) \middle| \begin{matrix} 0, \frac{1}{m_l+3} - 1 \\ 0 \end{matrix} \right). \end{aligned} \quad (57)$$

Now, the closed form expression for I_{18} can be obtained by using [45, Eq. (07.34.03.0271.01) and Eq. (07.34.03.0228.01)] for equivalent Meijer-G conversion of $(1 + \delta\gamma)^{-1}$ and exponential function, and then converting each Meijer-G term into the Fox-H function [49] using [45, Eq. (07.34.26.0008.01)]. The integral of I_{18} can be obtained using [50, Eq. (2.3)] in terms of H-function as,

$$\begin{aligned} I_{18} &= \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k C_1}{k! \ln(2) v} \left(\frac{m}{\tilde{\gamma}} \right)^{-(k+1)} \\ &\quad \times H_{1,0:1,1:r+1,u+1}^{0,1:1,1:u,1} \left(\begin{matrix} (-k : 1, 1) \\ - \end{matrix} \middle| \begin{matrix} (0, 1) \\ (0, 1) \end{matrix} \middle| \begin{matrix} s_3 \\ s_4, s_5 \end{matrix} \middle| \begin{matrix} \frac{\delta\tilde{\gamma}}{m}, \frac{c_v^{\frac{1}{v}}}{\mu, m} \end{matrix} \right), \end{aligned} \quad (58)$$

where, $s_3 = (k_5, [(v)^{-1}]_{r+1})$, $s_4 = (k_4, [(v)^{-1}]_u)$, $s_5 = (0, [(v)^{-1}]_{u+1})$. The integral of I_{19} can be obtained by using [45, Eq. (07.34.03.0271.01) and Eq. (07.34.03.0228.01)] for equivalent Meijer-G conversion of exponential and $(1 + \delta\gamma)^{-1}$ function and then converting each Meijer-G term in to the Fox-H function [49] using [45, Eq. (07.34.26.0008.01)]. Now, the expression of I_{19} turns to be in terms of H-function by using [50, Eq. (2.3)]

as,

$$\begin{aligned}
I_{19} &= \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k C_1 v_t^N}{k! \ln(2)v} (\frac{m}{\tilde{\gamma}})^{-(k+1)} \\
&\times H_{1,0:1,1:r+1,u+1}^{0,1:1,1:u,1} \left(\begin{matrix} (-k:1,1) \\ - \end{matrix} \middle| \begin{matrix} (0,1) \\ (0,1) \end{matrix} \middle| \begin{matrix} s_3 \\ s_4, s_5 \end{matrix} \middle| \frac{\delta \tilde{\gamma}}{m}, \frac{c^{\frac{1}{v}}}{\mu_r m} \right) \\
&- \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k C_1 N v_t^{N-1} \chi(\frac{m}{\tilde{\gamma}})^{-[(k+1)-\frac{1}{m_l+3}]} (\frac{1}{\tilde{\gamma}})^{\frac{-1}{m_l+3}}}{k! \ln(2)v} \\
&\times H_{1,0:1,1:r+1,u+1}^{0,1:1,1:u,1} \left(\begin{matrix} (-k+\frac{1}{m+3}:1,1) \\ - \end{matrix} \middle| \begin{matrix} (0,1) \\ (0,1) \end{matrix} \middle| \begin{matrix} s_3 \\ s_4, s_5 \end{matrix} \middle| \frac{\delta \tilde{\gamma}}{m}, \frac{c^{\frac{1}{v}}}{\mu_r m} \right). \quad (59)
\end{aligned}$$

By substituting the values of (56), (57), (58), and (59) in (54), the closed form expression for ergodic capacity of the considered cooperative system can be obtained .

$$\begin{aligned}
C &= \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k}{k! \ln(2)} G_{2,1}^{1,2} \left(\left(\frac{\delta \tilde{\gamma}}{m} \right) \middle| \begin{matrix} 0, -k \\ 0 \end{matrix} \right) - \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k v_t^N}{k! \ln(2)} G_{2,1}^{1,2} \left(\left(\frac{\delta \tilde{\gamma}}{m} \right) \middle| \begin{matrix} 0, -k \\ 0 \end{matrix} \right) + \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^{\frac{1}{m_l+3}-1} N v_t^{N-1} \chi(\frac{1}{\tilde{\gamma}})^{\frac{-1}{m_l+3}}}{k! \ln(2)} \\
&\times G_{2,1}^{1,2} \left(\left(\frac{\delta \tilde{\gamma}}{m} \right) \middle| \begin{matrix} 0, \frac{1}{m_l+3}-1 \\ 0 \end{matrix} \right) - \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k C_1}{k! \ln(2)v} (\frac{m}{\tilde{\gamma}})^{-(k+1)} H_{1,0:1,1:r+1,u+1}^{0,1:1,1:u,1} \left(\begin{matrix} (-k:1,1) \\ - \end{matrix} \middle| \begin{matrix} (0,1) \\ (0,1) \end{matrix} \middle| \begin{matrix} s_3 \\ s_4, s_5 \end{matrix} \middle| \frac{\delta \tilde{\gamma}}{m}, \frac{c^{\frac{1}{v}}}{\mu_r m} \right) \\
&+ \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k C_1 v_t^N}{k! \ln(2)v} (\frac{m}{\tilde{\gamma}})^{-(k+1)} H_{1,0:1,1:r+1,u+1}^{0,1:1,1:u,1} \left(\begin{matrix} (-k:1,1) \\ - \end{matrix} \middle| \begin{matrix} (0,1) \\ (0,1) \end{matrix} \middle| \begin{matrix} s_3 \\ s_4, s_5 \end{matrix} \middle| \frac{\delta \tilde{\gamma}}{m}, \frac{c^{\frac{1}{v}}}{\mu_r m} \right) \\
&- \sum_{k=0}^{m-1} \frac{(\frac{\tilde{\gamma}}{m})^k C_1 N v_t^{N-1} \chi(\frac{m}{\tilde{\gamma}})^{-[(k+1)-\frac{1}{m_l+3}]} (\frac{1}{\tilde{\gamma}})^{\frac{-1}{m_l+3}}}{k! \ln(2)v} H_{1,0:1,1:r+1,u+1}^{0,1:1,1:u,1} \left(\begin{matrix} (-k+\frac{1}{m+3}:1,1) \\ - \end{matrix} \middle| \begin{matrix} (0,1) \\ (0,1) \end{matrix} \middle| \begin{matrix} s_3 \\ s_4, s_5 \end{matrix} \middle| \frac{\delta \tilde{\gamma}}{m}, \frac{c^{\frac{1}{v}}}{\mu_r m} \right). \quad (60)
\end{aligned}$$

6 Numerical results

In this section, the numerical results for the outage probability, the average BER, and the ergodic capacity for a DF based triple-hop RF-FSO-VLC system are discussed. Here, both strong and moderate cases of atmospheric turbulence scenarios are considered, i.e., strong ($\alpha_1 = 1.8621$, $\alpha_2 = 1$, $\beta_1 = 0.5$, $\beta_2 = 1.8$, $\Omega_1 = 1.5074$, $\Omega_2 = 1$) and moderate ($\alpha_1 = 2.1690$, $\alpha_2 = 1$, $\beta_1 = 0.55$, $\beta_2 = 2.35$, $\Omega_1 = 1.5793$, $\Omega_2 = 1$)[42]. For the VLC link, transmitter semi-angle at half power $\theta_{1/2}$ is set at 60° and number of used LED luminaries are considered to be 6. The RF link undergoes Nakagami- m fading with parameter $m = 1$ and 5 in this cooperative communication system.

The outage probability of the mixed RF-FSO-VLC system for the heterodyne and direct detection techniques considering the conditions of strong, moderate turbulence for $m = 5$ and no of LED's are 6 is shown in Fig. 3. It is seen from the figure that the

Fig. 3 Outage probability of the DF based triple-hop RF-FSO-VLC system for different turbulence condition for both detection technique for $m = 5$ and $\epsilon = 1$.

Fig. 4 Outage probability vs. Avg. SNR of the DF based triple-hop RF-FSO-VLC system for different values of FOV of the photodetector and height of LEDs considering $\epsilon = 1$.

outage probability of the system is more while using direct compared to heterodyne detection. It is also seen from the figure that the outage probability of the system is higher in the strong turbulence environment as compared to moderate turbulence environment.

Fig. 5 Outage probability vs Avg. SNR of the DF based triple-hop RF-FSO-VLC system for different values of m and pointing errors ϵ

Fig. 6 BER vs Avg. SNR of the DF based triple-hop RF-FSO-VLC system for both heterodyne and IM/DD detection considering different values of atmospheric turbulence

The outage probability of this mixed RF-FSO-VLC system for different values of FOV of the photodetector and different heights of the LED luminaries considering $m = 5$, and pointing errors $\epsilon = 1$ for strong turbulence condition is shown in Fig. 4. It is observed from the figure that the outage probability of the system decreases with the reduction in FOV of the photodetector as well as reduction in the height

Fig. 7 Avg. BER vs. Avg. SNR of the triple-hop RF-FSO-VLC system for different modulation techniques considering perfect relaying

Fig. 8 The impact of ϵ on the ergodic capacity for strong and moderate turbulence condition

of the LED lights. This is due to the fact that, as FOV decrease, the power of the concentrator of the photodetector will increase, improving the outage performance of the considered cascaded system and a receiver with a wide FOV is susceptible to more ambient light noise as compared to a receiver with a narrow FOV.

Fig. 9 The impact of no of LED's on the ergodic capacity for different values of no of LED's and photodetector height L

Fig. 5 shows the outage performance of the considered system for different values of RF fading parameter and pointing errors. This shows that the outage probability of the system increases when the pointing errors effect is high and the effect of RF fading is high. For example, at average SNR = 10 dB and $m = 5$, the outage probability of the considered system are 3.845×10^{-1} and 4.633×10^{-1} , respectively. For $m = 1.7$ and $\epsilon = 5.2, 1$, the outage probability of the considered system are 4.24×10^{-1} and 4.977×10^{-1} for $\epsilon = 5.1, 1$, respectively. Again, for $m = 1$ and $\epsilon = 5.2, 1$, the outage probability of the considered system are 5.41×10^{-1} and 5.997×10^{-1} for $\epsilon = 5.1, 1$, respectively. It is also seen that as the RF fading parameter and the effect of pointing error decreases the outage performance of the system is poor, but for higher SNR the system gives better outage performance for less value of RF fading parameter and weak pointing error as compared to strong pointing error and weak RF fading parameter.

Fig. 6 shows that the BER performance of the considered system for heterodyne detection and IM/DD considering different values of atmospheric turbulence, $L = 2.5$ m, $m = 5$, pointing error $\epsilon = 1$, and FOV = 60° . It is observed from the figure that the heterodyne detection provides a better performance compared to IM/DD. It can also be seen that, for strong atmospheric turbulence the system provides better error performance.

In Fig. 7, the BER analysis for perfect relaying using different modulation schemes such as 8-QAM, 16-QAM and 16-PSK are presented considering $L = 2.5$ m, FOV = 60° , in the strong atmospheric turbulence with a pointing errors $\epsilon = 1$. It is clearly seen from the figure that MQAM gives better performance than the MPSK modulation techniques.

Furthermore, the ergodic capacity of mixed RF-FSO-VLC triple-hop communication system is evaluated in Fig. 8. It is observed that the capacity of the system decreases when the effects of pointing error and atmospheric turbulence are high. It is also seen that the capacity gap of the system is higher for strong atmospheric turbulence as compared to moderate atmospheric turbulence.

Fig. 9 shows the ergodic capacity of the mixed RF-FSO-VLC system for different VLC parameters, i.e., for different heights of photodetector and no of LED's considering strong turbulence condition. It is seen from the figure that the capacity of the system increases as the distance between the LED and photodetector decreases and the no of LEDs increases. For lower SNR, the capacity performance is more affected by height of photodetector and for higher SNR, the capacity performance is more affected by the no of LEDs.

7 Conclusion

The performance evaluation of the DF based cascaded RF-FSO-VLC communication system is proposed. The closed-form expressions for statistical characteristics of SNR of the considered system are obtained. These statistical characteristics of SNR are used to derive the analytical expressions for the outage probability, BER, and ergodic capacity of the DF based triple-hop communication system. The numerical results are obtained by varying different channel parameters such as RF fading parameter m , pointing error under the strong and moderate turbulence conditions for both the detection types, heterodyne and IM/DD. It is seen from the numerical results that the pointing errors and Nakagami- m parameter in different atmospheric turbulence conditions affect the system performance. The indoor environment performance is dominated by the field of view of the detector and height at which LED luminaries are present.

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9 Declaration

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