International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-10, August 2019

Cascaded Rf-Fso-Vlc System using Df Relays

Rima Deka, Sanya Anees

***Abstract** - This paper presents performance analysis of cascaded radio frequency-free space optical communication-visible light communication (RF-FSO-VLC) system. The proposed model comprises of the RF link as the core network, a terrestrial optical link for providing last mile connectivity with the indoor cell users communicating through VLC environment. The RF link undergoes Nakagami-m distributed fading, while the terrestrial optical link is modeled by Double Generalized Gamma (DGG) distributed turbulence and Rayleigh-distributed misalignment losses. VLC links are characterized by the randomness in users' position. Using statistical properties of system signal-to-noise ratio (SNR), outage and error performance of the proposed system is evaluated depending on whether the relays and the destination decode either perfectly or erroneously. The numerical results show that the system performance varies depending on field-of view (FOV) of the detector and user's position. This is because as FOV increases along with the height of the LED, the outage probability of the system increases. Error probability depends on the type of detection techniques, where a heterodyne detection system performs better than a direct detection system. Moreover, through results it is inferred that severe fading and misalignment losses result in poor error performance of the considered system errors on the performance of the considered cooperative system.*

***Index Terms**- Decode-and-forward, free space optical communication, subcarrier intensity modulation, outage probability, visible light communication.*

I. INTRODUCTION

Optical Wireless Communication (OWC) transmits information using signals from visible, infra-red, or ultraviolet spectrum. It has advantages such as it supports high speed communication, OWC transceivers are cost effective, use unlicensed band, and provide highly secure communication. The OWC is a promising communication technology which incorporates convenience of wireless and rate of optical communication. OWC systems can also be installed on those locations where wired communication is not feasible. The applications of OWC systems ranges from space-satellite links to terrestrial and underwater communication [1]–[3]. Where free space optical communication (FSO) is being considered for outdoor terrestrial communication, visible light communication (VLC) is being considered for indoor communication. Both are part of OWC but use optical signals of different frequency range, where FSO generally uses 850nm or 1500 nm, VLC uses 400-700 nm which is also employed in indoor LEDs [4], [5].

Manuscript published on 30 August 2019.
*Correspondence Author(s)
Rima Deka, Department of Electronics and Communication Engineering, Indian Institute of Information Technology Guwahati, Assam, India. Email: rimadekas@gmail.com,
Sanya Anees, Department of Electronics and Communication Engineering, Indian Institute of Information Technology Guwahati, Assam, India. Email: sanya@iiitg.ac.in

Apart from contributing a large unlicensed bandwidth as compared to radio spectrum, the VLC technology is clustered with numerous other benefits like availability, no electromagnetic interference etc. FSO communication uses lasers and photo detectors to carry out transmission in the infra-red or UV frequency band. However sky conditions, scintillations, and misalignment losses limits the range and performance of FSO systems. Although at the time of initial installation, FSO transceivers are perfectly aligned, but natural disasters cause misalignment losses. Various solutions to reduce their impact are hybrid RF/FSO communication [7], radio-on-FSO [6], multiple-input-multiple-output (MIMO) based FSO systems, and relay based FSO systems. By applying different types of relay techniques, the coverage area of the FSO systems can be increased and this also improves capacity and error and outage probability of FSO systems. In [8], [9] cascaded RF/FSO communication systems are analyzed for decoding-and-forwarding (DF) and amplifying and-forwarding (AF) relays, respectively. Outage probability of asymmetric RF/FSO/RF stratospheric cooperative system has been presented in [10], where source/destination nodes and relays interact through radio channels and inter-relay communication is established using optical channel. FSO link undergoes Gamma-Gamma fading, radio links are Rician distributed. Recently, asymmetric RF/FSO/RF based cooperative systems using DF and AF are analyzed in [11], which can be implemented to communicate between already established/new radio networks using very fast speed. This paper discusses asymmetric RF-FSO-VLC system in terms of outage and (BER) bit-error-rate for DF relays. Proposed system establishes communication between RF based core network, FSO link for intermediate communication, and VLC access points for last mile access to end users. Subcarrier-intensity modulation (SIM) is considered and the destination considering either heterodyne or direct detection techniques analyzed. Channel models for radio frequency link is Nakagami-*m* distribution, for FSO link is DGG distribution and misalignment losses, and VLC links are modeled by Lambertian pattern. As DF relay is considered, two scenarios are analyzed, (i) where it is assumed that the relay decode perfectly and (ii) where it is assumed that there can be possibility of erroneous detection. For both scenarios, outage probability (OP) and BER for different modulation schemes are computed using SNR statistics. Further analytical and simulation results show how channel and system parameters affect performance metrics of the proposed system.

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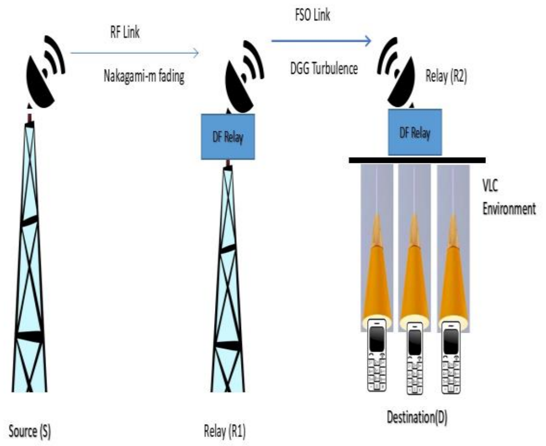

Fig. 1. System Model of DF based triple-hop RF-FSO-VLC system

II. SYSTEM MODEL

Communication through cascaded RF-FSO-VLC system using DF relays is depicted in Fig. 1. Relay R1 decodes electrical signal sent from source (S) re-encode it, then convert the electrical signal to optical signal further transmitting it via FSO link by using SIM scheme to R2. At R2, the photo detector at relay converts the received optical signal into its equivalent electrical form, re-encodes it to again optical signal and then transmits it through visible light environment to the end users. At the destination (D), again the photo detector present converts the optical signal in to the electrical signal through heterodyne or intensity modulation/direct detection (IM/DD) technique. In SIM, 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. The signal received at R1 can be expressed as

$$y_{s,r1} = h_{s,r1}x + e_{s,r1}, \tag{1}$$

where, x is transmit signal from S, $h_{s,r1}$RF channel gain, and $e_{s,r1}$is AWGN $N(0, \sigma^2_{r_1,r_2})$. $\gamma_{s,r_1} = |h_{s,r_1}|^2 \bar{\gamma}_{s,r_1}$ is SNR of RF link, where, $\bar{\gamma}_{s,r1}$denotes average SNR. Signal obtained by R2 is given by

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

where, $\eta_{r1,r2}$ represents photo electronic conversion ratio, $e_{r1,r2}$ represents the complex valued AWGN, and $I_{r1,r2}=I_l I_t I_p$ represents the atmospheric turbulence in R_1-R_2 links, representing path loss, irradiance, and pointing errors, respectively [12]. Instantaneous SNR of the considered link, $\gamma_{r1,r2}=I^2_{r1,r2}\mu_r$.

The average SNR, electrical SNR is defined as $\mu_{r1,r2} = \frac{(\eta E[I])^r}{N_0}\mu_{r1,r2}$, r denotes the type of detection method, i.e., r =1 for heterodyne and r =2 for direct detection. The signal received at destination D is given by

$$y_{r2,d} = \rho h_u P_r \hat{x}_2 + e_{r1,r2} \tag{3}$$

where, ρ is opto-electrical conversion ratio, $\hat{x}_2$ is the decoded signal at D, h_u represents constant channel gain of VLC link connecting optical source to u-*th* user, P_r represents transmit AWGN $N(0, \sigma^2_{r_1,r_2})$. Link SNR is given by $\gamma_{r2,d} = h_v{}^2\bar{\gamma}_{r2,d}$, in which average electrical SNR is defined as, $\bar{\gamma}_{r2,d} = \frac{\rho^2 P_r{}^2}{\sigma^2{}_{r2,d}}$.

III. CHANNEL MODEL

RF, FSO, and VLC channel models used for the proposed system are discussed along with the various factors affecting them.

A). RF Link: In this link, fading has Nakagami-*m* distribution. Thus, link SNR will be having Gamma distribution with PDF [9]

$$f_{\gamma_R}(\gamma) = \frac{m^m \gamma^{m-1}}{\Gamma(m)\bar{\gamma}^m} exp\left(-\frac{m\gamma}{\bar{\gamma}}\right), \tag{4}$$

where, $\Gamma(.)$ is a Gamma function and m is the fading parameter. CDF can be obtained as

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

where $\gamma(s,t)$is lower incomplete Gamma function.

B). FSO Link*:* FSO link SNR has independent effects of DGG irradiance and Rayleigh distributed misalignment losses. The unified PDF of the link SNR for both detection technique, is written as [12]

$$f_{\gamma_F}(\gamma) = \frac{A_1}{r\gamma} G^{\lambda+\sigma+1,0}_{1,\lambda+\sigma+1}\left(A_2 h^{\alpha_2\lambda}\left(\frac{\gamma}{\mu_r}\right)^{\frac{\alpha_2\lambda}{r}} \middle| \begin{matrix}\check{k}_2\\ \check{k}_1\end{matrix}\right), \tag{6}$$

where, $A_1 = \frac{\epsilon^2\sigma^{\beta_1-0.5}\lambda^{\beta_2-0.5}(2\pi)^{1-\frac{(\lambda+\sigma)}{2}}}{\Gamma(\beta_1)\Gamma(\beta_2)}$, $A_2 = \frac{\beta_1^\sigma,\beta_2^\lambda}{\lambda^\lambda\sigma^\sigma\Omega_1^\sigma\Omega^\lambda}$, $\frac{\lambda}{\sigma} = \frac{\alpha_1}{\alpha_2}$, $\tilde{k}_1 = \frac{\epsilon^2}{\alpha_2\lambda}$, $\Delta(\sigma:\beta_1), \Delta(\lambda:\beta_2)$, $\tilde{k}_2 = \frac{\alpha_2\lambda+\epsilon^2}{\alpha_2+\lambda}$.

Now, the CDF of SNR of FSO link is given by

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

where, $u = r(\lambda+\sigma+1)$, $c = \left(\frac{A_2 h^{\alpha_2\lambda}}{r^{\lambda+\sigma}}\right)^r$, $k_3 = \Delta(r:k_2)$, $k_4 = \Delta(r:k_1)$.

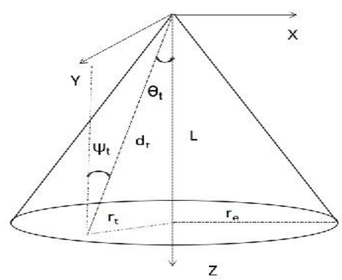

Fig. 2. Geometrical representation of VLC propagation model.

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C). VLC Link*:* The VLC model is used for indoor cell connectivity, where φc denotes photodiode's (FOV), LED - m_{th} user distance is L, incidence angle, Ψt, irradiance angle, θt, re denotes maximum radius a LED cell footprint as shown
in Fig. 2. The Euclidian distance d_t for the t_{th} user is given by $d_t = (r_t^2 + L^2)^{1/2}$ and $\cos(\Psi) = \cos(\varphi) = L/d_t$. PDF of channel gain can be written as [13]

$$f_{h_t}(h) = \frac{2}{r_e^2(m_l+3)}(\omega(m_l+1)L^{m_l+1})^{\frac{2}{m_l+3}} h^{-\left(\frac{2}{m_l+3}\right)-1}$$

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 , $\omega = \frac{1}{2\pi}AR_\rho U(\psi_t)g(\psi_t)$, A , is the photo detector area, $g(\psi)$ is the gain of optical concentrator, $R_0(\theta_t) = \frac{m_l+1}{2\pi}\cos_l{}^m(\theta_t), U(\psi) =$

$$\begin{cases} \frac{n^2}{\sin^2\phi_c} & \text{if } 0 \le \psi_t \le \phi_c \\ 0 & \text{if } \psi_t \ge \phi_c \end{cases},$$

n denotes refractive index, m_l is the order 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. From PDF of channel gain, system SNR's PDF, $\gamma_v = \bar{\gamma}_v h_t^2$, can be expressed by [13]

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

where, ρ is responsivity of photo detector , $\bar{\gamma}_V = \frac{\rho P^2}{N_0 B}$, P denotes transmit power, and N_0 is noise power
The CDF is given by

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

Using Binomial approximation in (10), CDF is given by [13]

$$F_{\gamma_V} = v_t^N - N v_t^{N-1}\chi\left(\frac{\gamma}{\bar{\gamma}_V}\right)^{-1/m_l+3}, \quad (11)$$

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

IV. STATISTICAL PROPERTIES OF INSTANTANEOUS SNR OF THE PROPOSED SYSTEM

A. CDF

For DF mixed based RF-FSO-VLC system, assuming that all relays are perfectly decoding the signal, the SNR is given
by,

$$\gamma_{eq} = \min(\gamma_R, \gamma_F, \gamma_V) \quad (12)$$

where, γ_R, γ_F, and γ_V are instantaneous SNRs of RF, FSO, and VLC links, respectively. From (12), CDF γ_{eq} can be expressed by

$$F_{eq} = 1 - [(1 - F_{\gamma_R})(1 - F_{\gamma_F})(1 - F_{\gamma_V})]. \quad (13)$$

By substituting (5), (7), and (11) in (13), closed-form expression for the CDF of instantaneous SNR of the considered system is obtained.

B. PDF

From (13), PDF of instantaneous SNR can be written as

$$f_{\gamma_{eq}} = f_{\gamma_R}F_{\gamma_F}F_{\gamma_V} + f_{\gamma_F}F_{\gamma_R}F_{\gamma_V} + f_{\gamma_V}F_{\gamma_F}F_{\gamma_R}. \quad (14)$$

By substituting the statistical characteristics of corresponding RF, FSO, and VLC links in (14), the final expression of PDF can be derived.

V. PERFORMANCE ANALYSIS

This section discusses performance of the DF based cascaded RF-FSO-VLC communication system is evaluated.

A. Outage Probability

Outage probability, P_{out}, for the proposed system can be expressed as

$$P_{out} = P_r[\gamma < \gamma_{th}] = F_\gamma(\gamma_{th}) . \quad (15)$$

Using (13), the OP for the cascaded system is given by

$$F_{eq} = 1 - \left(1 - F_{\gamma_R}(\gamma_{th})\right)\left(1 - F_{\gamma_F}(\gamma_{th})\right)(1 - F_{\gamma_V}(\gamma_{th})). \quad (16)$$

Substituting (5), (7) and, (11) in (16) the OP can be expressed
as

$$P_{out} = 1 - \left(1 - \frac{1}{\Gamma(m)}\gamma\left(m, \frac{m\gamma}{\bar{\gamma}}\right)\right) \times \left(1 - \frac{\epsilon^2\sigma^{\beta_1-0.5}\lambda^{\beta_2-0.5}(2\pi)^{1-\frac{r(\lambda+\sigma)}{2}}r^{\beta_1+\beta_1-2}}{\alpha_2\lambda\Gamma(\beta_1)\Gamma(\beta_2)} \times G_{r+1,u+1}^{u,1}\left(c\left(\frac{\gamma}{\mu_r}\right)^{\alpha_2\lambda}\middle|\begin{matrix}1, k_3\\ k_4, 0\end{matrix}\right)\right) \times \left(1 - v_t^N - N v_t^{N-1}\chi\left(\frac{\gamma}{\bar{\gamma}_V}\right)^{-1/m_l+3}\right). \quad (17)$$

TABLE I
BER PARAMETERS FOR VARIOUS MODULATION TECHNIQUES [25]

Modulation Techniques	u	v
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

B. BER

For BER calculation, two scenarios are considered, (1) in which perfect decoding by relays and destination is assumed and (2) where, erroneous decoding by relay and destination also taken into consideration.

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1) *Perfect Decoding:* BER computation formula used is as follow [14]

$$P_{e,perfect} = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) F_\gamma(\gamma) d\gamma, \qquad (18)$$

where, p and q are modulation techniques parameters as shownin Table I , $P_{e,perfect}$ denotes the average probability of error ofthe system for perfect relaying. Substituting $F_{\gamma_{eq}}(\gamma)$ from (13)in (18), the expression of BER of the RF-FSO-VLC system isgiven by

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

By substituting the values of F_{γ_R}, F_{γ_F} and, F_{γ_V}, the expression of BER is given by

$$P_{e,perfect} = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma) \times [1 - (X_1 - X_1 F_{\gamma_V} - X_1 F_{\gamma_F} + X_1 F_{\gamma_F} F_{\gamma_V})] d\gamma, \qquad (20)$$

where, $X_1 = exp\left(-\frac{m\gamma}{\bar{\gamma}}\right) \sum_{k=0}^{m-1} \frac{\left(\frac{m\gamma}{\bar{\gamma}}\right)^k}{k!}$. By simplifying, the BER can be derived as

$$P_{e,perfect} = I_1 + I_2 + I_3 + I_4 + I_5 \qquad (21)$$

where

$$I_1 = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, d\gamma,$$
$$I_2 = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, X_1\, d\gamma,$$
$$I_3 = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, X_1 F_{\gamma_V}\, d\gamma,$$
$$I_4 = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, X_1 F_{\gamma_F}\, d\gamma, and$$
$$I_5 = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, X_1 F_{\gamma_F} F_{\gamma_V} d\gamma \qquad (22)$$

I_1 and I_2 is calculated as

$$I_1 = \frac{1}{2}. \qquad (23)$$

$$I_2 = \sum_{k=0}^{m-1} Q_1 \left(\frac{\bar{\gamma}}{m + q\bar{\gamma}}\right)^{(p+k)} \Gamma(p+k), \qquad (24)$$

where, $Q_1 = \frac{q^p}{2\Gamma(p)} \frac{\left(\frac{m}{\bar{\gamma}}\right)^k}{k!}$. By substituting (5), (11) in (22), and using [15,Eqs.(8.4.3.1)], applying [16, Eq.(07.34.21.0013.01)] , I_3 is given by

$$I_3 = \sum_{k=0}^{m-1} Q_1 v_t^N \left(\frac{\bar{\gamma}}{m + q\bar{\gamma}}\right)^k \Gamma(p+k) - \sum_{k=0}^{m-1} Q_1 X_2 \times \left(\frac{\bar{\gamma}}{m+q\bar{\gamma}}\right)^{\frac{-1}{m_l+3}} \Gamma\left(p + k - \frac{1}{m_l+3}\right), \qquad (25)$$

where, $X_2 = N v_t^{N-1} \chi \left(\frac{1}{\bar{\gamma}_V}\right)^{\frac{-1}{m_l+3}}$. The integral of I_4 can be derived by putting (5), (7) in (22), and using [15,Eqs.(8.4.3.1)], [16, Eq.(07.34.21.0013.01)] as

$$I_4 = A_1 \sum_{k=0}^{m-1} Q_1 \left(-q + \frac{m}{\bar{\gamma}}\right)^{-(p+k)} \frac{\mathrm{v}^{\mathrm{p+k-0.5}}}{(2\pi)^{(\mathrm{v}-1)0.5}} \times G_{r+v+1,u+1}^{u,1+v} \left(c \left(\frac{v}{\left(-q+\frac{m}{\bar{\gamma}}\right)\mu_r}\right)^v \middle| \begin{matrix} 1, \frac{1-(p+k)}{v}, k_3 \\ k_4, 0 \end{matrix} \right), \qquad (26)$$

The integral of I_5 can be expressed by putting (5), (7), (11) in (22), and using [15, Eqs. (8.4.3.1)], [16, Eq. (07.34.21.0013.01)] as

$$I_5 = A_1 \sum_{k=0}^{m-1} Q_1 v_t^N \left(-q + \frac{m}{\bar{\gamma}}\right)^{-(p+k)} \frac{\mathrm{v}^{\mathrm{p+k-0.5}}}{(2\pi)^{(\mathrm{v}-1)0.5}} \times G_{r+v+1,u+1}^{u,1+v} \left(c \left(\frac{v}{\left(-q+\frac{m}{\bar{\gamma}}\right)\mu_r}\right)^v \middle| \begin{matrix} 1, \frac{1-(p+k)}{v}, k_3 \\ k_4, 0 \end{matrix} \right) - A_1 \sum_{k=0}^{m-1} Q_1 X_3 X_4 G_{r+v+1,u+1}^{u,1+v} \times \left(c \left(\frac{v}{\left(-q+\frac{m}{\bar{\gamma}}\right)\mu_r}\right)^v \middle| \begin{matrix} 1, \frac{1-\left(p+k-\frac{1}{m_l+3}\right)}{v}, k_3 \\ k_4, 0 \end{matrix} \right), \qquad (27)$$

where, $X_3 = N v_t^{N-1} \chi \left(\frac{1}{\bar{\gamma}_V}\right)^{\frac{-1}{m_l+3}} \left(-q + \frac{m}{\bar{\gamma}}\right)^{\left(p+k-\frac{-1}{m_l+3}\right)}$ and $X_4 = \frac{\mathrm{v}^{\left(\mathrm{p+k}-\frac{1}{m_l+3}\right)-0.5}}{(2\pi)^{(\mathrm{v}-1)0.5}}$. Now, by substituting (23), (24), (25), (26), and (27) in (20), the closed-form expression of BER for perfect decoding by nodes is obtained.

2) *Erroneous Relaying:* In DF based system, in case of binary modulation techniques, the received information is detected in each step, again encoding is done, further sent to other node. So, signal can be detected correctly or incorrectly at every step. So, the average BER of the system model must contain sum of all the possible scenarios in which the information can be decoded. It is given by

$$P_{e,error} = P_{e_R} P_{e_F} P_{e_V} + P_{e_R}(1 - P_{e_F})((1 - P_{e_V}) + (1 - P_{e_R}) P_{e_F} (1 - P_{e_V}) + (1 - P_{e_R}) P_{e_V} (1 - P_{e_F}), \qquad (28)$$

where, $P_{e,error}$ denotes the average probability of error of the system for errorneous relaying and P_{e_R}, $P_{e_{FSO}}$, and $P_{e_{VLC}}$ denote the error probabilities of RF, FSO, and VLC links, respectively. By using (18), the expression of BER for RF, FSO and VLC links are derived as follows.

a) *BER of RF link:* Substituting (5) in (18), BER can be written as

$$P_{e_R} = \frac{q^p}{2\Gamma(p)\Gamma(m)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, \gamma\left(m, \frac{m\gamma}{\bar{\gamma}}\right) d\gamma. \qquad (29)$$

Using [15, Eqs.(8.4.3.1) and (8.4.16.1)], BER of RF link is obtained as

$$P_{e_R} = \frac{1}{2\Gamma(p)\Gamma(m)} G_{2,2}^{1,2} \left(\frac{m}{q\bar{\gamma}} \middle| \begin{matrix} 1, 1-p \\ m, 0 \end{matrix} \right). \qquad (30)$$

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b) BER of FSO link: Substituting (7) in (18), error probability of FSO link can be derived as

$$P_{e_F} = \frac{p^q \epsilon^2 \sigma^{\beta_1-0.5} \lambda^{\beta_2-0.5} (2\pi)^{1-\frac{r(\lambda+\sigma)}{2}} r^{\beta_1+\beta_1-2}}{2\alpha_2 \lambda \Gamma(\beta_1)\Gamma(\beta_2)}$$
$$\int_0^\infty \gamma^{p-1} \exp(-q\gamma)\, G^{u,1}_{r+1,u+1}\left(c\left(\frac{\gamma}{\mu_r}\right)^v \middle| \begin{matrix} 1, k_3 \\ k_4, 0 \end{matrix}\right) d\gamma. \quad (31)$$

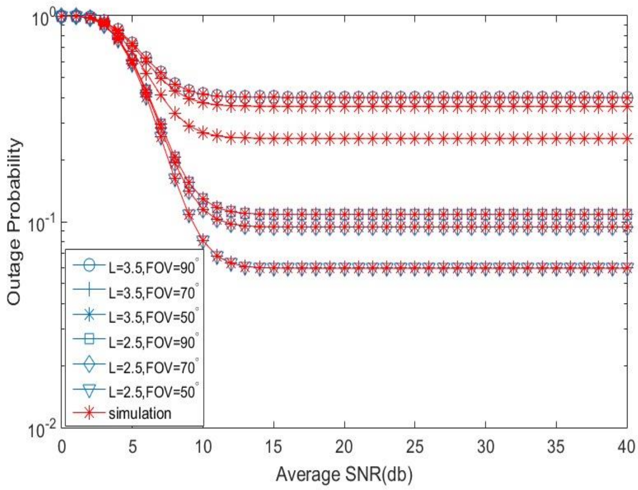

Fig. 3. Outage Probability of the DF based triple-hop RF-FSO-VLC system for different values of FOV of the photo detector and height of LEDs considering ϵ= 1.

Now by substituting [15, Eqs.(8.4.3.1)], applying [16, Eq.(07.34.21.0013.01)] in (31), BER is given by

$$P_{e_F} = \frac{p^q \epsilon^2 \sigma^{\beta_1-0.5} \lambda^{\beta_2-0.5} (2\pi)^{1-\frac{r(\lambda+\sigma)}{2}} r^{\beta_1+\beta_1-2}}{2\alpha_2 \lambda \Gamma(\beta_1)\Gamma(\beta_2)}$$
$$\times \frac{v^{p-0.5}}{(2\pi)^{(v-1)1.5}} G^{u,1+v}_{r+v+1,u+1}\left(c\left(\frac{v}{q\mu_r}\right)^v \middle| \begin{matrix} \Delta(v:1-p), 1, k_3 \\ k_4, 0 \end{matrix}\right), \quad (32)$$

where, $v = \alpha_2 \lambda$.

*c)Error Probability of a VLC link:*Substituting (11) in (18), BER of a VLC hop can be written as

$$P_{e_V} = \frac{q^p}{2\Gamma(p)} \int_0^\infty \gamma^{p-1} \exp(-q\gamma)$$
$$\times \left[{v_t}^N - N {v_t}^{N-1} \chi \left(\frac{\gamma}{\bar{\gamma}_V}\right)^{-1/m_l+3} \right] \mathrm{d}\gamma, \quad (33)$$
$$= \frac{{v_t}^N}{2} - \frac{N}{2\Gamma(p)} {v_t}^{N-1} q^{\frac{-1}{m_l+3}} \Gamma\left(p - \frac{-1}{m_l+3}\right) \quad (34)$$

After substituting (30), (32), and (34) in (28), the closed-form expression of BER for proposed system is obtained.

VI. Numerical Results

Numerical results for performance metrics derived in previous section are analyzed. The FSO link irradiance is assumed to be strong, i.e., (α_1 = 1.8621, α_2 = 1, β_1 = 0.5

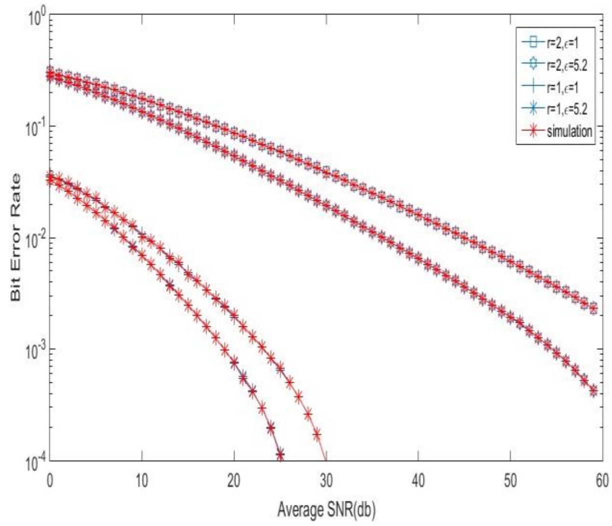

Fig. 4. BER of the triple-hop RF-FSO-VLC system for both heterodyne(r = 1) and IM/DD (r = 2) for different values of ϵ.

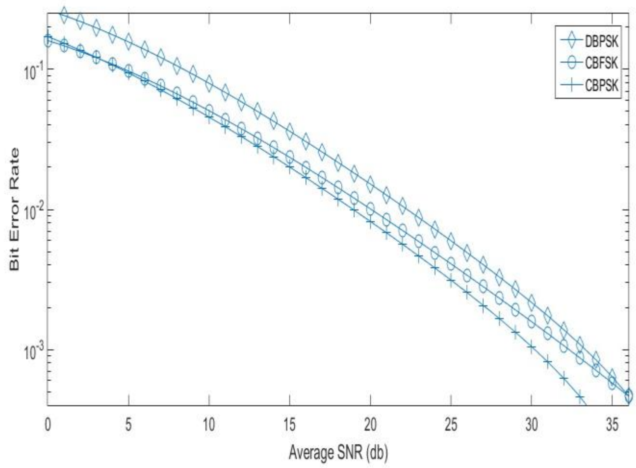

Fig. 5. BER of the RF-FSO-VLC system for various modulation scheme under fixed fading environment.

, β_2 = 1.8, Ω_1 = 1.5074, Ω_2 = 1). For the VLC link, transmitter semi angle at half power $\theta_{1/2}$ is set at 60^0 and number of used LED luminaries are considered to be 6 and m is taken as 5. The plots for OP of proposed system considering different height levels, different FOVs and strong irradiance scenarios is shown in Fig. 3. It is observed from the figure that the OP of the system decreases with the reduction in FOV of the photo detector as well as reduction in the height of the LED lights. It is because reduction in FOV, rises concentrator power for photo detector, thereby improving outage performance of considered cascaded system.

Fig. 4 shows BER performance in case of erroneous relaying for heterodyne detection and IM/DD considering different values of misalignment losses, L = 2.5 m, and FOV = 60^0 .

Retrieval Number: J98740881019/19©BEIESP
DOI: 10.35940/ijitee.J9874.0881019
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It is observed that heterodyne detection based systems perform better than direct detection based systems. It can also be seen that, for high misalignment losses, i.e., for lower value of ϵ, the error performance of the system decreases. In Fig. 5, BER analysis of erroneous relaying for different modulation schemes, i.e., CBPSK, CBFSK, NBFSK, DBPSK are presented considering L = 2.5m, FOV = 60^0, fixed fading parameters for outdoor radio and optical links and fixed number of LEDs in case of the VLC link as described above. It is clearly observed that CBPSK performs best.

VII. CONCLUSIONS

The performance evaluation of the cascaded RF-FSO-VLC system is proposed for DF relays. Using statistical properties of system SNR, are used to derive the analytical expressions for the OP and bit error rate are obtained. The numerical results are obtained by varying parameters like misalignment losses under the strong irradiance conditions for both the detection types, heterodyne and IM/DD. It is seen that misalignment losses along with the different irradiance conditions affect the system performance and 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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AUTHORS PROFILE

Rima Deka received Bachelor in Technology (Electronics and Communication Engineering) from North Eastern Hill University, Meghalaya, India in 2013 and Masters in Technology from Assam Don Bosco University, India, in 2016. Currently, she is a research scholar in the Department of Electronics and Communication Engineering, Indian Institute of Information Technology Guwahati, Assam, India. Her research interests include optical wireless communications and cooperative communications. In her Post-Graduation, she has been awarded University Gold medal-2014 2016 for being University Topper in Electronics & Communication Engg. Branch.

Sanya Anees (M'16) received Masters (W/D) in Communication Engineering from University of Manchester, U.K., in 2011 and received Ph.D. from the Indian Institute of Teaching Delhi, in 2016. Her research interests include optical wireless communications, MIMO systems, and cooperative communications.

Currently, she is working as an Assistant Professor in the Department of Electronics and Communication Engineering, Indian Institute of Information Technology Guwahati, Assam, India. She is reviewer of IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, IEEE Transactions on Aerospace and Electronic Systems, IEEE Access, IET Communications, and has reviewed various IEEE conference papers such as, ICC, Globecom, VTC, and WCNC. She has also served as TPC Member of IEEE NCC-2018, IEEE ICSC-2018, and IEEE CICT-2017. Recently she was awarded Early Career Research Award by SERB, DST. In her Graduation, she has been awarded University Gold medal-2010 for being University Topper in Electronics & Communication Engg. Branch, Shri Rawatpura Sarkar Gold medal-2010 for being University Topper amongst students from Electronics & Communication Engineering, Computer Science, and Information Technology, and Prof. S. T. Chakravati Gold medal-2010 for being University Topper amongst students from Electronics & Communication Engineering, Electrical Engineering, Mechanical Engineering, and Civil Engineering.

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