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A Novel Hybrid FSO-mm Wave System for Enhanced Mobile Network Capacity and Reliability

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ABSTRACT- The ever-growing demand for high-bandwidth communication in mobile networks necessitates innovative solutions that provide exceptional capacity and reliability. This paper introduces a novel dual hop hybrid system model that leverages the complementary strengths of free space optics (FSO) and millimeter-wave (mm W) communication, while incorporating a direct mm W link for added robustness. This paper analyzes the comprehensive performance of the proposed hybrid system using a single threshold selection combining. We consider a scenario where the channel state for the FSO link adheres to a Log-Normal distribution under conditions of weak turbulence. For the millimeter wave link, we assume it follows a Nakagami-m distribution, which encompasses a broad range of commonly encountered radio frequency (RF) fading distributions. The proposed system's performance is analyzed by deriving analytical expressions for average bit error rate (ABER) and outage probability (OP). The theoretical results of the proposed system, which are verified using Monte-Carlo simulations, unveil that under turbulence and adverse weather conditions, the performance of the proposed system over a standalone FSO system is improved significantly due to mm W backup link.

Keywords: Hybrid FSO/mm W; Outage Probability; Average Bit Error Rate; Selection Combining.

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1. INTRODUCTION

The rise of data-intensive applications, such as those in telecommunication networks, smart cities, and emerging technologies, has driven the exponential demand for high-speed wireless communication in recent years [1]. To meet this demand, researchers and engineers have been exploring novel approaches that combine different wireless communication technologies to leverage their respective strengths and mitigate their weaknesses. One such promising approach is the integration of free-space optics (FSO) and millimetre wave (mm W) technologies, often referred to as a hybrid FSO/mm W system [2]. Free-Space Optical communication utilizes the transmission of optical signals through the atmosphere. It offers high data rates, low latency, and immunity to electromagnetic interference [3,4]. However, FSO systems are vulnerable to atmospheric conditions like fog, rain, and turbulence, all of which can deteriorate signal quality and reliability, especially across extensive distances. Researchers have addressed the challenges in FSO links by utilizing two promising techniques: multiple-input multiple-output (MIMO) and cooperative relaying [5,6,7]. Authors in [8,9,10] explored diversity combining techniques (maximal ratio combing and selection combining) to further enhance FSO system performance. Researchers also explored the benefits of cooperative diversity in relay-assisted mixed free-Space optical /radio frequency systems. Prior research explored these systems using amplify and forward (AF) and decode and forward (DF) relaying techniques [11, 12]. In mixed FSO/RF configurations, the initial message transmission from the source to the relay frequently leverages the RF link due to its inherent reliability compared to the FSO link. However, the onward transmission from the relay to the destination can leverage the FSO link's high bandwidth, depending on the specific relaying protocol employed.

To address the limitations of Free-Space Optical (FSO) channels, researchers have explored hybrid FSO/RF wireless systems [13,14]. Millimetre waves, operating in the frequency range of 30 GHz to 300 GHz, offer high bandwidth and can penetrate obstacles better than higher frequency signals, making them suitable for high-speed communication in urban environments. However, mmW signals are prone to attenuation and blockage by atmospheric gases and obstacles, limiting their range and reliability. The integration of FSO and mmW technologies presents a unique opportunity to harness the advantages of both, while compensating for their individual limitations [15]. In a hybrid system, FSO serves as the primary communication link, offering high data rates and low latency, while mmW acts as a backup link or complements FSO by providing connectivity in adverse weather conditions or in situations where line-of-sight obstruction is present. By combining the advantages of FSO and mmW, the hybrid system delivers exceptional performance for outdoor uses [16]. This encompasses robust backhaul links with high capacity, dependable communication for vehicles, and seamless underwater connections, surpassing the limitations of conventional methods. Various architectures have been proposed for hybrid systems, including those where FSO and mmW links operate independently and others where they are integrated into a single coherent system. The performance of hybrid FSO/RF for over space–air–ground integrated network to provide broadband global mobile connectivity was analysed by the authors in [17]. The performance of UAV-Assisted Hybrid FSO/RF Communication Systems under Various Weather Conditions was analysed by the authors in [18]. The authors in [19] studied a UAV-assisted hybrid FSO/RF dual-hop system under amplify-and-forward protocol with variable gain. The performance of hybrid FSO/RF-THz relay communication system under different fading conditions is discussed in [20].

In this work, a dual-hop hybrid system with direct mmW link between source and destination nodes is considered for next-generation wireless networks. To assess the proposed system's performance, we analytically derive expressions for outage probability and average BER and validate these results through simulations. The following sections will delve deeper into the system architecture, analyse its performance under different channel conditions, and explore its potential benefits in real-world scenarios. The proposed system model is discussed in section 2. The statistical characteristics of the proposed system are outlined in section 3. Sections 4 and 5, respectively, derive analytical expressions for outage probability and average BER, followed by a discussion of the obtained numerical results. Finally, Section 6 summarizes the key takeaways of this work.

2. SYSTEM MODEL

Figure 1 illustrates a dual hop (DH) system employing a DF (Decode and Forward) relay, comprised of a source (S), a relay (R), and a destination (D) base station. We specifically consider a DH scenario with a reliable direct mmW link. When a direct link is unavailable, a dual hop system transmits data in two stages. First, the source base station sends the signal to the relay base station. The relay BS receives and decodes the signal. Then, in the subsequent phase, the relay BS then forwards the decoded information to the destination BS. If the source and destination can communicate directly, the source sends a signal in the first phase. This signal is received by both the relay and the destination BSs. The relay BS then decodes the signal and forwards it to the destination BS. At the destination BS, selection combining technique is used to extract the data from the original signal (received directly from the source) and the relayed signal. The following sub-section focuses on the mathematical modelling of signals received at the relay and destination base stations (BS) for FSO and mmW links.

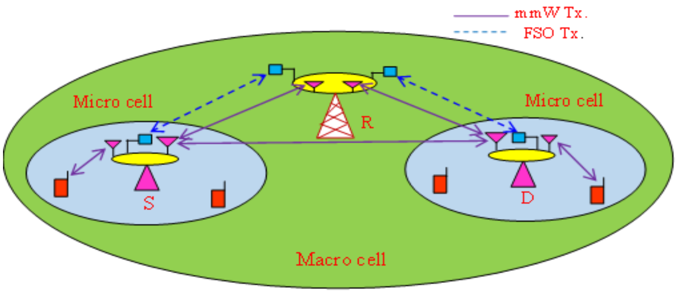

Figure 1. System model of hybrid FSO/mmW with direct mmW Link

2.1. Modelling received FSO signals across a network of base stations

An FSO system employs intensity modulation for data transmission where the transmitter controls the light intensity. The receiver then uses a direct detection scheme to convert the received light signal back into electrical data. The mathematical expression for the baseband signal received at the relay BS is given by,

$$z_{SR}^{fso-LN} = Y_{SR} I_{SR} G_{SR} S + x_{SR} \quad (1)$$

Following the signal decoding in the initial time slot, the relay BS transmits it to the destination BS during the subsequent time slot. The signal received at the destination BS is expressed as,

$$z_{RD}^{fso-LN} = Y_{RD} I_{RD} G_{RD} \tilde{S} + x_{RD} \quad (2)$$

where, S is the symbol transmitted by source BS with average energy Es, $\tilde{S}$ is the estimate of symbol S at relay BS after processing the received symbol, x_j is the zero-mean circularly symmetric complex Gaussian noise of j^{th} link, where $E\{n_j n_j^*\} = \sigma_n^2$, and $j \in \{SR,SD\}$. Y_j is receivers optical-to-electrical conversion coefficient, G_j is the average gain of the j^{th} FSO link, I_j represents the optical channel fading due to atmospheric turbulence of j^{th} link which is modelled as Log-Normal distribution [2]. The instantaneous electrical SNR at the output of the FSO receiver can be expressed as,

$$\gamma_j^{FSO} = \frac{y_j^2 G_j^2 E_s I_j^2}{\sigma_n^2} \quad (3)$$

In FSO communications with perfect alignment and mild turbulence, the Log-Normal (L-N) distribution effectively models the fading experienced on the link. This fading is characterized by the probability density function (PDF) of the fading channel coefficient (I_j), which is given by,

$$f_{I_j}^{LN}(I_j) = \frac{1}{\sqrt{8\pi} I\sigma_x} e^{-\frac{[\ln(I_j)-2\mu_x]^2}{8\sigma_x^2}} \tag{4}$$

In [17], it was shown that when E [Ij] = 1, it implies $\mu_x = -\sigma_x^2$, where μ_x and σ_x^2 represents the mean and variance of the L-N fading channel respectively. The pdf of the instantaneous SNR of a FSO link is derived by combining *equations (3) and (4).* The obtained equation is as follows:

$$f_{\gamma_j^{FSO}}^{LN}(\gamma) = \frac{1}{\sqrt{32\pi}\gamma\sigma_x} e^{-\frac{\left[\ln\left(\frac{\gamma}{\bar{\gamma}_j^{FSO}}\right)+8\sigma_x^2\right]^2}{32\sigma_x^2}} \tag{5}$$

where, $\bar{\gamma}_j^{FSO}$ represents the average SNR for the FSO link, as defined in reference [21], and is expressed as,

$$\bar{\gamma}_j^{FSO} = \frac{c_j^2 g_j^2 E_s}{\sigma_n^2} e^{4\sigma_x^2} \tag{6}$$

The cumulative distribution function (CDF) is obtained by integrating the PDF of γ_j^{FSO} across all possible values,

$$F_{\gamma_j^{FSO}}^{LN}(\gamma) = \int_0^{\gamma_j} f_{\gamma_j^{FSO}}^{LN}(\gamma)\, d\gamma \tag{7}$$

The CDF of γ_j^{FSO} can be represented utilizing the erfc(x) and erf(x) as described in reference [22], as follows,

$$F_{\gamma_j^{FSO}}^{LN}(\gamma) = 1 - \frac{1}{2}\operatorname{erfc}\left(\frac{\ln\left(\frac{\gamma}{\bar{\gamma}_j^{FSO}}\right)+8\sigma_x^2}{\sqrt{32\sigma_x^2}}\right) \tag{8}$$

2.2. Modelling received mmW signals across a network of base stations

The source BS transmits signals over the mmW link, which are then received by the relay BS and the destination BS. The mathematical representation of these signals is given as below,

$$z_{SR}^{mmW} = g_{SR}S + x_{SR}, \quad z_{SD}^{mmW} = g_{SD}S + x_{SD} \tag{9}$$

After decoding the symbol in the first time slot, the relay BS forwards it to the destination BS in the next time slot. The equation below describes the received symbol at the destination BS.

$$z_{RD}^{mmW} = g_{RD}\tilde{S} + x_{RD} \tag{10}$$

where, g_{SR}, g_{RD}, and g_{SD}, represent the fading channel gains experienced on the millimetre wave transmission paths. The instantaneous received SNR is expressed as $\gamma_j^{mmW} = \bar{\gamma}_j^{mmW} h^2$ where $\bar{\gamma}_j^{mmW}$ represents the average SNR of the mmW link. The PDF of γ_j^{mmW} follows the Gamma distribution as described in reference [23]. This function is expressed mathematically as,

$$f_{\gamma_j^{mmW}}(\gamma) = \left(\frac{m}{\bar{\gamma}_j^{mmW}}\right)^m \frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_j^{mmW}}} \tag{11}$$

Where, Γ(m) describes the extent of fading encountered by the channel with m representing the degree of fading. The CDF for γ_j^{mmW} can be determined by integrating its PDF, leading to the below expression,

$$F_{\gamma_j^{mmW}}(\gamma) = \int_0^{\gamma} f_{\gamma_j^{mmW}}(\gamma)\, d\gamma = \frac{1}{\Gamma(m)}\gamma\left(m, \frac{\gamma m}{\bar{\gamma}_j^{mmW}}\right) \tag{12}$$

where, ϒ(a, x) represents the lower incomplete gamma function and is expressed as,

$$\gamma(a,t) = \int_0^t x^{a-1} e^{-x} dx \tag{13}$$

3. STATISTICAL CHARACTERISTICS OF THE PROPOSED SYSTEM

This section analyses the statistical properties of the proposed system by deriving its CDF and PDF. This analysis employs the Nakagami-m fading model to characterize the signal fluctuations experienced on mmW links, while the Log-Normal fading model is used for FSO links. In two-stage relay systems, the system's overall performance is limited by the performance of the weakest link. As shown in reference [24], the equivalent output SNR (γ_{SRD}) is expressed as,

$$\gamma_{SRD} = \min(\gamma_{SR}, \gamma_{RD}) \tag{14}$$

For a dual-hop FSO transmission system, the CDF for the γ_{SRD} is given by,

$$F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma) = \text{prob}\left[\min(\gamma_{SR}^{FSO}, \gamma_{RD}^{FSO}) < \gamma\right] \tag{15}$$

After simplifying *equation (15)*, we obtain the following equivalent expression,

$$F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma) = 1 - \left[\text{prob}(\gamma_{SR}^{FSO} > \gamma)\text{prob}(\gamma_{RD}^{FSO} > \gamma)\right] \tag{16}$$

where γ_{SR}^{FSO} and γ_{RD}^{FSO} represents the instantaneous SNR values for the S-R and R-D links respectively, in FSO transmission. By using *equation (8)*, the CDF equation for the overall system can be derived as follows,

$$F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma) = 1 - \left[\frac{1}{2}\operatorname{erfc}\left(\frac{\ln\left(\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}+8\sigma_x^2\right)}{\sqrt{32}\sigma_x}\right)\frac{1}{2}\operatorname{erfc}\left(\frac{\ln\left(\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}+8\sigma_x^2\right)}{\sqrt{32}\sigma_x}\right)\right] \tag{17}$$

The PDF of γ_{SRD}^{FSO} is obtained by differentiating the CDF with respect to γ, and upon simplification, it can be expressed as follows:

$$f_{\gamma_{SRD}^{FSO}}^{LN}(\gamma) = Ae^{-\frac{\left[\ln\left(\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}\right)+8\sigma_x^2\right]^2}{32\sigma_x^2}} + Ae^{-\frac{\left[\ln\left(\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}\right)+8\sigma_x^2\right]^2}{32\sigma_x^2}} - Ae^{-\frac{\left[\ln\left(\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}\right)+8\sigma_x^2\right]^2}{32\sigma_x^2}}\left[1 - \frac{1}{2}erfc\left(\frac{\ln\left(\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}+8\sigma_x^2\right)}{\sqrt{32}\sigma_x}\right)\right] - Ae^{-\frac{\left[\ln\left(\frac{\gamma}{\bar{\gamma}_{RD}^{FSO}}\right)+8\sigma_x^2\right]^2}{32\sigma_x^2}}\left[1 - \frac{1}{2}erfc\left(\frac{\ln\left(\frac{\gamma}{\bar{\gamma}_{SR}^{FSO}}+8\sigma_x^2\right)}{\sqrt{32}\sigma_x}\right)\right] \tag{18}$$

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were, $A = \frac{1}{\sqrt{32\pi}\sigma_x \gamma}$. For dual-hop communication systems with a reliable direct link between the source and destination, a technique called selection combining (SC) can be used at the destination to improve the signal reception. SC is known for its simplicity and lower complexity compared to other combining techniques. During SC, the receiver chooses the link with better instantaneous SNR. We can express this mathematically as below,

$$\gamma_{SC} = \max(\gamma_{SD}, \gamma_{SRD}) \quad (19)$$

For millimetre wave transmission, the cumulative distribution function of the received signal strength (γ_{SC}^{mmW}) can be expressed mathematically as.

$$F_{\gamma_{SC}^{mmW}}(\gamma) = prob\left[\max(\gamma_{SD}^{mmW}, \gamma_{SRD}^{mmW}) < \gamma\right] \quad (20)$$

Where, γ_{SD}^{mmW} and γ_{SRD}^{mmW} denote the real-time SNR values of the source-destination and source-relay-destination links, respectively, for mmW transmission scenarios. We can express the CDF equation in the following form,

$$F_{\gamma_{SC}^{mmW}}(\gamma) = \frac{1}{\Gamma(m)}\gamma\left(m, \frac{\gamma m}{\bar{\gamma}_{SD}^{mmW}}\right)\left\{1 - \left(\frac{\Gamma(m, \frac{\gamma m}{\bar{\gamma}_{SR}^{mmW}})}{\Gamma(m)}\right)\left(\frac{\Gamma(m, \frac{\gamma m}{\bar{\gamma}_{RD}^{mmW}})}{\Gamma(m)}\right)\right\} \quad (21)$$

The PDF of γ_{SC}^{mmW} is obtained by differentiating the overall CDF with respect to γ. After simplification, the expression is obtained as,

$$f_{\gamma_{SC}^{mmW}}(\gamma) = \frac{1}{\Gamma(m)}\gamma\left(m, \frac{\gamma m}{\bar{\gamma}_{SD}^{mmW}}\right) f_{\gamma_{SRD}^{mmW}}(\gamma)\left(\frac{m}{\bar{\gamma}_{SD}^{mmW}}\right)^m \frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_{SD}^{mmW}}} F_{\gamma_{SRD}^{mmW}}(\gamma) \quad (22)$$

where, $F_{\gamma_{SRD}^{mmW}}(\gamma)$ and $f_{\gamma_{SRD}^{mmW}}(\gamma)$ are given by *equation (23)* and *equation (24)*, respectively.

$$F_{\gamma_{SRD}^{mmW}}(\gamma) = 1 - \left[\left(\frac{\Gamma(m, \frac{\gamma m}{\bar{\gamma}_{SR}^{mmW}})}{\Gamma(m)}\right)\left(\frac{\Gamma(m, \frac{\gamma m}{\bar{\gamma}_{RD}^{mmW}})}{\Gamma(m)}\right)\right] \quad (23)$$

$$f_{\gamma_{SRD}^{mmW}}(\gamma) = \left(\frac{m}{\bar{\gamma}_{SR}^{mmW}}\right)\frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_{SR}^{mmW}}} + \left(\frac{m}{\bar{\gamma}_{RD}^{mmW}}\right)\frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_{RD}^{mmW}}} - \left(\frac{m}{\bar{\gamma}_{SR}^{mmW}}\right)\frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_{SR}^{mmW}}} \frac{1}{\Gamma(m)}\gamma\left(m, \frac{\gamma m}{\bar{\gamma}_{RD}^{mmW}}\right) - \left(\frac{m}{\bar{\gamma}_{RD}^{mmW}}\right)\frac{(\gamma)^{m-1}}{\Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}_{RD}^{mmW}}} \frac{1}{\Gamma(m)}\gamma\left(m, \frac{\gamma m}{\bar{\gamma}_{SR}^{mmW}}\right) \quad (24)$$

4. PERFORMANCE ANALYSIS OF THE PROPOSED HYBRID DH SYSTEM

By deriving analytical expressions for outage probability and average BER, this section provides a comprehensive analysis of the proposed system's performance. We will consider a scenario with DH, where a direct millimeter wave connection is established between the S and D base stations. The following equation represents the outage probability for this specific DH system configuration.

$$P_{out}^{SC\_mmW} = F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma_{th}^{FSO}) F_{\gamma_{SC}^{mmW}}(\gamma_{th}^{mmW}) \quad (25)$$

where, $F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma_{th}^{FSO})$ is acquired by substituting γ in *equation (17)* with γ_{th}^{FSO} and $F_{\gamma_{SC}^{mmW}}(\gamma_{th}^{mmW})$ is acquired by substituting γ in *equation (21)* with γ_{th}^{mmW}. Following BPSK modulation, the data is then sent through either FSO or mmW links. For this analysis, we assume data is transmitted on both links at the same rate. As detailed in reference [21], the BER for BPSK modulation can be described by an equation that depends on the instantaneous Signal-to-Noise Ratio (SNR) is given by,

$$p(e/\gamma) = 0.5\, \mathrm{erfc}(\sqrt{\gamma}) \quad (26)$$

To determine the average BER experienced under normal operating conditions, we need to consider the weighted average of the average BERs from both the FSO and mmW links. The mathematical expression for this combined average BER is given by,

$$\bar{P}_b^{SC\_mmW} = \frac{B_{DH}^{LN}(\gamma_{th}^{FSO}) + F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma_{th}^{FSO}) B_{SC}^{mmW}(\gamma_{th}^{mmW})}{1 - P_{out}^{SC\_mmW}} \quad (27)$$

The expression for $P_{out}^{SC\_mmW}$ from *equation (25)* is utilized, while $F_{\gamma_{SRD}^{FSO}}^{LN}(\gamma_{th}^{FSO})$ is calculated by substituting γ with γ_{th}^{FSO} in *equation (18)*. The average BER experienced on an FSO link ($B_{DH}^{LN}(\gamma_{th}^{FSO})$) is determined by computing the average of the conditional BER of a BPSK signal. This calculation yields the following expression,

$$B_{DH}^{LN}(\gamma_{th}^{FSO}) = \int_{\gamma_{th}^{FSO}}^{\infty} p(e/\gamma)\, f_{\gamma_{SRD}^{FSO}}^{LN}(\gamma)\, d\gamma \quad (28)$$

where, $p(e/\gamma)$ and $f_{\gamma_{SRD}^{FSO}}^{LN}(\gamma)$ are determined by *equation (26)* and *equation (18)* respectively. The average BER experienced on a mmW link ($B_{SC}^{mmW}(\gamma_{th}^{mmW})$) is computed by averaging the conditional BER of BPSK signal. And its expression is given by,

$$B_{SC}^{mmW}(\gamma_{th}^{mmW}) = \int_{\gamma_{th}^{mmW}}^{\infty} p(e/\gamma)\, f_{\gamma_{SC}^{mmW}}(\gamma)\, d\gamma \quad (29)$$

Where, $p(e/\gamma)$ and $f_{\gamma_{SC}^{mmW}}(\gamma)$ are provided by *equation (26)* and *equation (22)* respectively. The average BER of the hybrid system is derived by substituting *equation (29)* and *equation (28)* into *equation (27)*.

5. NUMERICAL RESULTS AND DISCUSSION

This section evaluates the performance of the proposed system under various atmospheric conditions by examining the derived mathematical formulas for outage probability and average BER. The FSO connection is represented using a Log-Normal model with different variance values, while the mmW connection is described by using a Nakagami-m model.

The performance of the hybrid system and the FSO cooperative SC system is shown in *figure 2*. This comparison is based on their outage probability under varying average SNR conditions.

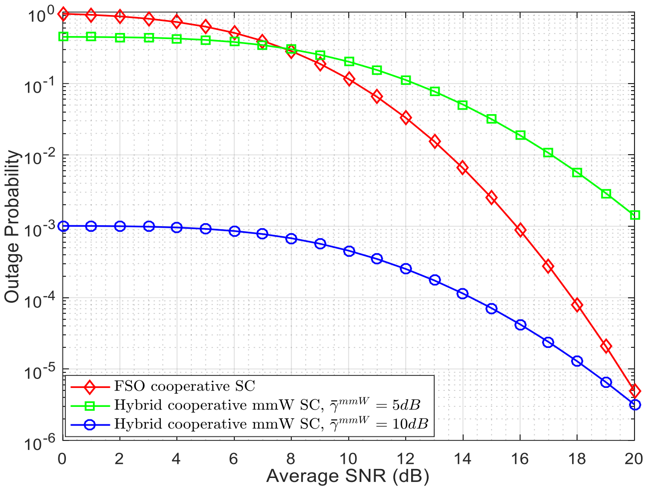

Figure 2. Outage probability vs Average SNR for different mm Wave links

Figure 2 shows that the suggested hybrid system outperforms the stand-alone FSO system, particularly when using a superior mmW connection. In comparison, a conventional FSO cooperative SC system experiences a higher OP of 1.1 × 10-1 at a typical SNR of 10 dB. In contrast, the proposed system offers significantly better performance, achieving outage probabilities ranging from 2.0 × 10-1 and 4.5 × 10-4 depending on mm Wave link quality.

Figure 3 below illustrates the fluctuation in outage probability for a hybrid cooperative system employing selection combining of mmW link, relative to the average SNR across various values of σ_x. As depicted in *figure 3*, the hybrid cooperative mmW-SC system exhibits superior performance for both σ_x values in comparison to the FSO cooperative SC system.

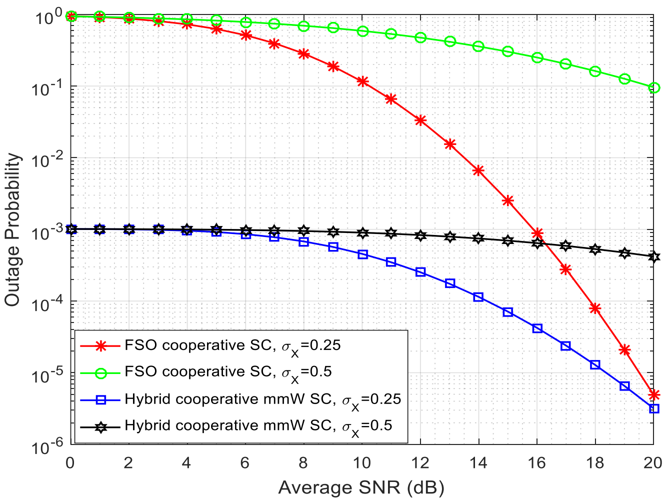

Figure 3. Outage probability vs Average SNR with different values of σx

For instance, at an average SNR of 10 dB, the hybrid system achieves significantly lower outage probabilities (4.5×10^{-4} and 9.0×10^{-4}) compared to the FSO cooperative SC system (1.1×10^{-1} and 5.8×10^{-1}) for σ_x values of 0.25 and 0.5, respectively.

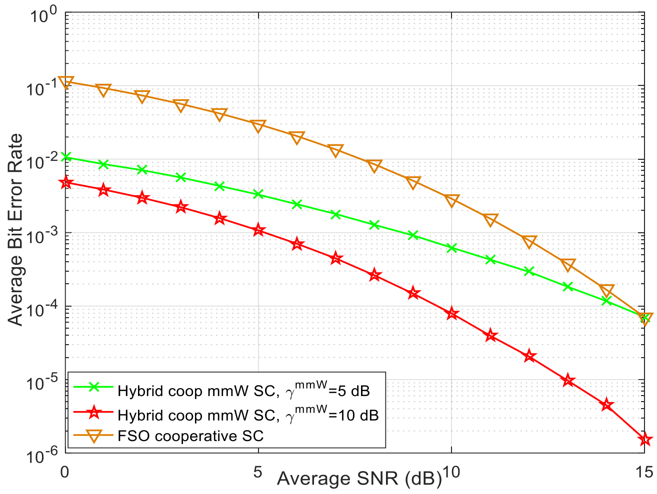

Figure 4. The average BER vs average SNR for different mmW connections

Figure 4 illustrates the change in average BER of a hybrid cooperative system with selection combining of mmW link concerning the average SNR. This analysis conducted at a constant threshold value of $\gamma_{th}^{mmW} = \gamma_{th}^{FSO} = 5dB$. The proposed hybrid system outperforms the FSO cooperative SC system in terms of average BER performance, as shown in *figure 4*.

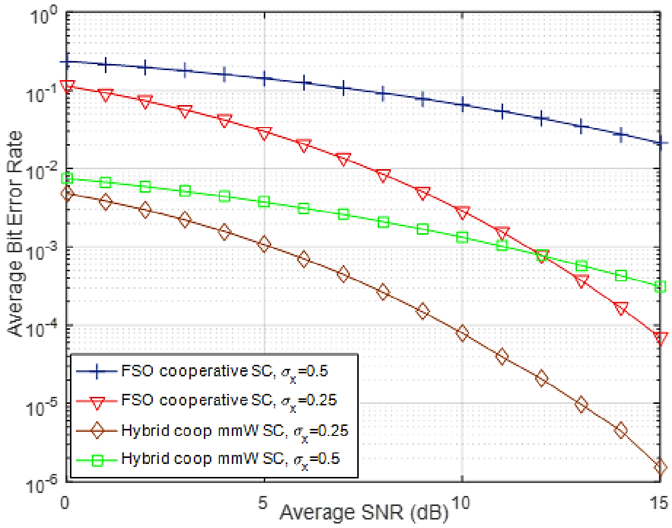

Figure 5: The average BER vs average SNR for different values of σ_x

For example, the FSO cooperative system achieves an average BER of 2.8×10^{-3} at an average SNR of 10 dB. In contrast, the suggested hybrid system attains 6.2×10^{-4} and 7.9×10^{-5} average BERs for $\gamma_{av}^{mmW} = 5$ dB and 10 dB mmW connections, respectively. In the above Figure 5, the fluctuation in the average BER of the proposed system is depicted in relation to the average SNR across various σ_x values. As illustrated in figure 5, the proposed system outperforms the FSO cooperative SC system for both σ_x values, showcasing superior performance.

Table 1. Average bit error rate of proposed system and FSO cooperative SC vs average SNR

S.No.	Avg. SNR (dB)	FSO cooperative SC		Proposed system	
		$\sigma_x = 0.25$	$\sigma_x = 0.5$	$\sigma_x = 0.25$	$\sigma_x = 0.5$
1	1	9.2×10^{-2}	2.1×10^{-1}	3.8×10^{-3}	6.6×10^{-3}
2	2	7.3×10^{-2}	1.9×10^{-1}	2.9×10^{-3}	5.8×10^{-3}
3	4	4.1×10^{-2}	1.5×10^{-1}	1.5×10^{-3}	4.4×10^{-3}
4	6	2.0×10^{-2}	1.2×10^{-1}	7.0×10^{-4}	3.1×10^{-3}
5	8	8.5×10^{-3}	9.2×10^{-2}	2.6×10^{-4}	2.1×10^{-3}
6	10	2.8×10^{-3}	6.5×10^{-2}	7.9×10^{-5}	1.3×10^{-3}
7	12	7.8×10^{-4}	4.3×10^{-2}	2.0×10^{-5}	7.7×10^{-4}
8	14	1.6×10^{-4}	2.7×10^{-2}	4.5×10^{-6}	4.3×10^{-4}

Table 1 presents the average BER values for both the proposed system and the FSO cooperative SC system across various σ_x values. The proposed hybrid system exhibits an average BER of 7.9×10^{-5} and 1.3×10^{-3}, respectively, for turbulence coefficients of 0.25 and 0.5 at an average SNR of 10 dB. In comparison, a free-space optical (FSO) cooperative SC system under the same conditions achieves an ABER of 2.8×10^{-3} and 6.5×10^{-2}, respectively.

6. CONCLUSIONS

This study investigates the performance of a hybrid FSO/mmW system incorporating a direct mmW link between the source and destination base stations. To achieve this, we analytically derive expressions for outage probability and average bit error rate (BER). We use a Log-Normal distribution to model the FSO link, and a Nakagami-m distribution to characterize the mmW link. Our numerical results demonstrate that the proposed hybrid system with a mmW backup link outperforms dual-hop FSO systems in terms of overall system performance. From the results, it is apparent that both the outage and average BER performances exhibit enhancement as the average SNR of the mmW link increases. This model presents a promising approach for realizing high-capacity and reliable communication in various applications, including 5G and beyond mobile network backhaul, high-speed internet access, and mission-critical data transmission.

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest.

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