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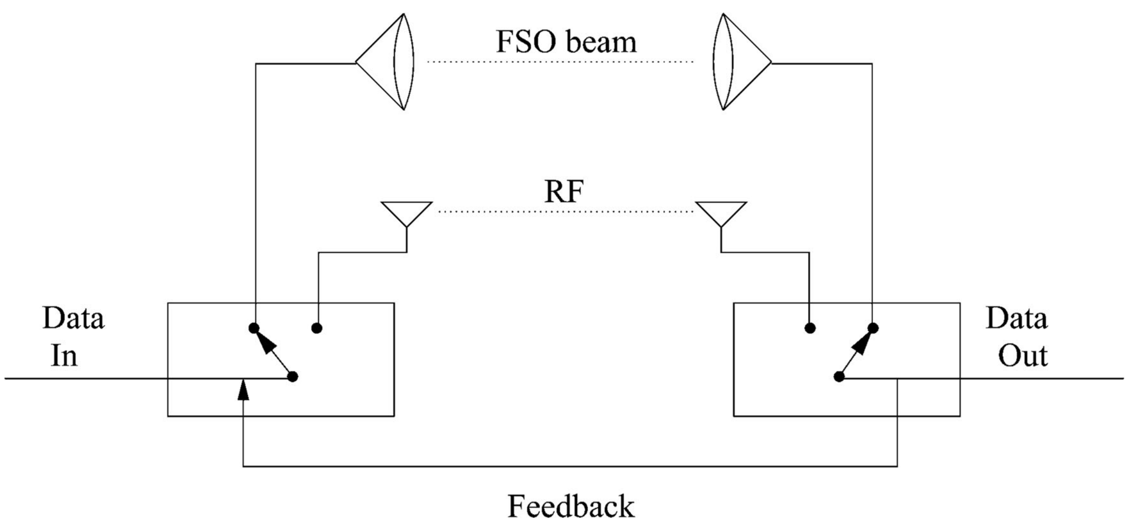

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Performance Evaluation of a Selection Combining Scheme for the Hybrid FSO/RF System

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Abstract: In this paper, an alternative implementation for the hybrid free-space optical (FSO)/radio frequency (RF) wireless communication system without requiring channel state information is presented. The proposed hybrid system transmits the same data with the same data rate over both links simultaneously. The well-known diversity selection combining scheme is implemented to combine the received signals in the electrical domain. New closed-form expressions for the average bit error rate and outage probability are derived in order to trace the system's performance over various channel turbulence conditions. The analysis of the proposed system's performance clearly indicates that the proposed system is advantageous as it exploits the complementary properties of the FSO and RF channels, even in strong turbulence conditions. In addition, the performance comparison demonstrates the proposed system's superior performance compared with the FSO-only system.

Index Terms: Optical systems, millimeter wavelength (MMW), hybrid free space optical/radio frequency (FSO/RF), diversity combining schemes

1. Introduction

Free space optical (FSO) communications have been adopted by an increasing number of wireless technology applications. Due to its obvious merits including wide bandwidth, low-cost deployment and license-free spectrum, FSO communications represent an attractive solution for wireless communication systems including the last mile connectivity problem [1]. However, the availability of the FSO link is greatly affected by adverse weather conditions such as fog and sandstorms; even in clear weather, the atmospheric turbulence may severely affect the link performance [2].

The hybrid free space optical/radio frequency (FSO/RF) technology is one possible solution for ensuring the availability of the link in different weather conditions. In the hybrid system, the RF link based on the (60 GHz) millimeter wave (MMW) technology, with an attractive high data rate that is comparable to that of the FSO link, is the perfect combination with the FSO link. This is because the links are affected differently by the weather conditions: the RF link is affected mainly by heavy rain, while the FSO channel suffers mostly from fog [3], [4]. Therefore, it is important to mitigate the effects of both channels by deploying the channel mitigation technique [5]. The diversity combining technique has been proposed for RF systems and recently for FSO systems to mitigate the atmospheric turbulence-induced fading channel effects in FSO systems [6].

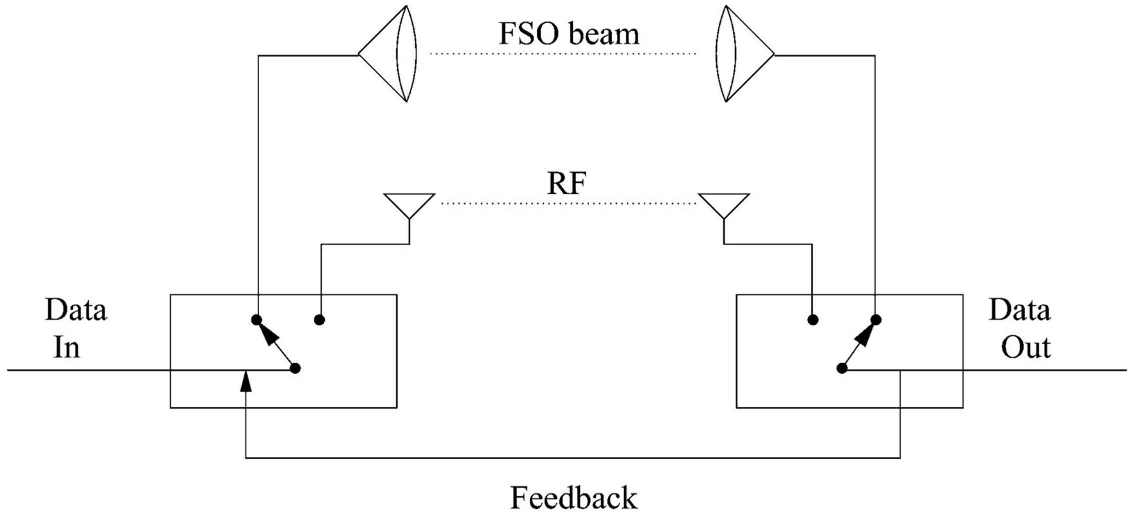

Fig. 1. Hybrid FSO/RF communication system using switching technique proposed in literature [12], [13].

The complementary properties of FSO and RF channels have led to many proposals for the hybrid FSO/RF link in communication systems. An adaptive coding technique for the hybrid FSO/RF system was introduced in [7], where the authors adjust the encoder rate based on the channel conditions. The adaptivity of the coding technique proposed in [7] for channel conditions depends on the availability of the channel state information (CSI) at the transmitter. In other research [8], the authors propose an adaptive hybrid system which includes an adjustment of the encoder rate, modem transmission rate, and modulation scheme of each channel. The adjustment processes are performed individually for each channel according to the varying channel states and assuming perfect CSI at the transceiver. In addition, a joint coding technique with and without a hybrid automatic repeat request for the hybrid system is presented in [9]. Despite the improvements in the system's performance in terms of throughput and outage probability, the proposed technique assumes perfect CSI knowledge at the receiver.

Despite transmitting over both links in [7]–[9] only the one signal that looks more reliable is processed by the receiver without deploying any combining technique to mitigate the channel effects. In addition, the efficiency of the previous schemes is strongly dependent on the availability of the feedback information or CSI availability at the transceivers.

In [10], the authors evaluate the deployment of the diversity combining technique and its impact on the bit error rate (BER) performance of the hybrid FSO/RF system. The BER versus the link distance performance is evaluated based on analytical and approximation expressions considering rain and fog channel conditions [10]. In our work we evaluate the BER and outage probability of the proposed hybrid system in terms of the signal-to-noise ratio (SNR) performance based on new exact closed-form expressions. For this purpose, we investigate the system performance under varying channel conditions (e.g., weak, moderate and strong turbulence channel situations). In addition, we provide an analytical performance comparison of the proposed system considering BPSK, QPSK, and 8PSK modulation techniques.

In other research by [11], the authors propose the use of the FSO link as the primary transmission channel combined with transmission over the RF link when the SNR of the FSO link falls below a threshold value. However, the receiver needs to measure the link's SNR frequently and then sends a feedback signal to activate the RF link. In our research, we propose redundant data transmission over both the FSO and MMW RF links and a diversity combining technique in order to maximize the channel spectrum utilization and mitigate the effects of turbulence channel impacts.

Fig. 1 shows one configuration for hybrid FSO/RF system that considers the FSO link as the primary transmission channel as long as its SNR is above a certain threshold value. When the SNR

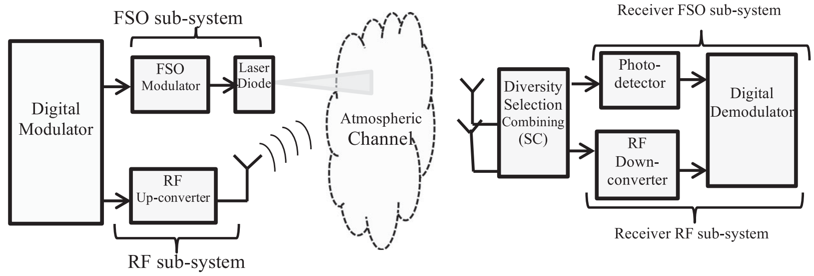

Fig. 2. The proposed hybrid FSO /RF system model block diagram.

of the FSO link falls below the threshold SNR, the receiver sends a feedback signal to activate the RF link for data transmission [12], [13]. Instead of using switching technique we propose an alternative implementation of hybrid FSO/RF system using the selection combining (SC) scheme to received signals from both links. The proposed implementation does not require feedback information or additional CSI at the transceiver. The system transmits data with the same data rates over both links simultaneously instead of transmission over one link. Thus, the proposed SC scheme for hybrid FSO/RF system benefits from FSO high data rate and the RF reliability without suffering from the over-switching schemes problem.

In this paper, new exact closed-form expressions of the average BER and outage probability (P_{out}) of the proposed hybrid FSO/RF system are derived. We investigate the performance of the proposed hybrid system takes into account atmospheric turbulence-induced fading channel conditions. In addition, we provide performance comparison investigations of the proposed hybrid system and the FSO-only link system over various channel situations. Our investigation is based on novel simulation results and a complete evaluation of the proposed system.

2. System and Channel Model

2.1 FSO Subsystem

At the transmitter of the proposed hybrid system, the information stream is modulated using the M-PSK digital scheme; the modulated signal is fed to both the FSO and RF sub-systems and transmitted over both links simultaneously as shown in Fig. 2.

The FSO sub-system adopts the intensity modulation and direct detection (IM/DD). A DC bias is added to the intensity-modulated signal by the laser diode to avoid the negative value of the modulated signal [14]. Then, the laser diode transmits the optical signal over the FSO channel.

At the receiver of the FSO sub-system, the photodetector diode converts the incident optical power into an electrical signal through direct detection. After the DC bias is filtered out, the electrical signal is demodulated to obtain the original information stream. The received signal y_{FSO} of the FSO sub-system is given by [14]:

$$y_{FSO} = \eta.\, x.\, I + n \tag{1}$$

The intensity I is a random variable that varies as the well-known gamma-gamma (G–G) distribution channel model, η is the receiver's optical-to-electrical conversion efficiency, x is the modulated signal and n is the additive white Gaussian noise (AWGN) with zero mean and variance of $(N_O^2/2)$. The instantaneous electrical SNR (γ_1) at the receiver of the FSO sub-system is expressed as [14]:

$$\gamma_1 = \frac{(I.\, \eta)^2}{N_o} \tag{2}$$

The average electrical SNR ($\overline{\gamma_1}$) is given by ($\overline{\gamma_1} = (\eta\, E[I])^2/N_o$), where $E[\cdot]$ is the expectation value. The probability density function (PDF) of the G–G channel model f_I in terms of the electrical

SNR, (γ_1) is given by [15]:

$$f_I(\gamma_1) = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\ \Gamma(\beta)\ \bar{\gamma}_1^{\frac{\alpha+\beta}{4}}}\ \gamma_1^{\frac{\alpha+\beta}{4}-1}\ K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\sqrt{\frac{\gamma_1}{\bar{\gamma}_1}}}\right) \tag{3}$$

where $\Gamma(.)$ is the gamma function ($\Gamma(z) = \int_0^\infty x^{z-1} e^x dx$), $K_{\alpha-\beta}$ (.) is the modified Bessel function of the second kind of order ($\alpha - \beta$). α is a positive parameter related to the effective number of large-scale cells of the scattering process, while β is the amount of fading parameters. α and β, can be directly related to atmospheric conditions through the following [16]:

$$\alpha = \left[exp\left(\frac{0.49\ \delta^2}{\left(1+0.18d^2+0.56\delta^{12/5}\right)^{7/6}}\right)-1\right]^{-1} \tag{4}$$

$$\beta = \left[exp\left(\frac{0.51\ \delta^2\left(1+0.69\delta^{12/5}\right)^{-5/6}}{\left(1+0.9d^2+0.62d^2\delta^{12/5}\right)^{5/6}}\right)-1\right]^{-1} \tag{5}$$

where $d = \sqrt{kD^2/4L}$, $k = 2\pi/\lambda$ is the optical wave number with optical wavelength λ, L is the length of the optical link and D is the optical receiver's aperture diameter. The parameter ($\delta^2 = 0.5C_n^2 k^{7/6}\ L^{11/6}$) is the Rytov variance with the atmospheric turbulence channel strength C_n^2 which is altitude-dependent [16]. The Hufnagel-Valley model is most commonly used to describe C_n^2 as shown in the following [16]:

$$C_n^2(h) = 0.00594(v/27)^2\left(10^{-5}h\right)^{10} exp\ (h/1000) + 2.7\ \times\ 10^{-6}\exp(-h/1500) + A\ exp\ (-h/1000) \tag{6}$$

where h is the altitude in meters (m), and v is the wind velocity in meters per second (m/sec), and A is the nominal value of $C_n^2(0)$ at the ground in $m^{-2/3}$. The cumulative distribution function (CDF) of the FSO channel with G–G distribution F_{γ_1} in terms of the link's SNR, γ_1, can be expressed by [14]:

$$F_{\gamma_1}(\gamma_1) = \frac{\left(\frac{\alpha\beta\gamma_1}{\bar{\gamma}_1}\right)^{\alpha+\beta/2}}{\Gamma(\alpha)\ \Gamma(\beta)}\ \ G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{7}$$

where $G_{r,s}^{m,n}(.)$ is the Meijer G-function. Now, let K be represented as $[K = ((\frac{\alpha\beta\gamma_1}{\bar{\gamma}_1})^{\alpha+\beta/2})/(\Gamma(\alpha)\ \Gamma(\beta))]$: by substituting K in (7), the CDF of the G–G distribution channel can be expressed as:

$$F_{\gamma_1}(\gamma_1) = K\ G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{8}$$

2.2 RF Subsystem

At the transmitter of the RF sub-system, the M-PSK modulated signal x is up-converted to MMW RF carrier frequency of (60 GHz) before it is transmitted through the RF link. At the receiver of the RF sub-system, the RF signal is down-converted and demodulated in order to retrieve the original data. The RF received signal y_{RF} is expressed as [17]:

$$y_{RF} = h_{RF}.\ x + n \tag{9}$$

where h_{RF} is the Rayleigh fading channel, x is the M-PSK transmitted signal, and n is the AWGN. The SNR at the receiver of the RF sub-system, γ_2, is expressed as [17]:

$$\gamma_2 = \frac{{h_{RF}}^2 P_{RF}}{N_o} \tag{10}$$

where P_{RF} is the power of the transmitted signal over the RF channel. The PDF of the Rayleigh fading channel f_{γ_2} in terms of the link's SNR, γ_2, is expressed as [17]:

$$f_{\gamma_2}(\gamma_2) = (1/\bar{\gamma}_2)\ exp\,(-\gamma_2/\overline{\gamma_2}) \tag{11}$$

where $\overline{\gamma_2}$ is the average SNR of the fading channel ($\overline{\gamma_2} = P_{RF}\ E[h_{RF}]^2/N_o$). The CDF of the Rayleigh channel F_{γ_2} in terms of the SNR of the RF link γ_2 is [17]:

$$F_{\gamma_2}(\gamma_2) = 1 - exp\,(-\gamma_2/\overline{\gamma_2}) \tag{12}$$

2.3 Selection Combining Scheme of the Hybrid FSO/RF System

The diversity SC scheme represents the simplest and most straightforward combining technique. The SC measures the electrical SNR of each link and selects the signal with the highest SNR value. Thus, the SNR of the selection combiner γ_{sc} can be expressed as [10]:

$$\gamma_{sc} = \max\ (\gamma_1, \gamma_2) \tag{13}$$

Hence, the CDF of the SNR of the selection combiner $F(\gamma_{sc})$ is given by [10]:

$$F\,(\gamma_{sc}) = F\,(\gamma_1)\,F\,(\gamma_2) \tag{14}$$

By substituting (8) and (12) in (14), the CDF of (γ_{sc}) will be given by,

$$F\,(\gamma_{sc}) = K\ G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, -\frac{\alpha+\beta}{2}\end{matrix}\right) - K\ \exp\,(-\gamma_2/\overline{\gamma_2})\,G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, -\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{15}$$

3. Average Bit Error Rate

In this section, a new closed-form expression for the average BER (P_b) of the proposed hybrid FSO/RF system is formulated in terms of the system SNR. This approach uses the BER expression of the dual-branch SC receiver in [18] as the following,

$$P_b = \frac{q^p}{2\Gamma\,(p)}\int_0^\infty exp\,(-q\gamma_{sc})\gamma_{sc}^{p\,-\,1}F\,(\gamma_{sc})\,d\gamma_{sc} \tag{16}$$

where $p = \frac{1}{2}$, $q = 1$ when $M = 2$ (BPSK), and $p = \frac{2}{\log_2 M}$, $q = \sin^2(\frac{\pi}{M})$ when $M > 2$ [19]. An extensive list of the modulation scheme parameters p and q is available in [19]. Then, by substituting (15) in (16) and utilizing [20, eq. (7.813.1)], the average BER expression is obtained as:

$$P_b = \frac{q^p}{2\Gamma\,(p)}q^{-p}K\,G_{2,3}^{2,2}\left(\frac{q\alpha\beta}{\bar{\gamma}_1}\middle|\begin{matrix}1-p,\ 1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, -\frac{\alpha+\beta}{2}\end{matrix}\right) - \frac{q^p}{2\Gamma\,(p)}K\left(q-\frac{1}{\bar{\gamma}_2}\right)^{-p}$$
$$\times\ G_{2,3}^{2,2}\left(\frac{\left(q-\frac{1}{\bar{\gamma}_1}\right)\alpha\beta}{\bar{\gamma}_1}\middle|\begin{matrix}1-p,\ 1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, -\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{17}$$

4. Outage Probability

The outage probability P_{out} represents the probability of the received signal SNR falling below a certain system SNR threshold value γ_{th}, and it is expressed by replacing the SNR value in the link's CDF equation by the SNR threshold value of γ_{th} [10].

Now, the closed-form expression of the outage probability of the proposed hybrid FSO/RF system is formulated by replacing the SNR value γ in (15) by the SNR threshold value γ_{th} of the system as

TABLE 1
System Parameters

FSO sub-system	
Parameter	Value
Wavelength, λ	1550 nm
Symbol rate	1 Gbits/s
Responsivity	0.5 1/v
Noise variance	10^{-14} A^2 /Hz
Optical to electrical conversion efficiency, η	1
Link range, L	1 Km
Receiver aperture diameter, D	0.02 m
RF sub-system	
Carrier frequency	60 GHz
Bandwidth	250 MHz
Noise power spectral density	−114 dBm/MHz

the following [15]:

$$P_{out} = F_{\gamma}\left(\gamma_{th}\right) \tag{18}$$

Hence, the P_{out} closed-form expression of the system will be as follows:

$$P_{out} = K\, G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_{th}}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) - K\exp\left(-\gamma_{th}/\overline{\gamma_2}\right).G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_{th}}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{19}$$

5. Results

In this section, the performance evaluation of the proposed hybrid FSO/RF system over various turbulence conditions is presented. The system performance is further compared with the performance of the FSO-only system with no combining, as a benchmarking scheme. Tables 1 and 2 display the adopted values of the proposed system, and channel respectively. The average SNR per bit for both the FSO and RF links is assumed to be equal.

The average BER performance of the proposed system with the BPSK modulation scheme is shown in Fig. 3, under weak, moderate and strong channel turbulence conditions. The results of the BER performance based on the average BER closed-form expressions as derived in the previous section are plotted as a function of the link's SNR. As can be observed from Fig. 3, the average BER values decreased as the values of the SNR increased as expected under all channel conditions. It can be shown as well that, as the atmospheric turbulence strength was increased, the BER values started to deteriorate. At the BER value of (10^{-6}), the proposed system at strong ($C_n^2 = 5 \times 10^{-14}$ $m^{-2/3}$) and moderate ($C_n^2 = 1.7 \times 10^{-14}$ $m^{-2/3}$) turbulence strength lost about (4.5 dB) and (1 dB) SNR compared with the system performance over a weak turbulence channel

TABLE 2
Channel Turbulence Parameters [14], [15]

Channel Turbulence Parameters	
Turbulence strength	C_n^2
Weak turbulence	8.4×10^{-15} m$^{-2/3}$
Moderate turbulence	1.7×10^{-14} m$^{-2/3}$
Strong turbulence	5×10^{-14} m$^{-2/3}$

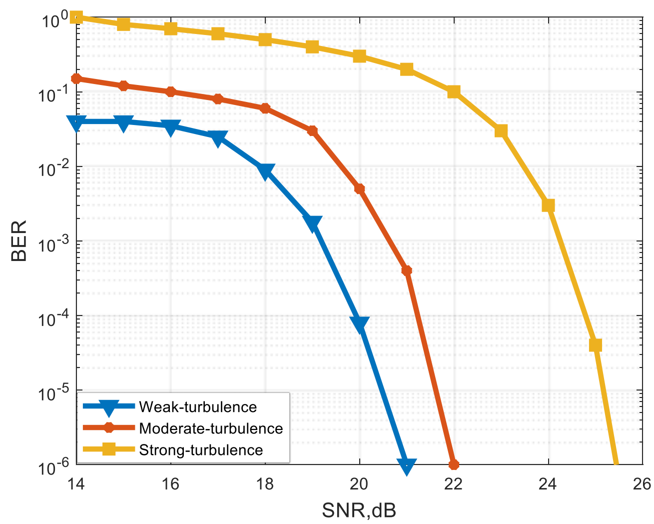

Fig. 3. Average BER performances of the proposed hybrid FSO/RF system under various turbulence conditions.

($C_n^2 = 8.4 \times 10^{-15}m^{-2/3}$). The degradation in severe channel conditions is expected due to the loss of the signal's line of sight.

Fig. 4 illustrates the comparison of the average BER performance of the proposed hybrid system that adopts the BPSK, QPSK and 8PSK modulation schemes under strong turbulence conditions ($C_n^2 = 5 \times 10^{-14}$ m$^{-2/3}$). As can be seen from Fig. 4, the system with the BPSK scheme performed better than the system with the QPSK and 8PSK modulation schemes. At (10^{-6}) BER, the BPSK scheme gained about (5 dB) and (10 dB) over the QPSK and 8PSK schemes. The deterioration of the system's BER performance with an increase in the modulation order is mainly due to an increase in the phase errors in higher order modulation scheme types under the same channel conditions.

In Fig. 5, the BER performance comparison of the proposed hybrid system and the FSO-only system with no combining scheme under various channel turbulence conditions is illustrated. The BPSK is considered as the modulation scheme for the two systems under consideration. Observation of the results in Fig. 5 indicates that the proposed hybrid system outperforms the FSO system under all channel conditions. At BER of (10^{-6}) and weak turbulence ($C_n^2 = 8.4 \times 10^{-15}$ m$^{-2/3}$), the hybrid system gained about (6 dB) compared with the FSO-only system, meanwhile, when the turbulence strength increased to ($C_n^2 = 5 \times 10^{-14}$ m$^{-2/3}$), the hybrid system gains about

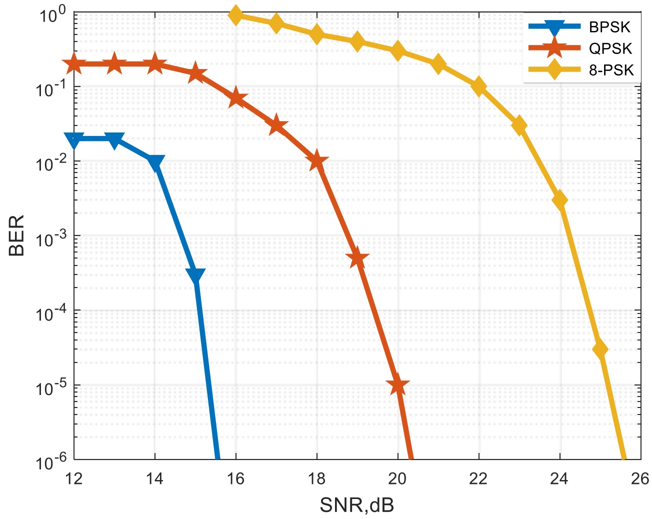

Fig. 4. Average BER of the proposed hybrid FSO/RF system with (BPSK, QPSK, 8PSK) modulation scheme under strong turbulence conditions.

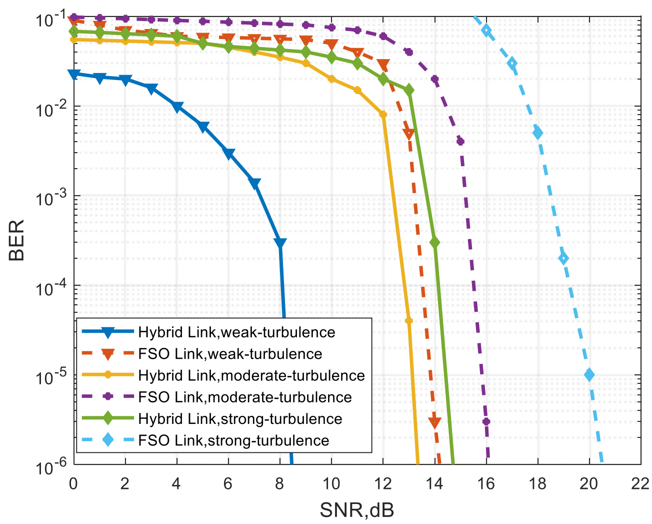

Fig. 5. BER performance comparison of the proposed hybrid FSO/RF and FSO-only systems under various turbulence conditions.

(6.5 dB) over the FSO system under the same channel conditions. Interestingly, the hybrid system at moderate turbulence of ($C_n^2 = 1.7 \times 10^{-14}$ m$^{-2/3}$) behaved similarly to the FSO system at ($C_n^2 = 8.4 \times 10^{-15}$ m$^{-2/3}$). The results presented in Fig. 4, clearly show that the proposed hybrid FSO/RF system with the combining scheme efficiently outperforms the FSO system under all channel conditions, whereby employment of the SC scheme led to efficient exploitation of the complementary nature of the FSO and RF channels.

Finally, Fig. 6, illustrates the outage probability performance of the proposed hybrid system versus the normalized average electrical SNR ($\frac{\gamma_{th}}{\bar{\gamma}}$) based on the closed-form expression of the outage probability of (19), under various channel conditions. The threshold SNR, γ_{th} of the system is (5 dB). It can be observed from the results illustrated in the figure that, as the effect of atmospheric turbulence increased, the system's performance was degraded: in order to reach the outage probability of (10^{-6}), the proposed system needed SNR of (17 dB), (25 dB) and (33 dB) under weak, moderate and strong turbulence conditions respectively.

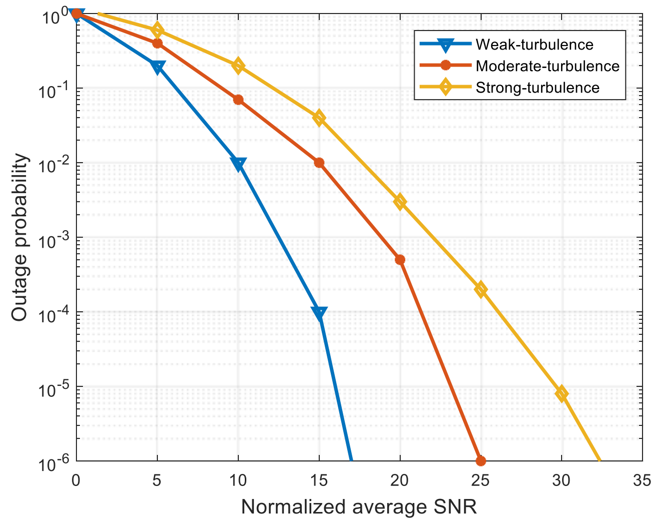

Fig. 6. Outage probability performance of the proposed hybrid FSO/RF under various turbulence conditions.

6. Conclusion

In this paper, an alternative implementation of the hybrid FSO/RF system with a receiver diversity combining scheme is introduced. The system supports the same data rate for both FSO and 60 GHz MMW RF links and combines the received signals using the SC scheme. New closed-form expressions of the average BER and outage probability are extracted to evaluate the proposed hybrid system performance over the atmospheric turbulence channels. The performance evaluation of the proposed hybrid system that adopts the BPSK modulation scheme showed that the average BER results are degraded with turbulence increasing from ($C_n^2 = 8.4 \times 10^{-15}\ m^{-2/3}$) to ($C_n^2 = 5 \times 10^{-14}\ m^{-2/3}$) by about (4.5 dB) at ($10^{-6}$) BER. The proposed hybrid system with BPSK showed a superior performance compared with the QPSK and 8PSK modulation schemes by about (5 dB) and (10 dB), respectively, under severe turbulence conditions of ($C_n^2 = 5 \times 10^{-14}\ m^{-2/3}$). In addition, the performance results showed the superiority and robustness of the hybrid FSO/RF system compared to the FSO-only system under various turbulence conditions. The system results clearly showed that the proposed hybrid FSO/RF efficiently exploits the complementary nature of FSO and RF channels under all turbulence conditions.

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