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

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***Abstract*—In this paper, an alternative implementation of the hybrid free space optical/radio frequency based on a millimeter wavelength 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 considered for combining the received signals in the electrical domain. A new closed-form expression for the average bit error rate and outage probability are derived in order to trace the system's performance over various turbulence channel conditions. The analysis of the results of the proposed system's performance clearly indicates that the proposed system is advantageous as it exploits the complementary properties of FSO and RF channels, even in strong turbulence channel conditions. In addition, the performance comparison demonstrates the proposed system's superior performance compared with the FSO-only system.**

I. 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 representing 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 sandstorm; even in clear weather the atmospheric turbulence may severely affect the link performance [2].

The hybrid FSO/radio frequency (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 of the FSO link. The RF link is the perfect combination with the FSO link since 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 complementary properties of FSO and RF channels have led to many proposals of the hybrid FSO/RF link in communication systems. An adaptive coding technique for the hybrid FSO/RF system was introduced in [6], the authors adjust the encoder rate based on the channel conditions. The adaptivity of the coding technique proposed in [6] for channel conditions depends on the availability of the channel state information (CSI) at the transmitter. In other research [7], 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 [8]. 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 [6]-[8] 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 [9], the authors evaluate the deployment of diversity combining technique 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 [9]. 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 a 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 digital modulation techniques.

In other research by [10], the authors propose the use of the FSO link as the primary transmission channel and combine with transmission over the RF link when the SNR of the

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FSO link falls below a threshold value. However, the receiver needs to measure the link's SNR frequently and 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 diversity combined technique in order to maximize the channel spectrum utilization and mitigate the effects of turbulence channel impacts. In addition, we provide performance comparison investigations of the proposed hybrid system and the FSO-only link system over various channel situations.

In some previous works [11],[12], a switching techniques for hybrid system is proposed. The authors consider the FSO link as the primary transmission channel and switched to transmission over the RF link when the SNR of the FSO link falls below a threshold value. Due to the switching technique, one link remains operational at a time which leads to increased bandwidth wastage [11],[12].

In this paper, an alternative hybrid FSO/RF implementation system is presented. The proposed implementation does not require a feedback information or additional CSI at the transceiver. The system transmits data with the same data rates over both links simultaneously. The received signals are combined using the selection combining (SC) scheme in the electrical domain to enable the FSO link bandwidth without giving up the RF link reliability. New exact closed-form expressions of the average bit error rate and outage probability (P_{out}) of the proposed hybrid FSO/RF system are derived. We investigate the performance of the proposed hybrid system under the effect of different turbulence channel conditions. Our investigation is based on novel simulation results and a complete evaluation of the proposed system.

II. SYSTEM AND CHANNEL MODEL

A. FSO and RF sub-systems

At the transmitter of the proposed hybrid system, the information stream is modulated using M-PSK digital scheme, the modulated signal, is fed to both FSO and RF sub-systems and transmitted over both links simultaneously as shown in Fig. (1).

The transmitter of the FSO sub-system is adopted 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 [13], then the laser diode is transmitted signal over the FSO channel.

At the receiver of the FSO sub-system, the photodetector diode is converted 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 [13]

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

The intensity I is a random variable that varies as the well-known gamma-gamma (*G-G*) distribution channel model when the signal passing through the FSO channel, 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 end of the FSO sub-system is expressed as [13]

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

The average electrical SNR is given by $(\overline{\gamma_1} = (\eta\, E[I])^2/N_o)$, where E[.] is the expectation value. The probability density function (PDF) of the *G*–G channel model in terms of the electrical SNR (γ_1) is given by [14]

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

where $K_{\alpha-\beta}$ (.) is the modified Bessel function of the second kind of order $(\alpha-\beta)$, $\Gamma(.)$ is the gamma function. 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 parameter, α and β can be directly related to atmospheric conditions through the following expressions [15]

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

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

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 $(\delta^2 = 1.23\, C_n^2\, k^{7/6} L^{11/6})$ is the Rytov variance with the atmospheric turbulence channel strength C_n^2 [15]. The cumulative distribution function (CDF) of the FSO channel with *G–G* distribution in term of link SNR, γ_1 can be expressed by [13]

$$F_{\gamma_1}(\gamma_1) = \frac{(\frac{\alpha\beta\gamma_1}{\bar{\gamma}_1})^{\alpha+\beta/2}}{\Gamma(\alpha)\,\Gamma(\beta)}\,G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\bar{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta+\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{6}$$

where $G_{r,s}^{m,n}(.)$ is the Meijer G-function. Now, let's K represents as $\left[K = ((\frac{\alpha\beta\gamma_1}{\bar{\gamma}_1})^{\alpha+\beta/2})/(\Gamma(\alpha)\,\Gamma(\beta))\right]$, by substituting K in (6), the CDF of the *G–G* distribution channel can be expressed as

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

At the transmitter of the MMW RF sub-system, the M-PSK modulated signal x is up-converted to MMW RF carrier frequency of (60 GHz) before it transmitted through the RF link. At the receiver end of the RF-subsystem, the RF signal is down-converted and demodulated, to retrieve the original information stream. The RF received signal y_{RF} is expressed as [16]

$$y_{RF} = h_{RF}.x + n \tag{8}$$

where h_{RF} is the Rayleigh fading channel of the RF link, x is the M-PSK transmitted signal, and n is the AWGN. The SNR at the output of the receiver of the RF sub-system (γ_2) is expressed as

$$\gamma_2 = \frac{{h_{RF}}^2 P_{RF}}{N_o} \tag{9}$$

where P_{RF} is the power of transmitted signal over the RF channel. The PDF of Rayleigh fading channel in terms of the link SNR (γ_2) is expressed as [16]

$$f_{\gamma_2}(\gamma_2) = (1/\overline{\gamma}_2)\exp(-\gamma_2/\overline{\gamma}_2) \tag{10}$$

where $\overline{\gamma_2}$ is the average SNR for the fading channel ($\overline{\gamma}_2 = P_{RF}\, E[h_{RF}]^2/N_o$). The CDF of the Rayleigh channel is,

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

B. Selection combining scheme for hybrid RF/FSO system

The selection combining (SC) scheme represents the simplest and most straightforward combining scheme, where the combiner measured the electrical SNR of each link and selected the signal with the highest SNR value. Thus, the SNR of the selection combiner γ_{sc} can be expressed as [9]

$$\gamma_{sc} = max\,(\gamma_1, \gamma_2) \tag{12}$$

Hence, the CDF of the signal to noise ratio of the selection combiner $F(\gamma_{sc})$ is given by [9]

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

By substituting (7) and (11) in equation (13), the CDF of (γ_{sc}) is given by,

$$(\gamma_{sc}) = K\, G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\overline{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) - K\exp(-\gamma_2/\overline{\gamma}_2)\, G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_1}{\overline{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{14}$$

III. AVERAGE BIT ERROR RATE

In this section, a closed-form expression for the average bit error rate (P_b) of the proposed hybrid RF/FSO system with the selection combining scheme will be formulated in term of the system SNR.

By using the BER expression of the dual-branch selection combining receiver [17] as the following,

$$P_b = \frac{q^p}{2\Gamma(p)}\int_0^\infty \exp(-q\gamma_{sc})\gamma_{sc}^{p-1}F(\gamma_{sc})d\gamma_{sc} \tag{15}$$

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 $M > 2$ [18], then by substituting the CDF expression of (14) in the BER expression of (15) and utilizing the following integral of the Meijer function rule as [19]

$$\int_0^\infty x^{-\rho}e^{-\beta x}\, G_{pq}^{mn}\left(\alpha x\middle|\begin{matrix}a_1 & \dots & a_p\\ b_1 & \dots & b_q\end{matrix}\right)dx = \beta^{\rho-1}\, G_{p+1,q}^{m,n+1}\left(\frac{\alpha}{\beta}\middle|\begin{matrix}\rho, a_1 & \dots & a_p\\ b_1 & \dots & b_q\end{matrix}\right) \tag{16}$$

Then the average BER of the proposed hybrid RF/FSO system with selection combining scheme is obtained as

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

IV. OUTAGE PROBABILITY

The outage probability P_{out}Pout represented the probability of the received signal SNR falls below a certain system SNR threshold value γ_{th}, and it expressed by replacing the SNR value in the link CDF equation by the SNR threshold value of γ_{th} [2].

Now, the closed-form expression of the outage probability of the proposed hybrid FSO/RF system is formulated by replacing the SNR value γ of the CDF equation of (14) by the SNR threshold value γ_{th} of the system as the following,

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

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

$$P_{out} = K G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_{th}}{\overline{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) - K\exp(-\gamma_{th}/\overline{\gamma}_2).\, G_{1,3}^{2,1}\left(\alpha\beta.\frac{\gamma_{th}}{\overline{\gamma}_1}\middle|\begin{matrix}1-\frac{\alpha+\beta}{2}\\ \frac{\alpha-\beta}{2},\frac{\beta-\alpha}{2},-\frac{\alpha+\beta}{2}\end{matrix}\right) \tag{19}$$

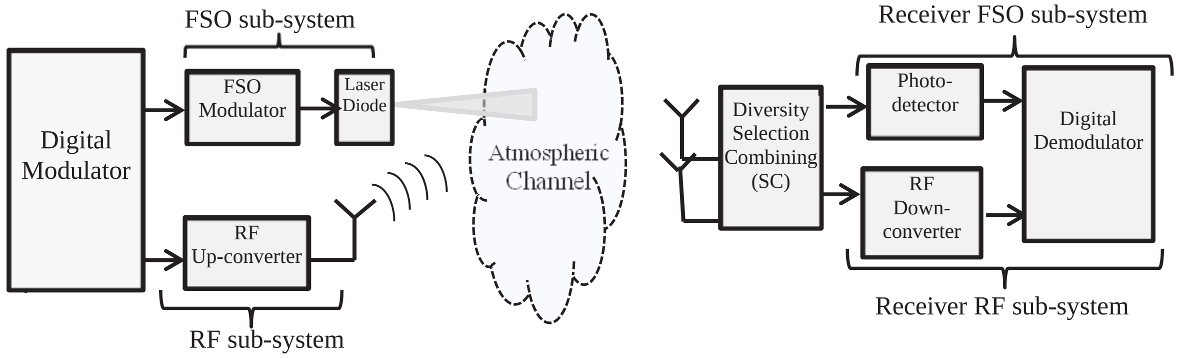

Fig. 1. The proposed hybrid FSO /RF system model block diagram

V. Results

In this section, the performance evaluation of the proposed hybrid RF/FSO system with selection combining scheme under various channel conditions is presented. The system performances will further compare with the only FSO system with no combining as a benchmarking scheme. Table I and II display the adopted values of the system and channel respectively. The average SNR per bit for both RF and FSO links is assumed to be equal.

TABLE I. System Parameters [6]

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

TABLE II. Channel Turbulence Parameters [13], [14]

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} $m^{-2/3}$

The average BER performance of the proposed system with BPSK modulation scheme is shown in Fig. 2, under weak, moderate and strong turbulence channel conditions. The results of the average BER performances based on the average BER closed-form expression that had been derived in the previous section are plotted as a function of the link SNR. It can be observed from Fig. 2, that the system's average BER values decrease as the values of SNR are increasing as expected under all channel conditions. It can be shown as well that as the atmospheric turbulence strength is increased, the BER values start to deteriorate. Where at BER of (10^{-6}), the proposed system at strong (C_n^2 =5×10^{-14} $m^{-2/3}$) and moderate (C_n^2 =1.7×$10^{-14}$$m^{-2/3}$) turbulence strength lost about (4.5 dB) and (1 dB) SNR comparing with the system performance under weak turbulence channel strength (C_n^2 =8.4×$10^{-15}$$m^{-2/3}$). The degradation performance in a severe channel condition is expected due to the loss the signal's line of sight.

Fig. 3, demonstrates the average BER performance comparison of the proposed hybrid system that adopting BPSK, QPSK and 8PSK modulation schemes under strong turbulence channel condition (C_n^2 =5×10^{-14} $m^{-2/3}$). As can be seen from Fig. 3, the system with BPSK performs much better than the system with QPSK and 8PSK modulation schemes. Where, at (10^{-6}) BER, BPSK scheme gains about (5 dB) and (10 dB) over QPSK and 8PSK schemes. The system BER performance's deteriorating with increasing the modulation order of the adopted modulation scheme is mainly due to increasing the phase errors in higher order modulation scheme types (QPSK, 8PSK) under the same channel conditions.

In Fig. 4, the BER performance comparison of the proposed hybrid system and the only FSO system with no combing scheme under various turbulence channel conditions are demonstrated. The BPSK is considered as the modulation scheme for the two systems under consideration. Observing the results of Fig. 4, indicate that the proposed hybrid system outperforms the FSO system under all channel conditions. At BER of (10^{-6}) and weak channel condition (C_n^2 =8.4×$10^{-15}$$m^{-2/3}$), the hybrid system gains about (6 dB) comparing with the only FSO system, while when the turbulence strength increases to (C_n^2 =5×$10^{-14}$$m^{-2/3}$), the hybrid system gains about (6.5 dB) over the FSO system under the same channel condition. Interestingly, the hybrid system at moderate channel condition of (C_n^2 =1.7×10^{-14} $m^{-2/3}$) behaves nearly similar to FSO system at (C_n^2 =8.4×$10^{-15}$$m^{-2/3}$). The results of Fig. 4, clearly showed that the proposed hybrid FSO/RF system with combining scheme is efficiently outperform the FSO system under all

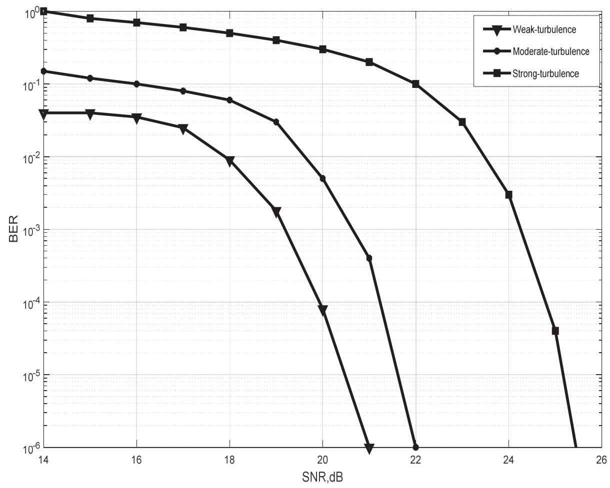

Fig. 2. Average BER performances of the proposed hybrid FSO/RF system under various turbulence channel condition

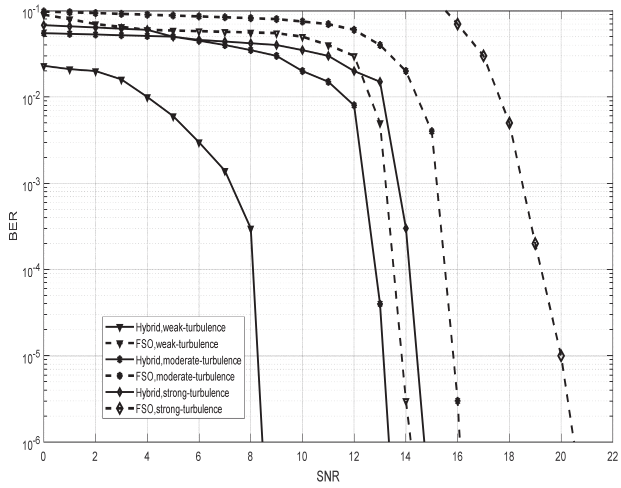

Fig. 4. BER performance comparison of the proposed hybrid FSO/RF system and FSO only system under various turbulence channel conditions

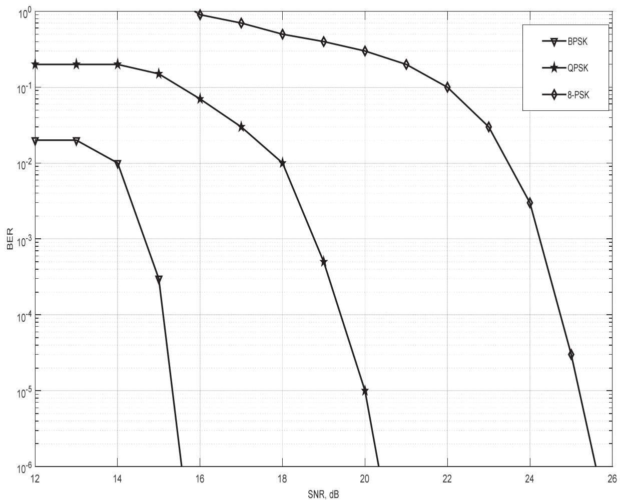

Fig. 3. Average BER of the proposed hybrid FSO/RF system with (BPSK, QPSK, 8PSK) modulation scheme under strong turbulence channel conditions

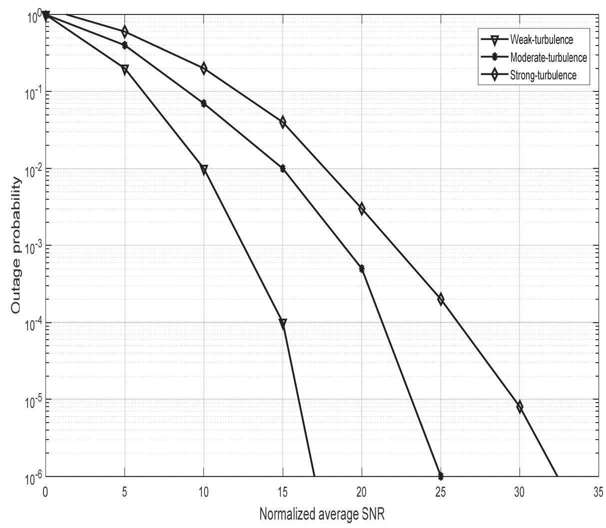

Fig. 5. Outage probability performances of the proposed hybrid FSO/RF under various turbulence channel conditions

channel conditions, where employment of the selection combining scheme led to efficiently exploits the complementary nature of the FSO and RF channels.

Finally, Fig. 5, 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 figure that as the effect of atmospheric turbulence increases, the system's performance is degraded. Where, to reach to outage probability of (10^{-6}), the proposed system need SNR of (17), (25) and (33) dB under weak, moderate and strong turbulence channel conditions.

VI. 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 superiority performance comparing with the QPSK and 8PSK modulation schemes by about (5 dB) and (10 dB), respectively, under severe turbulence channel 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 channel 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 channel conditions.

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