A Comparison of Modulation Formats for Modified Switching Scheme of Hybrid FSO/RF System

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ABSTRACT

Different modulation techniques with Intensity Modulation Direct Detection (IM/DD) have been used in free space optical (FSO) communication. In this paper, a comparative analysis of various modulation schemes for hybrid FSO/RF system is presented. The modulation schemes are on-off keying (OOK), binary-pulse position (B-PPM), binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-PSK, Differential Shift Keying (DPSK), and duo-binary. The performance is analyzed in terms of bit error rate (BER) under different conditions. Furthermore, the different modulation schemes are investigated in light of a modified switching scheme for the hybrid FSO/RF system. We have considered Nakagami-m channel model for RF and Gamma-Gamma channel model for FSO. Simulation results show that BPSK has better performance than other modulation formats under different turbulence conditions. We demonstrate that by increasing the average optical SNR and RF SNR, the BER performance improves.

Keywords- Free Space Optical (FSO), Hybrid FSO/RF, Modified Switching Scheme, Modulation Format, Bit Error Rate (BER).

1. INTRODUCTION

The free space optical (FSO) communication has proved its strong presence in the field of telecommunication because of its appreciated rewards over RF communication. However, the performance of an FSO link is highly hampered by climate conditions and the channel parameters of its installation location [1]. A RF link has been installed, to support the FSO link in the adverse weather conditions. This combined system is known as hybrid FSO/RF system which shows a high reliability along with high speed data transmission. Different modulation techniques like On-Off Keying (OOK) and Pulse Position Modulation (PPM) with Intensity Modulation Direct Detection (IM/DD) have been used in FSO. In OOK modulation, it has been observed that under atmospheric turbulence, adaptive threshold detector is a better option as compared to fixed threshold detector. Since adaptive threshold is not required for PPM, it can reach near optimum channel capacity and transmitter diversity can also be achieved without special coding [2]. M-ary PPM improves system performance by enhancing power and bandwidth efficiencies [3]. Digital pulse interval modulation (DPIM), [4] provides high transmission capacity by eliminating unused time slots. A comparison of OOK, PPM and DPIM modulation schemes for optical wireless communication given in [5]. DPIM modulation is equally suitable for both indoor and outdoor communications. Subcarrier binary phase shift keying intensity modulation (SIM-BPSK) was analyzed in [6], and observed that coherent modulation is a better alternative to OOK and BPPM. In [7], an experimental comparison of OOK and BPSK modulation is presented, under controlled turbulence channel conditions and the results show that BPSK outperforms widely used OOK modulation technique. Advantage of BPSK scheme comes at the cost of power and bandwidth efficiencies. BER performance of OOK, differential phase shift keying (DPSK), and differential quadrature phase shift keying (DQPSK) modulation formats, with and without space diversity reception technique (SDRT), are compared, in [8]. It is observed that DPSK and DQPSK are better in comparison to OOK modulation.

The above existing works do not shed light on the performance of modulation formats in the hybrid FSO/RF system. In this paper, we have tried to address this shortcoming by comparing the performance of the some of the most commonly used modulation schemes, namely, OOK, BPPM, BPSK, QPSK, 8-PSK, DPSK, and Duo-binary modulation formats for the hybrid FSO/RF system. Further, since the optical is the dominant link, we investigate the performance of the modulation schemes under weak to strong turbulence conditions for the optical channel.

The hybrid FSO/RF system changes its region of operation depending upon the current weather conditions, thus, a switching mechanism is required. Here, the modified switching scheme [9] is considered for this purpose. In this switching scheme, two threshold levels are defined for FSO link and one threshold level for RF link. This switching scheme is chosen since it is power efficient and shows better error performance over other existing switching schemes.

The rest of the paper is organized as follows: In Section II, channel models used in the analysis are dis cussed. Section III presents the channel models used for modeling the optical and RF channels. Section IV includes the performance analysis for different modulation schemes. Results and discussions are presented in Section V, followed by conclusions in Section VI.

2. CHANNEL MODELS

The hybrid FSO/RF system comprises of two channel, the optical channel and the RF channel. Here, the optical channel is modeled by the Gamma-Gamma fading model and the RF channel is modelled by Nakagami-m fading model. A brief discussion about each channel model is presented below.

2.1 OPTICAL CHANNEL MODEL

The wireless optical system can be modeled as follows:

$$y(t) = R.h.x(t) + n_o(t) \tag{1}$$

where $y(t)$ is received optical signal, *R* the responsivity of photodetector, hthe instantaneous optical channel intensity gain, or optical channel state, $x(t)$ the transmitted signal, and $n_o(t)$ the real–valued Additive White Gaussian Noise (AWGN) with zero mean and variance $\sigma_o^2 \triangleq \mathbb{E}[|n_0(t_i)|^2]$ respectively.The PDF of the gamma-gamma distributed atmospheric turbulence is [10]

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_a}\right) \quad (2)$$

In the above equation, $K_n(\cdot)$ is the Bessel function of the second kind and n^{th} order, and α and β are positive parameters representing the effective number of small scale and large scale eddies of the scattering environment. α and β are given by

$$\alpha = \left\{exp\left[\frac{0.49\,\sigma_R^2}{\left(1+1.11\,\sigma_R^{12/5}\right)^{7/6}}\right]-1\right\}^{-1} \quad (3)$$

$$\beta = \left\{exp\left[\frac{0.51\,\sigma_R^2}{\left(1+0.69\,\sigma_R^{12/5}\right)^{5/6}}\right]-1\right\}^{-1} \quad (4)$$

where, σ_R^2 is Raytov variance, and is given by $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$. Here L is the distance between transmitter and receiver, k the wave number $(k = 2\pi/\lambda)$ with wavelength λ, and C_n^2 the structure constant of refractive index fluctuations. The instantaneous optical received SNR is given by $S_o = \bar{S}_o |h|^2$, where $\bar{S}_o$ is average received optical SNR in IM/DD detector, given by [11], $\bar{S}_o = \frac{2R^2 P_{To}^2 G_o^2}{\sigma_x^2}$, where P_{To} is average transmitted optical power, G_o average gain of the FSO link depends on path loss. The pdf of the atmospheric turbulence (2) can be expressed in terms of instantaneous SNR, S_o as

$$f_{S_o}(S_o) = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)\bar{S}_o^{\frac{\alpha+\beta}{4}}} S_o^{\frac{\alpha+\beta}{4}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\sqrt{\frac{S_o}{\bar{S}_o}}}\right) \quad (5)$$

The Bessel function of the second kind can be expressed in terms of Meijer-G function by using [12], as $K_v(2\sqrt{x}) = \frac{1}{2} G_{0,2}^{2,0}\left(x\middle|_{v/2,\,-v/2}^{\,-}\right)$, and the above pdf is expressed as

$$f_{S_o}(S_o) = \frac{S_o^{-1}}{2\Gamma(\alpha)\Gamma(\beta)} G_{0,2}^{2,0}\left(\alpha\beta\sqrt{\frac{S_o}{\bar{S}_o}}\middle|_{\alpha,\beta}^{-}\right) \quad (6)$$

And the cumulative distribution function (CDF) can be expressed as

$$F_{S_o}(S_o) = \frac{1}{\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{2,1}\left[\alpha\beta\sqrt{\frac{S_o}{\bar{S}_o}}\middle|_{\alpha,\beta,0}^{1}\right] \quad (7)$$

2.2 RF CHANNEL MODEL

The RF link is modelled by Nakagami-m fading model, whose pdf is given as [10]

$$f_X(x) = \frac{2m^m}{\Gamma(m)\,\Omega^m} x^{2m-1} e^{-\frac{m}{\Omega}x^2} \quad (8)$$

where, $m = \frac{[E(x^2)]^2}{var(x^2)}$, , and $\Omega = 1$, The pdf and corresponding CDF of the RF fading channel in terms of received electrical SNR, S_{rf}, is given as

$$f_{S_{rf}}(S_{rf}) = \left(\frac{m}{S_{rf}}\right)^m \frac{1}{\Gamma(m)} S_{rf}^{\,m-1} e^{-\left(\frac{m}{\bar{S}_{rf}}\right)S_{rf}} \qquad (9)$$

$$F_{S_{rf}}(S_{rf}) = \frac{\Upsilon\left(m, \frac{m}{\bar{S}_{rf}} S_{rf}\right)}{\Gamma(m)} \qquad (10)$$

where, instantaneous SNR of RF link is related to the average SNR of RF link as $S_{rf} = |X|^2 \bar{S}_{rf}$, and average SNR is given by [11],$\bar{S}_{rf} = \frac{P_{T_{rf}} G_{rf}}{\sigma_n^2}$,where,$P_{T_{rf}}$is the transmitted RF signal power, G_{rf} the average power gain of the RF link, and σ_n^2 the noise variance of RF link.

3. PERFORMANCE ANALYSIS

The performance of the Hybrid FSO/RF System for differentmodulation schemes is studied under the modified switchingscheme. The average BER is given as

$$P_{FSO} = \int_0^\infty P_e(e/\gamma) f_\gamma(\gamma)\, d\gamma \qquad (11)$$

The$P_e(e/\gamma)$is the conditional error probability, depends on the modulation format. For some modulation formats the $P_e(e/\gamma)$ is given as

OOK: $P_e(e/S_o) = \frac{1}{2} erfc\left(\frac{\sqrt{S_o}}{2}\right)$

BPPM: $P_e(e/S_o) = \frac{1}{2} erfc\left(\frac{\sqrt{S_o}}{2}\right)$

BPSK: $P_e(e/S_o) = \frac{1}{2} erfc\left(\sqrt{S_o}\right)$

QPSK: $P_e = \frac{P_s}{\log_2 M}$ where M = 4, and P_s is symbol error rate (SER), $P_s = \frac{1}{2} erfc\left(\sqrt{\frac{S_o}{2}}\right)$

8-PSK: $P_e = \frac{P_s}{\log_2 M}$ where M = 8, and P_s is symbol error rate (SER), $P_s = \frac{1}{3} erfc\left(0.3826\sqrt{S_o}\right)$

DPSK: $P_e(e/S_o) = \frac{1}{2} exp(-S_o)$

Duo-binary (DB):$P_e(e/S_o) \approx \frac{3}{4} erfc\left(\frac{\pi}{4}\sqrt{S_o}\right)$; under the condition of high SNR.

The error probabilities of above said modulation formats can be represented by a general expression as

$$P_e = \frac{A}{2} erfc\left(B\sqrt{SNR}\right) \qquad (12)$$

where A and B are given in table-1

Table I: Values of A and B for different Modulation Formats

Modulation Format	A	B
OOK	1	$1/2$
BPPM	1	$1/2$
BPSK	1	1
QPSK	1	$1/\sqrt{2}$
8-PSK	2/3	0.3826
DPSK	2	1
DB	3/2	$\pi/4$

The complementary error function can be expressed in terms of Meijer-G function by using [12], as $erfc\left(\sqrt{x}\right) = \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0}\left(x\middle|\begin{matrix}1\\0,\ 1/2\end{matrix}\right)$.The BER of optical link is computed as

$$P_{FSO} = \frac{A 2^{\alpha+\beta-3}}{\Gamma(\alpha)\Gamma(\beta)\pi^{\frac{3}{2}}} G_{2,5}^{4,2}\left[\frac{(\alpha\beta)^2}{16\bar{S}_o B^2}\middle|\begin{matrix}\frac{1}{2}, 1\\ \frac{\alpha}{2}, \frac{\alpha+1}{2}, \frac{\beta}{2}, \frac{\beta+1}{2}, 0\end{matrix}\right] \qquad (13)$$

Similarly, the BER expression for RF link is obtained as

$$P_{RF} = \frac{A}{4}\left(\frac{m}{\bar{S}_{rf}}\right)^{m}\left(B^2 + \frac{m}{\bar{S}_{rf}}\right)^{-m} \qquad (14)$$

The BER of hybrid FSO/RF system with modified switching scheme is calculated as

$$BER_{avg} = \frac{1}{1-P_{out}}\begin{bmatrix}Prob(S_o > \lambda_1)P_{FSO}(S_o) + Prob(\lambda_2 < S_o < \lambda_1)P_{FSO+RF}(S_o + S_{rf})\\ + Prob(S_o < \lambda_2,\ S_{rf} > \phi_1)P_{rf}(S_{rf})\end{bmatrix} \qquad (15)$$

In (15), $P_{FSO}(S_o)$, $P_{FSO+RF}(S_o + S_{rf})$, and $P_{rf}(S_{rf})$ denotes the probability of error when data is transmitted via optical link only, both links simultaneously, and only RF link respectively, P_{out} denotes the outage probability of the system. Here, both optical and RF links are considered to be independent. The probabilities of the hybrid FSO/RF system operating in optical, hybrid and RF regions are respectively, given as

$$Prob(S_o > \lambda_1) = \int_{\lambda_1}^{\infty} f_{S_o}(S_o)\, dS_o = [1 - F_{S_o}(\lambda_1)]$$

$$Prob(\lambda_2 < S_o < \lambda_1) = [F_{S_o}(\lambda_1)] - [F_{S_o}(\lambda_2)]$$

$$Prob(S_o < \lambda_2,\ S_{rf} > \phi_1) = F_{S_o}(\lambda_2)\left[1 - F_{S_{rf}}(\phi_1)\right] \qquad (16)$$

The outage probability is computed as

$$Outage\ Prob. = \left[\int_0^{\lambda_2} f_{S_o}(S_o)\, dS_o\right] \times \left[\int_0^{\phi_1} f_{S_{rf}}(S_{rf})\, dS_{rf}\right] = [F_{S_o}(\lambda_2)] \times [F_{S_{rf}}(\phi_1)] \qquad (17)$$

4. RESULTS AND DISCUSSION

This section discusses performance of some well-knownmodulation schemes for the Modified Switching Scheme in the Hybrid FSO/RF system. The average optical SNR is variedfrom 0 to 50 dB. The lower optical threshold, λ_2 =5dB andthe upper optical threshold, λ_1 = 10 dB. The RF threshold, ϕ_1 = 5 dB. The results have been plotted to show the effectof strong turbulence (α = 4.2,β = 1.4) and weak turbulence(α = 4.0,β = 1.9) on the different modulation schemeswhen applied in conjunction with the modified switchingscheme in the Hybrid FSO/RF system. The average RF SNRhas been considered as 5 dB and 15 dB. The optical channelhas been modelled using Gamma-Gamma fading model forweak and strong turbulence and the RF channel is modelled byNakagami-m fading model for m = 5. The performanceis analyzed under the assumption of perfect alignment. Thesystem parameters considered for simulation are given in Table1 [9].

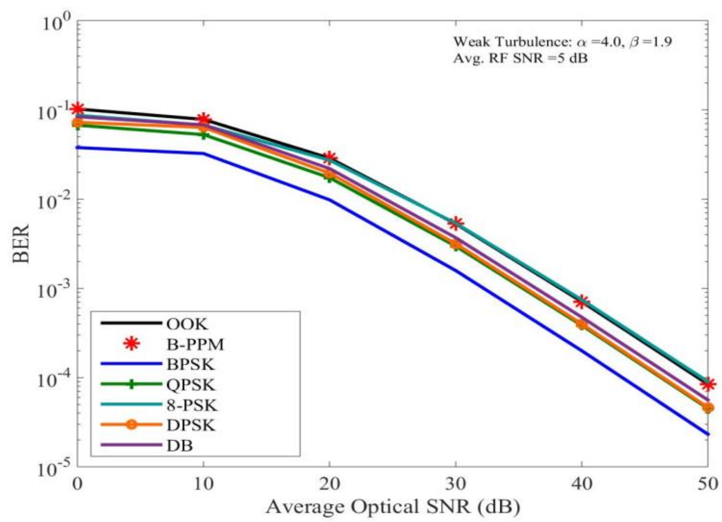

Fig. 1. BER comparison for different modulation formats for Hybrid FSO/RFsystem under weak turbulence for Modified Switching Scheme when Average RFSNR=5 dB

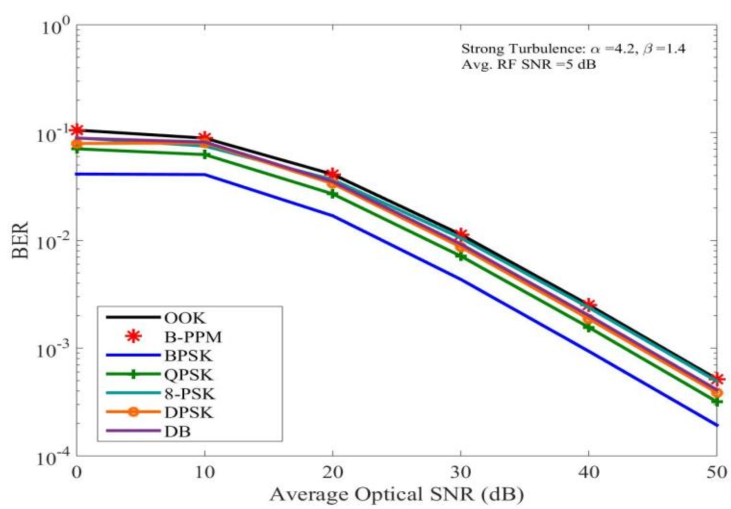

Fig. 2. BER comparison for different modulation formats for Hybrid FSO/RFsystem under strong turbulence for Modified Switching Scheme when Average RFSNR=5 dB

Figs. 1-4 show the effect of turbulence on the BER fordifferent modulation schemes. As expected the BER of all modulation schemes improves with the increase in the averageoptical SNR. Under the condition of weak turbulence, theBER is less affected as opposed to in the case of strongturbulence. The optical signal power is dissipated more in strong turbulentconditions, hence, at the receiver, the BER performancedegrades. Thus, the BER performance of the modulationschemes is better for weak turbulent conditions. Further, inFig.1 and Fig.3, the BER is presented for weak turbulence fordifferent values of average RF SNR. According to the modifiedswitching scheme, the hybrid FSO/RF system switches 'On' the RF link when the optical SNR is poor.

Following observations are made from the figures:

1. For low value of average SNR (i.e. 5dB) the performance of all modulation schemes, in terms of BER, improves with increase in average optical SNR irrespective of turbulence condition.

2. At high value of average RF SNR (i.e., 15dB) the performance of all modulation scheme first degrades and then improves when average optical SNR is increased from 0 dB irrespective of turbulence condition.

3. The performance of all modulation scheme, in terms of BER, improves with increase in average RF SNR irrespective of turbulence conditions.

4. OOK and B-PPM exhibit identical performance and BPSK demonstrates the best performance under all conditions.

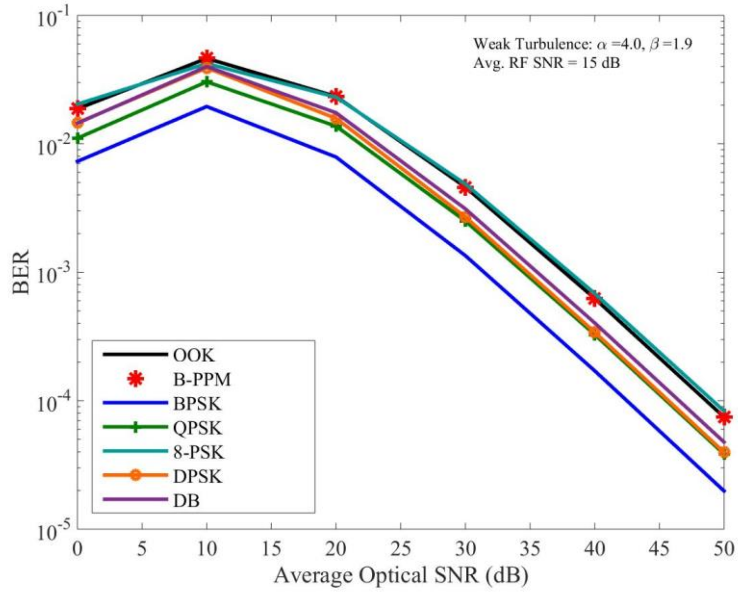

Fig. 3. BER comparison for different modulation formats for Hybrid FSO/RF system under weak turbulence for Modified Switching Scheme when Average RF SNR=15 dB

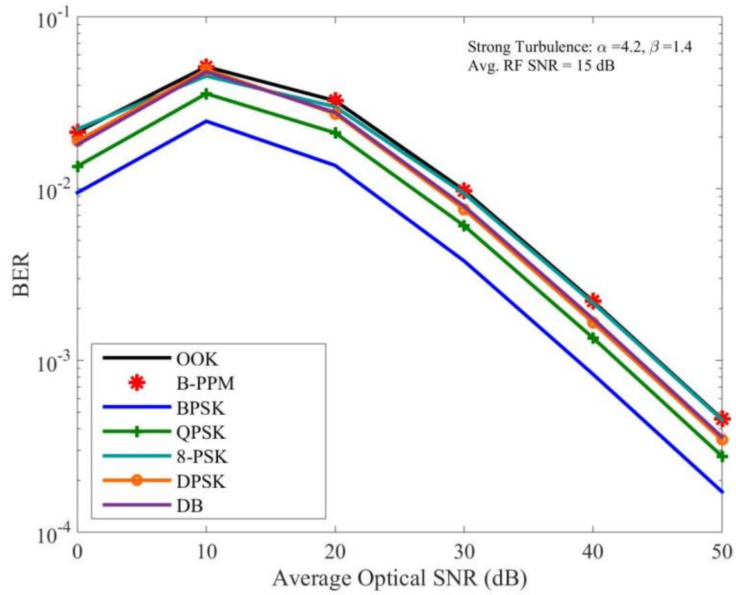

Fig. 4. BER comparison for different modulation formats for Hybrid FSO/RFsystem under strong turbulence for Modified Switching Scheme when Average RFSNR=15 dB

5. CONCLUSION

In this paper, we analyzed the BER performance for variouscommonly used modulation schemes under modified switchingscheme for hybrid FSO/RF system. After analyzing theperformance of OOK, B-PPM, BPSK, QPSK, 8-PSK, DPSKand DB modulation schemes for weak and strong turbulenceconditions, it is seen that BPSK shows the best performance.

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