A Spatial Diversity forFree Space Optical CommunicationsoverAtmospheric Turbulence Channel: A Performance Analysis

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Abstract

Free space optical (FSO) communication is a cost effective andhigh bandwidth access technique. The fading of received signal that induced by the atmospheric turbulence is the major impairment in the FSO links. Receiver spatial diversity is one of the atmospheric turbulence mitigation techniques that usedfor improving the system performance. This paper presents a performance analysis study of a single input multiple output (SIMO) spatial diversitytechnique for the terrestrial FSOlink. The achieved performance improvements over atmospheric turbulence channel for different turbulence levels show the effectiveness of the spatial diversity technique to mitigate the channel turbulence effects. A lower bit error ratesand higher diversity gain is achievedby increasing the number of receiver photodetectors.
Index Terms:- Atmospheric turbulence; free space optical communication; log-normal distribution; spatial diversity; fading channel.

الخلاصة

تتميز الاتصالات الضوئية الفضائية الحرة (FSO) بكونها فعالة من حيث التكلفة الاقتصادية اضافة التميزها بتقنية وصول ذات عرض نطاق ترددي واسع. يعتبر تلاشي الاشارة الضوئبة المستلمة الناجم عن اضطرابات الغلاف الجوي نقطة الضعف الرئيسية لوصلات الاتصالات الضوئية الفضائية الحرة . تعتبر تقنية التنوع المكاني للمستلم احد التقنيات المستخدمة لتقليل تاثيرالاضطرابات الجوية وبالتالي تحسين أداء هذه الانظمة. تقدم هذه الورقة ، دراسة تحليل اداء لتقنية التنوع المكاني ذات المدخل المفرد والمخارج المتعددة لوصلة ال (FSO) الارضية.اظهر تحسن الاداء المتحقق عبر قناة الاضطراب الجوي ولمختلف مستويات الاضطراب فعالية تقنية التنوع المكاني للتقليل من تاثير الاضطرابات الجوية. تم تحقيق نسبة خطأ BER اقل اضافة الى تحقيق ربح تنوع اعلى مع زيادة عدد أجهزة الاستشعار البصرية في جهة الاستقبال.
الكلمات الدالة: ـ الاضطراب الجوي ، مساحة حرة الاتصالات البصرية ، تسجيل طبيعي التوزيع، التنوع المكاني ، يتلاشى القناة.

Introduction

Althoughfree space optical (FSO) communication has attracted a wide spectrum of applications since it is a license free andhighly bandwidth access technique, butit has to overcome many challenges that originate from free space transfer media [Kaushal &Kaddoum 2015]. These challenges may include snow, fog, smog and aerosol scattering, which leave the terrestrial FSO communication link weak to adverse weather conditions. Atmosphere turbulence that causing by atmospheric temperature and pressure inhomogeneity is the major impairment in FSO link and this will lead to refractive index fluctuations [Hien & Ngoc, 2012]. When the transmitted optical signal passes through such a turbulent atmosphere, it will experience random fluctuations in the intensity which leading to fluctuations in the received signals' amplitude and phase. This phenomenon is termed as scintillation [Navidpour *et.al.*, 2007].Degradation of the FSO link performance is the direct effect of scintillation due to causing adeep signal fades and thus increasingthe bit error rate [Navidpour *et.al.*, 2007].

Many techniques are proposed to mitigate the effects of atmospheric turbulence including error control coding[García-Zambrana *et.al.*, 2015], adaptive optics [Li, M. &Cvijetic 2015],and diversity technique [Peppas&Mathiopoulos 2015].Error control codingschemes may introducea huge timing delay and efficiency performance degradation due to increasing in processing complexity and the number of redundant bits [García-Zambrana *et.al.*, 2015]. Adaptive optics schemes are mainly used in astronomical applications. However, these schemes introduce loss in signal energy whichcan be compact through longer observation time. Thus, these methods are not suitable for real-time communication applications purposes [Li, M. &Cvijetic, M., 2015].SIMO spatial diversity technique is based on using multiple separate photodetectors on reception side, these photodetectors will simultaneously receive multiple copy of the transmitted signal which experience differentchannel fade effects,then combining these copies of signal to mitigate the channel effects, and this leads to increasing in signal to noise ratio [Peppas &Mathiopoulos 2015].

In this paper, the performance of single input multiple outputs (SIMO)spatial diversity technique isusedto improve the performance of the optical wireless receiver overFSOatmospheric turbulence channel. At the receiver side, the received signalsare combined using equal gain combining (EGC) technique. The BER expressions of the M-ary pulse-position modulation (M-PPM) scheme over atmospheric turbulence channel with log-normal distribution are derived. The performance of FSO link is analyzedat differentturbulence levels in terms of BER and diversity gains.

2. A BACKGROUND OVERVIEW

The atmospheric turbulence degrades the performance of the FSO link by causing a random variation ofthereceived optical signal thatlead tosignal fluctuations. The atmospheric turbulence effects may include the electromagnetic scattering from the atmospheric molecules that causes optical energy redirection [Barua, *et al*. 2012]. The second effect is due tothe density inhomogeneity in the atmosphere,caused by pressure and temperature fluctuations, which create random variations ofrefraction index $n$throughout the optical signal transfer medium. These variations can be expressed as the summation of an average term and the fluctuation term as given in the following[Majumdar 2015]

$$n=n_0+\delta n \tag{1}$$

wheren_o is the average value of refractive index and (δ_n)is the fluctuation component induced by spatial variations of temperature and pressure in the atmosphere. The associated power spectral density $\Phi_n(k)$for the refractive index fluctuations is described by the widely accepted Kolmogorov model as the following [Majumdar 2015]

$$\Phi_n(k) = 0.033C_n^2 k^{-11/3}\ , \quad \frac{1}{L_0} \ll k \ll \frac{1}{l_0} \tag{2}$$

where$C_n^2$is the refractive index structure parameter, $k$is the spatial wave number, $l_o$is the inner scale of turbulence, and $L_o$is the outer scale of turbulence. The main effect of atmospheric turbulence is due to scintillation that causes random fluctuations in the amplitude and phase of the received signal.A common measure of magnitude of scintillation is known as scintillation index (σ_{sc}^2), that is given as [Ghassemlooy &Popoola 2008]

$$\sigma_{sc}^2 = \frac{<I^2>}{<I>^2} - 1 \tag{3}$$

where$<I>$is the intensity of the received signal. The most commonly used Huffnagel-Valley Boundary (HVB) model for modeling the terrestrialFSO communication link, described by [Ghassemlooy &Popoola 2008]

$$C_n^2\,(h) = 0.00594\,\left(\frac{v}{27}\right)^2 (10^{-5}\,h)^{10}\,exp\left(\frac{-h}{1000}\right) + 2.7 * 10^{-16}\,exp\left(\frac{-h}{1500}\right) + 1.7 * 10^{-14}\,exp\left(\frac{-h}{100}\right) \tag{4}$$

Here $h$is the altitude in meters (m), and v the wind velocity in meters per second (m/sec).

3. SYSTEM AND CHANNEL MODELS

In this paper, a receiver spatial diversity with EGC technique is used for the proposed system. Considering a single laser diode at the transmitter with A aperture area and Npositive-intrinsic-negative (PIN) photodetectors at the receiver, the received optical power will be equal to received signal intensity. At the receiver, the aperture area of each detector inthe *N*-photodetector system is assumed to be (A_r/N), where A_r is the aperture area of the PIN photodetector under single transmitter single receiver (SISO) system. The EGC creates a new signal by linear combination of all the received signals after weighted them by unity. The additive white Gaussian noise (AWGN) is modeled the noise channel. Assuming M-PPM modulation scheme at transmitter, the received signal at the n^{th}photodetectoris given as[Navidpour *et.al.*, 2007]

$$r_n = s\,\eta\, I_n + v_n \;,\; n = 1 \ldots . N \tag{5}$$

where$s$ is the transmittedinformation bits, η is the optical to electrical conversion efficiency of the receiver,$v_n$is the additive white Gaussian noise with zero mean and variance of$\sigma_v^2 = N_0/2$.The fading channel coefficientI_n which modelsthe FSO channel from the transmitter to the n^{th}photodetectoris given by [Navidpour *et.al.*, 2007]

$$I_n = I_0\, exp\,(2\, X_n) \tag{6}$$

where$I_o$is the received light intensity without the effects of the channel turbulence and X_n are identically distributed normal random variable with meanμ_x and varianceσ_x^2. The probability density function (PDF) of the received signal over log-normal channel model is given by [Ghassemlooy&Popoola 2008]

$$f(I_n) = \frac{1}{2\, I_n \sigma_x\, \sqrt{2\pi}}\, exp\left\{\frac{-\left[ln\left(\frac{I_n}{I_0}\right) - \mu_x\right]^2}{8\sigma_x^2}\right\} \tag{7}$$

where I_n is the received optical signal intensity in the presence ofchannel turbulence and $I_0$the received signal intensity without the effectof channel turbulence,$\sigma_x^2$is the log-intensity variance and $\mu_x$is the meanof log-intensity variance, which can be related to the scintillation index through the following ($\sigma_{sc}^2 = 4\sigma_x^2$), ($\mu_x = -4\sigma_x^2$) [Navidpour *et.al.*,2007].For spatial diversity with *N*-photodetectors, the total average received intensity is given by ($I = \frac{1}{N}\sum_{n=1}^{N} I_n$)[Ghassemlooy&Popoola 2008].

4. BER ANALYSISOF SIMOSPATIAL DIVERSITY

Considering the M-PPM scheme,the probability of error in ideal channel condition (i.e., in the absence of turbulence) is given by [Popoola&Ghassemlooy2009].

$$BER_0 = \frac{M}{2} \times Q\left(I_n R_P \sqrt{\frac{M log_2(M)}{2 R_b \sigma_{noise}^2}}\right) \tag{8}$$

where$M$ is themodulation order, R_p is the PIN receiver responsivity and $R_b$is the data rate. The noise variance$\sigma_{noise}^2$is the summation of the shot noise and the thermal noisevariances. The shot noise is caused by background light whilethe thermal noise is a result from thermal induced randomfluctuations in the charge carriers in the resistive element ofthe photodetector [EL-Mashade *et.al.*, 2016].$Q(.)$ is the Gaussian-Q function, which is given by the following expression [Olver 2010]

$$Q(x) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} exp\left(-\frac{x^2}{2\, sin^2\theta}\right)\, d\theta \tag{9}$$

The average BER can be obtained by averaging equation (8) over the PDF of I_n as:

$$BER = \frac{M}{2}\int_0^{\infty} Q\left(I_n R_P \sqrt{\frac{M log_2(M)}{2 R_b \sigma_{noise}^2}}\right)\; f(I_n)\; d\, I_n \tag{10}$$

Since no closed-form solution is available for theintegration in equation (10) we propose deploying a numerical solution based onHermite polynomial.Hermite polynomial approaches the solution through summation of its basis values which are the roots and the weights.The Hermite polynomial formula is given by [Olver 2010]

$$\int_{-\infty}^{\infty} g(x) \times e^{-x^2}\, dx \;\approx\; \sum_{i=1}^{Ns} w_i \times g(x_i) \tag{11}$$

where$[x_i]_{i=1}^{Ns}$ and $[w_i]_{i=1}^{Ns}$ are the roots and the weights of the N_s^{th} order Hermitepolynomial.It was shown in [Olver 2010] that accurate results can be obtained if$N_s \geq 10$.To apply the Hermite polynomial of equation (10), variable $x$is represented as the following

$$x = \frac{\left[ln\left(\frac{I_n}{I_0}\right) - \mu_x\right]}{\sqrt{8\sigma_x^2}} \quad (12)$$

From equation (12), the$I_n$and dI_n can be expressed in terms of x and dx as,

$$I_n = exp\ (\sqrt{8}\ \sigma_x x + \ \mu_v\ ) \quad (13)$$

$$dI_n = \ \sqrt{8}\, I_n \sigma_x\ \ dx \quad (14)$$

By substituting equations (13) and (14) in equation (10), equation (10) can be rewritten as

$$BER = \frac{M}{2}\int_{-\infty}^{\infty} Q\left(I_0 R_P\ exp(x\sqrt{8}\,\sigma_x)\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) \times \frac{1}{I_n\sqrt{8\pi}\,\sigma_x} \times exp(-x^2) \times \sqrt{8} I_n \sigma_x\ d\,x \quad (15)$$

By re-arranging equation (15),

$$BER = \frac{M}{2}\int_{-\infty}^{\infty} e^{-x^2} \times \frac{1}{\sqrt{\pi}}\ Q\left(I_0 R_P\ exp(x\sqrt{8\ \sigma_x^2}\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) d\,x \quad (16)$$

Applying the Hermite polynomial of equation (11), the BER expression of M-PPM over the log-normal fading channel using PIN detector can be approximated as

$$BER \approx \frac{M}{2}\sum_{i=-Ns}^{Ns}\frac{1}{\sqrt{\pi}} w_i \times Q\left(I_0 R_P exp(x_i\sqrt{8\ \sigma_x^2})\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) \quad (17)$$

Hence, the M-PPM final expression of bit error rate of N-PIN photodetector SIMO spatial diversity system is given by

$$BER \approx \frac{M}{2}\sum_{i=-Ns}^{Ns}\frac{1}{\sqrt{\pi}} w_i\ \times Q\left(I_0 R_P\ exp\left(x_i\sqrt{\frac{8\sigma_x^2}{N}}\right)\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) \quad (18)$$

The block diagram of the proposed system model is depicted in Fig. 1, where the information bits are modulated using M-PPM scheme. The laser diode is used to modulate the symbols. The transmitted light propagates over the log-normal fading channel. At the receiver, the PIN photodiode converts the light intensity into electrical current and EGCis used to estimate the transmitted information bits.

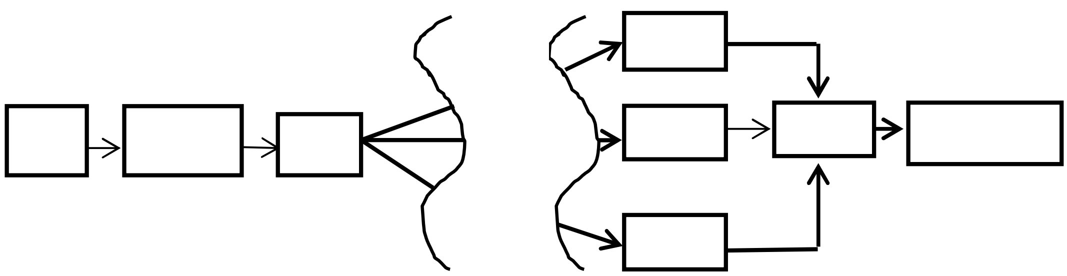

Fig.1. Block diagram of the proposed system model.

5. SPATIAL DIVERSITY GAINPERFORMANCE ANALYSIS

The Spatial diversity gain is defined as the ratio of SNR without diversity to that with spatial diversity for a certain channel turbulence level and can be describedas the following equation [Popoola, Ghassemlooy 2009]

$$m_{N,\sigma_x} = \frac{\gamma_{1,\sigma_x}}{\gamma_{N,\sigma_x}} \quad (19)$$

whereγ_{1,σ_x} is the electrical SNR of the M-PPM without diversity, while γ_{N,σ_x} is M-PPM electrical SNR of the *N* spatial diversity receivers,γ_{1,σ_x}can be described as the following [Popoola, Ghassemlooy 2009]

$$\gamma_{1,\sigma_x} = \frac{R_p^2 P^2}{M\ R_b\ \sigma_x^2} \quad (20)$$

P is the received optical power intensity;the spatial diversity receivers is $(\gamma_{N,\sigma_x} = \sum_{i=1}^{N} \gamma_{i,\sigma_x})$.

6. RESULTS AND DISCUSSIONS

For the following analysis, which simulated using MATLAB8.2.0.29 (R2013b), it is assumed that the proposed system adopts the 8-PPM modulation scheme and the order Hermite polynomial is (20), the other simulationparameters of the systemare listed in Table (1).

Table (1): System Parameters

Parameters	Value	Parameters	Value
Symbol data rate R_b	400 Mbps	Refractive index structure parameter C_n^2	1×10^{-15} $m^{-2/3}$
Modulation order$M$	8	Optical wavelength λ	850 nm
Sampling frequency	20 MHz	Receiver PIN photodetector responsivity	0.7 (A/W)
Transmitter Laser diode GaAs wavelength λ	850 nm	Receiveroptical to electrical conversion efficiency η	1
Link rang L	1 Km	Receiver aperture diameter	0.02 m
Noise standard deviation	10^{-7}A/Hz	Load resistance	50 Ω
Scintillation index σ_{sc}^2	1	Operating temperature	300 K

In Fig. 2, the BER performance for channel turbulence level of $(\sigma_x^2 = 0.5)$ and different values of the receiving power light intensity (I_o) with different number of detectors *N*is depicted. A performance improvement can be seenclearly with increasing the number of photodetectors. The results of Fig. 2 show that in case of *N* of (8) detectors, I_o decreased to (10 dB) comparing with nearly (20 dB) for the no diversity case (*N*=1) at (10^{-7}) BER.As the number of detectors are increased from (1) to (2), the performance is improved widely especially when (BER≤ 10^{-5}), extra performance improving is shown with the number of detectors increasing from (2) to (4). Further increasing of the detectors number does not gainedlargeextra performance improvement. It is clear that, increasing the number of receiver photodetectors will lead to decreasing the BER for the same receiving power, although that will come at the expense of increasing the system complexity cost.

The variation of spatial diversity gains, m_{N,σ_x} with the number of receiver photodetectors *N* at different turbulence level $\sigma_x^2$of the FSO channel is depicted in Fig. 3. Fig. 3 shows that for low turbulence level of $(\sigma_x^2 = 0.2)$, the spatial diversity receiving system has very poor diversity gain performance close to the case of no diversity (*N*=1) case, i.e., for (10) receiver detectors case, the system achieved only (3 dB) spatial gain comparing with (0 dB) gain for the case of no diversity. However, as the turbulence level increases, spatial diversity technique starts to perform higher gain values. Thus, for (0.5) turbulence level with 8-*N*detectors case, about (10 dB) gain achieved, while for high turbulence level of (1), the gain is rising to (23 dB). For the turbulence levels of $(0.5 \leq \sigma_x^2 \leq 1)$ the spatial gain is rises dramatically for $(2 \leq N \leq 5)$, however, increasing the number of receiver photodetectors*N* will lead to increasing the overall system complexity significantly. Thus, using a reasonable number of detectors ($N < 5$) to mitigate the effects of turbulence channel without increasing the system complexity will be perfect suggestion.

The plotting of BER performance of M-PPM scheme against the power received light intensity (I_o) with 2-N photodetectors at turbulence level of ($\sigma_x^2 = 0.7$) and various modulation order M is shown in Fig. 4. The results of Fig. 3, clearly indicate that the required (I_o) to achieved particular BER is decrease with increasing the modulation order M in M-PPM scheme. The 32-PPM requires (3dB), (7dB), (9.5dB), and (13.5dB) less power comparing with 16-PPM, 8-PPM, 4-PPM, and 2-PPM, for (10^{-6}) BER.

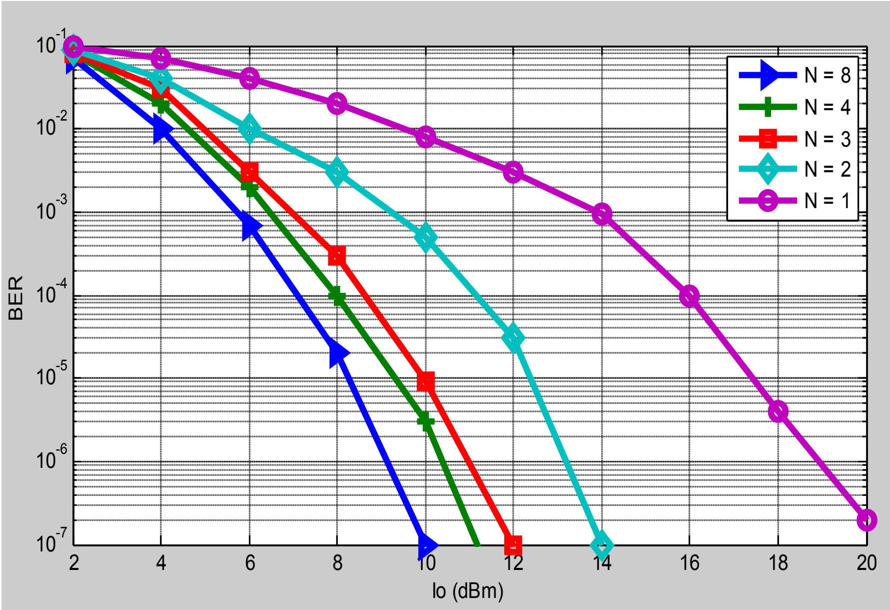

Fig.2. Variations of BER against the received light intensity (I_o)for various photodetector numbers.

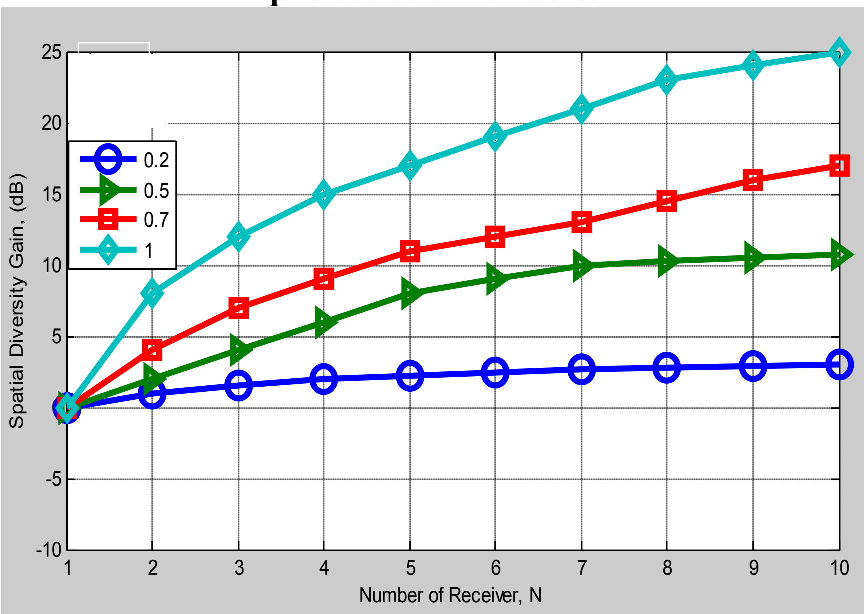

Fig.3. Variations of spatial diversity gain against the number of receiver detectors for various turbulence levels (σ_x^2= 0.2,0.5, 0.7,1).

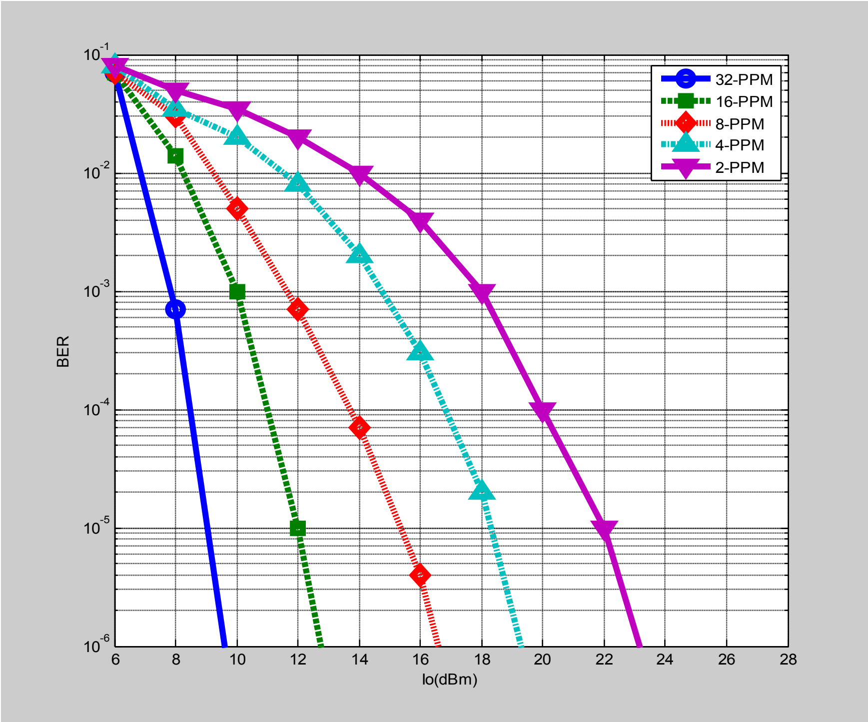

Fig.4. BER performance of M-PPM scheme against the received light intensity (I_o) with ($\sigma_x^2 = 0.7$).

7. CONCLUSIONS

This paper includes a performance analysis study for the effects of receiver diversity based on SIMO technique over the FSO atmospheric turbulence channel. A significant improvement in BER and diversity gain performances is achieved as the number of photodetectors increased. It was concluded that the impact of increasing the number of receiver photodetectorsis enhancing the spatial diversity gain significantly though it will increase the system complexity cost. It was also concluded that the M-PPM with higher modulation order (M) has more efficient BER performance comparing with M-PPM with lower (M) for the same number of the photodetectors.

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