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Performance Analysis Study of the Modulation Schemes using Diversity Reception Technique over FSO Atmospheric Turbulence Channel

دراسة تحليل ألاداء لطرق التضمين باستخدام تقنية التنوع المكاني للمستقبل عبر قناة الاضطراب الجوي الفضائية الضوئية الحرة

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Abstract:—

Free space optical (FSO) communication is a cost effective, high bandwidth access systems. The fading of the transmitted signal that induced by the channel atmospheric turbulence is the significant impairment in the FSO communication link, which caused severe performance degradation for different optical modulation schemes. Spatial diversity is one of the atmospheric turbulence mitigation techniques that used for improving the FSO system performance. In this paper, the BER expressions of the PPM, PAM and OOK modulation schemes over FSO atmospheric turbulence channel with log-normal distribution are derived. An important performances improvement of the system with a proposed receiver spatial diversity technique is observed with increasing the number of receiver photodetectors for various channel turbulence level. The performances comparison analysis of the PPM and PAM schemes is showed that for the same signal intensity power, PPM offered better BER performances, although PAM is showed better bandwidth performances.

Index Terms:— Atmospheric turbulence; free space optical; log-normal distribution; spatial diversity; fading channel; optical modulation schemes.

الخلاصة

تتمتع انظمة الاتصالات الضوئية الفضائية الحرة (FSO) بمميزات فعالة من حيث التكلفة الاقتصادية، وأنظمة وصول ذات عرض النطاق الترددي الواسع. يعتبر تلاشي او خمود الاشارة الضوئية المرسلة بسبب الاضطرابات الجوية في قناة الارسال نقطة الضعف الرئيسية لانظمة الاتصالات الضوئية الفضائية الحرة ويتسبب بتدهور شديد في اداء انظمة التضمين الضوئية المختلفة. تعتبر تقنية التنوع المكاني احد التقنيات المستخدمة لتقليل تاثير الاضطرابات الجوية لقناة الاتصال وبالتالي تحسين أداء انظمة الاتصالات الفضائية الحرة. في هذا البحث، يتم تقديم اشتقاق لمعادلات تمثل نسبة خطأ BER لانظمة التضمين الضوئية PPM, PAM, OOK المستخدمة للارسال عبر قناة الـ(FSO) ذات التوزيع الاحصائي نوع (Log-Normal). باستخدام تقنية التنوع المكاني المقترحة لوحظ تحسن كبير في أداء النظام مع زيادة عدد أجهزة الاستشعار البصرية في جهة الاستقبال ولمختلف مستويات الاضطراب في قناة الاتصال. وأظهر تحليل الأداء المقارن لاداء النظام باستخدام كل من طريقة التضمين نوع PPM و PAM ان طريقة التضمين PPM هي اكثر كفاءة نسبة الى نسبة الخطأ BER في حين ان طريقة التضمين نوع PAM اكثر كفاءة من حيث اداء عرض النطاق الترددي.

1. INTRODUCTION

Although free space optical (FSO) communication has attracted a wide spectrum of applications since it is a license free and highly bandwidth access technique [1], but it has to overcome many challenges that originate from free space propagation media. These problems 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 communication and this will lead to optical signal refractive index fluctuations [2]. When the optical signal passes through such a turbulent atmosphere, it will experience random fluctuation in the intensity and leads to variation in the received signals' amplitude and phase. This phenomenon is termed as scintillation [3]. Degradation of the FSO communication performance is the direct effect of scintillation due to causing deep signal fades and thus increasing the bit error rate [3].

Many techniques are proposed to mitigate the effects of atmospheric turbulence including error control coding [4], adaptive optics [5], and diversity technique [6]. Error control coding schemes may introduce a huge timing delay and efficiency performance degradation due to increasing the processing complexity and the number of redundant bits [4]. Adaptive optics schemes are mainly used in astronomical applications. However, these schemes introduce lose in signal energy which can be compact through longer observation time. Thus, these methods are not suitable for real-time communication applications purposes [5]. Receiver spatial diversity technique is based on using multiple separate photodetectors on the reception side. These photodetectors will simultaneously receive multiple copies of the transmitted signal, which experiences different channel fade effects, and then combine these copies of the signal to mitigate the channel effects, and this will lead to increasing the signal to noise ratio [6].

The ultimate goal of any modulation scheme is to send the largest amount of data over the smallest spectral with least power needed. Pulse Position Modulation (PPM), Pulse Amplitude Modulation (PAM) and On-Off Keying (OOK) are the most commonly used modulation techniques in FSO communication systems depending on the specific requirements of the individual optical system such as system simplicity, power and bandwidth efficiency [7].

The effect of atmospheric turbulence channel on the performances of optical modulation schemes is studied in many literatures; the bit error rate (BER) upper bound of M-ary PPM over the turbulent channel with an avalanche photodiode (APD) receiver is derived in [8]. The BER performance of the atmospheric turbulence FSO with APD receiver for binary PPM (BPPM) modulation using multiple inputs multiple outputs (MIMO) techniques is explained in [9].

In this paper, a proposed system based on spatial receiver diversity with selection combining (SelC) technique is introduced; the purpose of the proposed system is to mitigate the atmospheric turbulence channel effects on the optical signal that transmitted over the FSO channel. The BER expressions of the PPM, PAM and OOK modulation schemes over atmospheric turbulence channel with log-normal distribution are derived. The performance comparisons analysis for these three modulation schemes including the effect of different turbulence levels is presented. The performance comparisons include the effect of the number of receiver photodetectors, and the effect of variation of M-PPM, L-PAM modulation levels, on the system BER performance is presented. In addition, the performance comparison between the PPM and PAM schemes in term of the system bandwidth requirement is discussed in this work.

This paper is organized as follows: Section 2 includes an atmospheric turbulences description. Section 3 gives the system and channel models. In Section 4, the BER system performance expressions for the PPM, PAM and OOK modulation schemes with spatial diversity receiver are derived. Finally, results and conclusions are given in Section 5 and Section 6, respectively.

2. A Background Overview

The atmospheric turbulence phenomena degrade the performance of the FSO communications by causing a random variation of the received optical signal that leads to signal fluctuations. The atmospheric turbulence effects may include the electromagnetic scattering from the atmospheric molecules that causes optical energy redirection [10]. The second effect is due to the density inhomogeneity in the atmosphere, caused by pressure and temperature fluctuations, which create random variations of refraction index n throughout the optical signal propagation medium. These variations can be expressed as a sum of an average term and a fluctuating term as given in the following [11]

$$n=n_0+\delta n \qquad (1)$$

where n_o is, the average value of the refractive index and (δ_n) is the fluctuation component that induced by the spatial variations of temperature and pressure in the atmosphere. The Kolmogorov model describes the associated power spectral density $\Phi_n(k)$ of the refractive index fluctuations as the following [11]

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

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 optical signal. A common measure of scintillation is known as scintillation index (σ_{sc}^2), that is given as [12]

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

where $< I >$ is the received optical signal intensity. The Huffnagel-Valley Boundary (HVB) model is used for modeling the terrestrial FSO communication link, which can be described as [12]

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

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

3. SYSTEM AND CHANNEL MODELS

In this paper, a receiver spatial diversity with selection combining technique is proposed. Considering a single laser diode transmitter with (A) aperture area and N positive-intrinsic-negative (PIN) photodetectors at the receiver, the received power will be equal to received signal intensity. The aperture area of each detector in the N-photodetector receiver 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 SelC linear combiner compares all the received signals through its multiple branches and selects the branch with the highest signal intensity level. The output of the combiner is the signal with the highest intensity and this makes SelC technique less complexity compared to the maximum ratio combining (MRC) and equal gain combining (EGC) techniques. The additive white Gaussian noise (AWGN) is modeled the noise channel. The received signal at the n^{th} photodetector is given as [3]

$$r_n = s \, \eta \, I_n + v_n \;, \; n = 1 \, ... N \qquad (5)$$

where s is the transmitted information bits, η is 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 coefficient I_n which models the channel from the transmitter to the n^{th} photodetector is given by [3]

$$I_n = I_0 \; exp\,(2 \, X_n) \qquad (6)$$

where I_o is the signal light intensity without turbulence and X_n is the identically distributed normal random variable with mean μ_x, and variance σ_x^2. The probability density function (PDF) of the received signal over the log-normal channel model is given by [12]

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

where I_n is the received signal intensity in the presence of turbulence and I_0 is the received signal intensity without the effect of turbulence, σ_x^2 is the log-intensity variance and μ_x is the mean of log-intensity variance, which related to the scintillation index through the following ($\sigma_{sc}^2 = 4\sigma_x^2$), ($\mu_X = -2\sigma_x^2$) [3]. For spatial diversity system with N photodetectors, the total average received intensity power is given by ($I = \frac{1}{N}\sum_{n=1}^{N} I_n$) [12].

4. Derivation of BER expressions for the Receiver Spatial Diversity

Firstly, let's consider the OOK modulation scheme at the transmitter and spatial diversity with *N*-PIN detector at the receiver, the probability of error in ideal channel condition, i.e., in the absence of turbulence is given by [13]

$$BER_0 = Q\left(I_n R_P \sqrt{\frac{1}{R_b \sigma_v^2}}\right) \qquad (8)$$

where R_p is the PIN detector responsivity and R_b is the system data rate. The noise variance σ_v^2 is the summation of the shot noise and the thermal noise variances. The shot noise is caused by background light while the thermal noise is a result of thermally induced random fluctuations in the charge carriers in the resistive element of the photodetector [14]. $Q(.)$ is the Gaussian-Q function, which is given by the following expression [15],

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

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

$$BER = \int_0^{\infty} Q\left(I_n R_P \sqrt{\frac{1}{R_b \sigma_v^2}}\right)\ f(I_n\ )\ d\,I_n \qquad (10)$$

The integration of equation (10) has no closed form solution. So, we have to solve it numerically based on Hermite polynomial which gives approximately the same value through the summation of its basis values which are roots and weights. The Hermite polynomial formula is given by [15]

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

where $[x_i]_{i=1}^{Ns}$ and $[w_i]_{i=1}^{Ns}$ are the roots and the weights of the N_s^{th} order Hermite polynomial. It was shown in [14] that accurate results could be obtained if $N_s \geq 10$. To apply the Hermite polynomial of equation (10), variable x is represented as the following

$$x = \frac{\left[ln\left(\frac{I_n}{I_0}\right) - \mu_v\right]}{\sqrt{8\sigma_v^2}} \qquad (12)$$

From equation (12) I_n and dI_n in terms of x and dx from equation (12) as,

$$I_n = exp\ \left(\sqrt{8}\ \ \sigma_v\, x +\ \mu_v\ \right) \qquad (13)$$

$$dI_n =\ \sqrt{8}\, I_n\, \sigma_v\, dx \qquad (14)$$

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

$$BER = \frac{1}{2}\int_{-\infty}^{\infty} Q\left(I_0 R_P\ exp(x\sqrt{8}\ \sigma_v)\ \sqrt{\frac{1}{R_b\sigma_v^2}}\right) \times \frac{1}{I_n\sqrt{8\pi}\ \sigma_v} \times exp(-x^2) \times \sqrt{8}\, I_n \sigma_v\, d\,x \qquad (15)$$

Then,

$$BER = \frac{1}{2}\int_{-\infty}^{\infty} e^{-x^2} \times \frac{1}{\sqrt{\pi}}\ Q\left(I_0 R_P\ exp(x\sqrt{8\,\sigma_v^2}\sqrt{\frac{1}{R_b\sigma_v^2}}\right) d\,x \qquad (16)$$

By applying the Hermite polynomial of equation (11) to equation (16), the BER of OOK modulation scheme over the FSO log-normal fading channel can be expressed as

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

Hence, BER expression of *N*-photodetector spatial diversity system over log-normal channel with OOK modulation scheme at the transmitter is given by

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

Secondly, to drive the BER of M-PPM scheme over FSO channel, we follow the same steps for driving the BER of the OOK modulation scheme starting with the BER of M-PPM scheme without turbulence which is given by [13]

$$BER_0 = \frac{M}{2}\ \times Q\left(I_n R_P\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) \quad (19)$$

where, M is the M-PPM modulation order, taking into account the FSO turbulence effects, the BER of M-PPM scheme is

$$BER = \frac{M}{2}\int_0^{\infty} e^{-x^2}\times\frac{1}{\sqrt{\pi}}\ Q\left(I_0 R_P\ exp(x\sqrt{8\ \sigma_x^2}\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) d\,x \quad (20)$$

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

$$BER \approx \frac{M}{2}\sum_{i=-Ns}^{Ns}\frac{1}{\sqrt{\pi}}\ w_i \times Q\left(I_0 R_P exp(x_i\sqrt{8\ \sigma_x^2})\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) \quad (21)$$

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

$$BER \approx \frac{M}{2}\sum_{i=-Ns}^{Ns}\frac{1}{\sqrt{\pi}}\ w_i\ \times Q\left(I_0 R_P\ exp\left(x_i\sqrt{\frac{8\sigma_x^2}{N}}\right)\sqrt{\frac{Mlog_2(M)}{2R_b\sigma_{noise}^2}}\right) \quad (22)$$

Finley to find the BER expression of L-PAM scheme, we start with the L-PAM probability of error, without turbulence which gave by [13]

$$BER_0 = \frac{2(L-1)}{L\ Log_2(L)}\ \times Q\left(\frac{I_n R_P}{L-1}\sqrt{\frac{log_2(L)}{R_b\sigma_v^2}}\right) \quad (23)$$

where, *L* is the L-PPM modulation order, The BER of L-PAM over the FSO turbulence channel is given by,

$$BER = \frac{2(L-1)}{L\ Log_2(L)}\int_0^{\infty} e^{-x^2}\times\frac{1}{\sqrt{\pi}}\ Q\left(\frac{I_n R_P}{L-1}\ exp(x\sqrt{8\ \sigma_x^2}\sqrt{\frac{log_2(L)}{R_b\sigma_v^2}}\right) d\,x \quad (24)$$

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

$$BER \approx \frac{2(L-1)}{L\ Log_2(L)}\sum_{i=-Ns}^{Ns}\frac{1}{\sqrt{\pi}}\ w_i \times Q\left(\frac{I_n R_P}{L-1}\ exp(x\sqrt{8\ \sigma_x^2}\sqrt{\frac{log_2(L)}{R_b\sigma_v^2}}\right) \quad (25)$$

The final expression of the L-PAM bit error rate with *N*-photodetector spatial diversity system over log-normal FSO channel is given by

$$BER \approx \frac{2(L-1)}{L\ Log_2(L)}\sum_{i=-Ns}^{Ns}\frac{1}{\sqrt{\pi}}\ w_i\ \times Q\left(\frac{I_n R_P}{L-1}\ exp\left(x_i\sqrt{\frac{8\sigma_x^2}{N}}\right)\sqrt{\frac{log_2(L)}{R_b\sigma_v^2}}\right) \quad (26)$$

Another important indicator to evaluate the performance of FSO communication systems over the turbulence channel is the system requirements bandwidth [16]; which measures how much data can be transmitted over the spectral frequency in terms of modulation order and data bit rate. The bandwidth of the M-ary PPM (BW_{M-PPM}) scheme is given by [16]

$$BW_{M-PPM} = \frac{M}{log_2(M)} R_b \qquad (27)$$

While the bandwidth of L-ary PAM (BW_{L-PAM}) scheme is given by [16]

$$BW_{L-PAM} = \frac{1}{log_2(L)} R_b \qquad (28)$$

The block diagram of the proposed system model is depicted in Fig. 1, where the information bits are modulated using OOK, M-PPM or L-PAM 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 SelC is used to estimate the transmitted information bits.

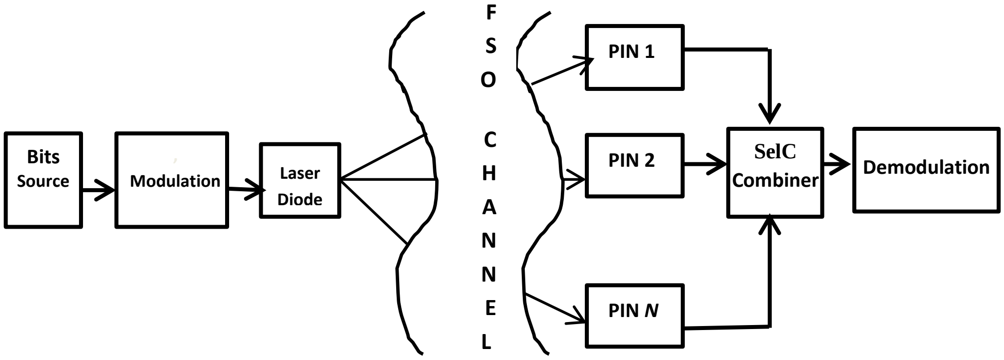

Fig.(1): Block diagram of the proposed system model.

5. RESULTS AND DISCUSSIONS

In the following analysis, it is assumed that the proposed system has N-PIN photodetectors and the order of Hermite polynomial is (20), the other parameters that adopted for system simulation using MATLAB 7.8 (R2009a) running on Intel processor P8400 (2.27GHz) are listed in Table (1).

Table (1): Simulation Parameters.

Parameter	Value	Parameter	Value
Symbol data rate R_b	800 Mbps	Refractive index structure parameter C_n^2	1×10^{-15} $m^{-2/3}$
Sampling frequency	40 MHz	Optical wavelength λ	650 nm
Transmitter Laser diode wavelength λ	650 nm	Receiver PIN photodetector responsivity	0.7 (A/W)
Optical Link distance L	1.5 Km	Receiver optical to electrical conversion efficiency η	1
Operating temperature	300 K	Receiver aperture diameter	0.02 m
Scintillation index σ_{sc}^2	1	Load resistance	50 Ω

In Fig.(2), BER performance comparison of binary PPM and PAM (M, L=2) modulation schemes versus the power light intensity (I_o) (which represent the system power requirements) is depicted. The FSO channel is with turbulence level of ($\sigma_x^2 = 0.3$) and the system had different number of photodetectors (N). The results of Fig.(2) shows that, the PPM modulation scheme achieving better BER performances than PAM modulation scheme for the various number of receiver photodetectors.

The results of Fig.(2), clearly indicated that increasing the number of receiver photodetectors will lead to decreasing BER of the same type of modulation scheme. The figure showed that for the case of (4) photodetectors, the PPM requires (1dB), (1.5dB), and (2dB) lower power than the case of (3), (2), and (1) photodetectors of the same modulation scheme at (10^{-6}) BER. While the PAM scheme with (4) photodetectors, requires (1dB), (2dB), and (3dB) lower power than the case of (3), (2), and (1) photodetectors, for the same value of BER.

For the case of receiver with (4) photodetectors, PAM scheme, needs extra (3.5 dB) to achieve (10^{-6}) BER comparing with the PPM for the same number of receiver photodetectors. For the case of (3) photodetectors, PPM gained (3 dB) comparing with PAM scheme at (10^{-6}) BER.

By observing the above results, one can say that increasing the number of receiver photodetectors (N) results in a decrease in the system power requirements and hence enhances the power efficiency for both PPM and PAM schemes, although PPM shows better performance comparing with PAM scheme in this case.

The plotting of BER performance of OOK, M-PPM, L-PAM schemes under a wide range of the operating power light intensity (I_o) is present in Fig.(3). The system had two photodetectors (N) at reception side with various modulation orders M and L, the FOS channel had turbulence level of ($\sigma_x^2 = 0.7$). The results of Fig.(3) show that as M increases of the M-PPM scheme, the required (I_o) decreases to achieved particular value of BER (which means lower power requirements and higher power efficiency in this case). In other hand, increasing the modulation order L of PAM scheme, has the effect of increasing the required (I_o) for the same value of BER (i.e., higher power requirements leading to lower power efficiency).

In addition, the results display that the BER performance of OOK scheme is equal to the performance of binary PPM (M=2), where, the curve of both OOK and 2- PPM are typically identical. The PPM scheme with (M=32) requires (3dB), (7dB), (9.5dB), and (13.5dB) less power comparing with 16-PPM, 8-PPM, 4-PPM, and 2-PPM, at (10^{-6}) BER, while PAM with (L=32) requires (1.5dB), (2.5dB), (3dB), and (3.5dB) higher power than 16-PAM, 8-PAM, 4-PAM, and 2-PAM for the same value of BER. The 32-PPM scheme requires (17.5dB) less power than 32-PAM scheme to achieve BER of (10^{-6}) which clearly indicates that the higher modulation order of the M-PPM scheme led to better BER performance comparing with other modulation schemes. Under our studying rang of I_o, the lowest power requirement, I_o= 9.5 dB, is achieved by PPM scheme with modulation order (M=32), while the largest value, I_o= 28 dB, occurs for PAM scheme with modulation order (L=2), at (10^{-6}) BER. From the above results, it can be seen that PPM scheme with modulation order (M=32), achieved lowest power requirements comparing with other modulation OOK and L-PPM for the same values of BER.

The required bandwidth performance comparison of the binary PPM and PAM (2-PPM & 2-PAM) schemes versus light intensity (I_o) for a different number of the receiver photodetectors (N) (1,4 and 8) is shown in Fig.(4) with turbulence level ($\sigma_x^2 = 0.9$). It can be seen from the figure that as N increases, the required power (I_o) is decreased to achieve the same bandwidth requirement for both PPM and PAM schemes. However, PAM shows slightly better bandwidth performances than the PPM scheme for all value of N. The figure shows that 8-N PAM scheme requires (15 dB) and (55 dB) less power than PAM with (N=4,1) photodetectors to achieve (1GHz) bandwidth, while the 8-N PPM scheme requires (10 dB) and (50 dB) less power than PPM with (N=4,1) photodetectors to achieve the same bandwidth value. From the above results, one can said that PAM scheme has higher bandwidth efficiency, which reflects on higher allowable bit rate than PPM scheme since PAM scheme required lower bandwidth values for the same (I_o) and N requirements. The flow chart of the system model is shown in Fig.(5).

6. CONCLUSIONS

This paper presents a performance analysis study for adopting the receiver spatial diversity technique for the optical modulation schemes OOK, M-PPM and L-PAM. The study utilizes a different aspect of design parameters (number of receiver photodetectors, power, and bandwidth requirements) to provide a detailed view of the characteristics of these optical modulation schemes under a different level of FSO turbulence level. The BER expressions of the three modulation techniques are derived for the log-normal distribution of FSO channel condition. As the number of photodetectors is increased, both PPM and PAM scheme require less power, and significant improvements in BER performance is achieved, although PPM shows the best BER performance comparing with PAM scheme. The simulation provided that OOK had identical BER performance with 2-PPM for the same values of power I_o and channel turbulence level σ_x^2. The performance comparison between modulation schemes also showed that M-PPM with higher modulation index (32-PPM) was the most power efficient scheme (had the lowest BER values). It was also concluded that L-PAM scheme was the most bandwidth efficient scheme compared with M-PPM, for the same channel turbulence level and the number of receiver photodetectors.

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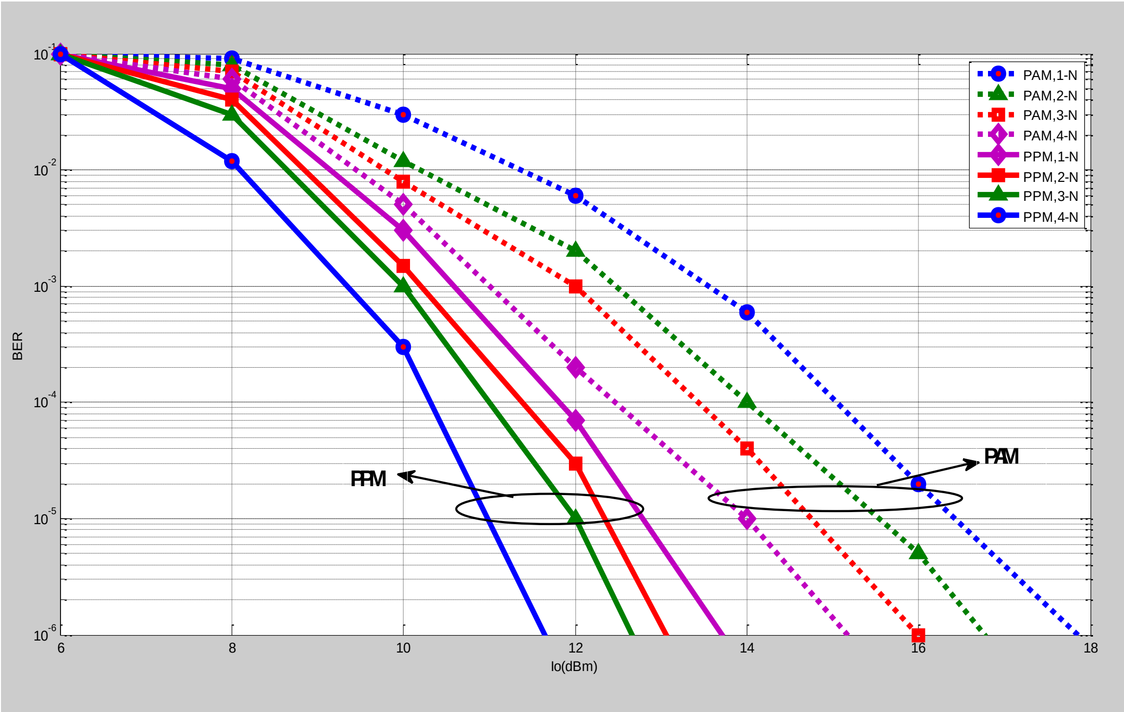

Fig.(2): BER performance comparsion of binary PPM, PAM schemes for different number of photodetectors (*N*).

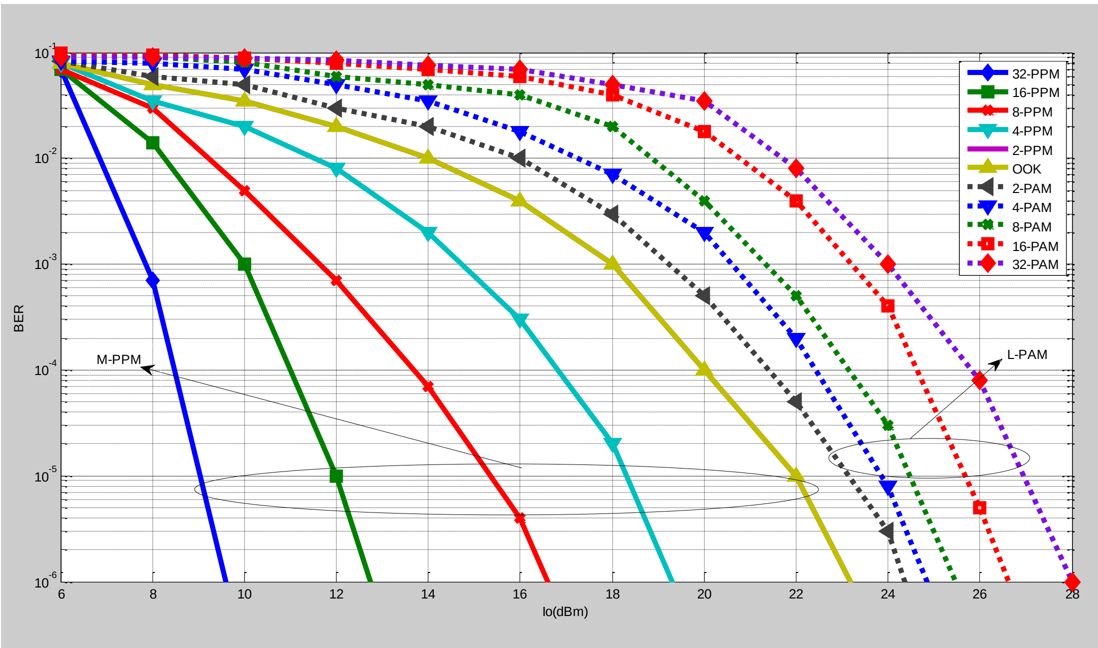

Fig.(3). BER performance comparison of modulation schemes for different values of modulation order (*M*,*L*).

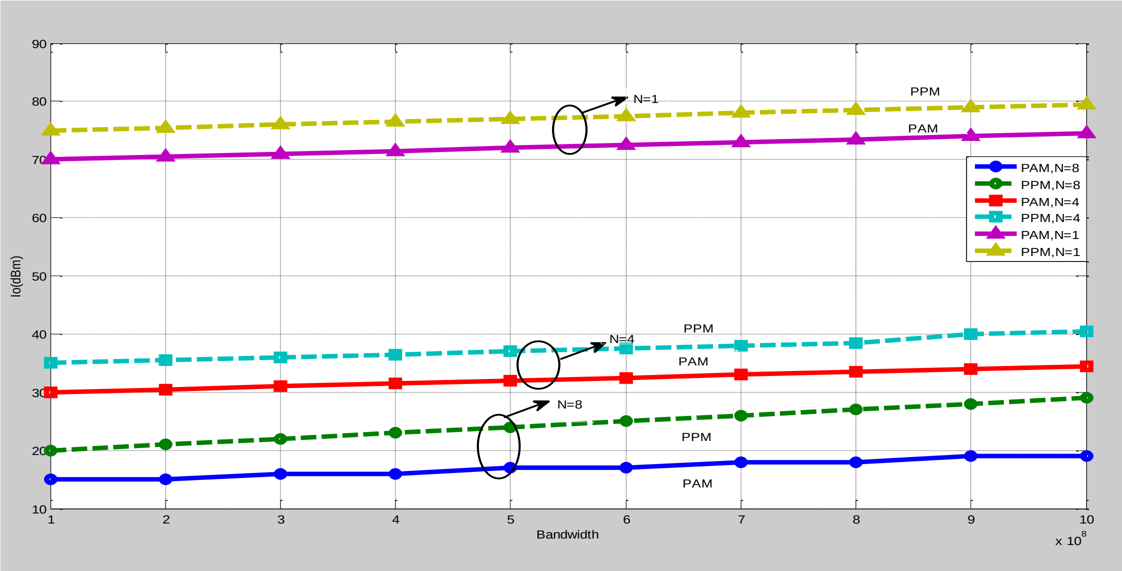

Fig.(4): Bandwidth performance comparsion of binary PPM, PAM schemes for different number of photodetectors (*N*).

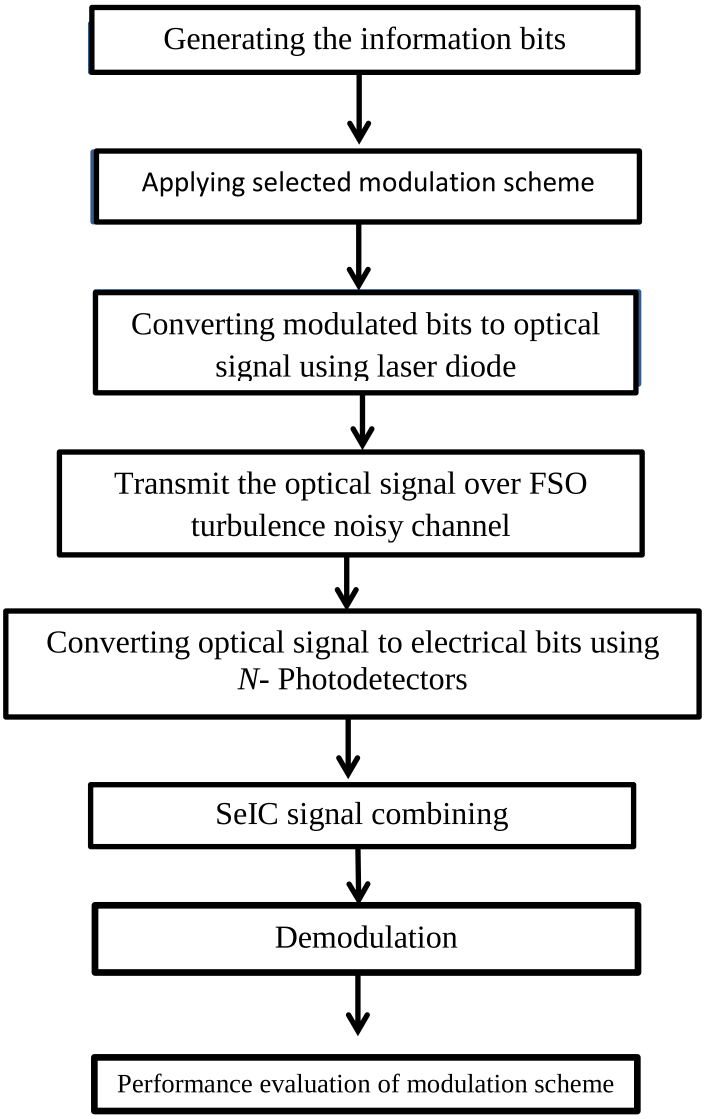

Fig.(5): Flow chart of the system model