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Unified performance parameters for IM/DD techniques over gamma-gamma fading channel with pointing errors

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Abstract. In this paper, we discuss the performance of different intensity modulation direct detection techniques (IM-DD) used in free space optical systems (FSO) under different channel impairments such as path loss, atmospheric turbulence, and pointing errors. We derived unified formulas for each of the average symbol error rate (SER) bounds and outage probability for different modulation techniques: OOK, MPPM, and LMPPM. The accuracy of the obtained formulas is validated through comparison with MC-simulation results. Finally, we investigate the effect of system parameters on FSO link performance.

1. Introduction

The demand for wireless communication has risen substantially in recent years, and the shortage of radio frequency (RF) spectrum is raising concerns about limited spectral efficiency[1]. Free space optical communication systems (FSO) are characterized by a large spectrum of unlicensed frequencies, low transmitted power, interception immunity, simple installation, and low cost [2]. However, in order to limit their consequences, various obstacles must be addressed. Atmospheric turbulence and pointing errors are two important problems in FSO systems [3]. They cause changes in the received signal's amplitude and phase, resulting in system deterioration. Researchers are motivated to model FS0 channels because of these two issues. Different statistical models have been introduced in the literature to describe atmospheric turbulence [4]. In [5], log-normal distribution has been proposed to represent the turbulence-induced irradiance fluctuations. Log-normal showed well representation under weak turbulence circumstances only. Farid et al. [6] suggested another model, the gamma-gamma (GG) distribution, to describe the irradiance. This distribution showed good matching with experimental measurements under moderate and strong turbulence. Thus, in our work, we use (GG) to describe the turbulence effect.

One of the main design elements that impact communication system performance is the choice of an appropriate modulation technique [7]. Intensity modulation direct detection (IM-DD) is commonly utilized in FSO communication due to transmitter and receiver simplicity. Many commercial FSO systems have successfully used on-off keying (OOK) and pulse-position modulation (PPM). Despite OOK being more bandwidth-efficient than PPM, fading channels require an adaptive decision threshold. Furthermore, extended repetitions of ones or zeros complicate the synchronization process. The so-called multi-pulse pulse position modulation (MPPM) had lately been offered as a possible contender for optical wireless communication systems for the reasons stated above [8]. However, PPM and MPPM have low spectral efficiencies. Thus, in this work, we investigate the performance parameters including outage probability and symbol error rate (SER) using the L-ary multipulse pulse position modulation (LMPPM) scheme which can achieve higher spectral efficiency compared with PPM and MPPM.

Finally, in our work, we will derive an expression for outage probability and two expressions for SER (average union bound symbol error rate (AUSER) and average looser bound symbol error rate (ALSER)) demonstrating the importance of choosing the optimum receiver beam waist radius W_L which achieves the best performance. The rest of this work is arranged as follows. In section 2, a mathematical model and simplified block diagram for the FSO link are presented. In section 3, the FSO channel model is demonstrated. In section 4 average looser and union-bound expressions for SER and outage probability are derived then numerical results are given in section 5. Lastly, the conclusion is given in section 6.

2. System model

Figure 1 shows a simple block diagram of the IM-DD FSO communication line of sight link. Data is modulated into the momentary intensity of an optical beam by the emitter. In our work, we consider a system using OOK, MPPM, and LMPPM modulation, which is easily employed in systems. The detector responsivity R relates the collected photocurrent signal to the incident optical power. Then the receiver is expected to integrate the photocurrent for each time slot, removing any constant bias caused by background illumination. Due to atmospheric turbulence and misalignment, as well as additive noise, the received electrical signal y seems to have a fluctuating signal intensity that can be well modeled as [9]

$$y = RhP_{avr} + n \tag{1}$$

Where, y is the resulted electric signal, n is signal-independent additive white Gaussian noise with variance σ_n^2 and P_{avr} is the optical power of the received symbol which related to the average transmitted optical power by the pass-loss factor $P_l = G_t G_r \eta_t \eta_r \left(\frac{\lambda}{4\pi L}\right)^2$ where $\eta_{\mathrm{T}}, \eta_{\mathrm{R}}$ are the optical efficiencies and $G_{\mathrm{T}} = (2\pi W/\lambda)^2$ and $G_{\mathrm{R}} = (\pi D_{\mathrm{R}}/\lambda)^2$ are the telescope gains of the Tx and the Rx, respectively. D_{R} is the receiver aperture diameter, λ is the wavelength, W is the Gaussian root mean square (RMS) beamwidth at the transmitter aperture, and L is the link distance. Here, h is the composite channel coefficient which can be given as follows:

$$h = h_l h_p h_a \tag{2}$$

where, h_l is the attenuation factor in clear weather, h_p is the geometrical spread and pointing errors, and h_a is the atmospheric turbulence fading. It's worth noting that h_l is deterministic, but h_p and h_a are random.

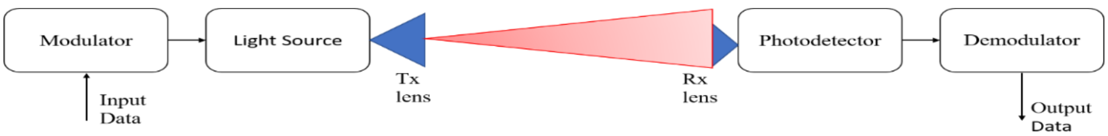

Figure 1. Block diagram of FSO link.

FSO system adopting LMPPM is considered in this paper and its performance is compared with OOK and MPPM. In the LMPPM technique, the duration of a symbol (T_s) is split into (N) time slots of (τ) duration. Only w time slots, where $w \leq N$, are used to send optical signals. During signal slots, the transmitter can send $K-1$ power levels using the LMPPM approach when $K=2$ it returns back to MPPM. The transmitted symbols are drawn equiprobably from constellation points such that $S_{OOK} \in \{0,2P_{avt}\}$ for OOK. The transmitted power signal of LMPPM is given by [10] as follows.

$$S_{LMPPM}(N,w,N_l,l) \in \{0,c\beta_1 P_t, c\beta_2 P_t, \dots, c\beta_{K-1} P_t\}^N: \quad (3)$$

$$f_s(\beta_i) = l_i \forall i \in \{1,2,\dots,N_l-1\} \sum_{i=1}^{K-1} l_i = w$$

where $\{0 \leqslant \beta_1 \leqslant \beta_2 \leqslant \cdots \leqslant \beta_K = 1\}$ are the attenuation factors, $f_s(\beta_i)$ is the repetition of each factor in the symbol and $c = \frac{2N(K-1)}{wK}$ to make the average transmitted optical power $P_{avt} = P_t$. The difference between attenuation factors should be equal, $\Delta\beta = \beta_i - \beta_{i-1} = 1/(K-1)$, to obtain optimal performance and the cardinality of this modulation technique is given by $(K-1)^w \times C_w^N$. Figure 2 depicts an example of the LMPPM symbol with $N=12, w=8, K=5, (\beta_1 = 0.25, \beta_2 = 0.5, \beta_3 = 0.75, \beta_4 = 1)$ and $(l_1 = 3, l_2 = 1, l_3 = 2, l_4 = 2)$. The received signal of LMPPM (x_{LMPPM}) is given as follows[11].

$$x_{LMPPM}(N,w,N_l,l) \in \{0, chR\beta_1 P_t, chR\beta_2 P_t, \dots, chR\beta_{K-1} P_t\}^N \quad (4)$$

Finally, we have another shape of the symbol called the normalized one ($\boldsymbol{N}_{LMPPM}$) given by $\boldsymbol{N}_{LMPPM}(N,w,K,l) \in \{0,\beta_1,\beta_2,\dots,\beta_{K-1}\}^N$ and its corresponding normalized euclidean distance(b_{ij}) where $\boldsymbol{b}_{ij} = \sqrt{\sum(\boldsymbol{N}_{LMPPM}^{(i)} - \boldsymbol{N}_{LMPPM}^{(j)})^2}$ **for** $\boldsymbol{i \neq}$ **j.**

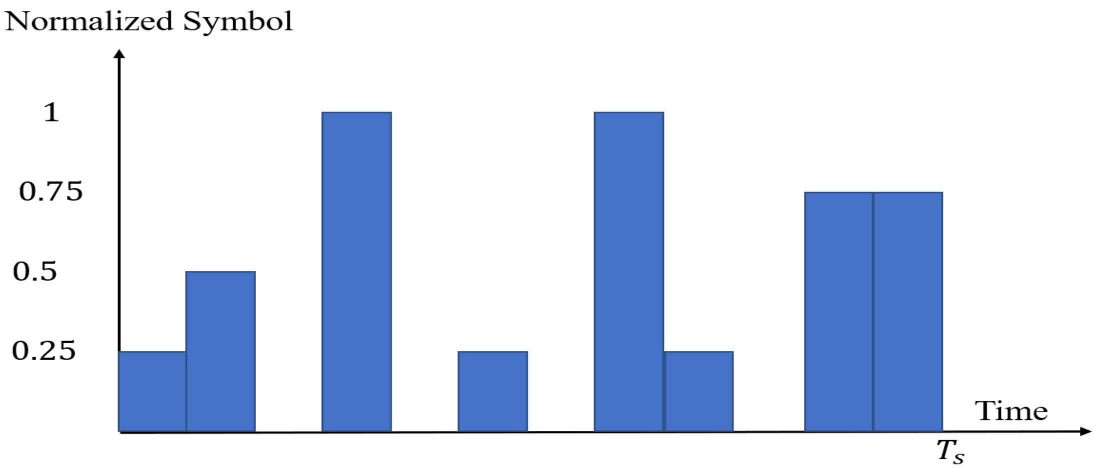

Figure 2. LMPPM (N, w, K-1) symbol with $N=12, w=8, K=5$.

3. FSO channel model

In this paper, we discuss different channel factors (path-loss, atmospheric turbulence, and pointing-errors) that affect the performance of FSO links. Attenuation factor h_l is a deterministic attenuation factor. It is determined by the scattering particles' size and dispersion, as well as the wavelength used. It may be measured directly from the atmosphere and represented in terms of visibility [**11**]. The exponential Beers-Lambert Law describes the optical attenuation through the atmosphere as:

$$h_l(L) = \frac{P(0)}{P(L)} = \exp(\sigma L) \quad (5)$$

where $h_l(L)$ denotes the loss along a length L propagation route distance, $P(L)$ is the laser power at distance L, and σ is the attenuation coefficient. Atmospheric turbulence fading coefficient h_a is a random variable that can be well represented by the GG distribution, with probability density function $f_{h_a}(h_a)$ given as follows [12]:

$$f_{h_a}(h_a) = \frac{2(\rho_1\rho_2)^{\frac{(\rho_1+\rho_2)}{2}}}{\Gamma(\rho_1)\Gamma(\rho_2)} h_a^{\frac{\rho_1+\rho_2}{2}-1} k_{\rho_1-\rho_2}\left(2\sqrt{\rho_1\rho_2 h_a}\right) \tag{6}$$

where, $1/\rho_1$ and $1/\rho_2$ are the variances of the small- and large-scale eddies given by equations (7) respectively [12], and $k_x(y)$ is the modified Bessel function of the second type. The Gamma-Gamma pdf has been proven to be in good agreement with measurements under a range of turbulence situations.

$$\begin{aligned} \rho_1 &= \frac{1}{\exp\left[\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{12/5}\right)^{7/6}}\right]-1} \\ \rho_2 &= \exp\left[\frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{5/6}}\right]-1 \end{aligned} \tag{7}$$

where, σ_R^2 is the Rytov variance which is given as follows:

$$\sigma_R^2 = 1.23C_n^2(z)k^{7/6}L^{11/6} \tag{8}$$

where $C_n^2(z)$ denotes the index of refraction structural parameter at height z (assumed to be constant throughout the horizontal route), $k = 2\pi/\lambda$ denotes the optical wavenumber.

Pointing precision is an important factor in determining the performance and dependability of line-of-sight FSO communication links. Wind loads and thermal expansions, on the other hand, produce unpredictable building sways, which results in aiming mistakes and signal to fade at the receiver [13]. As in prior work [13], consider separate identical Gaussian distributions for elevation and horizontal displacement (sway). A Rayleigh distribution is utilized to describe the radial displacement r at the receiver given by:

$$f_{\mathrm{r}}(r) = \frac{r}{\sigma_s^2}\exp\left(-\frac{r^2}{2\sigma_s^2}\right),\ r > 0 \tag{9}$$

Where σ_s^2 is a jitter variation at the receiver. Considering the Gaussian optical beam [14], the pointing error coefficient h_p can be expressed as:

$$h_{\mathrm{p}}(r; l) \approx A_0 \exp\left(-\frac{2r^2}{W_{Leq}^2}\right) \tag{10}$$

Where, $A_o = [\mathrm{erf}(v)]^2$ is part of the collected power at $r = 0, W_{Leq}^2 = \frac{W_L^2 erf(v)\sqrt{\pi}}{2ve^{-v^2}}$ is the equivalent beam waist, $v = \frac{a}{W_L}\sqrt{0.5\pi}$ and W_L is beam waist at distance L. The probability distribution of h_p can be represented by combining equations (9) and (10) as:

$$f_{h_p}(h_p) = \frac{\gamma^2}{A_o^{\gamma^2}} h_p^{\gamma^2-1},\ 0 < h_p < A_o \tag{11}$$

where the ratio of the equivalent beam radius at the receiver to the jitter standard deviation producing errors is $\gamma = w_{\mathrm{Leq}}/2\sigma_s$.

The probability density function of the channel state h is derived from the preceding probability density functions for turbulence and misalignment fading [15] and can be written as follows:

$$f_h(h) = \frac{\rho_1 \rho_2 \gamma^2}{A_o h_l \Gamma(\rho_1)\Gamma(\rho_2)} \mathrm{G}_{1,3}^{3,0}\left[\frac{\rho_1 \rho_2 h}{A_o h_l} \mid \begin{matrix} \gamma^2 \\ \gamma^2 - 1, \rho_1 - 1, \rho_2 - 1 \end{matrix}\right] \tag{12}$$

4. Average *SER* and Outage probability

In this section, we derive an analytical formula average SER and outage probability for systems adopting any intensity modulation techniques (OOK, MPPM, LMPPM) over a turbulent channel with pointing errors.

4.1 Average SER

Using the union bound of the symbol error rate ($USER$) of the IM/DD approach is obtained as follows[16].

$$USER = \frac{1}{2U} \sum_{i=1}^{U} \sum_{\substack{j=1 \\ j \neq i}}^{U} \mathrm{erfc}\left(\frac{d_{ij}}{2\sqrt{N_0}}\right) \tag{13}$$

where, N_o is the power spectral density of noise, U is the modulation constellation cardinality which is equal to 2, ${}_{w}^{N}c$ and ${}_{w}^{N}c * (K-1)^w$ for OOK, MPPM, and LMPPM respectively and d_{ij} is the euclidean distance between i^{th} and j^{th} symbols for $i \neq j$ in the modulation constellation set, which is defined as:

$$d_{ij}^2 = \int_0^{T_s} |x_{LMPPM}^{(i)} - x_{LMPPM}^{(j)}|^2 dt \tag{14}$$

Defining the minimum euclidean distance of the constellation as $d_{\min} = \min(d_{ij})$, we can simplify the previous inequality as the looser bound symbol error rate ($LSER$).

$$LSER = \frac{U-1}{2} \mathrm{erfc}\left(\frac{d_{\min}}{2\sqrt{N_0}}\right) \tag{15}$$

Thus, at the output of photo-detector (PD) at the receiver, we can obtain the ratio between the minimum euclidean distance and the twice of the root of the noise power spectral density as:

$$\frac{d_{\min}}{2\sqrt{N_0}} = \frac{Z_{\mathrm{mod}} R h P_{avr}}{\sigma_n} \tag{16}$$

Where the value of Z_{mod} depends on the modulation technique parameters so $Z_{\mathrm{mod}} = 1, \frac{N}{\sqrt{2w}}, \frac{N}{wK}$ for OOK, MPPM, and LMPPM respectively, then substitute into (15) by (16), we get the looser bound of *SER* as:

$$LSER(h) = \frac{U-1}{2} erfc\left(\frac{Z_{\mathrm{mod}} R h P_{avr}}{\sigma_n}\right) \tag{17}$$

By using the MeijerG function to represent the erfc special function [17] [eq, 07.34.03.0619.01], we can rewrite equation (17) as follows:

$$LSER(h) = \frac{U-1}{2\sqrt{\pi}} \mathrm{G}_{1,2}^{2,0}\left[\left(\frac{Z_{\mathrm{mod}} R h P_{avr}}{\sigma_n}\right)^2 \mid \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix}\right] \tag{18}$$

Then, the average looser bound symbol error rate ($ALSER$) can be gotten by averaging the previous equation over $f_h(h)$ given in (12):

$$ALSER = \frac{U-1}{2\sqrt{\pi}} \frac{\rho_1\rho_2\gamma^2}{A_o h_l \Gamma(\rho_1)\Gamma(\rho_2)} \int_0^\infty \mathrm{G}_{1,2}^{2,0}\left[\left(\frac{Z_{\mathrm{mod}} RhP_{avr}}{\sigma_n}\right)^2 \middle| \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix}\right] \times \mathrm{G}_{1,3}^{3,0}\left[\frac{\rho_1\rho_2 h}{A_o h_l} \middle| \begin{matrix} \gamma^2 \\ \gamma^2-1, \rho_1-1, \rho_2-1 \end{matrix}\right] dh \tag{19}$$

By using the Meijer formula for integration given in [17][eq, 07.34.21.0013.01], the $ALSER$ as a function of the received power is given by:

$$ALSER = \frac{(U-1)\gamma^2 2^{\rho_1+\rho_2-4}}{\pi^{1.5}\Gamma(\rho_1)\Gamma(\rho_2)} \mathrm{G}_{7,4}^{2,6}\left[\left(4\frac{Z_{\mathrm{mod}} RP_{avr}A_o h_l}{\rho_1\rho_2\sigma_n}\right)^2 \middle| \begin{matrix} \frac{1-\gamma^2}{2}, \frac{2-\gamma^2}{2}, \frac{1-\rho_1}{2}, \frac{2-\rho_1}{2}, \frac{1-\rho_2}{2}, \frac{2-\rho_2}{2}, 1 \\ 0, \frac{1}{2}, \frac{-\gamma^2}{2}, \frac{1-\gamma^2}{2} \end{matrix}\right] \tag{20}$$

Where $ALSER$ becomes $ASER$ for OOK only and by repeating the derivation to find the average union bound of the symbol error rate ($AUSER$) by using normalized euclidean distance (b_{ij}) which is related to euclidean distance (d_{ij}) by $\frac{d_{\mathrm{ij}}}{2\sqrt{N_0}} = \frac{N(K-1)RhP_{avr}}{wK\sigma_n} b_{\mathrm{ij}}$ and defining two-parameter $(b(i), R_{ep}(i))$ where b is a distinct normalized distance and R_{ep} is the corresponding repetition, so we have $AUSER$ as follows:

$$AUSER = \frac{\gamma^2 2^{\rho_1+\rho_2-4}}{\pi^{1.5}\Gamma(\rho_1)\Gamma(\rho_2)U} \times \sum_i R_{ep}(i)\mathrm{G}_{7,4}^{2,6}\left[\left(2b(i)\frac{cRP_{avr}A_o h_l}{\rho_1\rho_2\sigma_n}\right)^2 \middle| \begin{matrix} \frac{1-\gamma^2}{2}, \frac{2-\gamma^2}{2}, \frac{1-\rho_1}{2}, \frac{2-\rho_1}{2}, \frac{1-\rho_2}{2}, \frac{2-\rho_2}{2}, 1 \\ 0, \frac{1}{2}, \frac{-\gamma^2}{2}, \frac{1-\gamma^2}{2} \end{matrix}\right] \tag{21}$$

4.2 Outage probability

Outage probability (P_{Out}) is an important performance metric in the case of fading channels. P_{Out} is the probability that the instantaneous *SNR* of the link is less than a threshold *SNR* (γ_{Th}) or the probability that the instantaneous channel capacity is less than a certain rate because the channel capacity is monotonically increasing in *SNR*. The outage probability can be given as:

$$P_{\mathrm{Out}}(Th) = \mathrm{Prob}(SNR(h) \le \gamma_{Th}) \tag{22}$$

where, the instantaneous value of the *SNR* can be defined as follows:

$$SNR(h) = \frac{G_{\mathrm{mod}} h^2 R^2 P_{avr}^2}{\sigma_n^2} \tag{23}$$

where $G_{\mathrm{mod}} = 2, N/w, 2N(2K-1)/(3wK)$ is the power distribution parameter for OOK, MPPM, and LMPPM, respectively. In our work, we define it as the probability that instantaneous channel state h is less than a specified threshold h_{Th}, where h_{Th} is corresponding to the *SNR* threshold (γ_{Th}). The probability of outage at a specific threshold SNR may be written as follows by combining (22) and (23).

$$P_{\mathrm{Out}}(Th) = \mathrm{Prob}\left(\frac{G_{mod} h^2 R^2 P_{av}^2}{\sigma_n^2} \le \gamma_{Th}\right) \tag{24}$$

Defining $h_{Th} = \frac{\sigma_n\sqrt{\gamma_{Th}}}{RP_{avr}\sqrt{G_{\mathrm{mod}}}}$ to simplify the outage probability as:

$$P_{\mathrm{Out}} = \mathrm{Prob}(h \le h_{Th}) = \int_0^{h_{Th}} f_h(h)dh \tag{25}$$

A relationship for P_{Out} as a function of P_{avr} is given by integrating the channel pdf $f_h(h)$ by using the Meijer formula for integration explained in [16] [eq, 07.34.21.0001.01].

$$P_{\mathrm{Out}} = \frac{\gamma^2}{\Gamma(\rho_1)\Gamma(\rho_2)} \mathrm{G}_{2,4}^{3,1}\left[\frac{\rho_1\rho_2 h_{Th}}{A_o h_l} \middle| \begin{matrix} 1, \gamma^2+1 \\ \gamma^2, \rho_1, \rho_2, 0 \end{matrix}\right] \tag{26}$$

5. Numerical results and discussion

In this section, we numerically investigate the accuracy of derived expressions for the average outage probability, average union bound symbol error rate, and average looser bound symbol error rate for different types of modulation techniques under different channel conditions by comparing them with Monte Carlo simulation results. The system parameters used in calculation and simulation are given in table 1.

Table 1. System and simulation parameters.

Parameter	Symbol	Value	Parameter	Symbol	Value
Jitter standard deviation	σ_s	0.1-0.5 m	Responsively	R	0.5 A/W
Optical transmitted power	P_{avt}	0 – 30 dBm	Rytov variance	σ_R	0.5–5
Attenuation factor at clear weather	h_l	0.9 dB/km	Link distance	L	1–5 km
Transmit divergence at $1/e^2$	θ_T	2.5 mrad	Receiver diameter	$2a$	0.2 m
Beam waist at the receiver	W_L	0.1– 4 m	Transmission rate	R_b	1 Gbps
Refraction structural parameter	C_n^2	$5 \times 10^{-14}\ m^{-2/3}$	Wavelength	λ	1550 nm
Noise standard deviation	σ_n	5×10^{-7}A/W	Optic efficiencies	η_t, η_r	10 dB

First of all, we have to discuss the difference between the union bound and the looser bound in symbol error rate so we will suppose two systems MPPM (4,2) and LMPPM (4,2,2) and we choose these to facilitate calculations of the normalized euclidean distances (b) which is given in table 2.

Table 2. Normalized euclidean distances distribution (b)

	MPPM (4,2)		LMPPM (4,2,2)											
b	$\sqrt{2}$	2	0.5	0.707	0.866	1	1.11	1.22	1.32	1.41	1.5	1.58	1.8	2
$\boldsymbol{R_{ep}}$	24	6	48	72	48	6	96	96	24	48	48	36	24	6

As shown in figure 3, the union and looser bound in MPPM are closing two each other than in LMPPM because the ratio of minimum distance is 80% and 8.6% for MPPM and LMPPM respectively. The average looser SER versus W_L is presented in figure 4 for the link distances of 1km and $\frac{\sigma_s}{a} = 3$. As can be seen, the performance improves while W_L increases reaching the optimal value ($W_L \approx 1.1m$) then they begin to deteriorate again because the received power density will decrease causing decreasing in the captured power by the detector and we get a strong AWGN effect on the performance.

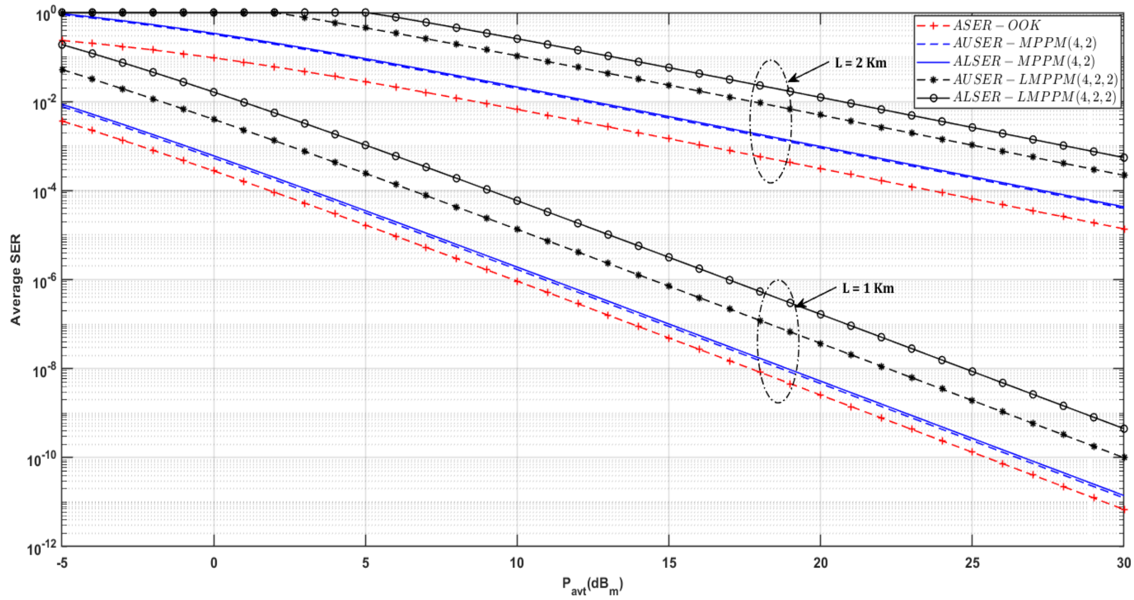

Figure 3. Average SER versus average transmitted power for FSO link distance of L = 1, 2 km.

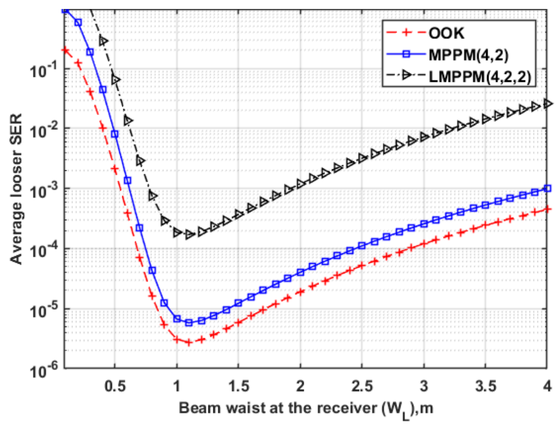

Figure 4. Average looser SER versus the beam waist radius W_L at the receiver for FSO the link distance L = 1 km and $P_{avt} = 10\ dBm$.

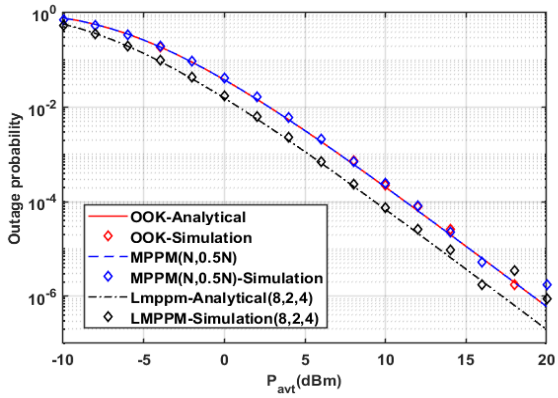

Figure 5. Outage probability (analytical and simulation) versus average transmitted power for $\sigma_R = 0.99$ at distance L=1km.

In figure 5, the performance of the derived analytical expressions for outage probability given in equation (26) is highlighted by comparing with MC-simulation results. The moderate turbulence channel with $\sigma_R^2 = 0.99$ is considered. Generally, the outage probability is proportional to the average transmitted power where increasing transmitted power tends to decrease the channel threshold value h_{Th} then it decreases the outage probability and gets better performance. Depending on the modulation technique, the threshold level will change because G_{mod} is a function of modulation parameters (N,w,K) so we had an enhancement in LMPPM than OOK and MPPM with $N = 0.5w$ because they are the same $G_{mod} = 2$ in addition, MPPM has a bad spectral efficiency compared with OOK but LMPPM (8,2,4) has the same spectral efficiency as OOK. From an outage probability point of view, we find the LMPPM outperforms the others.

The outage probability versus W_L is presented in figure 6 for the link distances of 1km and $\frac{\sigma_s}{a} = 3$. As can be seen, the performance improves while W_L increases because of overcoming pointing errors reaching optimal value ($W_L \approx 1.1m$) then they begin to deteriorate again agreeing with the result in figure 4. For instance, it can be observed that the outage probability depends on the modulation technique and normalized jitter standard deviation but is also affected by the beam waist at the Rx end. It is clear that changing the parameters of (LMPPM) changes the performance and changing the pointing errors σ_s changes the optimum beam waist and for a large beam waist the outage becomes independent of the pointing errors. Therefore, by adjusting the beam divergence angle at the Tx based on the maximum radial displacement, the outage probability and average SER can be significantly improved.

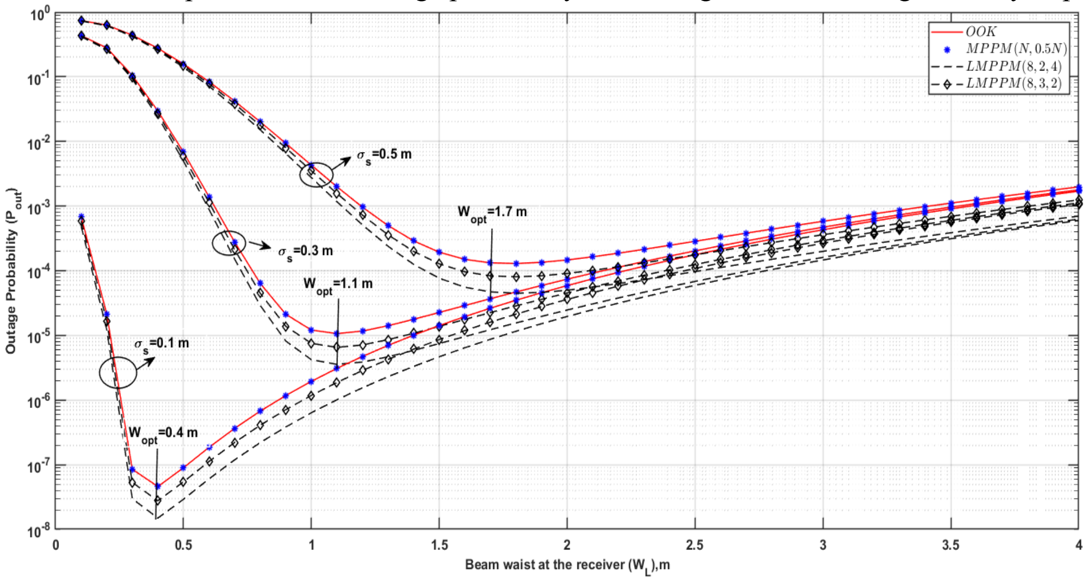

Figure 6. Outage probability versus the beam waist radius W_L at the receiver for FSO link of distance L = 1 km, $P_{avt} = 10\ dBm$ and different σ_s.

6. Conclusion and future work

The performance of MPPM and LMPPM modulation techniques has been investigated. The average SER and the outage probability performances of the IM/DD schemes under gamma-gamma turbulent FSO channel with pointing errors have been investigated including the effect of the number of signal slots w and the MPPM cardinality as well as the number of levels of FSO systems adopting the new technique LMPPM. The importance of selecting a beam waist at the receiver to minimize the average SER and the outage probability is discussed. In future work, we will try to obtain a formula for the optimum beam waist radius at the receiver as a function of the channel parameters.

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