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The Performance of Error and Outage Capacity in SIMO and MISO FSO Links

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***Abstract*— In spite of the several technical advantages of a free-space optical (FSO) communication, atmospheric turbulence can severely degrade the performance of a FSO link, because it creates random fluctuations in the phase and the amplitude of the received signal. The simultaneous usage of multiple transmit/receive apertures (MIMO) can mitigate the fading effects, that is particularly crucial for strong turbulent channels. However comparing to SIMO and MISO schemes, MIMO system it has more complexity and less applicability. In this paper, we investigate the performance of symbol-error-rate (SER) and outage capacity in FSO links with *Q*-Ary Pulse Position Modulation (PPM) in these schemes, both in the weak and strong turbulence conditions. Our results show that in a defined received energy per bit, employing diversity and adding the number of resources at the receiver end is more efficient than the transmitter both in the weak and strong atmospheric turbulence scenarios.**

***Index Terms*— Atmospheric Turbulence, Outage Capacity, Free-Space Optics, PPM Modulation and Symbol-Error-Rate**

I. INTRODUCTION

FREE-SPACE optical communication is an interesting alternative for a variety of applications in telecommunications. FSO has advantages over fiber-based systems such as operating at unlicensed optical wavelengths, providing broadband capacity, high security because of their direct line-of-sight, low cost of installation and deployment, protocol transparency, full-duplex transmission, and compact equipment has emerged these systems as a complement to radio frequency (RF) counterparts. Despite their significant advantages, there are some major undesirable effects that hamper the widespread deployment of FSO systems. The main challenge lies in their high vulnerability to adverse atmospheric conditions. Even in a clear sky, FSO links suffer from random change of refractive index caused by the variation of air temperature and pressure that causes rapid fluctuations of the received optical signal, which is called scintillation, similar to the fading effect in RF wireless communications [1].

So far fading mitigation techniques such as diversity techniques have been extensively studied in the literature. Spatial diversity involves the usage of multiple transmitters and multiple receivers in FSO communication. With spatial diversity as reducing the probability of beam blockage, system can cover longer distances [1]. However, sometimes the spatial correlation among the apertures and sub-channels in a FSO link is not negligible and play a key role in determining link performance [2]. SIMO (Single-Input Multiple-Output) and MISO (Multiple-Input Single-Output) FSO links have been proposed as another approach with less complexity than the MIMO (Multiple-Input Multiple-Output) design. The performance of a link with M-Array based receivers and a single transmitter using OOK (On-Off Keying) modulation has been investigated in [3]. It is shown that in these systems there is a smaller critical link range in comparison with a decrease in the SNR for higher values of M [4]. Temporal diversity as another solution is studied in [5], however it often imposes long delays and necessitates using large memories for storing long data frames. Over the years, a number of statistical channel models have been proposed to describe weak or strong atmospheric turbulent channels [5]. For weak turbulence regime, the probability density function (PDF) of the intensity fluctuations is modeled as log-normal distribution, whereas for strong regime K-distribution and negative exponential model [6] show an excellent agreement between theoretical and experimental data [7]. In a K-distributed turbulence channel, the error performance with pointing errors [8], outage probability and capacity [9] and DPSK modulation [2] of FSO links are studied. These papers results signify that a SISO link severely suffers from strong turbulence therefore justifying the usage of mitigation techniques such as robust modulations (for example PPM) and spatial diversity, which are our focus in this paper. In our simulations we assume that M laser sources that all are pointed toward an array of N photodetectors. We study the influence of both weak and strong atmospheric turbulences.

The rest of this paper is organized as follow: in section II, we outline the theoretical analysis for turbulence estimation model and PPM modulation is introduced. In section III, symbol error rate for a diversity based system is described in

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different cases. Outage channel capacity is introduced in section IV. Numerical results and comparison between systems are assessed in section V. Finally conclusions are provided in section VI.

II. THEORY OF ANALYSIS

When an optical beam propagates through the atmosphere, the beam is distorted due to absorption, scattering and refractive index fluctuation (turbulence) [10]. For a plane wave Rytov suggested a variance for the log intensity fluctuations in weak turbulence conditions [11] is described by:

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{1}$$

where $k = 2\pi/\lambda$ is the wave-number, L is the range and the C_n^2 is the refractive index structure coefficient. In practice Equation (1) only predicts the correct variance provided $\sigma_R^2 < 0.3$ (weak turbulence).

An attribute of an optical beam is intensity, which can be used to transmit information. Considering that the atmosphere turbulence mainly affects the light intensity (and OOK is so susceptible in this case), PPM is commonly used in FSO communication. An *Q-Ary* PPM scheme transmits $L=\log_2 Q$ bits per symbol, providing high power efficiency. Each symbol consists of a pulse of constant power occupying one slot, along with *Q-1* empty slots. The position of the pulse corresponds to the decimal value of the $L=\log_2 Q$ data bits. Hence, the information is encoded by the position of the pulse within the symbol. In this scheme, the tolerance to the atmospheric turbulence improves, because different *Q-Ary* PPM symbols experience different atmospheric turbulence conditions. Each laser power, measured at the receiver after all link losses, is a constant P_r/M watts. Thus, P_r/M represents the peak power, and the received optical energy per symbol in the absence of fading is $E_s = P_r T = P_r T_s / Q$ joules, where the signaling interval of T_s (symbol duration) is divided into Q slots and T is the slot time. This can be related to the energy per information bit by $E_s = E_b \log_2 Q$. In absence of fading, due to the Poisson point process [12], the effective count of photoelectrons is:

$$n_s = \frac{\eta P_r T}{hf} = \frac{\eta E_s}{hf} \quad photoelectrons/slot \tag{2}$$

where η is the quantum efficiency, h is the Planck's constant and f is the optical wave frequency.

III. SYMBOL ERROR RATE ANALYSIS

We analyze the error performance in two cases: non-faded and faded channels assuming the absence of background light. In the former, the "one" error results if adapted slot in receiver side register "zero" count and "zero" error is not probable because of first assume (no background light). The Poisson property expresses the symbol error probability as:

$$P_s = \frac{Q-1}{Q}\left[e^{-M\eta(P_r/M)T_s/hfQ}\right]^N = \frac{Q-1}{Q} e^{-\eta E_s N/hf} \tag{3}$$

In the latter, and presence of turbulence, we investigate two conditions: weak and strong atmospheric turbulence conditions.

A. Weak Turbulence

In a weak regime the probability error in Equation (3) must be averaged over the intensity fluctuation corresponding to a received "one". With designation a as the received light intensity that follows a log-normal distribution [13]:

$$f_A(a) = \frac{1}{\left(2\pi\sigma_R^2\right)^{1/2} a} \exp\left(-\frac{(\ln a - \mu_x)^2}{2\sigma_R^2}\right) \tag{4}$$

where μ_x is mean and σ_x^2 is variance of received irradiance.

With appropriate deposition of M transmitter and N receiver, there are $M\times N$ path gains that each of them experience independent fade, so considering Equation (3) and averaging over the PDF of received intensity, the average symbol error results:

$$P_s = \frac{Q-1}{Q}\left\{\left[\int e^{-a^2\eta(E_s/M)/hf} f_A(a)da\right]^N\right\}^M \tag{5}$$

B. Strong Turbulence

The K-distributed channel is classified as strong turbulence, which is characterized by a scintillation index (S.I.) greater than 1 that is calculated as [7]:

$$SI \cong \frac{\beta+2}{\beta} \tag{6}$$

This model is valid for propagation distances more than 100 m or several kilometers. The PDF of the K-modeled signal irradiance a, that can be considered as a product of two independent models (exponential distribution and gamma distribution) is given by [7]:

$$f_A(a) = \frac{2\beta^{(\beta+1)/2}}{\Gamma(\beta)} a^{(\beta-1)/2} K_{\beta-1}(2\sqrt{\beta a}) \tag{7}$$

where $\Gamma(.)$ is the gamma function, $K_v(.)$ is the modified Bessel function of the second kind of order v, while the parameter β is related to the effective number of discrete scatterers in the atmospheric channel. As noted earlier, we are encountered with the situation which the value of *S.I.* exceeds *1*. The SER (P_s) over the K-distributed channel can be obtained by averaging (3) over the irradiance fluctuations a:

$$P_s = \frac{Q-1}{Q}\left\{\left[\int_0^\infty f_A(a)\; e^{-a^2\eta(E_s/M)/hf} da\right]^N\right\}^M \tag{8}$$

This time-consuming integral can be estimated by expressing $K_v(.)$ as Meijer G-functions[14]:

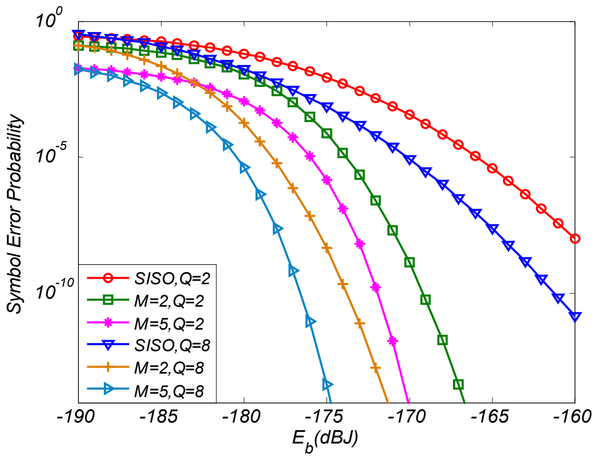

Figure 1. SER vs. bit energy in MISO system at weak turbulence

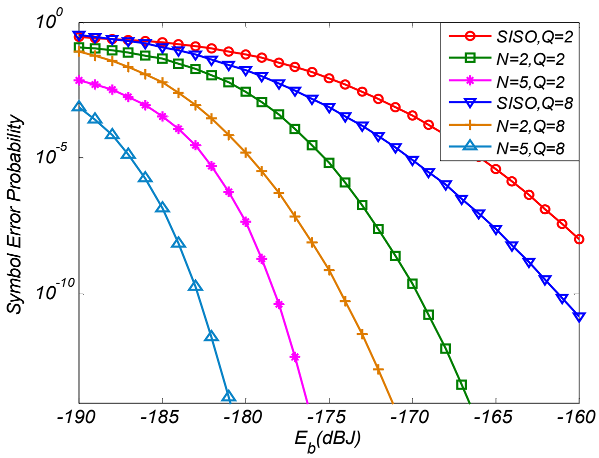

Figure 2. SER vs. bit energy in SIMO system at weak turbulence

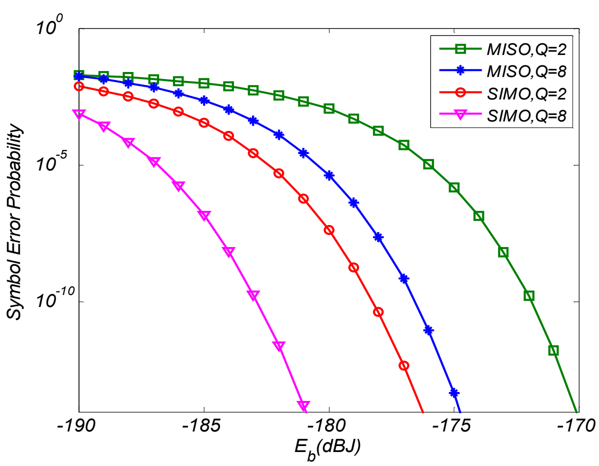

Figure 3. SER vs. bit energy in MISO and SIMO systems with M=N=5 at weak turbulence

$$K_v(x) = \frac{1}{2} G^{2,0}_{0,2}\left(\frac{x^2}{4} \middle| \begin{matrix} - \\ -\frac{v}{2}, \frac{v}{2} \end{matrix} \right) \tag{9}$$

which is a standard built-in function that can be estimated instantly with the most of the mathematical software packages. This operator is a very general function which reduces to simpler special functions in many common cases.

$$P_s = \frac{Q-1}{Q} \left\{ \frac{2^{\beta-1}}{\pi\ \Gamma(\beta)} G^{1,4}_{4,1}\left[\frac{16\eta E_s}{Mhf} \middle| \begin{matrix} \frac{1-\beta}{2}, \frac{2-\beta}{2}, 0, 0.5 \\ 0 \end{matrix} \right] \right\}^{N\times M} \tag{10}$$

IV. Outage Capacity

The outage capacity is an important metric for digital communication system in turbulent environment. This parameter measures whether the probability of the capacity of the system is greater than a pre-defined threshold value.

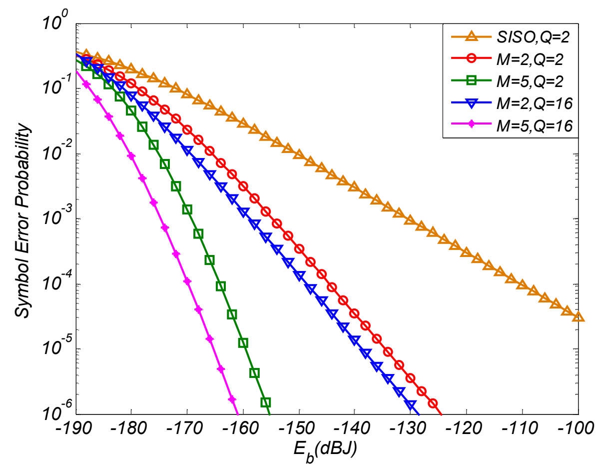

Figure 4. SER vs. bit energy in MISO system at strong turbulence

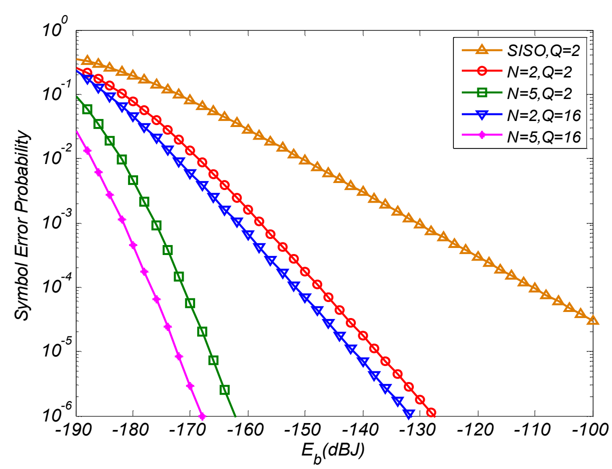

Figure 5. SER vs. bit energy in SIMO system at strong turbulence

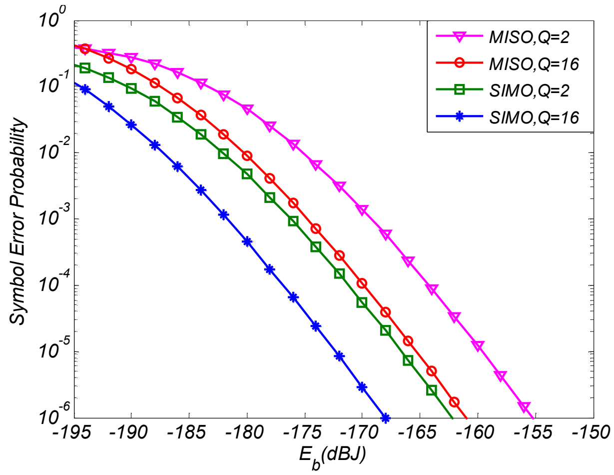

Figure 6. SER vs. bit energy in MISO and SIMO systems with M=N=5 at strong turbulence

Unlike the average SER which does not reflect the channel fading degree instantaneously, the outage capacity reflects this as it compares the instantaneous expected capacity with a threshold value. This threshold is assumed to be $0.5\log_2 Q$ (half of the maximum capacity in a channel). This maximum achievable data rate, at which reliable transmission of information over the channel is possible, has been derived in [15] for weak turbulence condition (by using log-normal model) and multiple receive/transmit apertures. Thereby and using K-distribution model for strong turbulence circumstances the capacity is calculated and it is compared with assumed threshold:

$$0.5\log_2 Q \underset{Link\,Establish}{\overset{Link\,Outage}{\gtrless}} \log_2 Q(1-\prod_{m=1}^{M}\prod_{n=1}^{N}\int_0^{\infty} f_A(a)e^{-\frac{x^2\eta E_s}{hfM}}dx) \quad (11)$$

Equivalently, in our analyze $P_{out}=1$ means that the link is out of service and $P_{out}=0$ means that the link is reestablished.

IV. RESULTS AND DISCUSSION

Following the analytical study presented in section III, we plot the SER performance and outage channel capacity results of a FSO link for various numbers of transmit/receive apertures. η, σ_R^2, and $S.I.$ are assumed to be 0.5, 0.3 and 1.5, respectively. Regarding Eq.2 and as a calibration point $E_s=10^{-16}$ joules corresponds to about 80 photons/symbol received. Fig.1 illustrates the SER parameter for MISO links. The performance of a SISO link is also included as a benchmark in $Q=2,8$. It shows that SISO links have a distinct difference in error rate from diversity-based transmitters, particularly in higher received energies. Also as the Fig.1 clearly shows, increasing the number of transmit apertures leads to better performance which is the result of reducing atmospheric variance by a factor of M. Moreover the performance is improved for higher values of Q, however as Q increases, for a fixed bit rate the peak power needs to be increased to maintain fixed energy per symbol. Fig.2 illustrates the performance of a SIMO link showing that in all atmospheric conditions enhancement of the E_b (or transmitted power) causes a decrease of the SER.As expressed for a MISO system, increasing the number of receive apertures and Q parameter cause to better efficiency, but in this scheme the effect of adding diversity appears more intense for $N\geq 5$.

Fig. 3 shows the comparison between the two systems mentioned above for the case of $M=N=5$. Although the overall behavior of these cases is similar to each other, some major differences are observed. It can be observed that the performance of a SIMO link is better than MISO type. For example, in $E_b = -180\,dBJ$ an improvement about five orders of magnitude (10^{-5}) is achieved for $Q=2$. On the other hand, in a SIMO system the required energy (E_b) for a fixed SER is lower than a MISO link. Furthermore SIMO outperforms MISO with increment of aperture numbers.

Fig.4 shows the error performance of MISO FSO links with $M=2,5$ transmit apertures employing $Q=2,16$-PPM over a K-distributed channel.

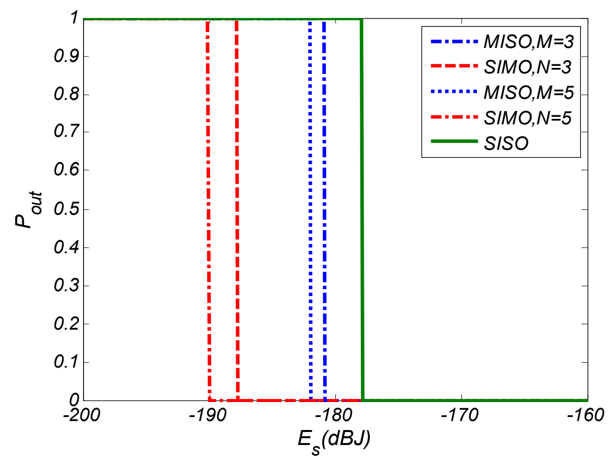

Figure 7. P_{out} vs. symbol energy in weak turbulence

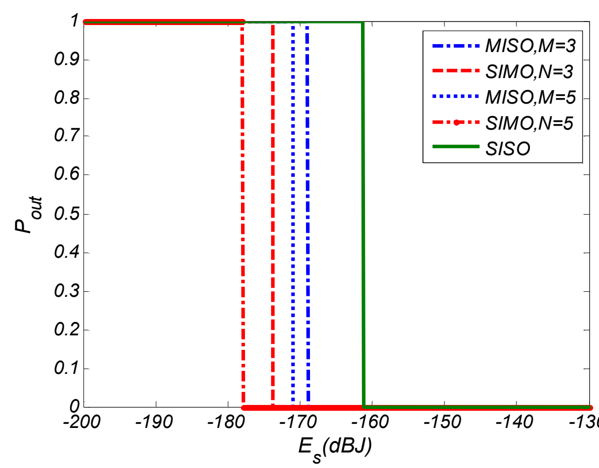

Figure 8. P_{out} vs. symbol energy in strong turbulence

It is obvious that even for high values of received energy (for example [-*140*,-*100*] dBJ) SER is not exceeding 10^{-5}, which is not an acceptable rate for practical communication systems, which is the rational reason to use spatial diversity. It is shown that the SER is significantly improved as the number of apertures increases. Moreover, with $M=5$ apertures an improvement of about *90dBJ* can be obtained at SER=10^{-6} in contrast to SISO link.

The overall treat of Fig.5 shows that the SIMO links performance is similar to MISO systems with better error rates. It is noticeable that increasing the value N affects the SER more than the Q increment.

Fig.6 demonstrates the comparison between SIMO and MISO links in a fixed Q, we can see the better performance of SIMO link with an approximately constant difference respect to a MISO one.

We show in Fig.7 outage channel capacity versus symbol energy for SIMO and MISO system with $M=3,5$ or $N=3,5$ and $Q=8$. It is shown that the SISO link requires the highest received energy to establish the connectivity between transmitter and receiver. SIMO link has better performance than the MISO scheme for example in $N=M=5$, and this is about 8dBJ in E_s . It also can be noted if one were choosing between multiple receivers or multiple transmitters it would be more advantageous to have extra resources at receiver end (the difference between $N=3$ and $N=5$ is double of which in $M=3$ and $M=5$), where the increased aperture size can be exploited due to aperture averaging technique (assuming the total power at transmitter apertures is fixed in a defined number of transmitters).

In a similar way and in strong turbulence outage probability of capacity is shown in Fig.8. At first, a considerable difference can be seen between the energy required in both strong and weak turbulence in all cases (for example 18dBJ in SISO link between two atmospheric conditions). Increasing the number of receivers in this condition leads to a better performance in energy consuming too, but the energy required for SIMO and MISO links to switch from $P_{out}=1$ to $P_{out}=0$ is smaller than the weak turbulence.

V. CONCLUSION

In this paper, we have investigated the SER performance of FSO links over both the log-normal and K-distributed fading channels using Q-PPM modulation. It is shown that a SISO link cannot deliver an acceptable SER particularly in strong atmospheric turbulences. Because of further complexity in implementation of MIMO links, we conclude that employing the SIMO and MISO types is superior. Comparison of SIMO and MISO links shows that the efficiency of adding diversity in error rate and outage capacity appears more in SIMO, both in the weak and strong turbulence conditions.

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