Original Research Article

Performance Evaluation of FSO System with MIMO Technique in Different Operating Environments

Abstract

Free Space Optical (FSO) communication is a promising solution for the need of very high data rate point-to-point communications. However, the wireless optical communications in the atmosphere were influenced by atmospheric absorption, scattering and turbulence which lead to signal attenuation and result in considerable degradation of the system performance. Since the average transmitted power is limited owing to the requirements for safety of human eye, prudent measures must be taken into account in the design of the basic units of such type of communication systems in order to exploit its great benefits under all weather conditions.

In this paper, our objective is to design a MIMO-FSO link and analyze its performance in difficult background conditions. The achievable performance improvements, including received power levels, bit error rate (BER) and Q-factor, are demonstrated in the presence of atmospheric attenuation. Our numerical results are obtained for SISO as well as MIMO system with elements varying from 2 to 4. For each one of these schemes, along with the evaluation of received power, Q-factor, and BER, the system performance is predicted through the analysis of the eye diagram. It was found that, the received power is increased by approximately 12 dB in the case of MIMO system with 4 elements when the operating environment is slightly foggy. On the other hand, higher Q-factor, 64.7, and lower BER are achieved by the same system in the case where the background is ideal.

Index Terms:- Free space optical (FSO) communications, wireless optical communications (WOC), MIMO system, non return to zero (NRZ), return to zero (RZ), Avalanche photodiode (APD), bit error rate (BER), Q-factor.

I. INTRODUCTION

Owing to the unfeasibility of cable and the inadequately of RF communications to high-bandwidth data links, free-space optical (FSO) communication is a promising technology for achieving this crucial requirement. FSO is a laser driven technology which uses light sources and detectors to send and receive information, through the atmosphere somehow same as optical fiber communication link, which uses light sources and detectors to send and receive information but through a fiber optic cable. The motivation for FSO is to eliminate the cost, time, and effort of installing fiber optic cable, yet to retain the benefit of high data rates (up to 1 GB/s and beyond) for transmission of voice, data, images, and video. Additionally, operating at unlicensed optical wavelengths, providing broadband capacity, high security because of their directionality, low cost and more compact equipment have emerged these systems as a complement to radio frequency (RF) and microwave counterparts. They are currently being considered for various applications, e. g. as an alternative for fiber optic links between buildings, reconfigurable and mobile communication links for military operations, or ground-satellite optical communication [1-3].

Despite their significant advantages, there are some major detrimental effects that hamper their widespread deployment. Firstly, they require clear as well as alignment LOS. Secondly, the use of air as a transmitting medium between transmitters and receivers makes their link's performance sensitive to various weather conditions. In this situation, the terrestrial FSO channels provide a considerably complex environment, with attenuators like fog, scintillation, ambient light, rain and snow which all of them contribute to reduce the practical capacities, but the main challenge is their high vulnerability to optical intensity variations. Even in a clear sky, FSO links suffer from random change of refractive index caused by the variation of air temperature and pressure. This causes rapid fluctuations of the received optical signal and consequently degrades the performance of the FSO link. In other words, FSO system can encounter significant losses in a clear sky condition due to in-homogeneities in temperature and pressure [4, 5]. So, the scintillation severely limits the reliability of FSO links as it deteriorates the signal intensity at the receiving end and can even result in complete loss of communication links [6, 7].

For the system performance to be improved, scintillation must be mitigated through the reduction of the spatial coherence of the transmitted beam and the spatial diversity which are accomplished by employing multiple transmitted beams and multiple receivers. Partially coherent beams with reduced spatial coherence show lower scintillation at the cost of larger divergence angle and lower average received power [8]. The use of multiple light sources, on the other hand, allows the transmitter to produce a number of spatially separated channels which can be used to improve channel characteristics or to improve spectral efficiency when coupled with multiple receivers. Multiple receive elements afford a level of spatial diversity to the receiver. This spatial diversity makes the receiver to be capable of spatially rejecting the localized noise sources as well as separating multipath components for the channel reliability to be enhanced. Therefore, in order to handle the transmission under strong atmospheric turbulence, the concept of multi-laser multi-detector (MLMD) must be constructed. Fig.(1-a) shows a Single-Input Single-Output (SISO) system operating in the presence of clouds and turbulence, whilst Fig.(1-b) replaces SISO by MIMO system of two elements where sum of the areas of smaller multiple receiving apertures is supposed to be equal to that of the single aperture receiver.

In this paper, we analyze MIMO FSO communication system with NRZ and APDs in the receiver array taking into account that the operating environment is contaminated with an atmospheric turbulence. The objective is to design multiple MIMO FSO link and simulate its performance. The size of MIMO system varies from single up to four elements for the purpose of demonstrating the impact of the MIMO size on the system performance. The received power in each case is evaluated and investigations are done on 1.25 Gb/s bit rates for different sizes of MIMO. The remainder of this paper is organized as follows. The mathematical model is presented in Section II. Based on the presented theory of FSO, the numerical treatment along with the corresponding simulation results for an FSO link in the presence of atmospheric attenuation are outlined in Section III. Section IV includes our discussion along with our concluded remarks.

II. THEORETICAL MODEL AND PROBLEM FORMULATION

A. Atmospheric Attenuation

One of the challenges of the FSO channel which may lead to signal loss and link failure is the atmospheric attenuation [10]. Additionally, scattering and turbulence phenomena highly affect the power of the transmitted signal [11]. Rayleigh, Mie, and geometrical are different types of scattering that are related to the size of particles in the atmospheric environment and the wavelength of the transmitted signal of an FSO link [12].

Atmospheric attenuation due to scattering is modeled for different weather and particle's size conditions. Kim [12], Kruse [13] and Al-Naboulsi [14] are some of the famous models that treated the effect of scattering on the transmitted beam in FSO channel. The Beers-Lambert law, on the other hand, represents the power relation between the transmitted "P_T" and received "P_R" signals in the presence of atmospheric attenuation [12].

If the atmospheric attenuation coefficient is denoted by "α " and if the link range is Z, then the received power can be calculated as a function of the transmitted power through the relation [12]:

$$P_R = P_T \exp(-\alpha Z) \tag{1}$$

The coefficient of atmospheric attenuation depends on the type of scattering, signal wavelength, size of the particles of the atmosphere and the link visibility as was described by Kim’s Model. It has a mathematical form given by [12]:

$$\alpha = \frac{3.912}{V} \left(\frac{\lambda}{550nm} \right)^{-q} \tag{2}$$

Where V is the visibility (in km) and q is the size distribution of the scattering particles. A straightforward definition of visibility is that distance at which the human eye can clearly distinct the white boundary from that of the black. For calculating the atmospheric attenuation, we need to know the particle's size "q". According to Kim's model, the parameter "q" takes the given listed values which are varied in accordance with the various weather conditions [12].

$$q = \begin{cases} 1.6 & \textit{for high visibility } (V > 50\, Km) \\ 1.3 & \textit{for average visibility } (6\, Km < V < 50\, Km) \\ 0.16V + 0.34 & \textit{for haze visibility } (1 Km < V < 6\, Km) \\ V - 0.5 & \textit{for mist visibility } (0.5 Km < V < 1 Km) \\ 0 & \textit{for fog visibility } (V < 0.5\, Km) \end{cases} \tag{3}$$

For different cases of weather conditions, we will calculate the attenuation value that is introduced on the intensity of a transmitted signal of 1550 nm wavelength. The atmospheric attenuation that arises from the propagation of the transmitted signal a distance "Z" is given by Beer's Law [12]

$$\tau(z) = \exp(-\alpha z) \quad \textit{or} \quad \tau(z) = 10 \log\left(e^{-\alpha Z}\right) \quad d\mathbf{B} \tag{4}$$

B. <u>Optical Wireless Channel</u>

Atmospheric attenuation, free space path loss, transmitter and receiver gains, types of detectors, efficiencies and pointing loss factors are considered as the main factors that highly affect the link budget calculations. The link budget model is introduced by Friis transmission formula [15-17]. The optical wireless channel can be modeled by a mathematical equation [15], where the optical received power, P_R is:

$$P_R = P_T\, \eta_T\, \eta_R \left(\frac{\lambda}{4\pi Z}\right)^2 G_T\, G_R\, L_T\, L_R \tag{5}$$

The factor between parentheses represents the free space path loss [15,16], P_T is the transmitted optical power; η_R denotes the optical efficiency of the receiver, while η_T symbolizes the same thing for the transmitter, λ is the signal's wavelength; Z represents the separation between the transmitter and receiver, G_T is the transmitter telescope gain, while G_R denotes the same thing for the receiver, L_T symbolizes the pointing loss factor of the transmitter while L_R symbolizes the same thing for the receiver [17].

$$L_j \triangleq \exp\left(-G_j\theta^2\right) \quad \textit{and} \quad G_j \triangleq \left(\frac{\pi D_j}{\lambda}\right)^2 , \quad j = R \;\; or \;\; T \tag{6}$$

This pointing loss factor "L" defines the attenuation of the received signal due to inaccurate pointing and is given by the above relation for the receiver and the transmitter. The parameter "θ" denotes the radial pointing error angle. When the transmitter is assumed to be uniformly illuminated from a circle aperture, the out beam cross section is considered as a Gaussian beam and the receiver antenna is a circular aperture [16]. In this situation, the transmitter and receiver gain expressions are as given by Eq.(6), where D_T and D_R represent the transmitter and receiver aperture diameters.

C. MIMO Wireless Channel

MIMO technology is the most widely used in wireless communication systems because it provides a large increase in data throughput and link range without additional neither bandwidth nor transmitted power. It transmits its required power over the antennas to achieve an array gain that improves the spectral efficiency. It also enhances the link reliability and reduces the fading effect. Because of these merits of MIMO technique, it becomes an important part of the modern wireless systems [18-19]. A MIMO channel can be mathematically treated as:

$$y = H x + n \tag{7}$$

where y & x represent the received and transmitted vectors, H and n denote the channel matrix and the noise vector, respectively. The channel matrix H has a general mathematical form given by:

$$H = \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1M} \\ H_{21} & H_{22} & \cdots & H_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ H_{N1} & H_{N2} & \cdots & H_{NM} \end{bmatrix} \quad (8)$$

In this representation, N symbolizes the number of transmitters whilst M denotes the number of receivers in a MIMO channel. Both the transmitters and receivers are assumed to be uncorrelated and independent of each other. In addition, the MIMO channel inputs as well as its outputs are supposed to be nonnegative and real [19]. Moreover, instead of additive complex white Gaussian noise, the signal dependent shot noise is considered as the major factor that limits the high performance of the underlined system [18]. It is well-known that the use of MIMO channel provides a performance gain, in comparison with the SISO communication scheme, into the system given that the transmitted power is held unchanged.

III. SYSTEM DESIGN MODEL

An FSO channel is designed, using Matlab software, in the presence of atmospheric losses and is integrated into OptiSystem. MIMO system of up to 4 units is modeled, with the aid of OptiSystem Version 7.0, for the purpose of enhancing the performance of FSO link. The available wavelength range for FSO communications is extending from 850 nm to 1550 nm. Here, the transmitted wavelength is chosen to be 1550 nm because the attenuation caused by Rayleigh and Mie scattering is inversely proportional to the operating wavelength. So, the longest possible wavelength of 1550 nm is selected in order to obtain the lowest scattering attenuation that may be induced on the optical signal during the operation of FSO communications. Also, it is assumed that there are no particles obstructing the light signal, but it is allowed for small particles such as haze and fog to be present within the light signal's way. Additionally, the total transmitted power is supposed to be the same for the SISO and the MIMO systems in order to compare their performances in an easy manner. A single photo-detector is used in the focal plane of each receiving aperture and the total collected noise is assumed to be the same for both systems. The SISO and MIMO constructions are modeled with the basic FSO components as Fig.(2) illustrates. These components are:

A. Transmitter

The transmitter consists of four components. The first one is the pseudo-random bit sequence generator. This generator represents the information or data that needs to be transmitted. The resulting signal is then passed to a NRZ pulse generator which generates the corresponding non return to zero coded signals. The rise and fall edges of NRZ generated pulse are of 0.05 bit extend [20]. An optical modulator modifies the intensity of the output light signal according to the incoming electrical signal. The employed optical source is assumed to be a continuous wave (CW) laser, whose power level is set at 10 dBm and of line-width of 10 MHz. In this model, we use up to four transmitter units to send the light signal through the wireless propagating channel.

B. Optical Wireless Channel

In the OptiSystem software, the FSO channel lies between an optical transmitter with 2.5 cm optical antenna and an optical receiver with 8 cm optical antenna. The transmitter and receiver gains are taken to be of 0 dB. In addition, the transmitting and receiving antennas are assumed to be ideal with an optical efficiency of 100% which means that there are no pointing errors.

C. Receiver

The receiving end of the optical wireless communication link consists of a photodiode, a low pass filter, regenerator and a visualizer. The photo-detector used here has a gain of 3, responsivity of 1 A/W and a dark current of 10 nA. An Avalanche photodiode (APD) can be used in long distance free space optical data transmission due to its merits of producing high amplification for low or weak light signals. The next processing step for the received signal is to pass it through a low pass Bessel filter of cutoff frequency of 75% of the bit rate in order to limit its bandwidth. The 3R regenerator is a subsystem used to regenerate an electrical signal of the same original bit sequence and a modulated electrical signal similar to that produced by the transmitter for the purpose of achieving the BER evaluation. The output of the 3R regenerator is connected to the eye diagram analyzer which gives the maximum Q-factor, minimum BER, eye height and threshold.

D. Performance Measures

The right choice of the performance evaluation criteria for the characterization of optical transmission links constitutes one of the key issues for an effective design of future long-haul optical systems. The most widely used measures of performance are: Q-factor which represents the signal-to-noise ratio (SNR) at the receiver decision circuit, BER which gives the upper limit for the signal before some degradation introducing to it at the receiving end, and the eye opening which considers only samples at the optimum sampling instants. The last evaluating parameter represents the difference between the minimum value of those samples decided as logical "1" and the maximum value of those ones decided as logical "0". On the other hand, the estimated value of BER can be mathematically calculated as:

$$BER = \frac{1}{2}\ erfc\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{Q\sqrt{2\pi}}\ \exp\left(-\frac{Q^2}{2}\right) \tag{9}$$

IV. SIMULATION RESULTS AND DISCUSSION

Based on the above system model, the behavior of FSO link, for multiple sizes of MIMO technique, against strong turbulence in non-homogeneous version of operating environments is evaluated. Performance simulation of the proposed link at 1550 nm wavelength and a propagation distance "L" of 1km with NRZ line code and APD receiver under various weather conditions is carried out. Optical spectrum analyzer, optical power meter and BER analyzer are employed to determine the transmitted and received signal power levels as well as the system BER.

According to the previously discussed mathematical model and by using Matlab programming language, a power loss generation corresponding to different weather conditions is accomplished and the numerical values are outlined in Table I. For clear air and high visibility (V = 23 km), the effect of atmosphere on the signal power levels is almost negligible. On the contrary, the situation is changed in the case of haze and fog conditions. For haze (V = 2 km), the visibility starts to decrease and the effect of the scattering particles begins to appear. For light fog, the visibility decreases to 0.8 km and consequently the attenuation is lowered to become 15.56 dB/km. The worst case is that obtained for moderate fog, as Table I demonstrates.

Table I: Calculated atmospheric attenuation at wavelength 1550 nm for different weather conditions

Weather Condition	Attenuation (dB/km)
Clear air high visibility (V= 23 km)	0.1408
Haze (V= 2 km)	4.2872
Light fog (V= 0.8 km)	15.5633
Moderate fog (V= 0.6 km)	25.5291

Atmospheric weather conditions have a noticeable effect on the performance of FSO links. Their effect is related to the size distribution of the scattering particles "q" and the visibility "V". In addition, they affect the signal power levels due to the dependence of the FSO on the operating wavelength.

Table II presents the values of the parameters which will be used in simulating the FSO link with the aid of Optisystem 7.0. Since the components of different weather conditions are not available in Optisystem, we have written the necessary programs in MATLAB and linked s

Table II: Parameters used in FSO simulation

Parameter (Symbol)	Value
Operating signal wavelength (λ)	1550 nm
Transmission Rate	1.25 Gbps
Link Distance (z)	1 km
Optical Transmitted Power (P_T)	10 dBm
Transmitter and Receiver Apertures (D_T, D_R)	2.5 , 8 cm
Transmitter and Receiver Gain	0 dB
APD Photodetector Gain	3 dB
APD Responsivity	1 A/W
APD Dark Current	10 nA
Transmitter and Receiver Optics Efficiency (η_T, η	0.75, 0.8
Low Pass Filter Cutoff Frequency (at receiver	0.75× Bit rate

Now, Using Optisystem 7.0, an FSO link is constructed, taking into account the previous mathematical model, which is provided by the system specifications that are selected in accordance with the practical FSO links given in Table II as well as the atmospheric loss factor calculated in Table I. Link construction is presented in Fig.(2) for SISO and MIMO of units up to 4 elements. Fig.(3) displays the relationship between the received power and the number of units of the MIMO system for different weather conditions. It is clear that, in all cases the received signal power enhances as the size of the MIMO system increases. In other words, the introduction of the MIMO technique will improve the level of the received signal power. On the other hand, the noticeable improvement in the behavior of FSO starts at a two elements (2x2) MIMO. It is also observed that the highest values of the received power for clear, haze, light and moderate fogs are -12.4, -16.5, -27.8 and -37.8 dBm, respectively, in the case of using a MIMO system of four units (4x4).

Let us now turn our attention to show to what extent the size of the MIMO algorithm can affect the behavior of the FSO communication system. Fig.(4) depicts the eye diagram for several situations of weather conditions. It is evident that the significance of a wider eye opening occurs in the case of clear air, where the occurrence of data errors is small, as indicated in Fig.(4-a). In the case of bad weather conditions, however, the narrower eye opening is observed, where the worst system performance is obtained as indicated in Fig.(4-b). Moreover, in the case of difficult weather conditions, where the attenuation factor decreases the visibility, the size of the eye opening becomes smaller. Furthermore, the size of eye opening is very small for the situation of very difficult weather conditions SISO system, where there is no splitting of power. In this case, it is hardly to establish a communication link. Fig.(5) illustrates the same thing as that indicated in Fig.(4) for the SISO as well as 4x4 MIMO combinations in the case of haze weather condition. It is apparent that increasing the number of MIMO units will increase the size of the eye opening owing to the reduction in the signal jitters. It is well-known that a wider eye opening means that the occurrence of the data errors is reduced. Generally, the wider the eye opening is, the better the system performance becomes. Additionally, it is noticed that as the number of transmitters and receivers increases, the size of eye opening increases and the resulting jitter decreases. Moreover, for SISO system, there is no splitting of power and the size of the eye opening is very small. In this situation of operation, the established communication link is bad. On the contrary, the MIMO technique enhances the performance of FSO network and as the size of the MIMO system augments, the improvement in the quality of FSO communication link becomes evident.

Performance evaluation of the proposed link at 1550 nm with NRZ line codes (NRZ line code achieves a better performance than RZ by providing higher level of received signal and better BER parameter) and APD receivers under various weather conditions is numerically computed. Figs.(6-a, 6-b) display the output received signal power versus the operating wavelength for SISO and MIMO scheme with four units (4x4), respectively. In this situation of operation, haze weather is studied with the same power level which is mentioned in Table II. As the weather conditions get worse, the loss factor of atmospheric attenuation increases and this in turn affects the received power. It is clear that, the MIMO algorithm with four units achieves the highest performance, whilst the conventional SISO system gives the worst one.

From the eye diagram, it is easy to deduce the values of Q-factor along with the minimum BER. A BER of value lower than 10^{-9} is taken in order to achieve an error free communication, as this is the limit up to which successful communication can take place. Beyond this value of BER, the communication link breaks. A graph is plotted to demonstrate the variation of Q-factor with the number of elements of MIMO system and it is illustrated in Fig.(7). The examination of this scene indicates that one can get a large value of Q-factor (64.7) by using four-unit MIMO technique, which is higher by 56 than that obtained for SISO system, in the case of clear air. It is evident that the number of elements of MIMO system plays an important role in its performance, where 4x4 MIMO system gives Q-factor higher by 10 and 23 than that obtained for 3x3 MIMO and 2x2 MIMO procedures, respectively, given that the operating condition is held unchanged at the clear air. In the case of haze, on the other hand, a Q-factor of 34 is realized by 4x4 MIMO technique with an amelioration of 31 than that achieved by the conventional SISO construction. These results demonstrate that the introduction of MIMO algorithm will improve the link performance and the rate of enhancement increases as the number of MIMO elements augments.

Now, let us go to examine the effect of transmitted power on the performance of FSO link. By varying the value of the transmitted power and indicating the resulting value of Q-factor under numerous operating conditions, one obtains a group of graphs like those displayed in Figs.(8-11). Each one of this category of graphs represents the Q-factor as a function of the transmitted optical power and parametric in the number of MIMO elements which is varied from 2 to 4 as well as the normal SISO structure. Transmitted power levels are assumed to be varied from -4 to 38 dBm. The minimum values of transmitted power required to establish a communication channel for different weather conditions and several sizes of MIMO system are listed in Table III.

Table III: Technical data of minimum power required for operation in different weather conditions

No of MIMO	Minimum required value of Transmitted Power (dBm)			
	Clear ai	Haze	Light fo	Moderate fog
1x1 MIMO	8.91	13.02	24.31	38.79
2x2 MIMO	-0.18	3.98	15.27	25.23
3x3 MIMO	-1.89	2.24	13.51	23.47
4x4 MIMO	-3.17	0.98	12.26	22.23

It is investigated that for a transmitted power level of 10 dBm, there is no established communication channel in the case of moderate fog weather condition, so the transmitted power should be increased. However, one gets larger values of Q-factor and lower values of BER, for the same level of transmitted power, when 4x4 MIMO technique is employed. It is observed that as the transmitted power increases, the value of Q-factor increases in the case of good weather conditions. But in the case of bad weather conditions, the communication channel is not constructed until the transmitted power attains its sufficient level. By performing simulation, minimum value of transmitted power required in each case is calculated. It is of importance to note that, for bad weather conditions, the higher transmitted power is required, whilst by increasing the number of MIMO elements, the necessary transmitted power for establishing successful channel is reduced. Fig.(8) illustrates the variation of the quality factor with the transmitted power when the signal passes without obstruction and in accordance with high visibility (the size distribution of the scattering particles equals 1.6). In this case, lower transmitted power is indicated. Fig.(9) repeats the same thing for haze weather conditions. From the obtained results of these two figures, it is clear that the maximum achievable quality factor occurs in the case of 4x4 MIMO algorithm taking into account that the transmitted power is of level 16 dBm. The fog is the worst case of operating conditions where more attenuation is introduced on the transmitted signal. Fig.(10) demonstrates that the effect of the scattering particles in the case of light fog will result in a visibility of level less than 0.8 km. In this situation, the transmitted power required for establishing a communication channel is 24.31 dBm and this value will be reduced, by approximately 50%, if the number of units of the MIMO system is augmented to four. On the other hand, in the case of strong turbulence (moderate fog), there is no constructed channel for the SISO system, until the level of the transmitted power becomes larger than 36 dBm, as Fig.(11) displays. However, by increasing the number of the MIMO units to four, one can get a Q-factor of 72 with the same level of the transmitted power.

V. Conclusions

The MIMO wireless optical link is a multi-element link which exploits spatial dimensions to achieve gains in reliability and spectral efficiency. For this reason, this paper is devoted to analyze the MIMO FSO link design methodologies. Different weather conditions including the more difficult ones are treated in the operation of such a link that employs NRZ line coding and APD photo-detector in its receiver. For this link, the power loss due to different weather conditions is numerically evaluated through a MATLAB program and the results are graphically displayed. The obtained results demonstrate that the procedure of MIMO enhances the performance of FSO system and the rate of enhancement increases as the size of its elements augments where the received power is ameliorated.

The examination of the given results shows that doubling the number of MIMO elements can effectively increase the received power. In light fog operating conditions, the using of 4x4 MIMO system can improve the received power by 12 dBm; from -39.826 dBm for SISO to -27.785 dBm. Additionally, higher value (64) of Q-factor, which is greater by 56 than that obtained for SISO system, is achieved by including such procedure when the operating environment is ideal (clear air). In the case of haze, a Q-factor of 34 is realized for the underlined MIMO system while its corresponding value is 3 for SISO technique. Furthermore, the minimum required value of the transmitted power is 8.91 dBm in the case of clear air and this value can be reduced to -3.17 dBm through the use of four-unit MIMO. Moreover, the minimum level of the transmitted power is 38.79

dBm in the case of moderate fog and this value can be lowered to 22.23 dBm by employing 4x4 MIMO technique.

Finally, it is concluded that, for a SISO link, communication is not possible in the case of light fog. But, when two-unit (2x2) MIMO system is employed, the communication link starts working well. Moreover, in poor weather conditions, data can be transmitted with good bit error rate performance. A higher performance can be achieved with 4x4 MIMO FSO link. Therefore, utilizing the MIMO in FSO link enhances its performance and a higher combination of MIMO elements gives further improvement. The displayed results would provide a useful approach for the optimization of diversity configuration to maximize channel capacity of MIMO FSO links over a variety of atmospheric turbulence conditions.

REFERENCES

[1]F. Xu, M.A. Khalighi, S. Bourennane, "Pulse Position Modulation for FSO Systems: Capacity and Channel Coding", International conference on telecommunication, pp. 31–38, 2009

[2]X. Zhu and J. Kahn, "Free space optical communication through atmospheric turbulence channels", IEEE Trans. Communication, vol. 50, no. 8, pp. 1293–1300, 2002.

[3]E. Leitgeb, O.Koudelkat, S.Sheikh Muhammad, "Multilevel Modulation and Channel Codes for Terrestrial FSO links", Proc. 2nd Int. Symp. Wireless Communication Systems, pp.795–799, 2005.

[4]N. Cvijetic, S.G. Wilson, and Brandt- Pearce M., "Receiver optimization in turbulent free-space optical MIMO Channels with APDs and Q-ary PPM", IEEE Photon Tehnol. Lett, vol.18, pp.1491-1493, 2006.

[5]J. Strohbehn, "Laser Beam Propagation in the Atmosphere", New York: Springer, 1978.

[6]L. C. Andrews, R. L. Phillips, C. Y. Hopen, M. A. Al-Habash, "Theory of Optical Scintillation", J. Opt. Soc. Am.,vol. 16, pp. 1417–1429,1999.

[7]S.G. Wilson, M. Brands-Pearce, Q. Cao, and J.J.H. Leveque,III, "Free-Space optical MIMO transmission with Q-ary PPM", IEEE Trans. Commun., vol.53,pp. 1402-1412, 2005.

[8]S. M. Navidpour, M. Uysal, M. Kavehrad, "BER Performance of Free-Space Optical Transmission with Spatial Diversity", IEEE Transactions on Wireless Communications, vol. 6, no. 8, pp. 2813-2819, 2007.

[9]Peng Deng, Mohsen Kavehrad, Zhiwen Liu, Zhou Zhou and XiuHua Yuan, "Capacity of MIMO free space optical communications using multiple partially coherent beams propagation through non-Kolmogorov strong turbulence", OPTICS EXPRESS, Vol. 21, No. 13, July 2013, pp.

[10]E. J. Lee and V.W.S. Chan, "Part 1: Optical Communication Over the Clear Turbulent Atmospheric Channel Using Diversity", IEEE Journal on Selected Areas in Communications, Optical Communications and Networking, Vol. 22, No. 9, pp. 1896–1906, 2004.

[11]S. Bloom, E. Korevaar, J. chuster and H. Willebrand, "Understanding The Performance of Free-Space Optics", J. Opt. Netw., vol. 2, no. 6, pp. 178-200, 2003.

[12]W.O. Popoola, Z. Ghassemlooy, C.G. Lee and A.C. Boucouvalas, "Scintillation Effect On Intensity Modulated Laser Communication Systems A Laboratory Demonstration", J. Optic Laser Technol., vol. 42, no. 4, pp. 682-692, 2009.

[13]I. I. Kim, B. McArthur and E. Korevaar, "Comparison of Laser Beam Propagation at 785 nm and 1550 nm in Fog and Haze for Optical Wireless Communications", In: Proc. SPIE, vol. 4214, pp. 26-37, 2001.

[14]M. S. Awan, Marzuki, E. Leitgeb, F. Nadeem, M. S. Khan and C. Capsoni, "Fog Attenuation Dependence On Atmospheric Visibility At Two Wavelengths For Fso Link Planning", Loughborough Antennas & Propagation Conference, UK, pp. 193-196, 2010.

[15]H. Manor and S. Arnon, "Performance of an Optical Wireless Communication System as a Function of Wavelength", Appl. Opt., vol. 42, no. 21, pp. 4285-4294, 2003.

[16]Liu X., "Free-Space Optics Optimization Models for Building Sway and Atmospheric Interference Using Variable Wavelength", IEEE Trans. Commun., vol. 57, no. 2, pp. 492-498, 2009.

[17]Nazmi A. Mohammed, Amr S. El-Wakeel and Moustafa H. Aly, "Performance Evaluation of FSO Link Under NRZ-RZ Line Codes, Different Weather Conditions and Receiver Types in the Presence of Pointing Errors", Open Electrical & Electronic Engineering Journal, vol. 6, pp. 28-35, 2012.

[18]James H. Leveque, Maïté Brandt-Pearce, Qianling Cao, Stephen G. Wilson, "Free-Space Optical MIMO Transmission With Q-ary PPM", IEEE Transactions on Communications, Vol. 53, No. 8, pp. 1402-1412, 2005.

[19]Abolfazl Chaman-motlagh and Mehdi Mofidi, "Error and Channel Capacity Analysis of SIMO and MISO Free-Space Optical Communications", Conference on Electrical Engg.Tehran, Iran, vol.20, pp. 1414-1418, 2012.

[20]Liu, X, "Optimal transmitter power of an inter-satellite optical communication system with reciprocal Pareto fading", Applied Optics, vol. 49, NO. 49, pp. 915-919, 2010.

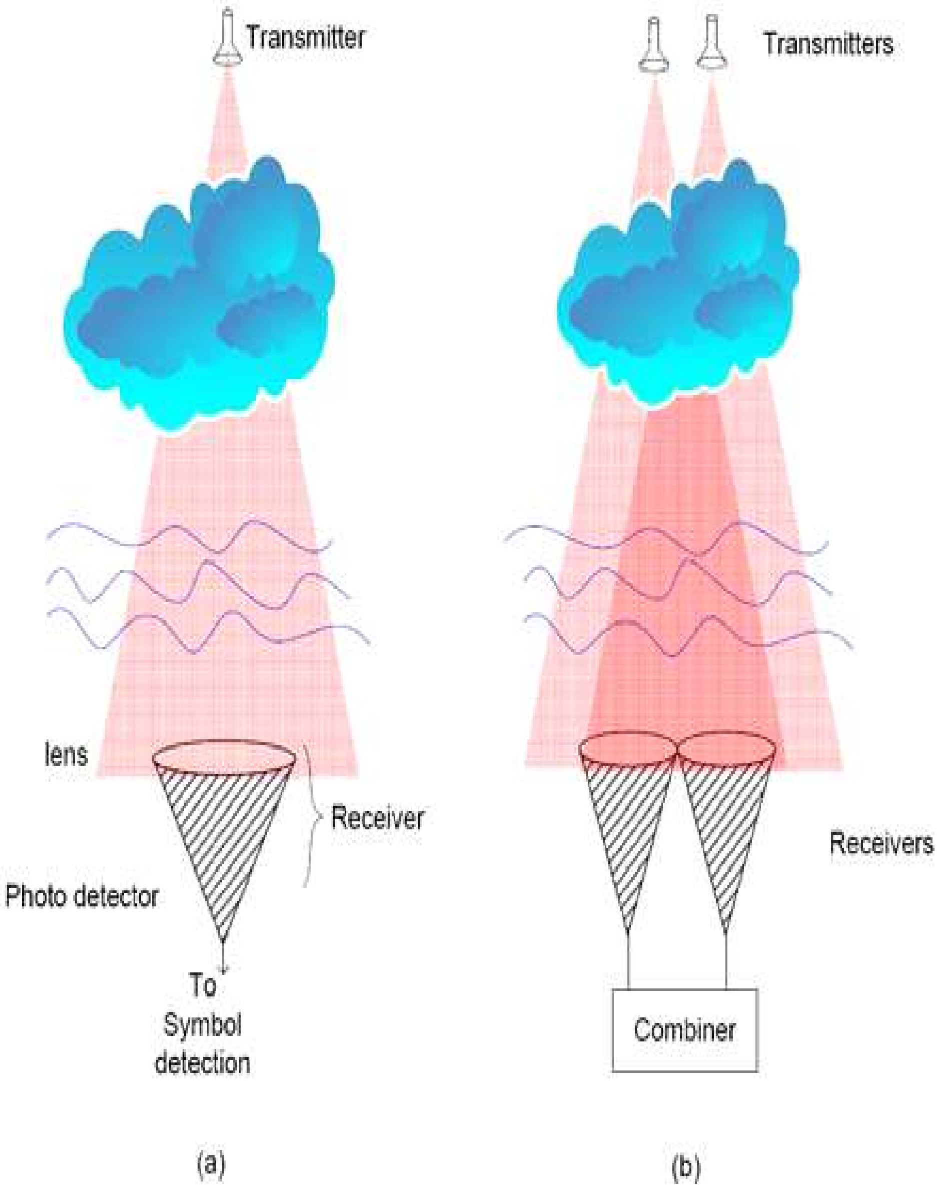


Fig.(1) Free space optical communication systems in difficult atmospheric conditions a) SISO and b) 2x2 MIMO

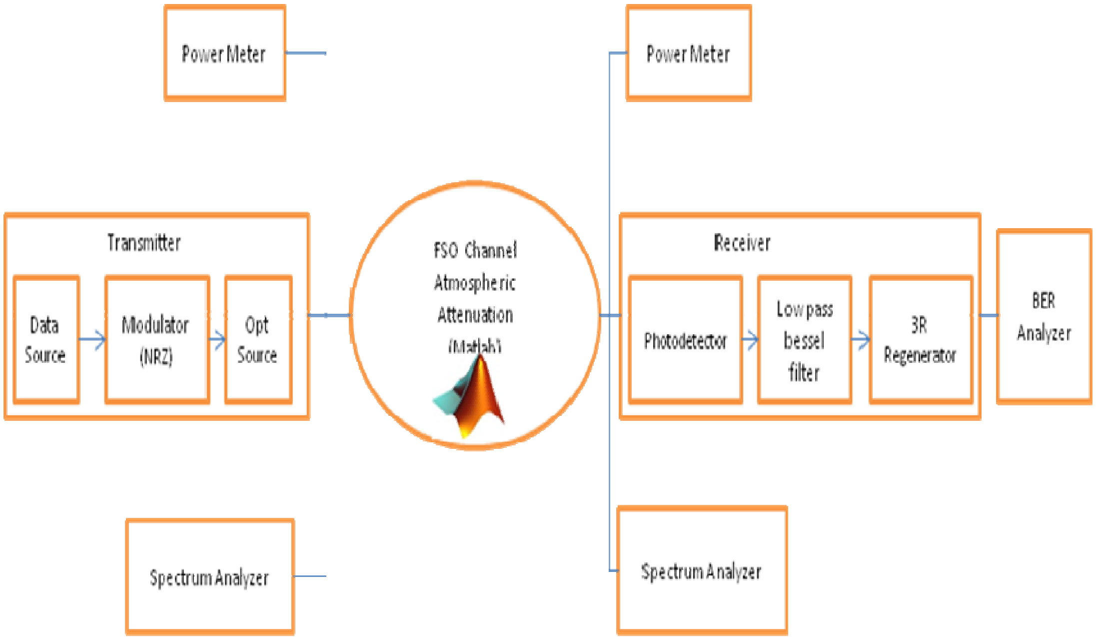


Fig.(2) SISO FSO system design model.

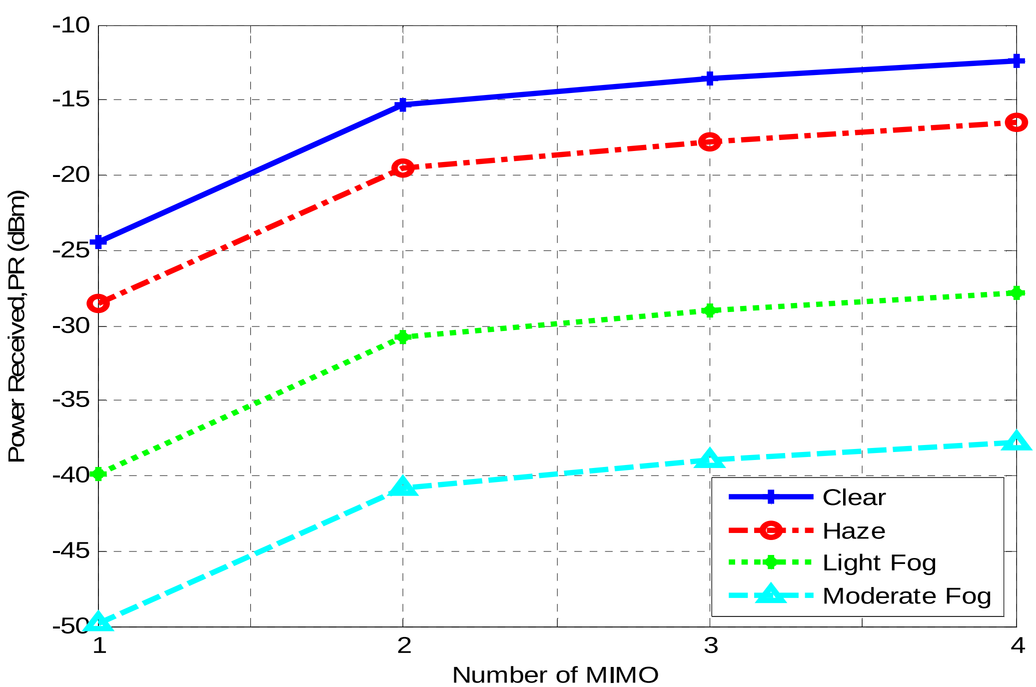
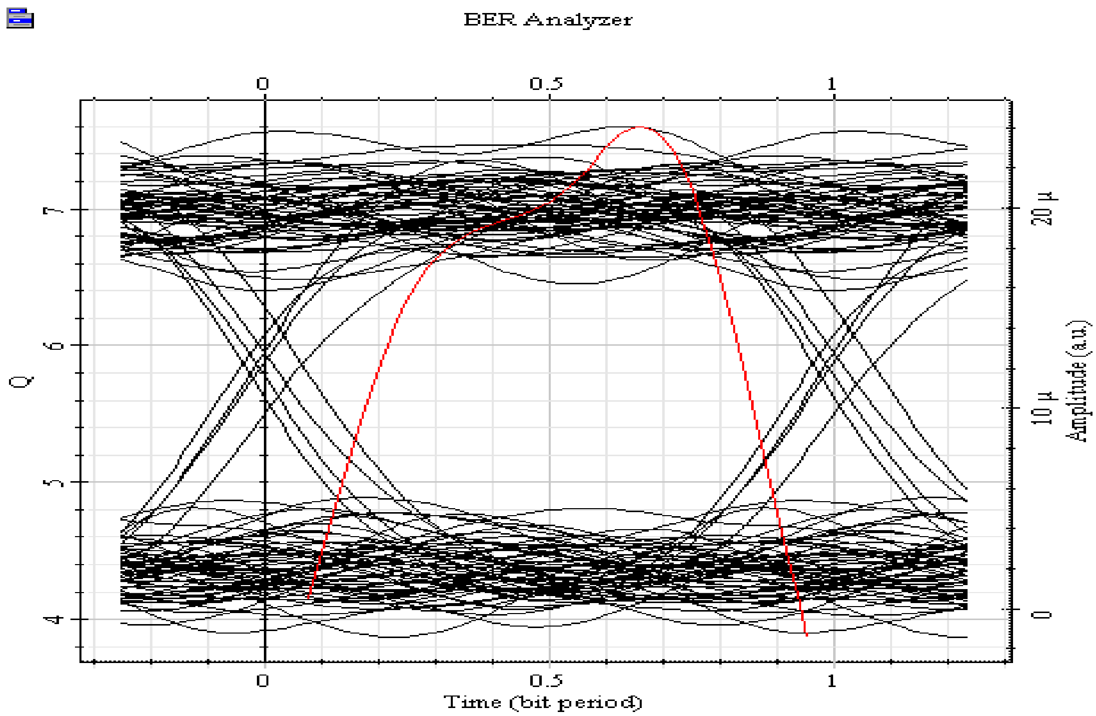
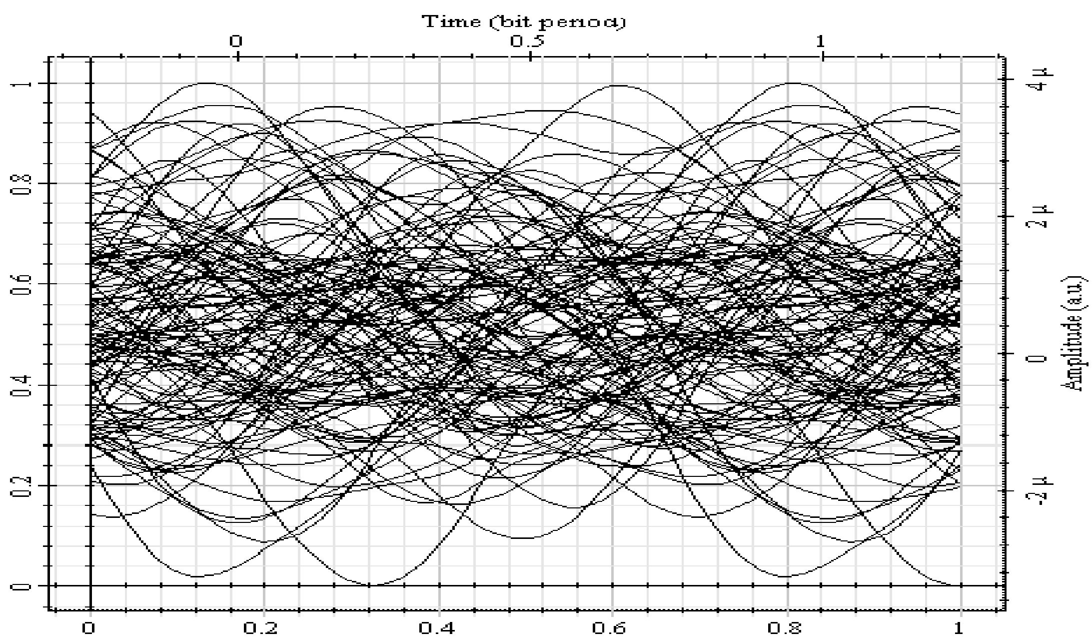


Fig.(3) Received power vs. size of MIMO system in different weather conditions.

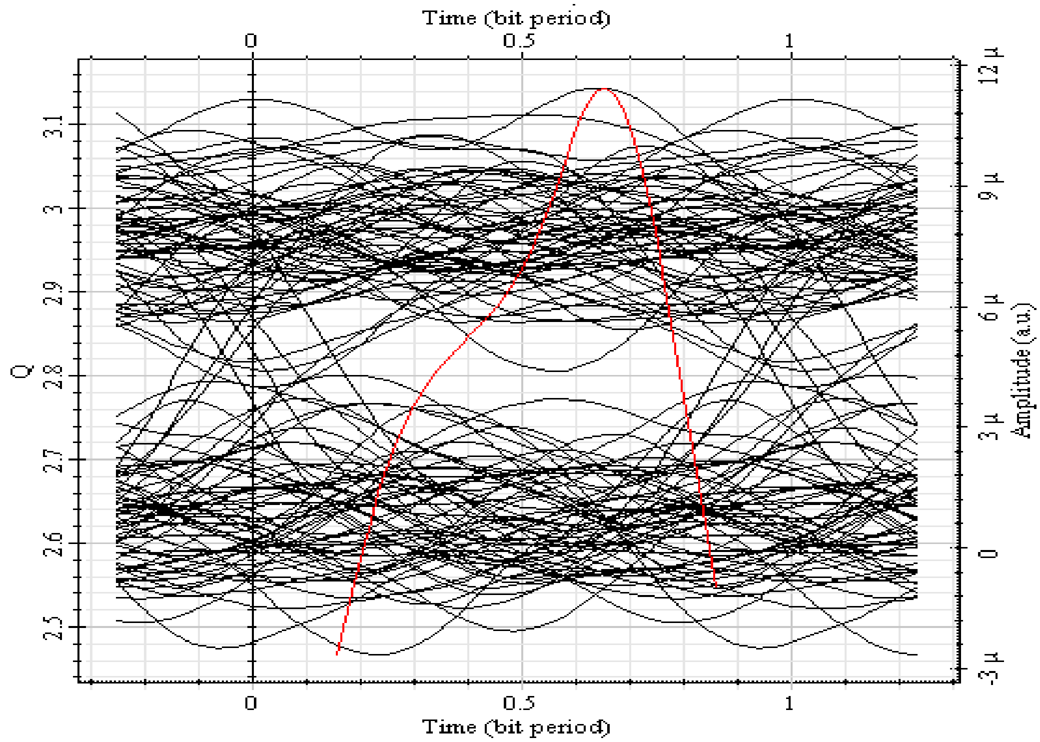


(a)

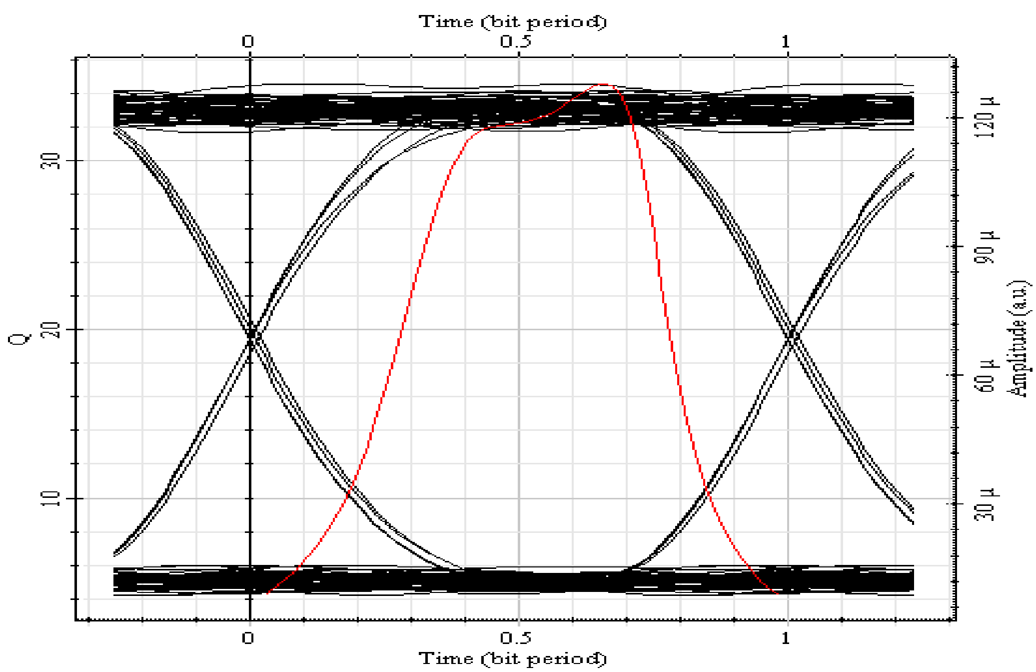


(b)

Fig.(4) Eye diagram for SISO in different weather conditions
a) Clear air   b) Light fog

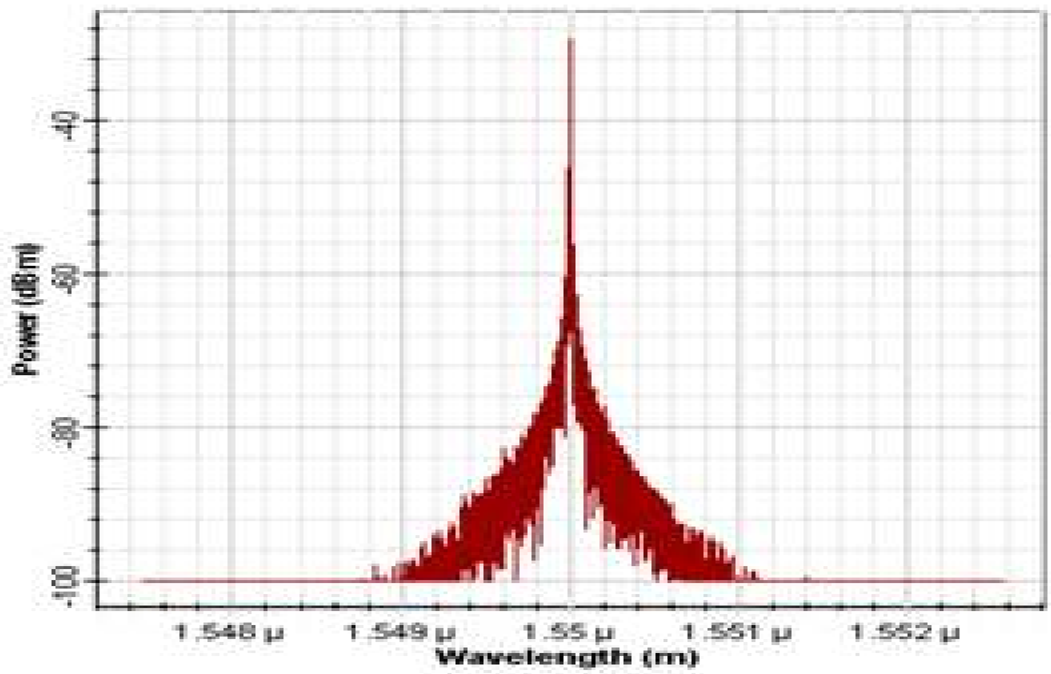


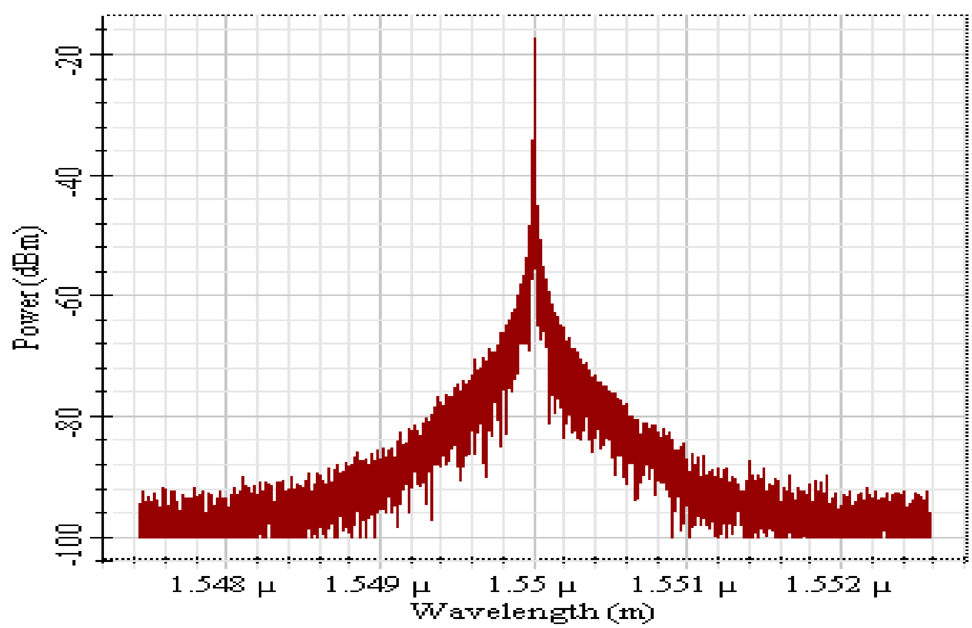
(a)



(b)

Fig. (5) Eye diagram for haze weather condition (a) SISO (b) 4x4 MIMO





(b)

Fig.(6) Signal power at receiver for haze weather condition
a)SISO b)4x4 MIMO

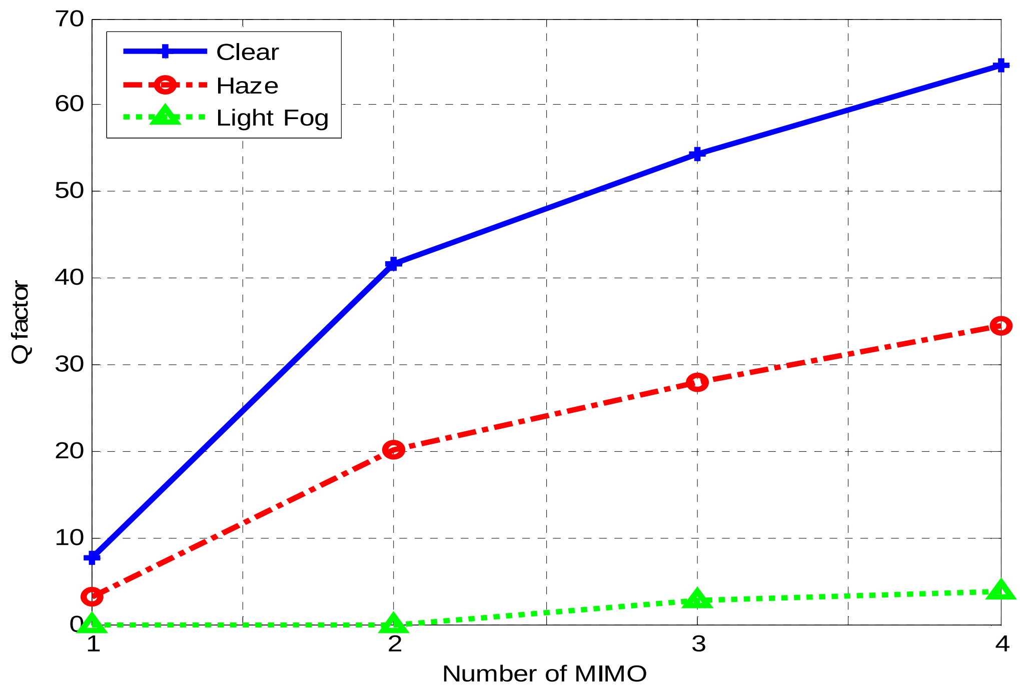


Fig.(7) Q-factor vs. number of units of MIMO at 10 dBm transmitted power.

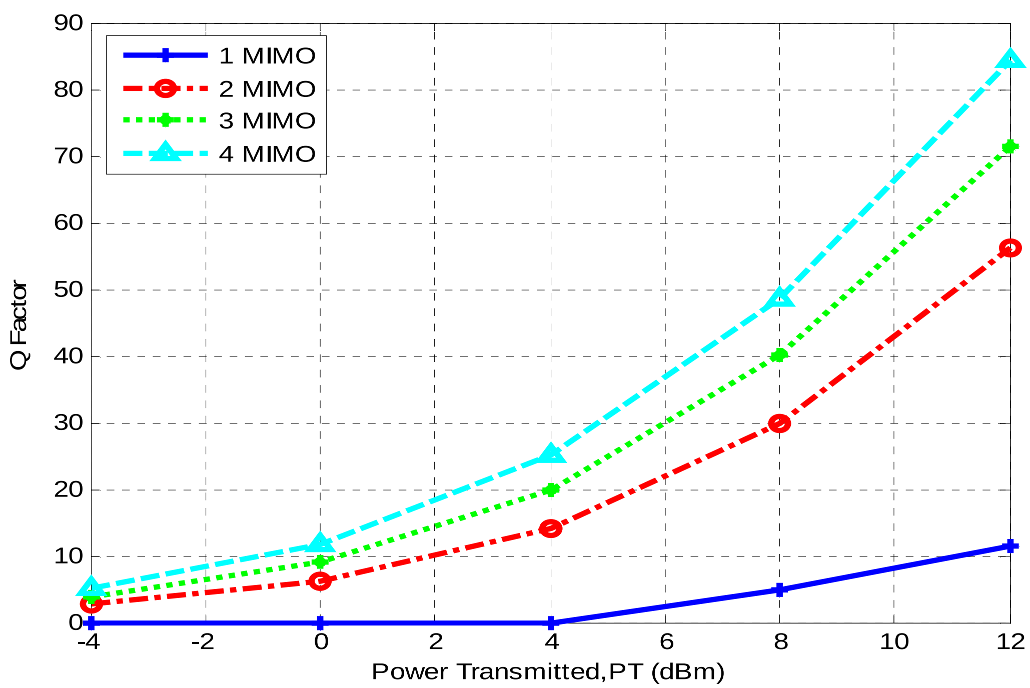


Fig.(8) Q-factor vs. transmitted power for clear air weather condition.

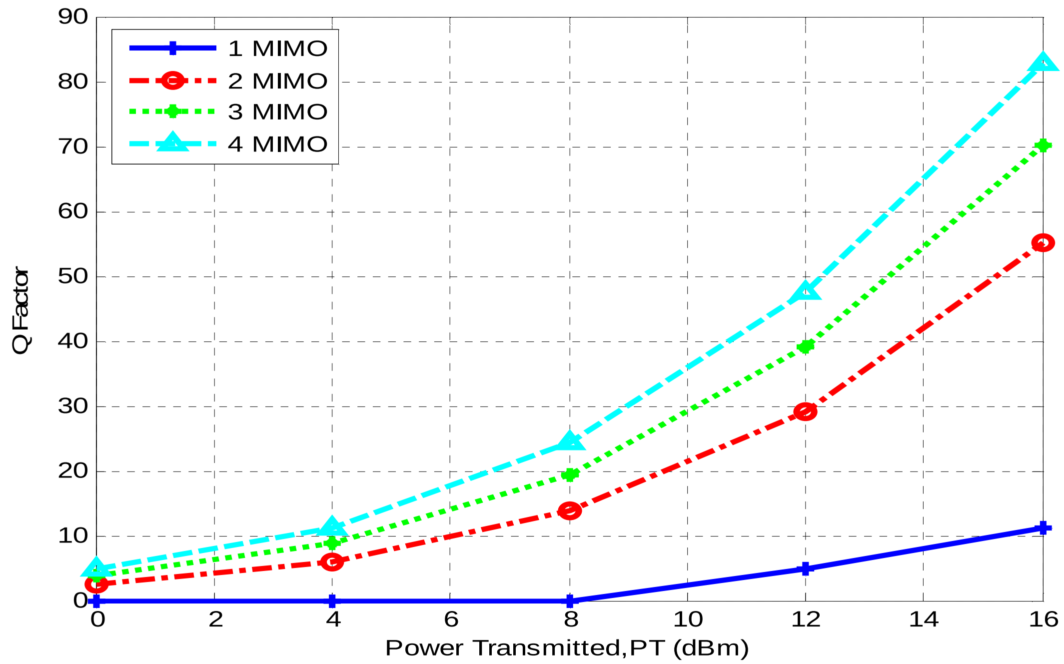


Fig.(9) Q-factor vs. transmitted power for haze weather condition.

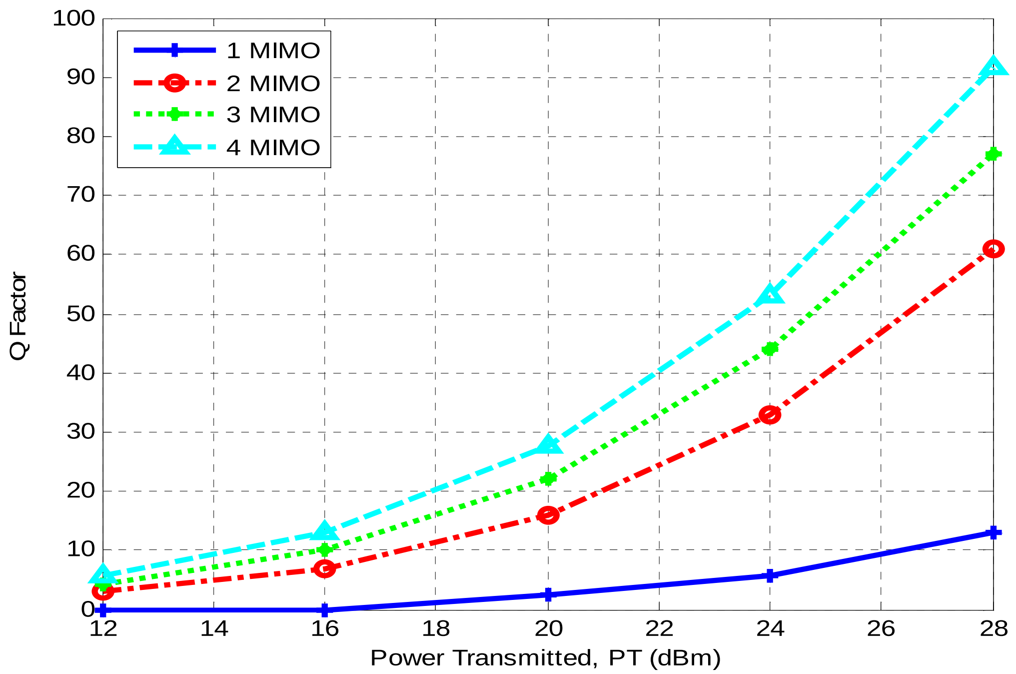


Fig.(10) Q-factor vs. transmitted power for light fog weather condition.

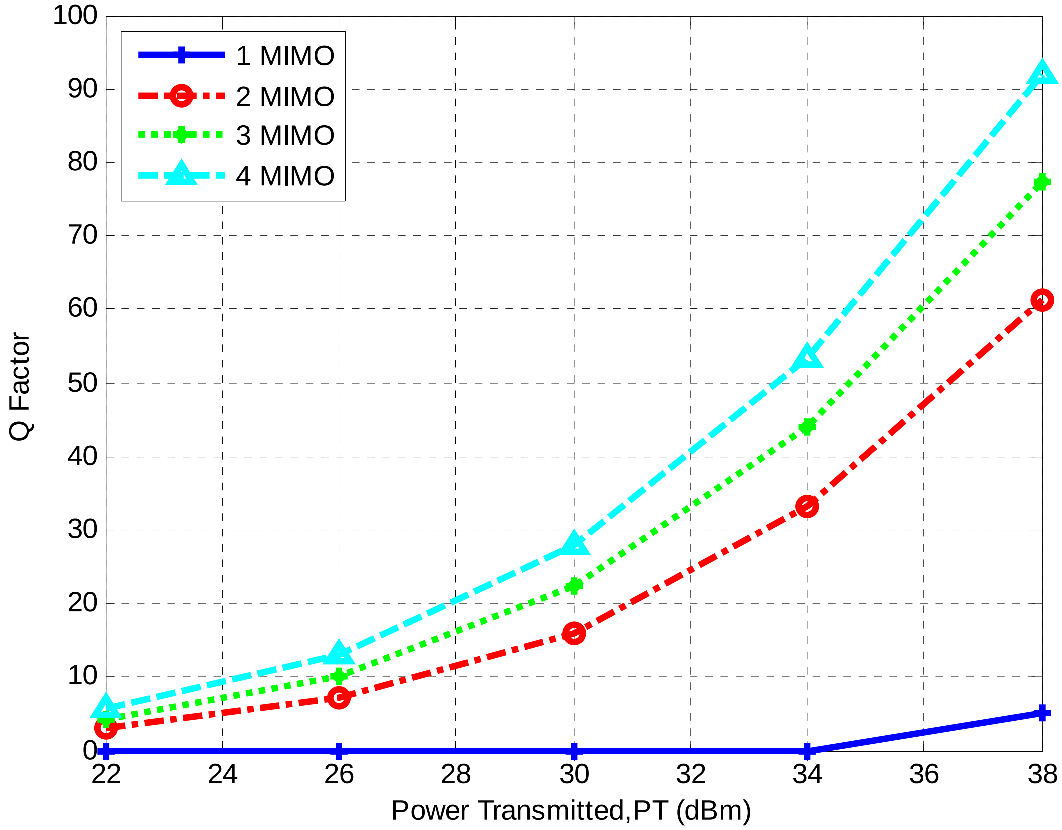


Fig.(11) Q-factor vs. transmitted power for moderate fog weather condition.