Original Research Article

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

Abstract

Free Space Optical (FSO) wireless communication is a promising solution for the need of very high data rate point-to-point communications. However, the promised enormous data rates are only available under clear weather conditions. Atmospheric phenomena such as clouds, fog, and even turbulence can dramatically degrade the FSO system performance. Therefore, 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 potentials under all weather conditions.

In this paper, our objective is to design 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 discussed within the effect of atmospheric attenuation. In our numerical results, we consider the number of the MIMO elements to vary from 1 to 4 and the power received in each case is calculated. By analyzing the eye diagram, the system performance can be predicted. Additionally, the Q factor and BER are evaluated in the absence as well as in the presence of MIMO technique. 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 of type light fog. On the other hand, higher value of Q-factor, 64.7, and lower value of BER are obtained by using the same system in the case of ideal background.

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 communications (FSOC) is a promising technology for achieving this crucial requirement. This interesting type of communication systems has demonstrated its capability to deliver data faster than any other state-of-the-art wireless communication technology. In other words, FSOC is a cost effective and high bandwidth access technique, which is receiving growing attention with recent commercialization successes. FSO transmission is unlicensed and only must subscribe to safety standards for potential eye damage. In this regard, use of infrared wavelengths is advantageous since eye hazards are less problematic, and a large technology base exists from the fiber-optic world. It is 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. However, to exploit all potentials of FSOC systems, the designers have to overcome some of the major challenges related to the optical wave propagation through the atmosphere. The link performance of FSOC can be severely degraded by atmospheric turbulence induced effects including intensity fluctuation, phase fluctuations, beam wandering and beam jittering. In other words, an optical wave propagating through the air experiences fluctuations in amplitude and phase due to atmospheric turbulence. This intensity fluctuation, also known as scintillation, is one of the most important factors degrading the performance of an FSOC link, even under the clear sky conditions. To enable the transmission under the strong atmospheric turbulence the use of the multi-laser multi-detector (MLMD) concept has been reported.

FSO communication links have some distinct advantages over conventional microwave and optical fiber communication systems by virtue of their high carrier frequencies that permit large capacity, enhanced security, high data rate, needless of spectrum license and so on. But, beside these advantages, FSO communications requires clear as well as alignment LOS. The major challenge that faces FSO is that it uses air as a transmitting medium between transmitters and receivers, where various weather conditions can affect its link's performance. It also suffers from many problems like noise and bit error rate due to its atmosphere propagation. This imposed noise causes attenuation in the transmitted signal and this, in turn, results in high bit error rate or signal loss at the receiver end [2]. There are various factors that affect the signal and make it difficult to achieve the desired level of performance. Major factors are fog, snow and rain [3].

Atmospheric turbulence-induced fading represents one of the main impairments that affecting FSO communications. Optical signal propagation in free space is influenced by atmospheric turbulence and pointing errors, which fade the signal at the receiving end and deteriorate the link performance. The reliability of an FSO communications system is greatly dependent on the atmospheric conditions. FSO 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 receiver and can even result in complete loss of communication links. The effect of scintillation is more severe for small aperture receivers [6, 7].

Fig.(1-a) shows a Single-Input Single-Output (SISO) system operating in presence of clouds and turbulence. In Fig.(1-b), on the other hand, the SISO system is replaced by a MIMO system of two elements. Sum of the areas of smaller multiple receiving apertures is supposed to be equal to that of the single aperture receiver.

To mitigate the deleterious effects of scattering and turbulence, multiple transmitters and receivers can be used. Hence, it would be possible to exploit the benefits of spatial diversity and received multiple independent copies of the same signal. The effectiveness of MIMO system in combating the lognormal amplitude fading has been demonstrated in the literature [2, 8, 9].

In this paper, we analyze MIMO FSO communication systems 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 the multiple MIMO FSO links and analyze their performance. The size of MIMO system varies from single up to four elements. The received power in each case is calculated .Investigations are done on 1.25 Gb/s bit rates for different sizes of MIMO. It is observed that there is an enhancement in the system performance as the size of its MIMO increases. The remainder of this paper is organized as follows. The mathematical model is presented in Section II. Based on the presented theory of FSO, our numerical treatment along with our 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 obtained as a function of the transmitted power through the relation:

$$P_R = P_T \exp(-\alpha Z) \qquad (1)$$

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 [12]. It has a mathematical form given by:

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

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.

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

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]

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

B. Optical Wireless Channel

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. The optical received power, P_R , becomes:

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

The factor between parentheses represents the free space path loss [15,16], P_T is the transmitter optical power; η_R denotes the optical efficiency of the receiver, while η_T denotes the same thing for the transmitter, λ is the signal's wavelength; Z is 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.

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

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 be 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:

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

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 into the system for a fixed transmitted power.

III. SYSTEM DESIGN MODEL

An FSO channel is designed using Matlab software for atmospheric losses and is integrated into OptiSystem. MIMO system of up to 4 units is modeled to enhance the performance of FSO link by using the OptiSystem Version 7.0. 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 is induced on the optical signal during the operation of FSO communications.

Here, 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 systems are modeled with the basic communication components of FSO as illustrated in Fig.(2). 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 times of NRZ pulse generator are 0.05 bit [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 wireless 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 performance of FSO links for multiple size of MIMO through strong turbulence is evaluated in different operating conditions. Performance simulation of the proposed link at 1550 nm and the 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 used to determine the transmitted and received signal power levels and the system BER.

According to the mathematical model presented previously and by using Matlab, we regenerate power loss due to different weather conditions as indicated 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 appears as outlined in Table I.

TableI: 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.

Performance Analysis of FSO Link at 10dBm transmitted power

Table II presents the values of the parameters which will be used in simulated the FSO link using Optisystem 7.0. Since the components of different weather conditions are not available in Optisystem, we have written programs in MATLAB and linked them with Optisystem for the simulation to be completed and in the same time including operating weather conditions along the link.

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_R)	0.75, 0.8
Low Pass Filter Cutoff Frequency (at receiver)	0.75× Bit rate

Now, Using Optisystem 7.0, we constructed an FSO link, taking into account the previous mathematical model, which is supplied by the system specifications that are chosen from practical FSO links given in Table II and 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 MIMO for different weather conditions. It is clear that, in all cases the received signal power increases with the added number of MIMO. In other words, the combination of MIMO system enhances the received signal power. On the other hand, the noticeable improvement in the behavior of FSO starts at a two elements MIMO. It is 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. Fig.(4) shows 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 1MIMO and 4MIMO 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. The significance of a wider eye opening is 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 a 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 number of MIMO elements increases, 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 level) and APD receivers under various weather conditions is numerically calculated. Figs.(6-a, 6-b) display the output received signal power versus the operating wavelength for SISO and a MIMO system of four units, respectively. In this situation of operation, haze weather is studied with the same power level 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 system of four units achieves the best performance, whilst the SISO system presents the worst performance.

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 displayed in Fig.(7). The examination of this scene illustrates that one can get a large value of Q factor (64.7) by using four-unit MIMO system, which is higher by 56 than that obtained by SISO system, in case of clear air. It is evident that the number of elements of MIMO system plays an important part in its performance, where four-unit MIMO system gives Q factor higher by 10 and 23 than that obtained by three-unit MIMO and two-unit MIMO systems, respectively, given that the operating condition rests unchanged at the clear air. In the case of haze, on the other hand, a Q factor of 34 is realized by using four-unit MIMO system with an amelioration of 31 than that achieved by SISO system. These results demonstrate that the

MIMO system improves the link performance and the rate of enhancement increases as the number of MIMO elements increases.

Effect of Transmitted Power on FSO link Performance

Here, the effect of transmitted power on FSO link is examined. 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 1 to 4. Transmitted power values are taken from -4 to 38 dBm. The minimum values of transmitted power required for establishing communication channel for different weather conditions and varying number of MIMO elements are listed in Table III.

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

No of MIMO	Minimum required value of Transmitted Power (dBm)			
	Clear air	Haze	Light fog	Moderate fog
1MIMO	8.91	13.02	24.31	38.79
2 MIMO	-0.18	3.98	15.27	25.23
3 MIMO	-1.89	2.24	13.51	23.47
4 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 large value of Q factor and small value of BER with the same level of transmitted power in the case of four-unit MIMO system. 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, there is no communication channel 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 input transmitted power is required, whilst by increasing the number of MIMO elements, the transmitted power required 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 according to high visibility (the size distribution of the scattering particles equals 1.6). In this case, lower transmitted power is required. 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 when the transmitted power is of level 16 dBm occurs in the case of four-unit MIMO system.

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 increased to four. On the other hand, in the case of strong turbulence (moderate fog), there is no constructed communication channel for the SISO system, until the used transmitted power becomes larger than 36 dBm, as Fig.(11) displays. However, by increasing the size of MIMO elements to four, one can get a Q factor of 72 with the same level of transmitted power.

V. Conclusions

The aim of this paper is to analyze an optical FSO MIMO link design methodologies. Different weather conditions including the difficult ones are treated in the operation of a communication system employing NRZ line coding and APD photo-detector in its receiver. One can enhance the performance of FSO network by introducing the MIMO technique to it. Power loss due to different weather conditions is numerically solved through a MATLAB program and the results are graphically displayed. The performance of FSO system enhances as the size of its MIMO technique increases where the received power is increased.

In this way, doubling the number of MIMO can effectively increase the received power. For four-unit MIMO, the received power improves by 12 dBm, from -39.826 dBm to -27.785 dBm, in case of light fog. It was found that, higher value of Q factor of 64, which is greater by 56 than that obtained for SISO system, is achieved by using four-unit MIMO system in the case of clear air. Additionally, a Q factor of 34 is realized for the underlined MIMO system while its corresponding value is 3 for SISO technique in case of haze.

It is observed that, for a SISO link, communication is not possible in the case of light fog. But, when two-unit 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 very high performance is achieved with four-unit MIMO FSO link.

It is found that the minimum transmitted power required in the case of clear air is 8.91 dBm and this value is reduced to -3.17 dBm by using four-unit MIMO, the minimum transmitted power required in the case of moderate fog is 38.79 dBm and this value can be reduced to 22.23 dBm by using four-unit MIMO system. Utilizing the MIMO in FSO link enhances its performance and a higher combination of MIMO elements gives further improvement.

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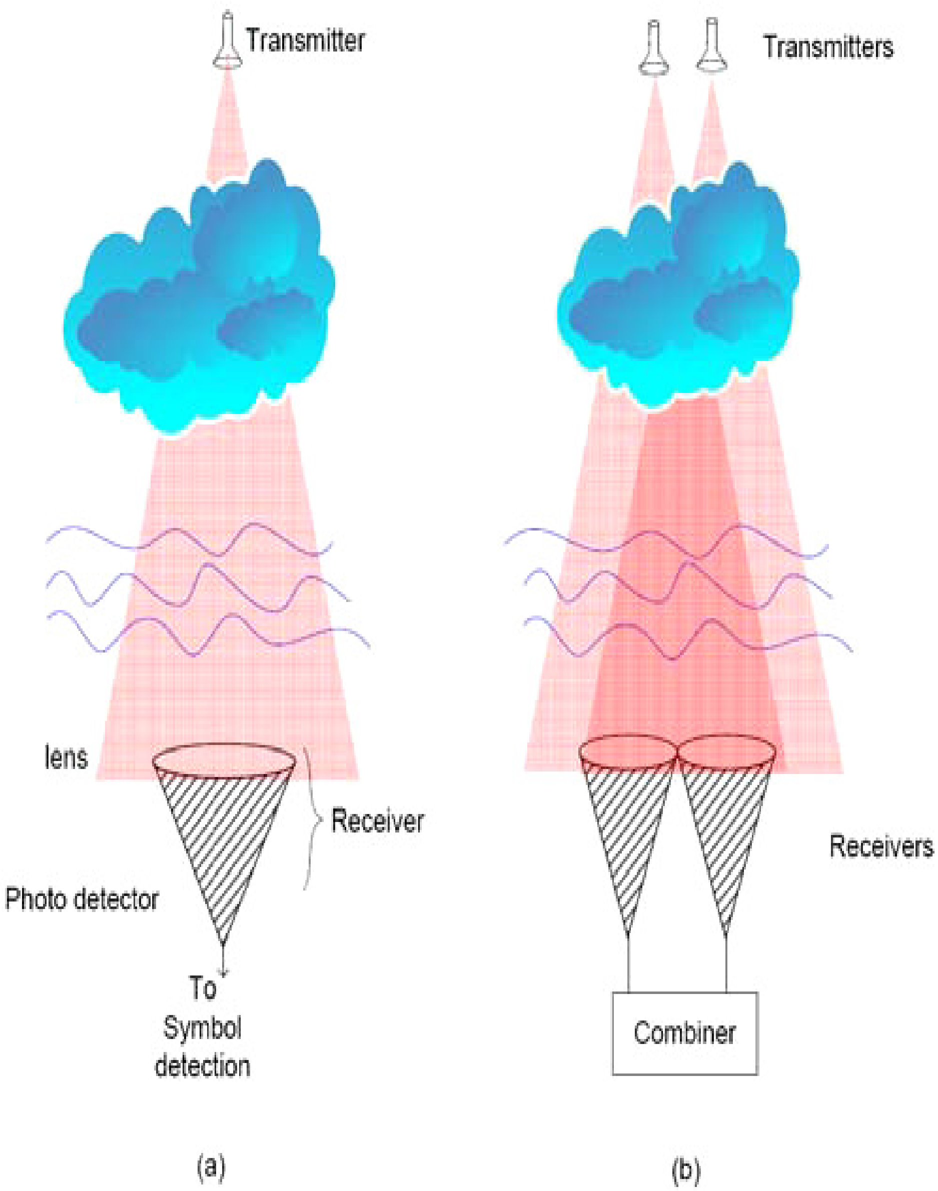


Fig. (1) a- SISO and b- 2 MIMO communications systems in difficult atmospheric conditions

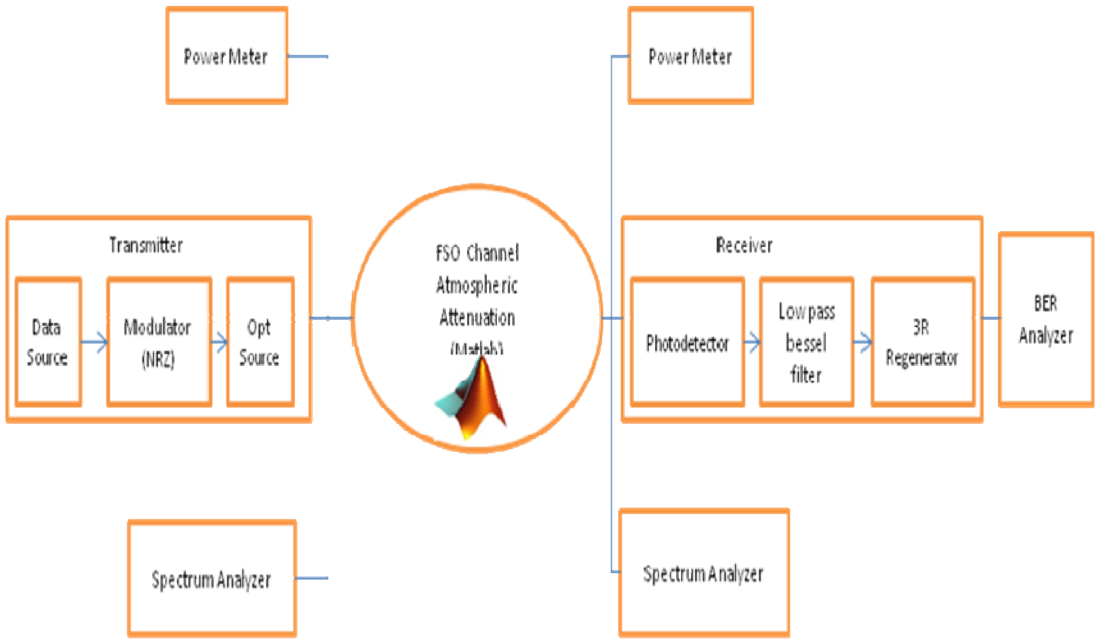


Fig.(2) SISO FSO system design model.

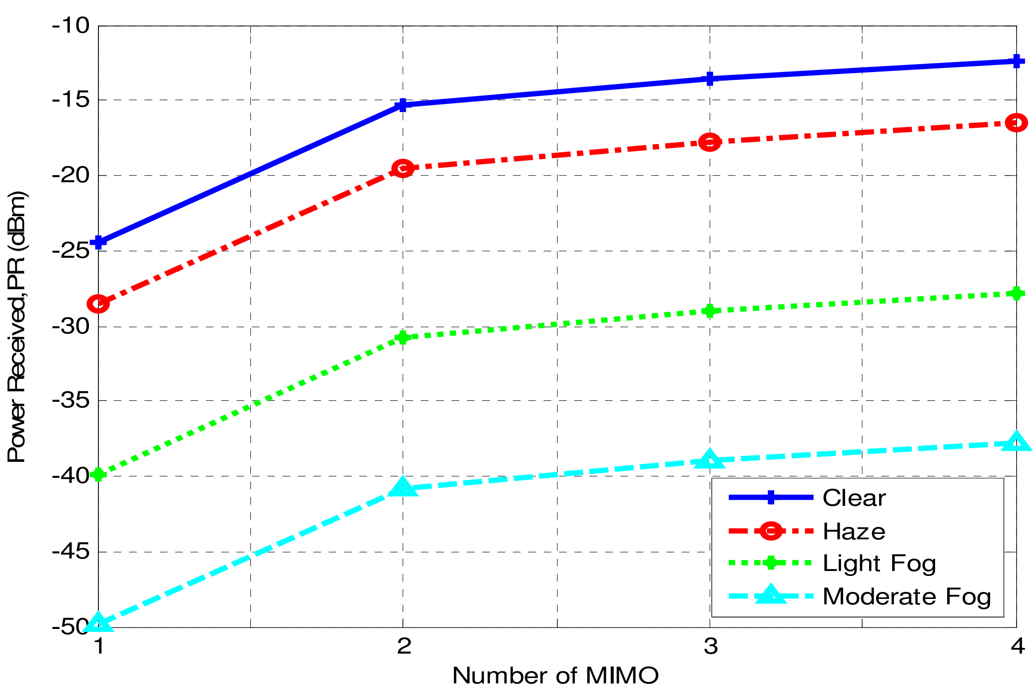
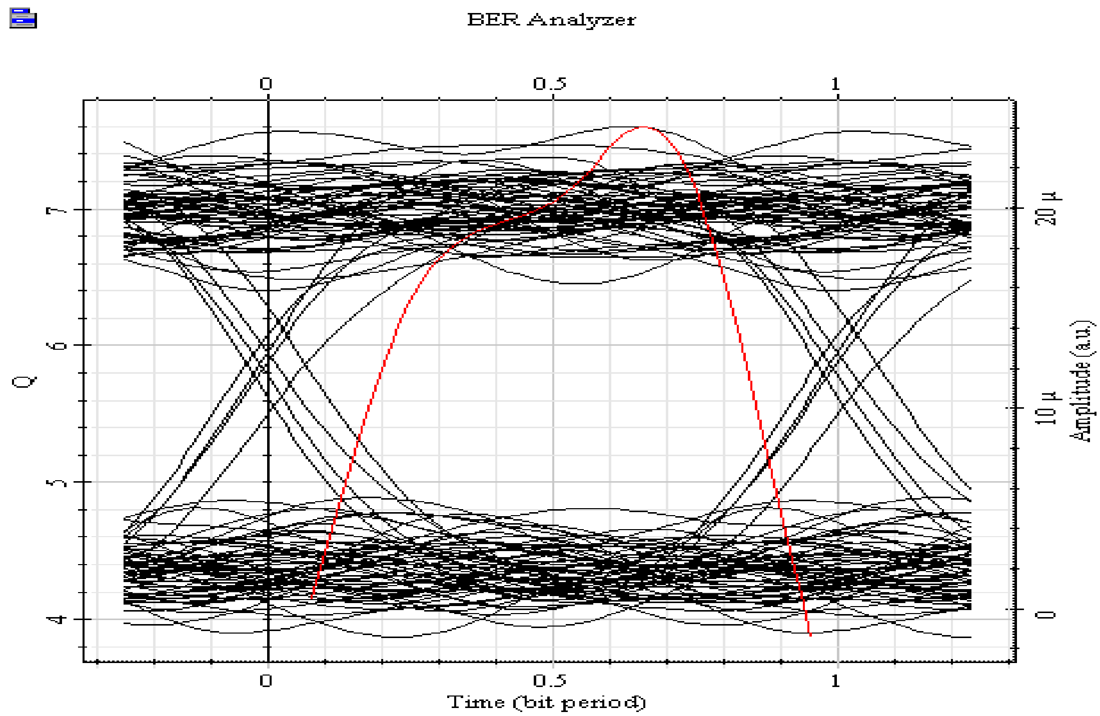
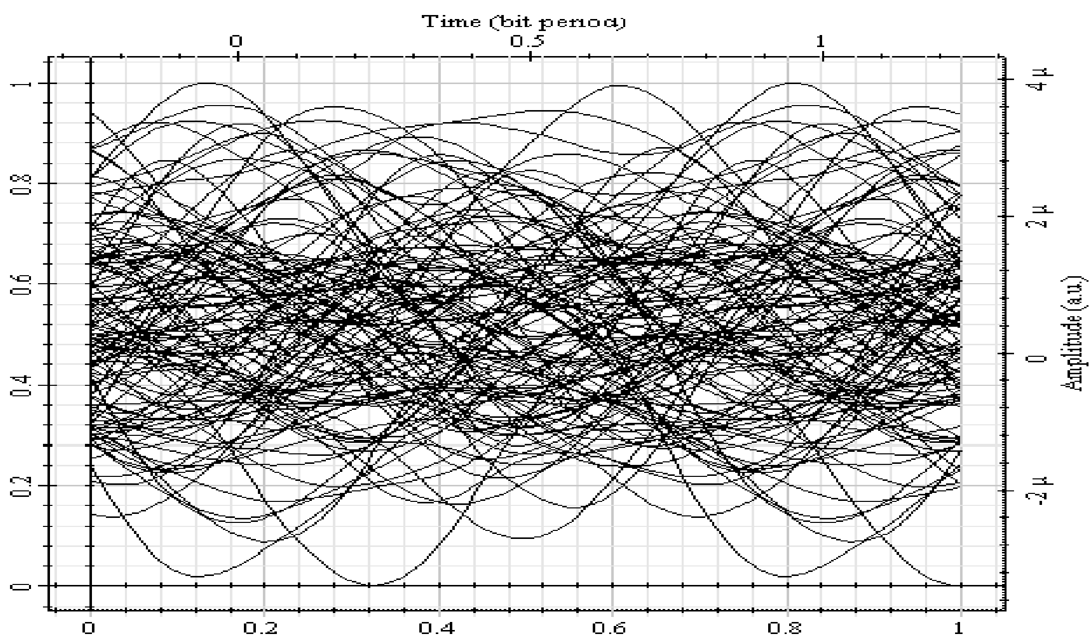


Fig.(3) Received power vs. number of MIMO in different weather conditions.

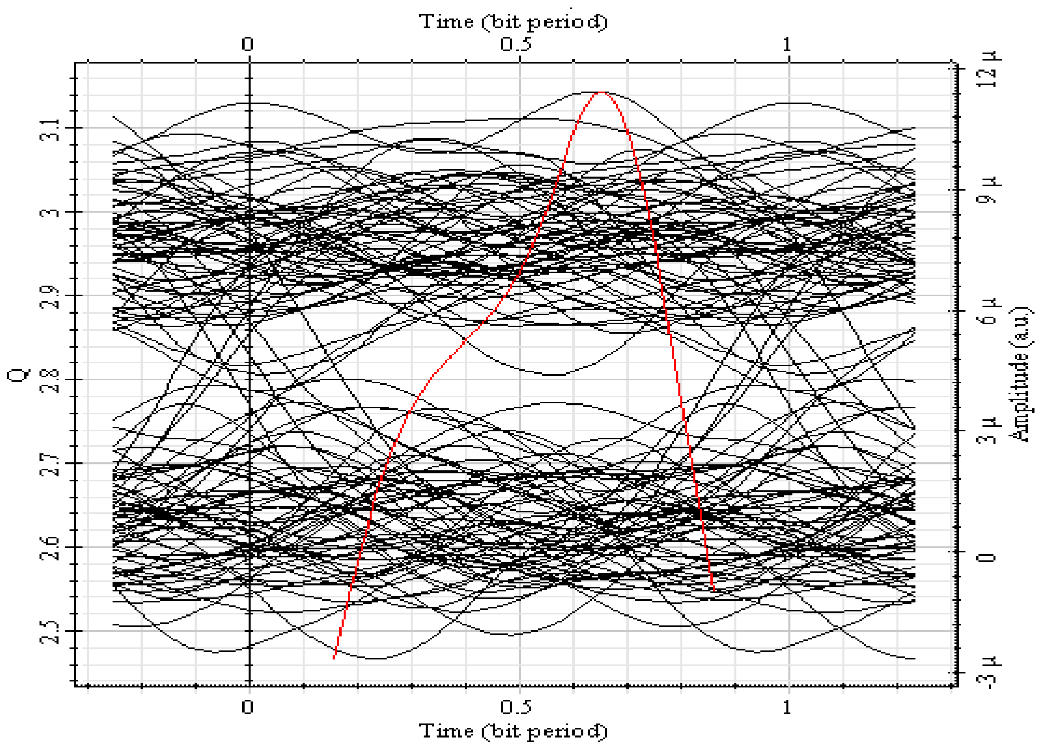


(a)

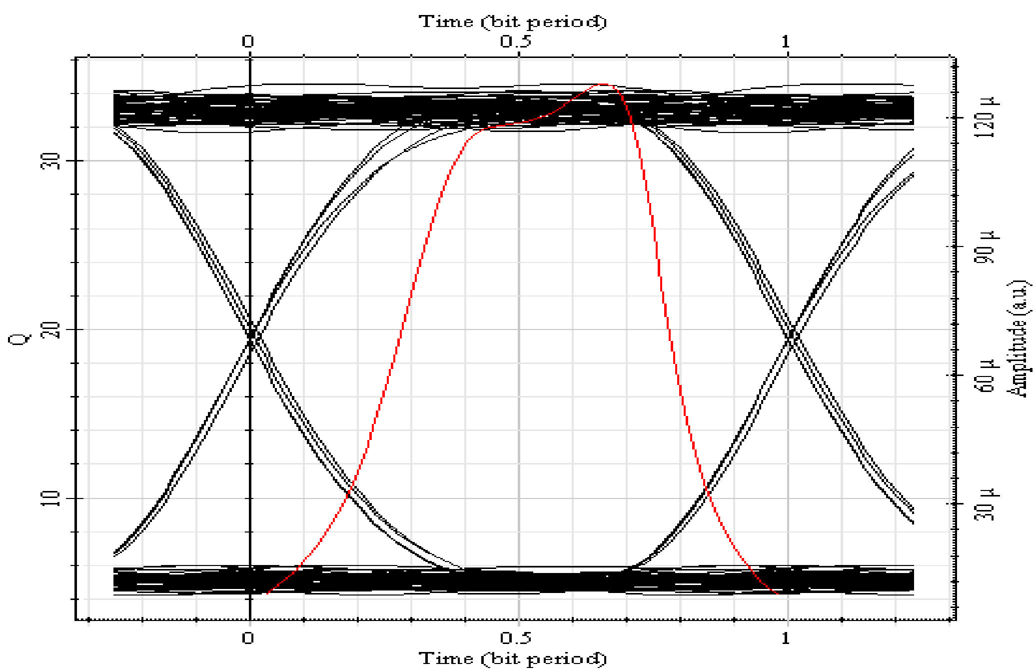


(b)

Fig.(4) Eye diagram for SISO with different weather condition a- Clear air b- Light fog

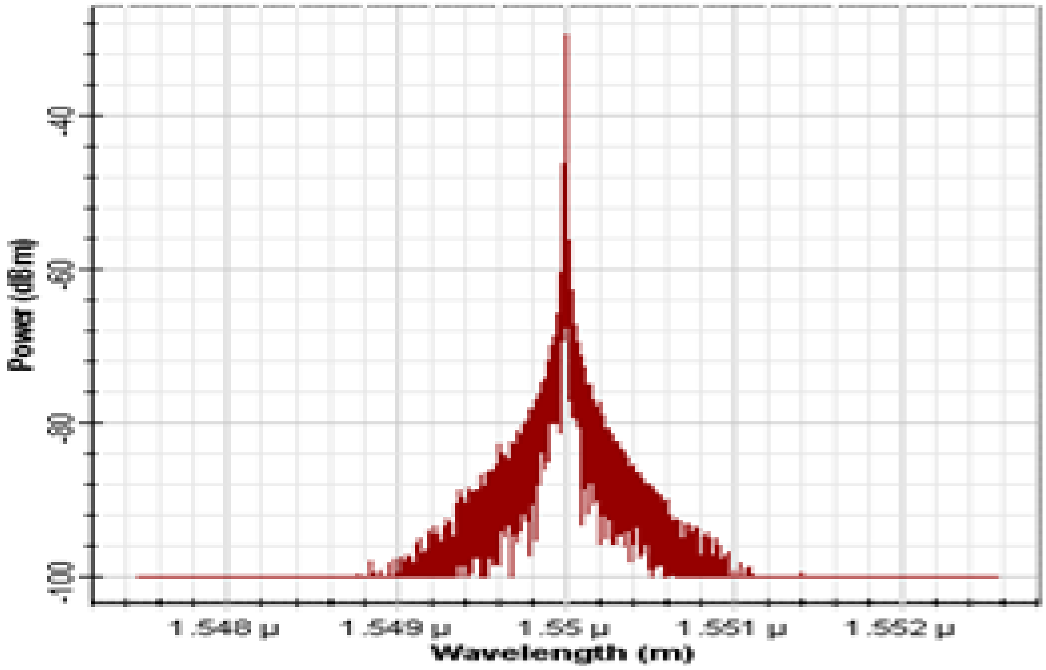


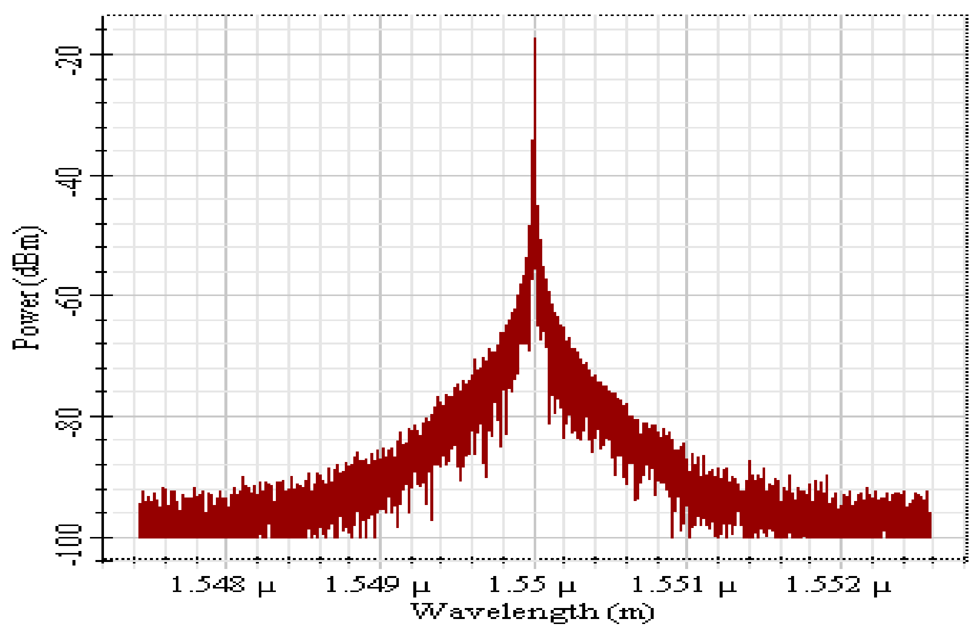
(a)



(b)

Fig. (5) Eye diagram for haze weather condition (a) 1MIMO (b) 4 MIMO





(b)

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

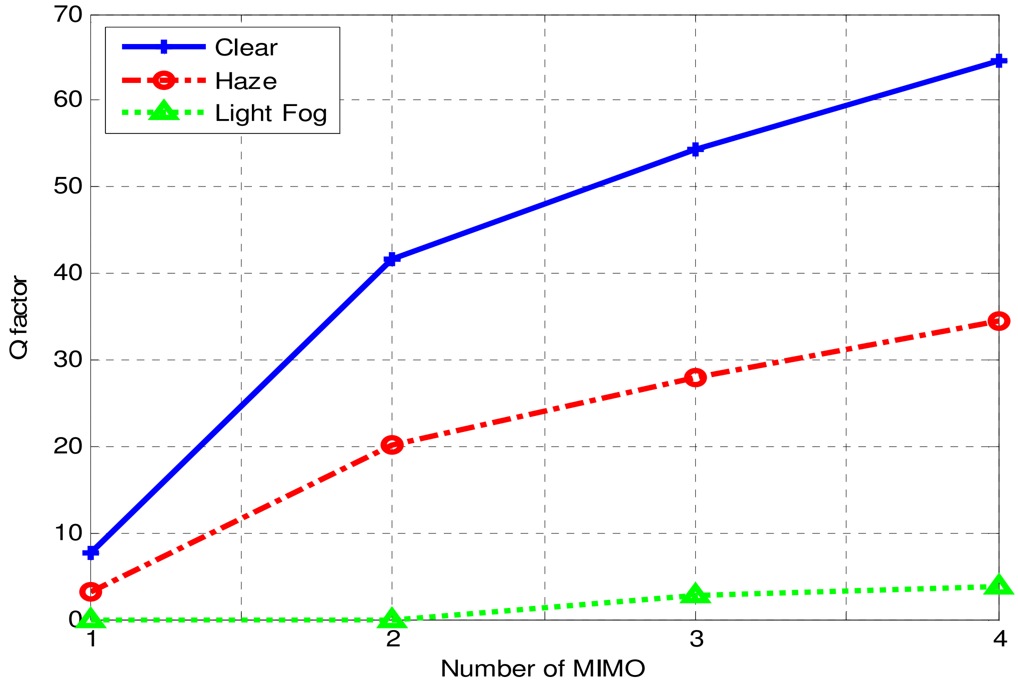


Fig.(7) Q factor vs. number of MIMO at 10 dBm transmitted power.

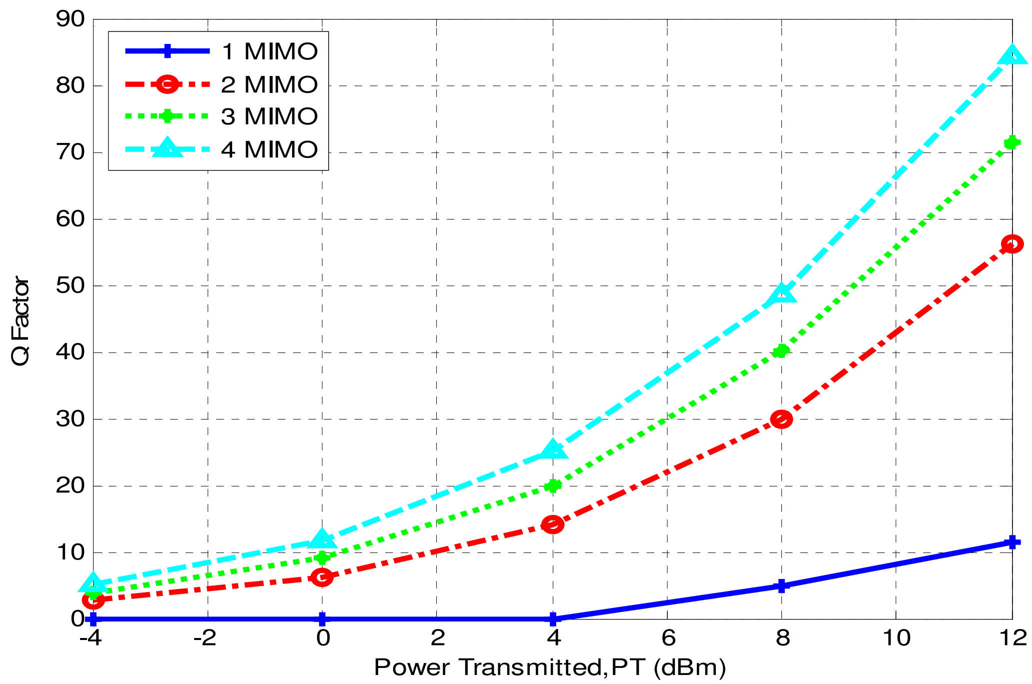


Fig.(8) Q factor vs. transmitted power for clear air weather condition.

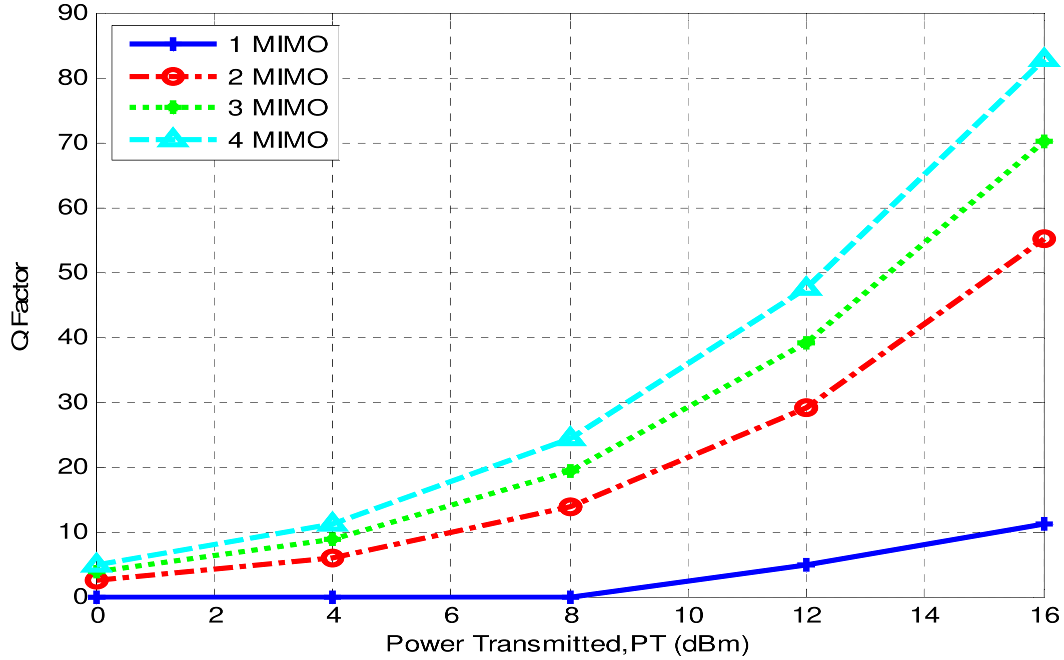


Fig.(9) Q factor vs. transmitted power for haze weather condition.

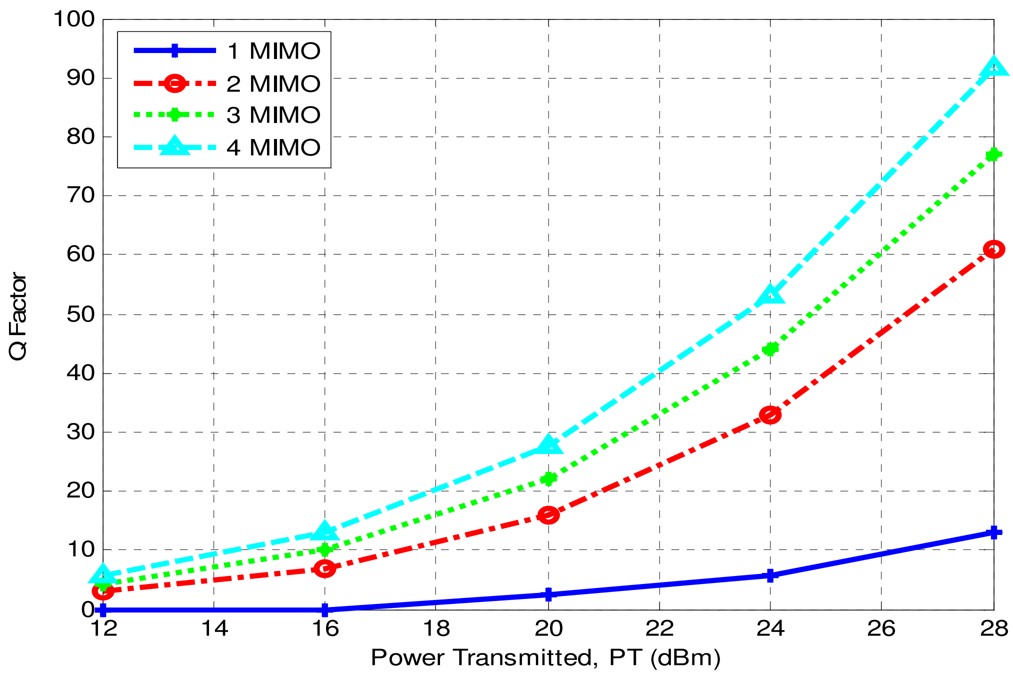


Fig.(10) Q factor vs. transmitted power for light fog weather condition.

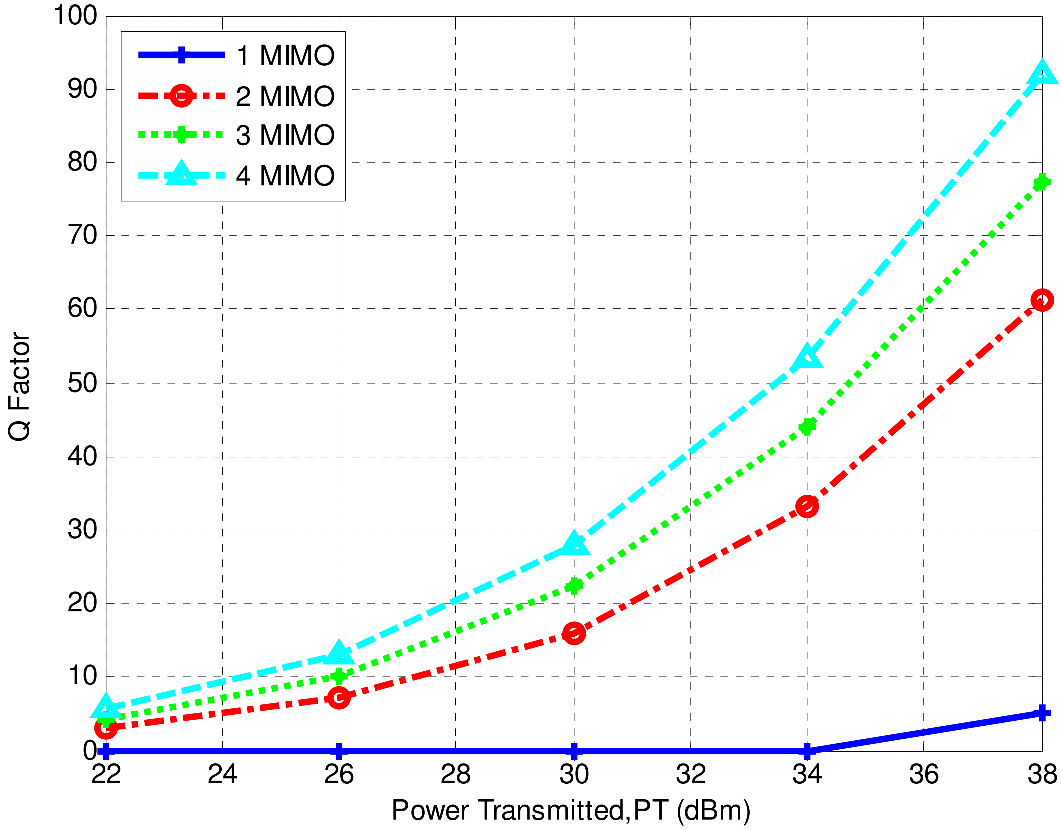


Fig.(11) Q factor vs. transmitted power for moderate fog weather condition.