Feasibility Evaluation of MIMO Based FSO Links

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Abstract —Free space optical communication (FSO) has evolved as a substitute to radio frequency communication over the few years. It gives a promising solution to the high-speed point-to-point communication. However, atmospheric absorption, scattering and turbulence cause considerable degradation of the wireless optical communication, which degrades system performance. Another major factor which concerns the system performance is the attenuation of signals due to the aforementioned atmospheric reasons. There are different factors in which the atmospheric turbulence conditions are observed using Gamma Gamma Model. Simulations have been carried out in the OptiSystem 14.0 software to study the impact of different weather conditions (clear, haze and fog) on the performance of the channel. Simulation results show that by implementing Multiple Input Multiple Output (MIMO) techniques for FSO systems, it is possible to reduce the BER for different range and achieve the accurate transmitted data at the receiver side. The performance improvements vis-a-vis, received power levels, bit error rate (BER), Q-factor and link distance range have been demonstrated in the presence of atmospheric turbulence conditions like haze, fog, clear sky etc.

Index Terms—Bit Error Rate, FSO, MIMO, OptiSystem 14.0, Q-Factor, SISO.

I. Introduction

FSO communication is also known as optical wireless communication (OWC). These days many technologies are available such as coaxial cables, copper wires and optical fibers. These advances have a few constraints, i.e., congested spectrum and range, low information rate, security issues, costly authorization and high cost of establishment and installment [1]. FSO is a technique that transmits the data via the free space optical channel. Transmission of visible and infrared (IR) beams through the atmosphere is inferred from this channel. The motive of FSO is to eliminate the time, effort and cost of installing fiber optic cable, and it also retain the benefit of high data rates (up to 1 GB/s or beyond) for transmission of data, images, voice and video [1]. In this project, we have noticed the bit error rates and eye diagrams for different atmospheric conditions like haze, clear sky and fog. The main challenges we faced while designing this FSO model is to get optimal values which was achieved by using different models like SISO, MIMO and observe the results. Here we have used atmospheric turbulence model to analyze different conditions which is mentioned in this paper. For improvement in the system performance, scintillation must be mitigated. A reduction in the spatial diversity and spatial coherence of the transmitted beam can be accomplished by employing multiple receivers and multiple transmitted beams. Lower scintillation at the cost of lower power at the receiver and a bigger divergence angle and is seen by the partially coherent beams with diminished spatial coherence [4]. The use of multiple light sources, allows the transmitter to produce a number of spatially separated channels which can be used to improve to improve spectral efficiency when coupled with multiple receivers or channel characteristics [1]. This spatial diversity makes the receiver to be capable of spatially separating multi-path components for the channel reliability to be enhanced [2]. Therefore, in order to handle the transmission under strong and weak atmospheric turbulence, the concept of MIMO and SISO must be constructed.

In this paper, we analyze Multiple Input Multiple Output (MIMO) and Single Input Single Output (SISO) FSO communication system with Non Return to Zero (NRZ) and Avalanche Photodiode (APD) on the receiver side which is then connected to the generator to analyze the BER performance for different atmospheric turbulences. The objective is to design MIMO and SISO FSO link and simulate its performance. On increasing the number of transmitters and receivers in the MIMO system, the efficiency can be increased, which lowers the BER value. The remaining part of the paper is organized as follows. The mathematical model is presented in Section II. The simulation and the observations are made in Section III. Section IV includes discussion along with concluded remarks.

II. Theoritcal Model and Problem Formulation

A. Free Space Optical (FSO) System

FSO system consists of three main functional elements: transmitter-receiver and atmospheric channel as shown in the figure. At the transmitter, the data signal is modulated by modulator with the help of intensity modulation and the electrical signal is converted into an optical signal using optical sources like LED or LASER. For data transmission, light sources are used [2]. It propagates via free space to the receiver and transmits data at high data rates [3]. For optical communication, light sources adopted must have the appropriate wavelength, line- width, high modulation bandwidth and numerical aperture. Communication medium or channel is either free space or air or vacuum. Data transmits through this medium from the transmitter to the receiver. There are some

Manuscript received May 25, 2018; revised February 21, 2019.
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doi:10.12720/jcm.14.3.187-193

atmospheric parameters that affect the transmission [2]. These include fog, rain, dust, smoke, physical obstacles etc. At the receiver side, the optical detector is used to detect the received data. The detectors are PIN photo detector or APD photodetector [4]. The photodetector is a square-law optoelectronics transducer that creates an electrical signal which corresponds to the square of the optical field impinging on its surface. Consequently, the signal generated by photodetector is constantly corresponding to the (received) optical power. Since the optical signal is usually frail, having travelled via the communication channel, the photodetector must, thus, meet stringent execution necessities, for example, high sensitivity within its operational scope of wavelengths, reduced noise level and a sufficient transfer speed to oblige the coveted information rate. The optical signal is changed back to the electrical signal by the receiver an coordinated to the amplifier. Finally, an optical filter is used to ensure to prevent the passage of any wavelength apart from the signal [5].

B. Atmospheric Turbulence Model

Absorption of solar radiations closer to the surface of the earth results in less dense and warmer air, due to which the air temperature gets non-uniformly fluctuated [5]. Inhomogeneities caused as a result of turbulence can be visualized as discrete cells or eddies of varying temperature acting like refractive prisms of varied sizes. Atmospheric turbulence categorized in regimes relying upon magnitude of index of refraction variation and inhomogeneities. These regimes are basically functions of distances traversed by the optical radiation through the atmosphere and classified into four stages: weak, moderate, strong and saturation. This turbulence leads to signal fading and degradation in the performance of the system [6].

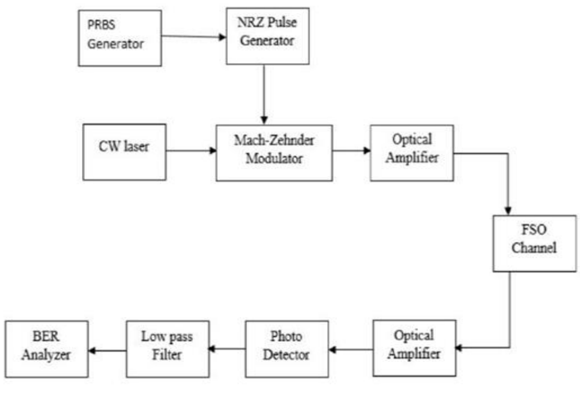


Fig. 1. FSO block diagram

The statistical channel model is given by:

$$y = sx + n \quad (1)$$

$$= Ix + n \quad (2)$$

where, y = the signal at the receiver, s = I is the instantaneous intensity gain,= effective photocurrent conversion ratio of the receiver, I = normalized irradiance, x = modulated signal, n = AWGN with zero mean and variance $N_0/2$.

C. Gamma- Gamma Turbulence Model

It is known that Gamma-Gamma Model has weak to strong turbulence condition such that PDF of its intensity I is the product. of two gamma random variables which indicates fluctuations from large and small turbulence [14]. The two random variables are indicated as X and Y. The received Intensity I is; I = XY. The PDF of I is given by,

$$p(I) = 2\frac{(\alpha\beta)^{\wedge}(\frac{\alpha+\beta}{2})}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta/2)-1} k_{\alpha-\beta}(\sqrt{\alpha\beta I}),\ I > 0 \quad (3)$$

where,

α = no. of large eddies, β = no. of small eddies, I= Irradiance, $\Gamma(.)$ = Gamma Function, $K(\alpha, \beta)$ = Bessel function of Second Order, α and β given by equation,

$$\alpha = [\exp\left(\frac{0.49\,\sigma i^2}{(1+1.11\sigma i^{\frac{12}{5}})^{\wedge}(\frac{7}{6})}\right) - 1]^{-1} \quad (4)$$

$$\beta = [\exp\left(\frac{0.51\,\sigma i^2}{(1+0.69\sigma i^{\frac{12}{5}})^{\wedge}(\frac{5}{6})}\right) - 1]^{-1} \quad (5)$$

Scintillation Index (SI)

The Scintillation Index (SI) which is use to describe the quantity of turbulence for Gamma-Gamma Channel Model.

$$\sigma_N^2 = [\exp\left(\frac{0.49\,\sigma i^2}{(1+1.11\sigma i^{\frac{12}{5}})^{\wedge}(\frac{7}{6})} + \frac{0.49\,\sigma i^2}{(1+1.11\sigma i^{\frac{12}{5}})^{\wedge}(\frac{7}{6})}\right) - 1] \quad (6)$$

D. MIMO Wireless Channel

MIMO technology is considered as the most widely used technology in wireless communication system because it pro- vides increment in data throughput along with link range with- out increase in bandwidth or transmitted power [8]. It transmits the required power over the antennas to achieve an array gain that enhances the spectral efficiency. Link reliability is improved and fading effect is also reduced simultaneously. Owing to these merits of MIMO technology, it becomes a significant part of the present day wireless systems [9]. Mathematical expression of MIMO channel can be written as:

$$y = Hx + n \quad (7)$$

where y & x represent the received and transmitted vectors, H and n denote the channel matrix and the noise vector respectively.

E. System Design Model

In the presence of atmospheric disturbances, FSO channel is designed in OptiSystem. In order to improve the link performance of FSO, MIMO channel is used to 4 units. The range of wavelength for FSO extends from 850 nm to 1550 nm [7]. The transmitted wavelength is selected to be 1550 nm due to the attenuation caused by Rayleigh scattering which is inversely proportional to the wavelength. Therefore, the longest wavelength of 1550 nm is opted to obtain the lowest scattering attenuation .It is assumed that there are no particles in the path of light but particles of fog and haze are observed [10]. The total transmitted power is considered to be the same for the MIMO and the SISO systems to tally their performances in a simplified manner. The MIMO and SISO constructions are modeled with the basic FSO components as Fig. 2 depict. These components are:

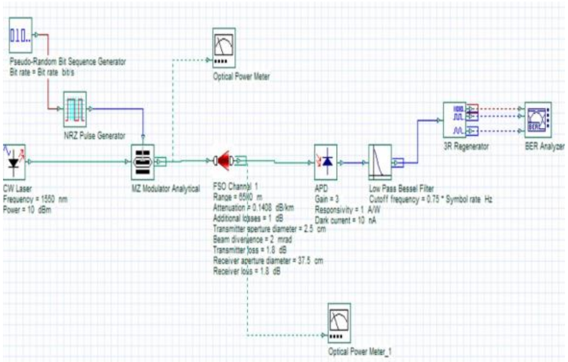


Fig. 2. SISO system - block diagram

1) Transmitter

It has four components. The first is the pseudo-random bit sequence generator (PRBS). This generator represents the information or data that is needed for transmission. The output signal which is generated after PRBS is passed to a NRZ pulse generator which generates the coded signals. The fall and rise edges are of 0.05 bit NRZ generated pulse [12]. The optical modulator modifies the intensity of the output light signal. The optical source is assumed to be a continuous wave (CW) laser, whose power level is set at 10 dBm. In this model, we use SISO, 2x2 MIMO and 4x4 MIMO.

2) Optical wireless channel

In OptiSystem software, the FSO channel is ranged between an optical transmitter with optical receiver with 8 cm optical antenna and .2.5 cm optical antenna .The assumptions for transmitter and receiver gain is 0 db. In at the receiving and transmitting antennas are assumed to be ideal with no pointing errors with the optical efficiency of 100 percent [11].

3) Receiver

The receiver consists of a photodiode, a low pass filter, visualizer and a generator. The photo-detector which has been 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 for long distances as it helps in providing amplification to weak signals [12]. The received signal is then pass through a low pass Bessel filter of cutoff frequency of 75 percent of the bit rate to make its bandwidth limited. The 3R regenerator is used to regenerate modulated electrical signal similar to that of produced by the transmitter and an electrical signal of the same original bit sequence for the purpose of BER evaluation [8]. The eye diagram analyzer is connected to the output of the generator which gives the, minimum BER, eye height, maximum Q-factor and threshold [12].

F. FSO Systems

1) SISO FSO systems

The elements that form an FSO sys- tem are: transmitter, FSO channel and receiver. The transmitter elements include: laser source (650nm, 850nm and 1550nm), NRZ (Non-Return to Zero) pulse generator, PRBS (Pseudo Random Bit Sequence) generator and MZM (Mach -Zehnder Modulator). The optical signals from the FSO channel are received by the APD photodetector [13]. The simulation uses two visualizers elements, that are, the optical power meter used to measure the power received (in dB and Watts), and BER analyzer that is used to calculate the BER value, Q-factor and display the eye diagram.

2) MIMO FSO systems

In FSO, optimal designing can be done by two different MIMO systems. By using two transmitters and two receivers FSO system to increase the efficiency of communication [16]. Use of multiple transmitters and receivers increases the efficiency of communication. Fig. 3 and Fig. 4 depicts the type of MIMO systems depending on the number of transmitters and receivers. If the number of transceivers is 2 then it is known as 2x2 MIMO and if the number of transceivers are 4, it is known as 4x4 MIMO.

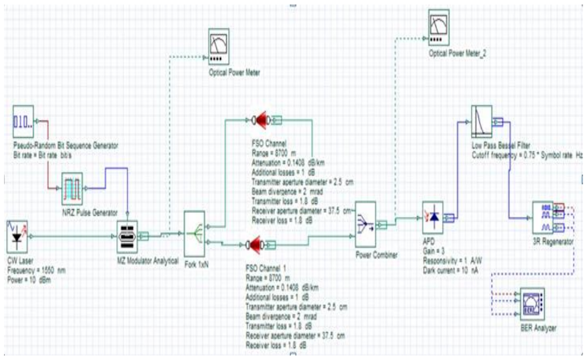


Fig. 3. 2X2 MIMO

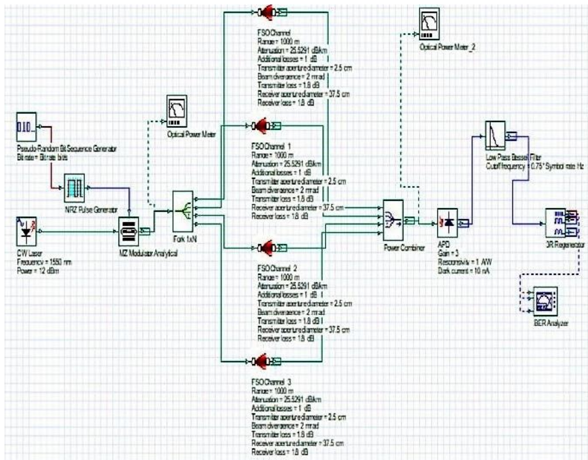


Fig. 4. 4X4 MIMO

III. SIMULATION RESULTS AND DISCUSSION

Based on the above FSO model, analysis is done or different types of models that is on increasing the no. of transmitters and receivers. Performance simulation of the communication link at propagation distance "L" of 1km with NRZ line code and 1550 nm wavelength and APD receiver for various atmospheric conditions is done. Optical spectrum analyzer, BER analyzer and optical power meter are included in the model to determine the system BER and the received and transmitted signal power levels. The parameters here are taken such that the the maximum range can be achieved for a constant bit rate of 1 Gbps and the maximum bit rate can be achieved for a constant range of 1 km. The changes were then implemented and compared to check their efficiency. Based on the results, a system was chosen that provided the maximum bit rate and the maximum range [14].

TABLE I: PARAMETER SELECTION

PARAMETER	VALUE
Data Rate	2.5 Gbps
Wavelength	1550 nm
Sequence length	128
Sample per bit	64
Number of samples	8192
Extinction Ratio	30 dB
Transmitter Aperture	2.5 cm
Transmitter Loss	1.8 dB
Receiver Aperture	37.5 cm
Receiver Loss	1.8 dB
Additional Loss	1 dB
Geometric Loss	YES
Beam Divergence	2 mrad
Cut-off Frequency	0.75 X Data Rate
APD Gain	3 dB
APD Responsivity	1 A/W
APD Dark Current	10 nA

Table I represents the values of the parameters which will be used in simulation of FSO link with the help of Optisystem. In accordance to the mathematical model and by using MATLAB, a power loss generation corresponding to different weather conditions is accomplished and the numerical values are outlined in Table II [1]. 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 is noticed. 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 II demonstrates [1]. Their effect is related the visibility "V". In addition, they affect the signal power levels due to the dependence of the FSO on the operating wavelength.

Table III shows the result when the constant bit rate of 1 Gbps is given and the range according to different systems is analyzed and noted. Similarly, in Table IV, vice-versa is done that is maximum BER is noted for the constant range of 1 km.

TABLE II: ATTENUATION FOR DIFFERENT WEATHER CONDITIONS

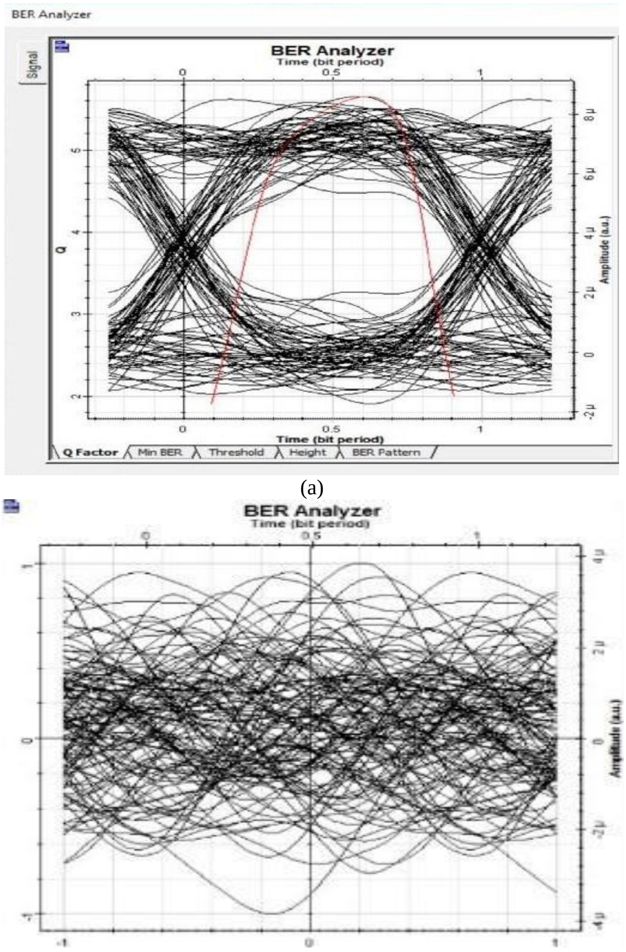
Weather Conditions	Attenuation (dB/km)
Clear air	0.1408
Haze	4.2872
Light Fog	15.5633
Moderate Fog	25.5291

TABLE III: CONSTANT BIT RATE (1 GBPS) MAXIMUM RANGE ACHIEVED

FSO System	Clear Sky	Haze	Fog
SISO	6450 m	2340 m	1046 m
4x4 MIMO	12000 m	3150 m	1330 m

TABLE IV: CONSTANT RANGE (1 KM) MAXIMUM BIT RATE SUPPORTED (IN BPS)

FSO System	Clear Sky	Haze	Fog
SISO	5.3e9	5.35e9	4.5e9
4x4 MIMO	5.2e9	5e9	5.25e9



(a)

(b)

Fig. 5. (a) Eye Diagram and BER for clear sky in SISO systems and (b) Eye Diagram and BER for difficult weather conditions in SISO systems.

The behavior of FSO Communication system is affected by different MIMO algorithms. Fig. 5 depicts the eye diagram for different situations of weather conditions. It is observed that the eye opens wider in case of clear air, where the data errors are small, as indicated in Fig. 5(a).

The narrower eye opening is observed in the case of bad weather conditions where the worst system performance is obtained as indicated in Fig. 5(b). In the case of strong weather conditions, the eye opening becomes smaller when the attenuation factor decreases.

In addition, the size of eye opening is very small for difficult weather conditions SISO system, where there is no power is split. Fig. 6 illustrates the same thing as that indicated in Fig. 5 for MIMO combinations in the case of haze weather condition. It is observed that as we increase the number of transmitters and receivers, the size of eye opening increases which reduces the no. of jitters which makes the performance better. For SISO system, the established communication link is bad and the size of the eye opening remains small as no power is split. On the other hand, as the size of MIMO increases the established communication link becomes better which enhances the performance.

Performance evaluation of link at 1550 nm with NRZ line codes as it achieves a better performance than RZ by providing higher level of received signal and better BER performance. The loss factor of atmospheric attenuation increases as the atmospheric conditions get worse due to which the received power also changes.

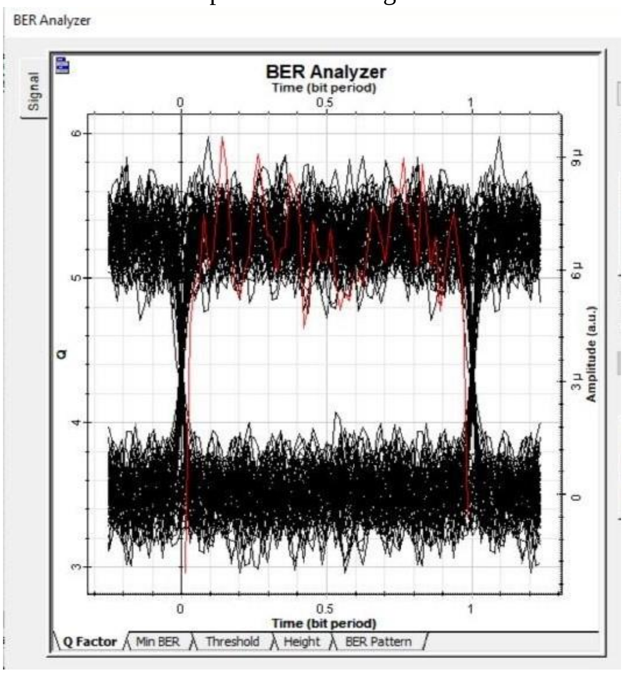
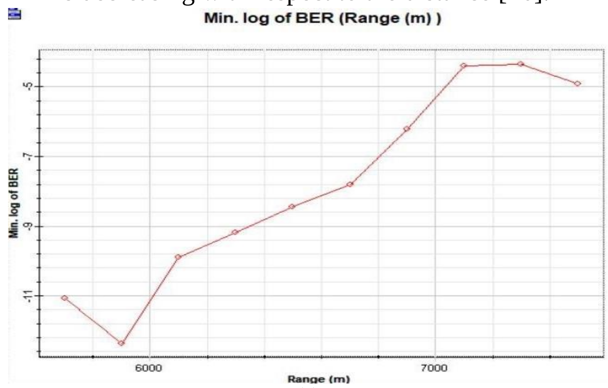
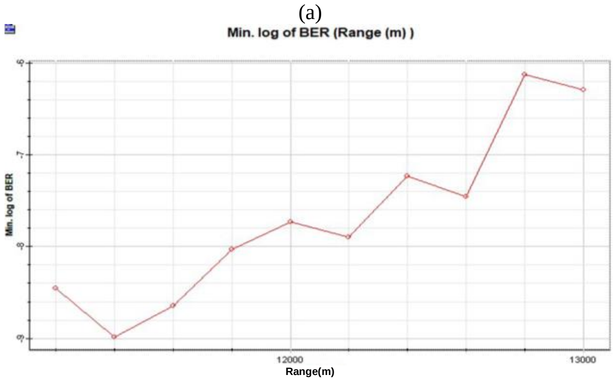


Fig. 6. Eye diagram and BER in 4x4 MIMO systems

From the above eye diagram, it is easy to conclude the minimum BER with the values of Q-factor. In order to achieve an error-free communication BER of value lower than 10^{-9} is taken. The communication link breaks beyond this BER value. The simulation results show the results of BER vs Distance for the Gamma-Gamma turbulence model for SISO and MIMO FSO system. The wavelength of the FSO system is 1550nm. Fig. 7 illustrates the comparison between SISO FSO and MIMO FSO in term of BER. Fig. 7 shows the simulation results of Gamma-Gamma turbulence channel model. The results show that as number of transmitter and receiver are increasing the BER is decreasing with respect to the distance [16].

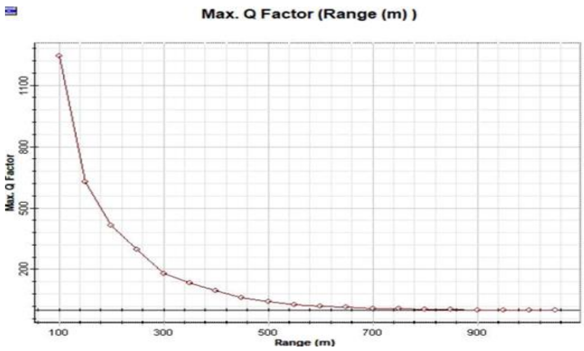


(a)



(b)

Fig. 7 (a) Minimum log of BER vs Range in SISO system and (b) Minimum log of BER vs Range in MIMO system.



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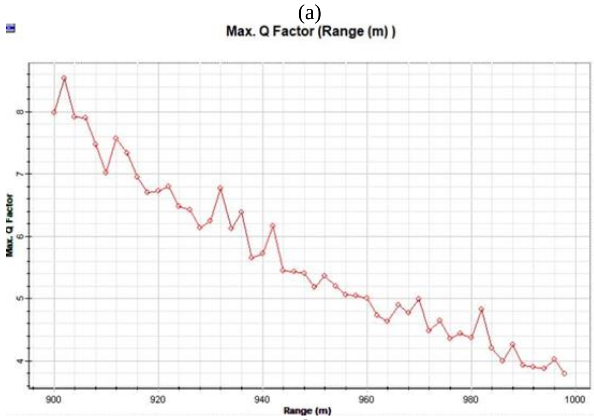
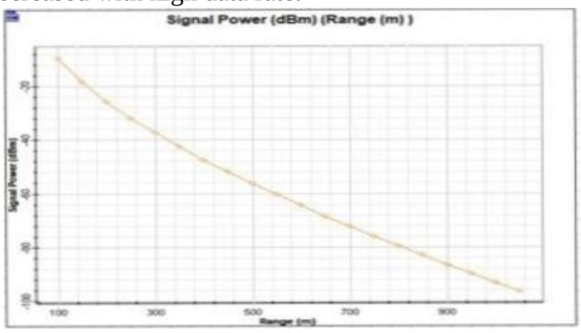


(b)

Fig. 8 (a) Maximum Q-Factor vs range (SISO system) and (b) Maximum Q-Factor vs range (MIMO Systems)

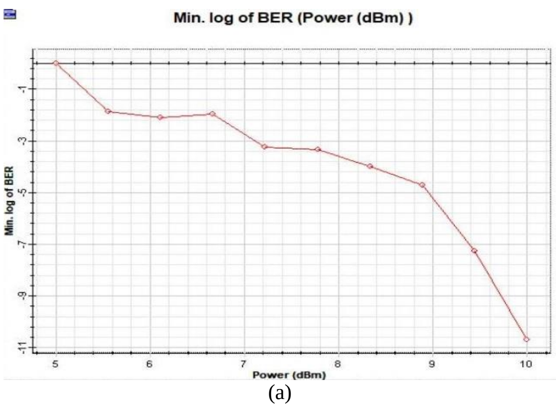
The simulation is observed for various parameters such as the maximum Q factor. In the case of moderate fog and haze weather condition, no communication channel is established as the transmitted power level is of 10dBm. Therefore, in order to set up the communication transmitted power should be increased which can be achieved by MIMO technique. However, one gets lower values of BER and larger values of Q-factor for the same level of transmitted power, when 4x4 MIMO technique is adopted. But in the case of adverse atmospheric conditions no communication link is setup until the transmitted power attains certain limit. By simulation, minimum value of transmitted power required in each system is calculated. In case of good weather conditions, the transmitted power increases as the Q-factor increases. Fig. 8 represent the performance of SISO and MIMO system at strong weather conditions by measuring maximum link range could this system reached. It is observed that as the range increases the value of Q-factor decreases for the data rate of 2.5Gbps. As in the Table IV data rates for constant 1km range is calculated for different FSO systems and is observed that Q-factor is decreased with high data rate.



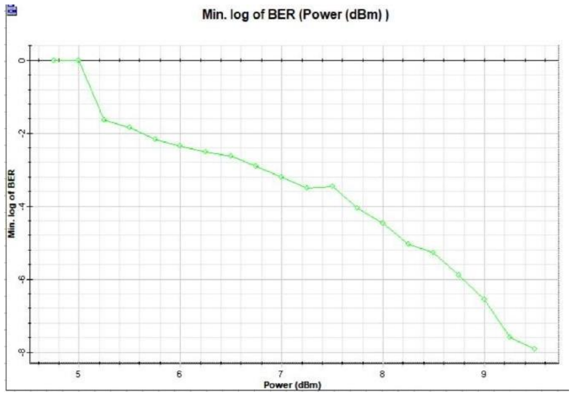
(a)

(b)

Fig. 9. (a) Maximum signal power vs range (SISO system) and (b) Maximum signal power vs range (MIMO system)



(a)



(b)

Fig. 10 (a) Minimum log of BER vs Power (SISO systems) and (b) Minimum log of BER vs Power (MIMO systems)

In Fig. 9 comparison is done between signal power and range. As the range increases, the value of signal power decreases. The graph is also plotted between BER vs power for both SISO and MIMO systems as shown in the Fig. 10.

IV. Conclusions

The obtained results demonstrate that the procedure of MIMO enhancing the performance of FSO system and the rate of enhancement increases as the size of its elements augments where the received power is ameliorated [9]. The examination of the given results shows that doubling the number of MIMO elements can effectively increase the received power. Finally, it is concluded that, for a SISO link, communication is not possible in the case of heavy fog. But, when a 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 with a 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.

V. Future Work

We have analyzed Multiple Input Multiple Output (MIMO) and Single Input Single Output (SISO) FSO communication system with Non Return To Zero (NRZ) and Avalanche Photodiode (APD) to analyze the BER performance for different atmospheric turbulences. The comparative analysis of BER can be done for channel models with varied receiving aperture area and increasing the distance between transmitter and receiver. Performance comparison for high data rates can be done for different type of FSO Systems. MIMO analysis can also be done for heterogeneous networks. In order to select optimal choice of coding rates, we can study the M-QPPM MIMO capacity.

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