IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 3 Issue 8, August 2016
ISSN (Online) 2348 – 7968 | Impact Factor (2015) - 4.332
www.ijiset.com

Characterization Study and Simulation of MIMO Free Space Optical Communication under Different Atmospheric Channel

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Abstract

Free Space Optical (FSO) communication is a wireless optical data transmission technology from one place to another using laser in the near Infrared IR band (750nm - 1600nm). The main advantages of FSO systems are: high security, fast installation, license free spectrum and high capacity. The atmospheric conditions like fog, haze, rain, snow effects on the performance of FSO system. To mitigating the adverse effects on FSO systems with turbulent atmospheric channel multiple laser sources and multiple optical detectors MIMO technique have been used. In this paper, simulate and analyze the performance of MIMO configurations under clear, haze and fog conditions and compare the results with single input/single output SISO technique, MIMO take benefit from the spatial diversity and receive multiple independent copies of the same signal at the receiver, hence resulting increased signal to noise ratio and BER. A commercial optical system simulation software (OptiSystem7.0) from Optiwave was used.

Keywords: *FSO, SISO, MIMO, OptiSystem 7.0, Visibility, BER and Q-Factor.*

1. Introduction

Optical wireless communication is one of the important type of communication that has generated a vast number of interesting solutions to very complicated communication challenges, For example high data rate and minimum links interference for short and long range communications [1]. Certainly, quality of delivered signal, the data rate and transceiver technologies have been improved greatly from traditional optical wireless technologies to modern one. In many applications Free Space Optical (FSO) communication links have already succeeded in becoming part of our daily lives at offices and homes for example TV remote control [2].

In the next generation broadband networks, FSO technology will be become prominent for multi Gb/s rates over distances up to a few kilometers, unlicensed spectrum, excellent security and quick and inexpensive Setup among its most attractive features [3]. However, FSO links assumed to be line-of-sight uses the atmosphere as a propagation medium, optical links in the propagation channel are significantly influenced by different weather conditions and scintillations resulting in the increasing signal losses and fades, which seriously affect the communication performance [4].

MIMO technology can be significantly improve the data capacity through spatial multiplexing by increasing the numbers of points at the transmitter and/or receiver as shown in Figure (1). The MIMO technology cannot only increase the data rate but also improve the system reliability through spatial diversity [5].

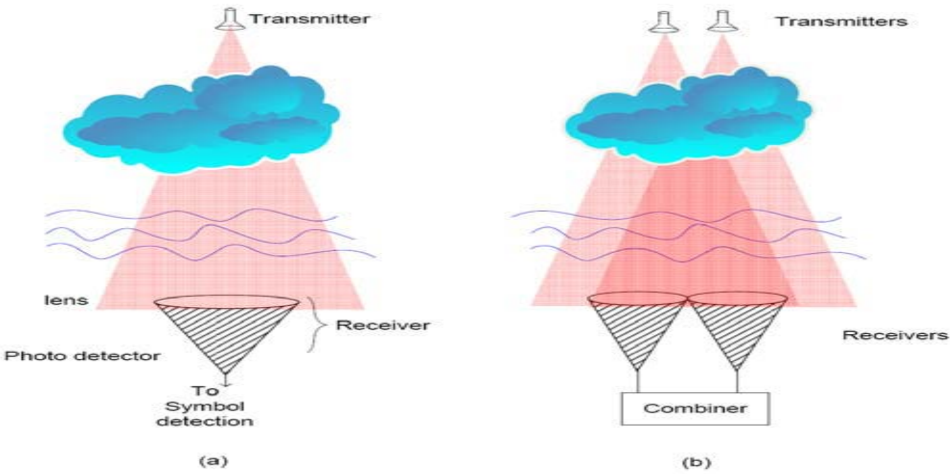

Fig. (1) (a) SISO and (b) MIMO communications systems

1.1 FSO Communication System

All of communication systems is consisting from three main stages: transmitter, link channel and optical receiver. Laser diodes (LDs) or Light Emitting Diodes (LEDs) can be used as a modulated light source (transmitter). Each light source has distinctive differentiators, the most obvious being (optical power, cost and size), and thus reasons for using it in corresponding applications [6]. Link channel in FSO is the atmosphere, where the absorption and scattering are the main effectiveness on the FSO system, especially in adverse weather conditions (cloud, rain, smoke, gasses, temperature variation, fog and aerosol). The combined effects of direct scattering and absorption of laser light can be described by a single path-dependent attenuation coefficient (α). The received power P_R for a receiver with receiver range **L**, area **A**, and beam divergence angle Θ for transmitting power $\mathbf{P_T}$ varies as [7]:

$$P_R \approx \frac{A}{\pi \Theta^2 L^2} e^{-\alpha L} P_T \text{ .... (1)}$$

The optical received signal convert to electronic signals by photodetector, two commonly types of photodetectors are be used; PIN detector and avalanche photodiode (APD) detector because they are commercially and they have good quantum efficiency. For optimal design of the receiving system, it is important to understand the characteristics of these photodiodes and the noise associated with optical signal detection [7].

2.1 Bit Error Rate

There are several ways of measuring the rate of error occurrence in a digital data system. One common approach is shown in equation below [8]:

$$\text{BER}= \frac{N_e}{N_t} = \frac{N_e}{Bt} \text{ .... (2)}$$

Where N_e: the number of errors occurring over a certain time interval, N_t: the number of pulses (ones and zeros) transmitted during this interval and B_t: the bit rate ($B= 1/T_b$) [8].

The BER expressed by a number which states that; for example one error occurs for every billion pulses sent, this BER depends on the signal to noise ratio at the receiver. Another way to compute BER, a signal was assumed (which can be either a desired information- bearing signal or a noise disturbance).

It has Gaussian probability distribution function with mean value at any arbitrary time t_1, if the signal voltage level sampled as (t), the probability that the measured samples (t_1) fall in the ranges to s+ds is given by [8]:

$$F(s)\, ds = \frac{1}{\sqrt{2\pi\sigma^2}}\; e^{-(s-m)^2/2\sigma^2} ds \text{ .... (3)}$$

Where f(s) represent the probability density function, σ^2 is the noise variance and its square root σ is the standard deviation, which is a measured of the width of the probability distribution.

The probability density function use to determine the probability of error in a data system in which the 1 pulse are all of amplitude v. The mean and variance of the Gaussian output for a 1 pulse they are born and σ_{on}^2, respectively. And for a 0 pulse they are b_{off} and σ_{off}^2, respectively. First, we consider the case of 0 pulses sent, so that no pulses present at the decoding time. The probability of error in this case is the probability that the noise will exceed the threshold voltage V_{th} and be mistaken for a 1 pulse. The probability of error $P_0(v_{th})$ is given by [9]:

$$P_0(v_{th})= \frac{1}{\sqrt{2\pi}\,\sigma_{off}} \int_{v_{th}}^{\infty} \exp[-\frac{(v-b_{off})^2}{2\sigma_{off}^2}]\, dv\text{.......(4)}$$

Where the subscript 0 denotes the presence of a 0 bit.

Similarly, the probability of error that a transmitted 1 is misinterpreted as a 0 by the equalizer. This probability of error is the likelihood that the sampled signal –pulse – noise pulse falls below:

$$P_1(v_{th})=\frac{1}{\sqrt{2\pi}\sigma_{on}} \int_{-\infty}^{v_{th}} \exp[-\frac{b_{on}-v}{2\sigma_{on}^2}]dv\text{........ (5)}$$

Where the subscript denotes the presence of a 1 bit.

If the probabilities of 0 and 1 pulses assumed equally likely then the BER becomes

$$\text{BER}=\frac{1}{\sqrt{2\pi}} \frac{e^{-Q^2/2}}{Q}\text{............. (6)}$$

The parameter (Q) define as [8]:

$$Q = \frac{v_{th}- b_{off}}{Q_{off}} = \frac{b_{on}-v_{th}}{\sigma_{on}} \text{ .... (7)}$$

The factor (Q) is widely used to specify receiver performance, since it is related to the signal – to – noise ratio required to achieve a specific bit – error rate.

In particular, it takes into account that in optical fiber systems the variances in the noise powers generally are different for received logical 0 and 1 pulses. A commonly quoted (Q) value is 6, since this corresponds to a BER = 10^{-9}.

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2.2 FSO Challenges

In FSO communication system, optical channel attenuation occurs mainly by scattering and absorption events caused by fog, snow, rain, smoke and dust. The main challenge is a fog which is formed by the condensation of water vapor on condensation nuclei that are always present in natural air. This can result as soon as the relative humidity of the air exceeds saturation by a fraction of 1%. In highly polluted air the nuclei may grow sufficiently to cause fog at humidity of 95% or less near ground level and sufficiently dense to reduce horizontally visibility to less than 100m. Another way is to use visibility data to predict specific attenuation [10]. Kruse and Kim models are use these approach and predict specific attenuation using visibility. The specific attenuation for both Kim and Kruse model is given by [11]:

$$\gamma(\lambda)=\frac{3.921}{V}\left(\frac{\lambda}{550}\right)^{-q} \quad \ldots\ldots\ldots\ (8)$$

Where λ is the wavelength (nm), V is the visibility (m), and q is the particle size distribution. For Kruse model:

$$q=\begin{cases} 1.6 & \text{if } V>50\text{ km} \\ 1.3 & \text{if } 6\text{km}<V<50\text{ km} \\ 0.585\,V^{1/3}+0.34 & \text{if } V<6\text{ km} \end{cases} \quad \ldots..\ (9)$$

Equation (9) shows that for any weather condition, there will be less attenuation for higher wavelengths. Kim unacceptable such wavelength dependent attenuation for low visibility in dense fog. Equation (10) shows the *q* variable in the equation (8) for Kim model:

$$q=\begin{cases} 1.6 & \text{if } V>50\text{km} \\ 1.3 & \text{if } 6\text{ km}<V<50\text{ km} \\ 0.16V+0.34 & \text{if } 1\text{km}<V<6\text{km} \\ V-0.5 & \text{if } 0.5\text{ km}<V<1\text{km} \\ 0 & \text{if } V<0.5\text{ km} \end{cases} \quad \ldots\ldots\ldots\ldots..\ (10)$$

Design and Simulations

3.1 Case 1: Study the Basic Parameters of FSO System

The first step in designing a wireless communication system is knowing what happens to the signal when travels through these mediums, this task is usually accomplished by measuring or simulating the channel impulse response. The enormous bandwidth promising by FSO communications is available only under clear atmospheric conditions. However this is not a realistic situation, the great potentials of FSO communications and suitable measures should be used in transmitter and receiver designs. Using OptiSystem (7.0) simulation software, FSO systems have been designed and studied the effect of wavelength, beam divergence angle and data rate on the performance of the system under different weather conditions [12]. A Simulation layout of Single Input-Single Output (SISO) FSO system shown in figure (2).

The fundamental elements that form any FSO system are: transmitter (T_x), FSO channel and receiver (R_x).The transmitter includes: laser source (650nm, 850nm and 1550nm) was used, PRBS (Pseudo Random Bit Sequence) generator, NRZ (Non-Return to Zero) pulse generator and MZM (Mach Zehnder Modulator). The apertures of the transmitter and the receiver are set to 2.5 cm and 8 cm, the beam divergence is 2 mrad and power of laser was equal 300 mW. In practical case there is an attenuation in the received signal due to atmospheric conditions of the channel. Initially, the attenuation value is set at 0.25 dB/Km in clear weather, 2.6 dB/Km in haze or moderate rain (13 mm/hr) weather, 12.6 dB/Km in light fog or snow and cloud burst, 21 dB/Km in moderate fog or heavy snow; finally heavy fog have been applied. In addition of these losses transmitter and receiver losses was set to 1dB for each one [13].

The optical signals from FSO channel are received by APD photodetector. This simulation use two visualizer's elements namely optical power meter to measure the power received in both dB and Watts, and BER analyzer automatically calculates the BER value, Q-factor and display eye diagram [14].

To complete the study, the beam divergence angle changed to 1 mrad with fixed other parameters and observe the behavers of the system. At finally high data rate 5 Gbps applied and performance evaluation of the system under different conditions and compare it with 155 Mbps data rate.

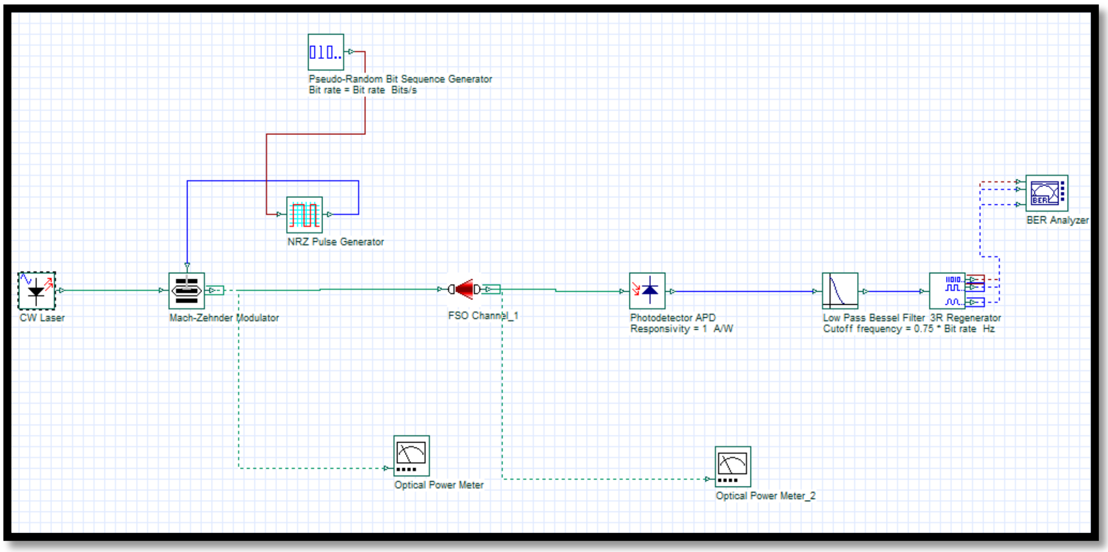


Fig. (2) Simulation layout of (1TX/1RX) FSO system

3.2 Case 2: Comparison between SISO and MIMO Techniques

From case1, in clear weather and haze or rain the SISO system operate good without problem but when the weather get worse like fog or snow the link will be failed, so MIMO technique used to improve the communication. In figure (3) shown simulation layout of MIMO system with two transceiver, some of components use just in MIMO technique like a fork which is use to duplicate the number of output ports so that each of the signals coming out from fork's output has the same value with the output signal from the previous component connected to it. Fork produced multiple beam of laser, these laser beams are combined by the power combiner. At the receiver side power coming from FSO channel by a power combined and then fed to the optical receiver. Optical power meter and BER analyzer are two visualizers used in the simulation. One Gbps used as a data rate and made a comparison between this system and the previous one (SISO system) with used same properties for both systems for distance of communication equal to 1Km.

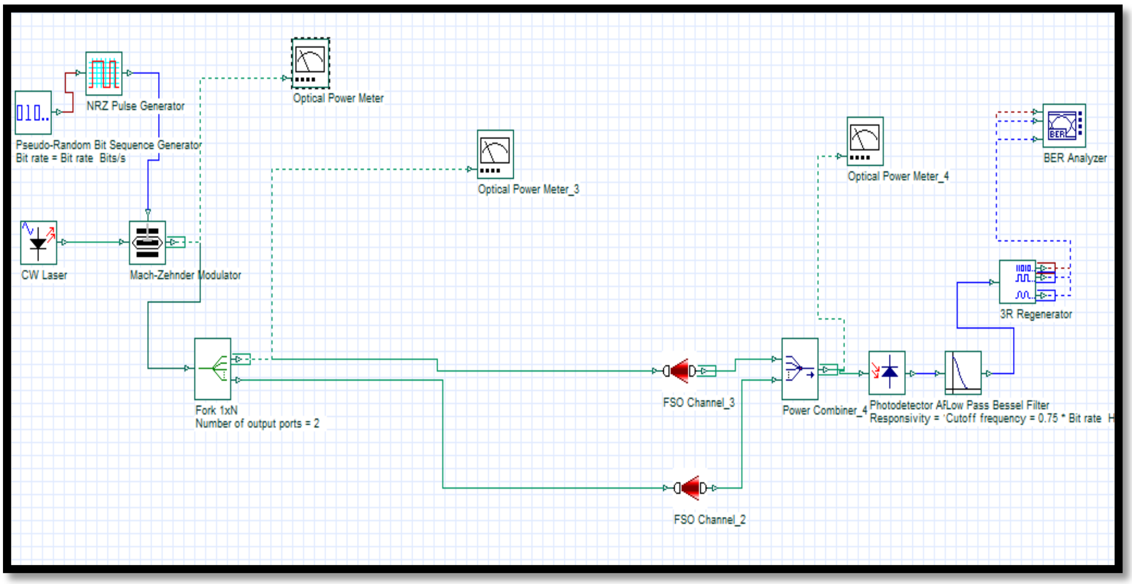


Fig. (3) Simulation layout of 2 TX/2 RX FSO system

3.3 Case 3: Optimal Design of MIMO Technique

In this case optimal design has been done by using four transmitters and four receivers (4Tx/4Rx) FSO system to increase an efficiency of communication, after that we made a comparison between it and (2Tx/2Rx) system which mention in previous case. In the other words, there are two systems: the first one is MIMO with two transceiver and the other one is also MIMO but with four transceiver (which considered as an optimal design).

In this work different weather condition have been applied to observe the behaver of systems under variable atmosphere effect by calculating link margin for every condition (the link margin value shows how much margin a system has at a given range to compensate for absorption, scattering and scintillation losses). Figure (4) shown a simulation layout of optimal MIMO design with four transceiver.

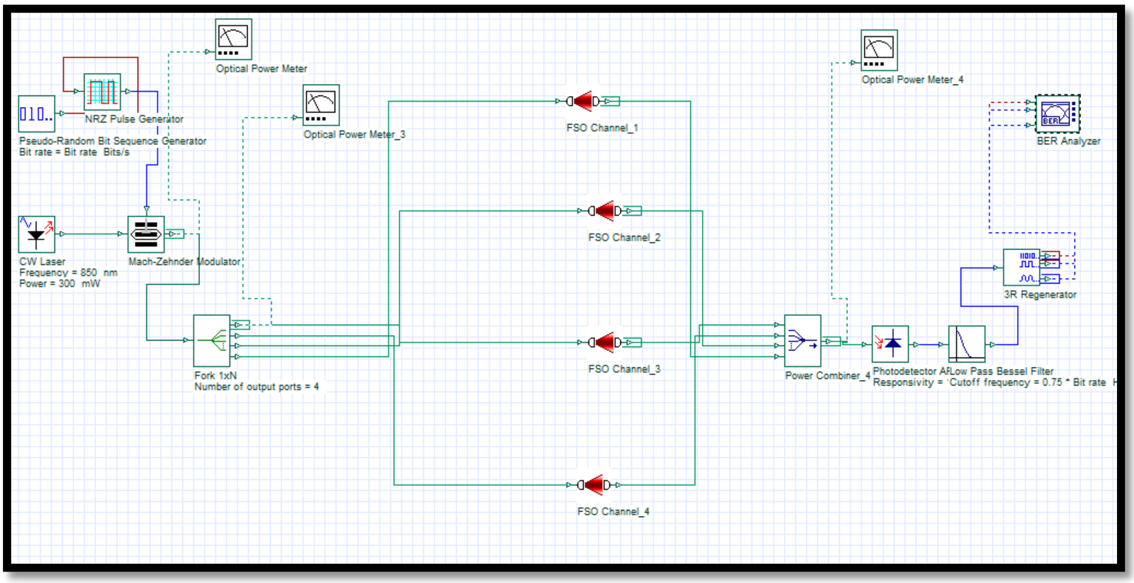


Fig. (4) Simulation layout of 4 TX/4 RX FSO system

Results and Discussions

4.1 Case 1: Measuring the Basic Parameters of FSO System

Simulations of (1Tx/1Rx) FSO systems with laser power 300 mW and data rate (155 Mbps) are analyzed in all-weather condition. In figure (5) visibility plotted versus attenuation for different attenuation values which represent different weather condition for three wavelength. From this figure it can be observed the wavelength range is inversely proportional with atmospheric attenuation in clear and turbulent weather condition but with very turbulent weather.

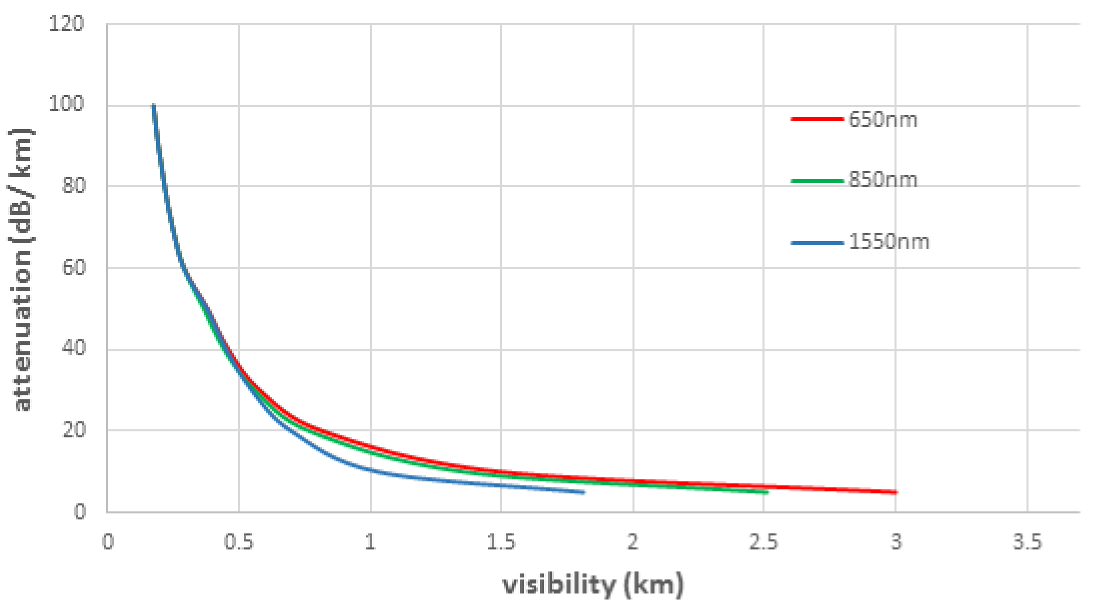


Fig. (5) Total attenuation verses visibility for three wavelength

Figure (6) represent the performance of SISO system at different weather conditions by measuring maximum link range could this system reached. Also in this figure the comparison between two values of beam divergence was accomplished and it's shown clearly the maximum link range of FSO communication increasing with decrease the divergence angle of the laser beam at the same wavelength.

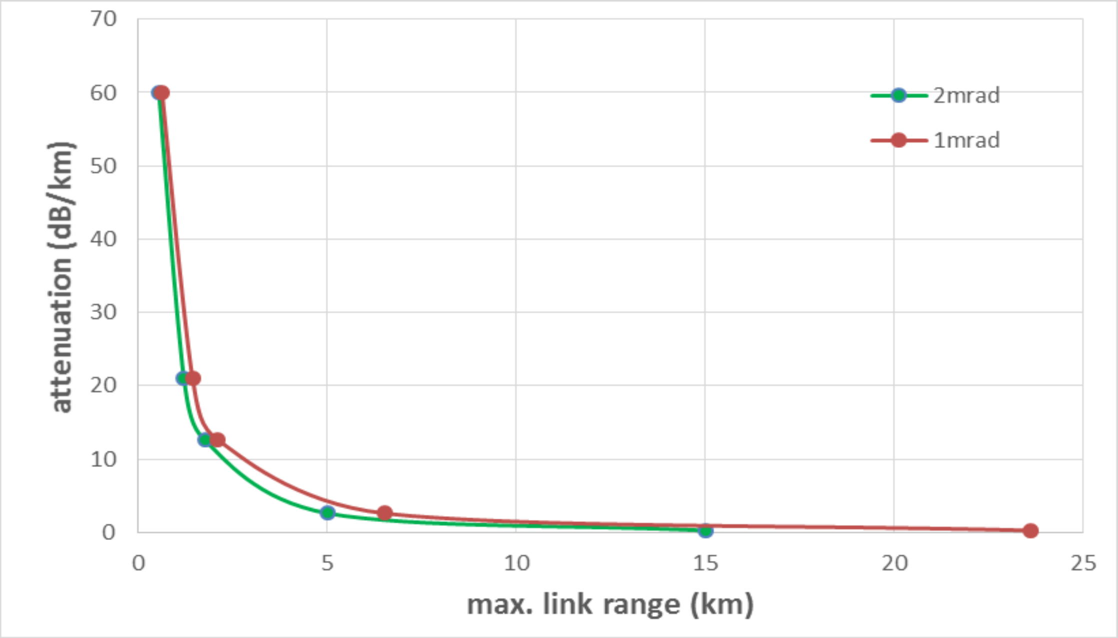


Fig. (6) Total attenuation verses maximum link range for two beam divergence

After that high data rate communication applied (5Gbps) and observed the effect of it on Q-factor at different range with fixing attenuation on 5 dB/Km, figure (7) shown Q-factor versus range of communication and its clear the Q-factor decreased when the range increased and also its decrease with high data rate or we can say the data rate of FSO communication system is inversely proportional with communication link.

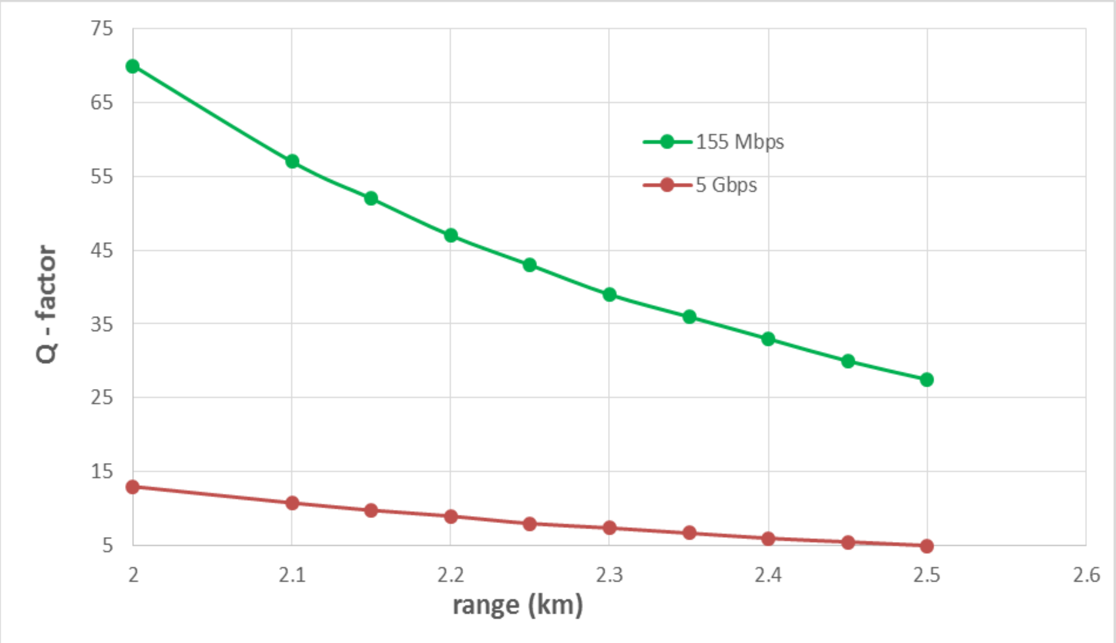


Fig. (7) range of the link verses Q-factor in two different data rate

4.2 Case 2: Comparison Results between SISO and MIMO Techniques

In clear weather and haze or rain can get a signal from SISO system, but this signal may loosed easily under other strong turbulence like foggy weather so MIMO technique will be used that enhance the communication then make the system confirm with the turbulent weather as shown in figure (8) which represent a comparison between SISO and MIMO system under snow and fog conditions by measuring Q-factor for different power of transmitter.

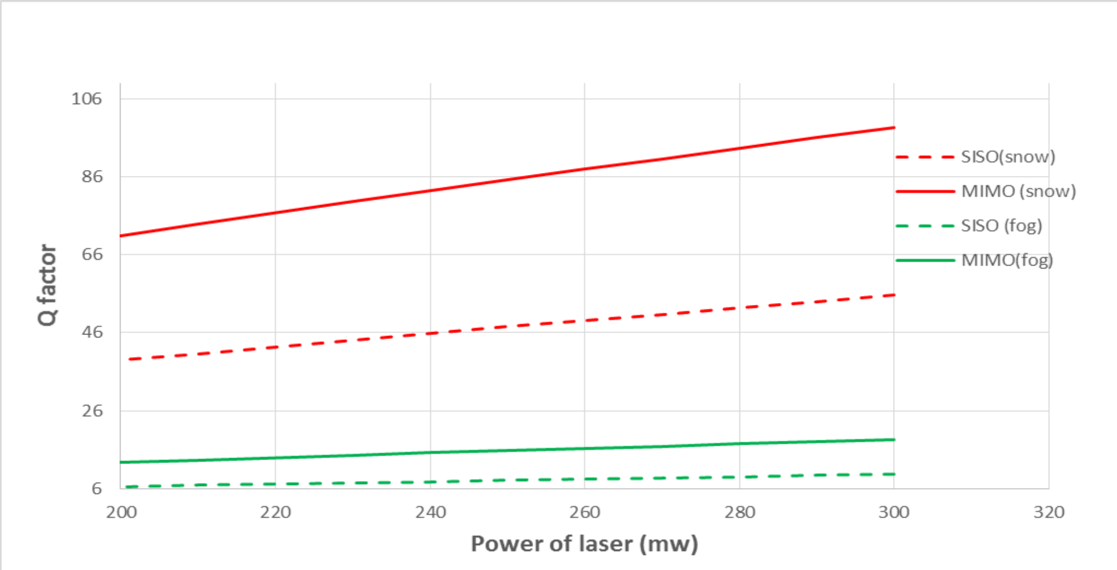
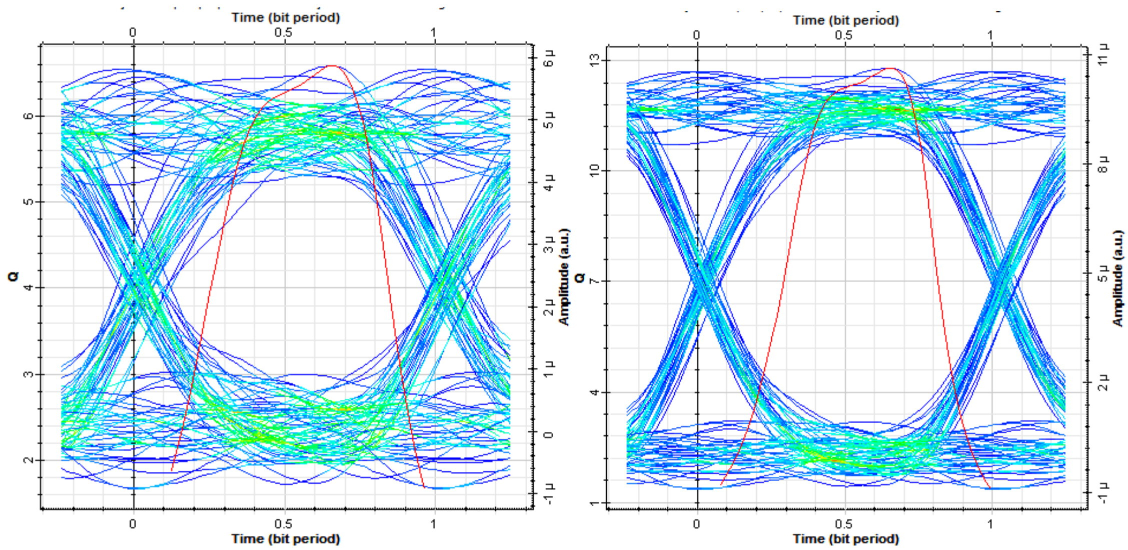


Fig. (8) Power of laser verses Q-factor in SISO and MIMO systems under foggy weather

Figure (9) shown eye diagram for the two system (SISO and MIMO) under same condition, as its show MIMO technique have a higher Q-factor that mean its work better than SISO.



(a) (b)

Fig. (9): Eye diagram under foggy weather and P_{laser}=200mW (a): SISO, (b): MIMO

4.3 Case 3: Measuring and Results of Optimal Design of MIMO Technique

In this case we apply different condition on the MIMO systems and performance evaluating them by plotting the link margin verses link range. Figures (10) and (11) shown how the weather condition effect on the communication link. These figures explain how we get a more robust FSO system by using optimal MIMO technique where figure (10) represent MIMO system with (2Tx/ 2Rx) and figure (11) represent MIMO system with (4Tx/ 4Rx), it can be noted how link range increase by using optimal MIMO design.

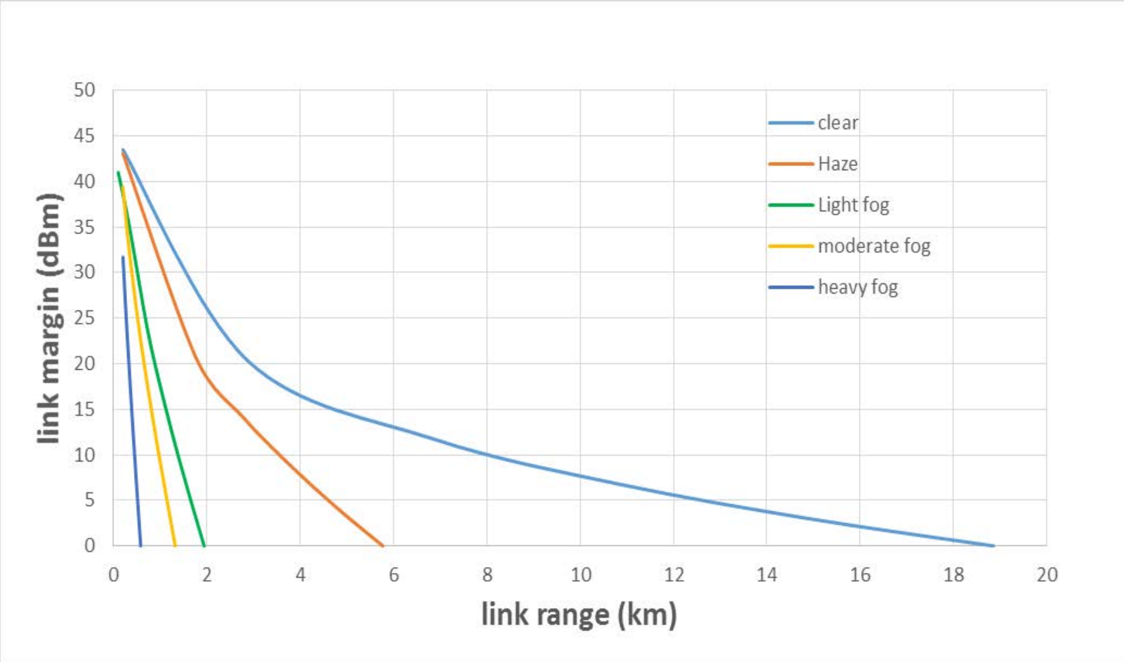


Fig. (10) Link margin versus link range in MIMO system (2Tx/ 2Rx)

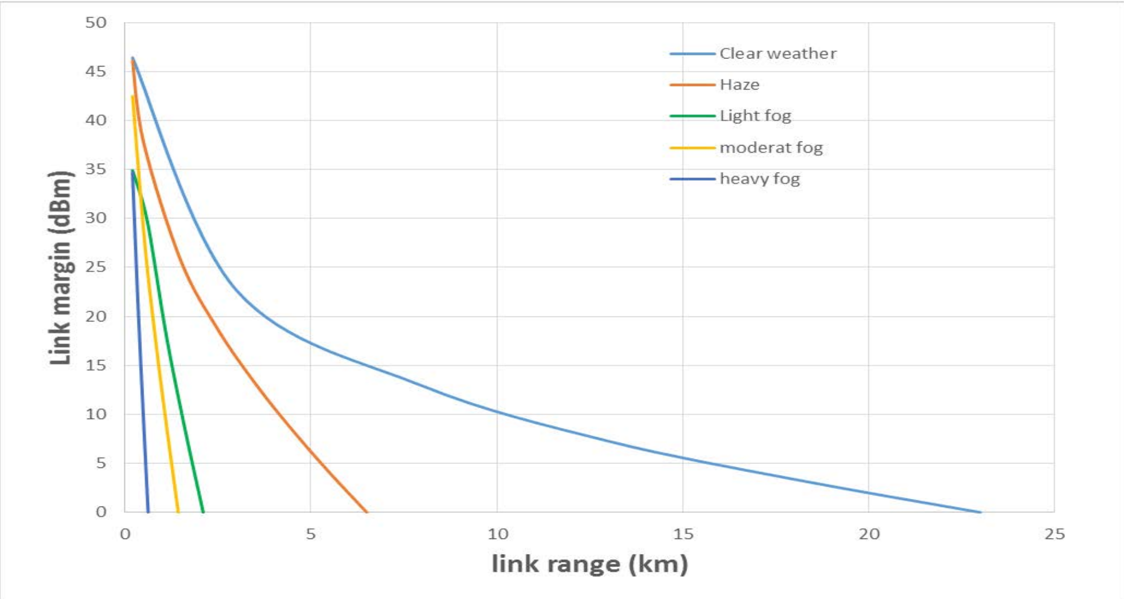


Fig. (11) Link margin versus link range in MIMO system (4Tx/ 4Rx)

Conclusions

The performance evaluation conclusions of optical (MIMO-FSO) system shows:

1. MIMO-FSO system performance over a different atmospheric turbulence condition channel, it has been observed that increasing the system channel capacity was almost1 linearly with the number of transmitting units. Also the effectiveness of multi transmitters and receiver diversity helps in mitigating amplitude1 fading through overcome both amplitude and phase fluctuations. MIMO-FSO systems perform slightly better than an equivalent1 SISO-FSO system in the presence of log-normal amplitude attenuation.
2. Even though Q factor of an FSO system decreases on increasing attenuations, the (4TX /4RX) and (2TX /2RX) as a MIMO-FSO system shows a higher Q factor1, so better performance by increasing the number of apertures, MIMO system performance1 improves compared to the SISO counterpart. Also increasing the link range lead to

decrease link margin, MIMO technique1 can be solve this problem by increasing the link margin at the same condition.

3. Also in poor weather conditions data can be transmitted with good bit error rate performance1. This can be possible only when data is modulated on a carrier. But modulation technique is also an important parameter that induces the bit error. Modulated 0ptical (MIMO-FSO) transmission shows more robust to channel1 fading than (SISO-FSO). Also, it is necessary to use a better modulation technique. In this work channel capacity, which depends upon many1 factors like signal energy, bandwidth and signal to noise ratio is shown for both (RZ and NRZ) of (OOK) modulation technique. On (MIMO-FSO) channel the result shows that (NRZ-OOK) channel capacity is higher than the (RZ-FSO) modulation1 technique.

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