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Design of an Optimum Massive MIMO FSO System and Analysis of its Performance in Different Weather Conditions

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ABSTRACT

This aim of this work is to propose a massive MIMO FSO system with optimum design parameters and analyze its performance in various turbulent weather conditions by simulating the model in Optisystem 18.0. In recent years, the need for high speed data transfer for real time communication has become a necessity. Implementation of massive MIMO system has already gained remarkable achievement using the conventional RF transmission system. Although it is very much efficient in its application, it has some problems, such as licensing restrictions, bandwidth depletion, fragmentation. In this respect, Free space optics (FSO) is an efficient method for high speed data transfer as it does not have above limitations. Different researches conducted using MIMO FSO models have shown promising results. The use of massive MIMO system (more than 8×8 array of antennas) will enhance data rate further. In this research work, an optimum massive MIMO FSO system has been designed with 16×16 array of antennas. The performance of this system is analyzed in different weather conditions and compared with that of 8×8 system. The analysis of performance is done by power penalty and receiver sensitivity plots. A significant transmission range and an optimum performance is obtained by using this system at a data rate of 40 Gbps. However, data transmission rate can be much more enhanced in this system at the cost of reduced performance and a shorter transmission range.

1. INTRODUCTION

Wireless communication technology has progressed remarkably over the years due to its increasingly high demand. The requirement for higher data rate and bandwidth is also increasing correspondingly with the number of multimedia services (Israr *et al.*, 2019). Modern wireless communication system depends on the use of Radio Frequency (RF) signals as the carrier of information. For the time being, the use of RF signals is satisfactory, however, with the rapid increase of internet services, the depletion of bandwidth of RF signals is imminent requiring the need to find a wider band of spectrum. Free Space Optical (FSO) communication can be an optimum solution to this problem. It is being considered as the most promising alternative to RF signals (Chauhan *et al.*, 2021). It has several benefits over RF signals such as license-free spectrum, larger bandwidth, low power consumption, better security and simple and quick installation (Bhatnagar *et al.*, 2016). Besides RF communication, FSO can also be considered as an alternative to optical fibre communication as it retains the characteristics of the optical fibre at lower power consumption and easier installation and maintenance (Chatti *et al.*, 2019).

Free Space Optical (FSO) system requires a direct line of sight (LOS) for the communication between transmitter and receiver. Optical wavelengths of 850 nm, 1300 nm and 1550 nm are used for transmitting information (Israr et al., 2019). Because of being a LOS dependent system, the performance of FSO communication is greatly degraded due to the presence of atmospheric turbulence (Badar *et al.*, 2017). Various atmospheric processes such as, haze, fog, snow, smoke, clouds, dust, rain etc. can cause signal attenuation due to absorption and scattering of information carrying optical signal (Naboulsi *et al.*, 2004). The refractive index fluctuates due to atmospheric turbulence which in turn creates hindrance to the transmitted light. The received power as a result falls the below the required optimum value. Consequently, the bit error rate (BER) gets increased. This problem may seem to be solved by the use of high-power lasers on the transmitting end, however, the laser power cannot be increased more than a particular value (10 dBm) by taking practical feasibility and more importantly health safety into considerations.

Recent researches show that the inclusion of the Multiple Input Multiple Output (MIMO) technology can minimize the adverse effects due to atmospheric turbulence to a great extent (Thandapani *et al.*, 2021). MIMO technology enables the transmission of data via multiple redundant paths to achieve very low Bit Error Rate (BER). Besides mitigating the turbulence induced fading MIMO technology can substantially also improve the coverage, better gain in diversity and the total capacity which is proportional to the number of beams used (Zhang, *et al., 2017*). Considering atmospheric turbulence, the FSO channel can be characterized by various statistical models such as Gamma-Gamma distribution model, Kolmogorov spectrum model, Log normal model, K-channel model, etc. The Gamma-Gamma model is the most popular of these models due to its ability to characterize from weak to strong turbulences (Anandkumar, 2021). Analyses conducted under 1 km show very good results by using the MIMO technique in several weather conditions (Sangeetha *et al.*, 2019). The performance can be further improved by addition of more transmitting and receiving antennas.

The objective of this research is to analyse a massive MIMO FSO system in various turbulent weather conditions and to observe its performance in terms of BER, power consumption, transmission distance etc. and to obtain the optimum parameters of the system. The massive MIMO FSO system of diversity order 16 has been selected for the analysis taking practical implementation and cost-effectiveness into consideration. The performance results of this system are further compared to an 8 × 8 system showing the improvement.

2. BRIEF THEORETICAL BACKGROUND

A. FSO System

FSO communication system transmits light as the carrier of information through free space as the transmission medium (El-Mashade *et al.*, 2015). In this system, a Line of Sight (LOS) linking the transmitter and the receiver is needed for successful data transmission (Dubey, 2020). Since the transmission medium is free space, the atmospheric turbulence becomes a major obstacle causing irradiance fluctuations. With the consideration of atmospheric turbulence, the FSO channel can characterized by several statistical models such as Gamma-Gamma distribution model, Negative exponential model, Kolmogorov spectrum model, Lognormal model. Among these, the Gamma-Gamma model is chosen for this analysis as it gives better results under strong, moderate and weak atmospheric turbulences. Here, the probability density function, $f(I)$ is used to express the Gamma-Gamma model, stated in Equation (1) (Kumar & Khandelwal, 2019):

$$f(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})\,2\,, \quad I > 0 \tag{1}$$

where, 'I' = intensity of the received signal and the parameters 'α' & 'β' are defined small to large scale fading created by atmospheric turbulence, expressed in Equations (2) and (3) (Kumar & Khandelwal, 2019):

$$\alpha = (exp(\frac{0.49\sigma^2{}_R}{(1+1.11\sigma^{\frac{12}{5}}{}_R)^{\frac{7}{6}}}) - 1)^{-1} \tag{2}$$

$$\beta = (exp(\frac{0.51\sigma^2{}_R}{(1+0.69\sigma^{\frac{12}{5}}{}_R)^{\frac{5}{6}}}) - 1)^{-1} \tag{3}$$

The Rytov Variance can be expressed as,

$$\sigma^2{}_R = 1.23C^2{}_n K^{\frac{7}{6}} L^{\frac{11}{6}} \tag{4}$$

where, L = length of propagation path, K = optical wave number, C_2^n is a measure of the variations of refractive index which indicates the turbulence strength. Values of C_2^n span from $10^{-17}\,m^{-2/3}$ to $10^{-13}\,m^{-2/3}$ for weak to strong turbulences (Jarangal, *et al.*, 2018).

B. Massive MIMO System

In this age of wireless communication, uninterrupted data transfer at a high transmission rate is of great necessity. The massive Multiple Input Multiple Output (mMIMO) system uses large array of antennas in transmitting and receiving sides. Transmission rate of the system increases appreciably by the increased number of antennas. The massive MIMO is an extension of the prevailing MIMO system (Albreem *et al.*, 2019). In MIMO systems, a highest of 8 × 8 array of antennas can be used (Khwandah *et al.*, 2021). However, in massive MIMO systems, both the transmitting and receiving ends must contain an array of antennas greater than 8. The use of higher number of antennas creates multiple redundant paths for the transmission of data streams. This helps to achieve higher data transmission speed at a low bit error rate. Studies show that data transmission rate as high as 5.5 Gbps can be obtained in conventional radio frequency (RF) systems by using a 20 × 12 array of antennas (Tsai *et al.*, 2018). A massive MIMO system can have infinite array of antennas from theoretical perspective. However, some problems like low cost- efficiency, and intricacy of the system are encountered during the employment of a large number of antennas (Lu *et al.*, 2014). So, an optimal number of antenna elements needs to be chosen for designing a massive MIMO system. The MIMO channel can be mathematically expressed as (Sangeetha *et al.*, 2019):

$$Y = HX + N \tag{5}$$

Here, 'X' and 'Y' denote the transmitted and received vectors respectively. 'H' is used to represent the channel matrix and 'N' indicates the noise vector.

3. SIMULATION PARAMETERS

The proposed massive MIMO FSO system was simulated in Optisystem 18.0 and MATLAB R2018a was used to show the graphical outputs. Different parameters used in this simulation of the $16x16$ FSO model are listed in Table 1.

The FSO channel is characterized by the following attenuation coefficients for different weather conditions. The attenuation coefficients are listed in Table 2 (Mansour *et al.*, 2017).

Table 1
Simulation Parameters

Different parameters	Values
FSO Channel	Gamma-Gamma Model
Optical Wavelength	1550 nm
Data Rate	40 Gbps
Distance	1.79 km
M - Z Modulator Extinction Ratio	30 dB
Refractive Index Parameter (C_n^2)	10^{-17}-10^{-13} $m^{-2/3}$
Transmitter Aperture Diameter	2.5 cm
Receiver Aperture Diameter	37.5 cm
Absolute Noise Temperature	298 K
Responsivity (APD)	1 A/W
Dark Current (APD)	10nA
Avalanche Photo Diode Gain	3
Receiver Load Resistance	50 Ω
Beam Divergence	2 mrad
Bessel Filter Cut-off Frequency	7.5 GHz
Loss in Transmitting end	1.8 dB
Loss in Receiving end	1.8 dB
Auxiliary Losses	1 dB

Table 2
Attenuation Values of FSO Channel in Various Turbulent Weather conditions

Weather Condition	Attenuation Coefficients, dB/km
Clear Weather	0.43
Haze	4.2
Moderate Rain	5.8
Heavy Rain	9.2

4. SIMULATION LAYOUT

Simulation block diagram and layout of the 16 × 16 FSO system are shown in Figure 1 and Figure 2. In this model, a CW laser source has been used as the light carrier. At first, the random bit sequence is produced by using a Pseudo-Random Bit Sequence (PRBS) generator. This data stream is then converted to voltage levels by a Non-Return to Zero (NRZ) Pulse Generator. The optical carrier is modulated with the baseband signal by Mach-Zehnder (MZ) modulator. This modulated optical signal is transmitted through the FSO channel by the continuous wave (CW) lasers at the transmitting end. In the receiving end, Avalanche Photo Diode (APD) detector receives this signal and Low Pass Filter (LPF) and 3R Regenerator are used to reconstruct the original data. A Bit Error Rate (BER) analyzer has been used to analyze the received signal.

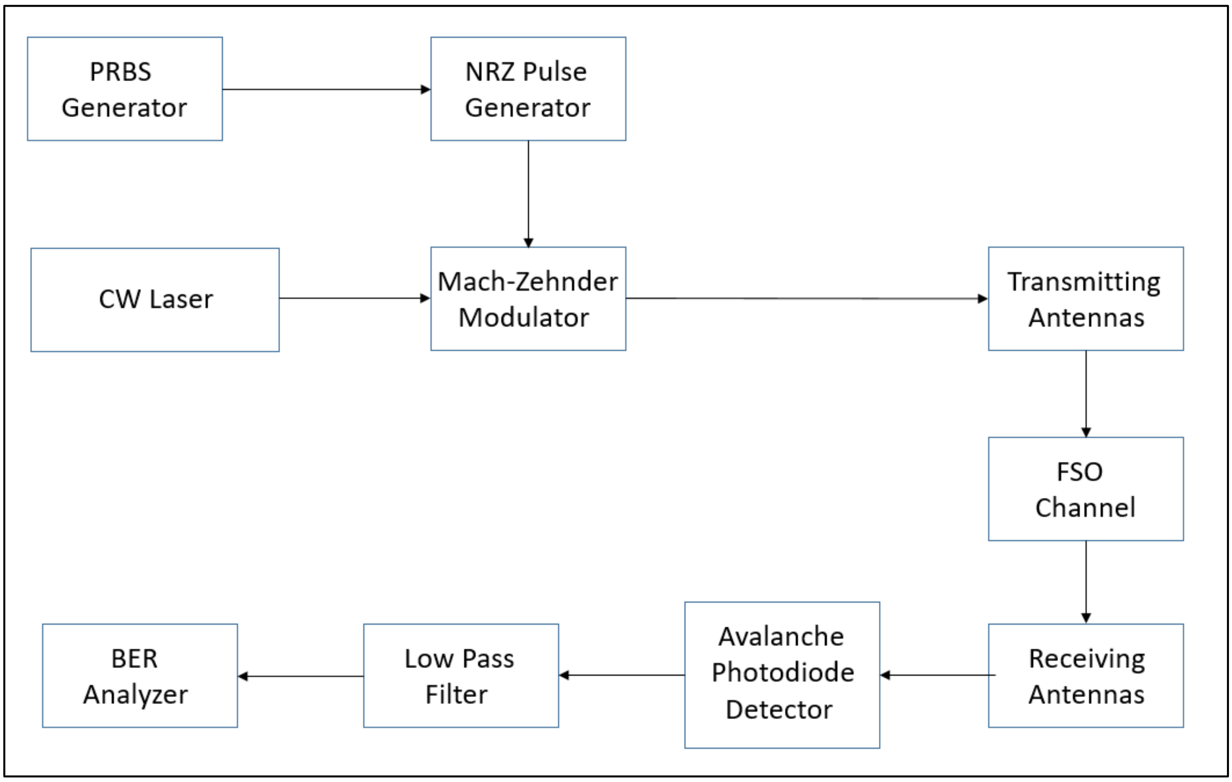


Figure 1: Illustration of a massive MIMO FSO System

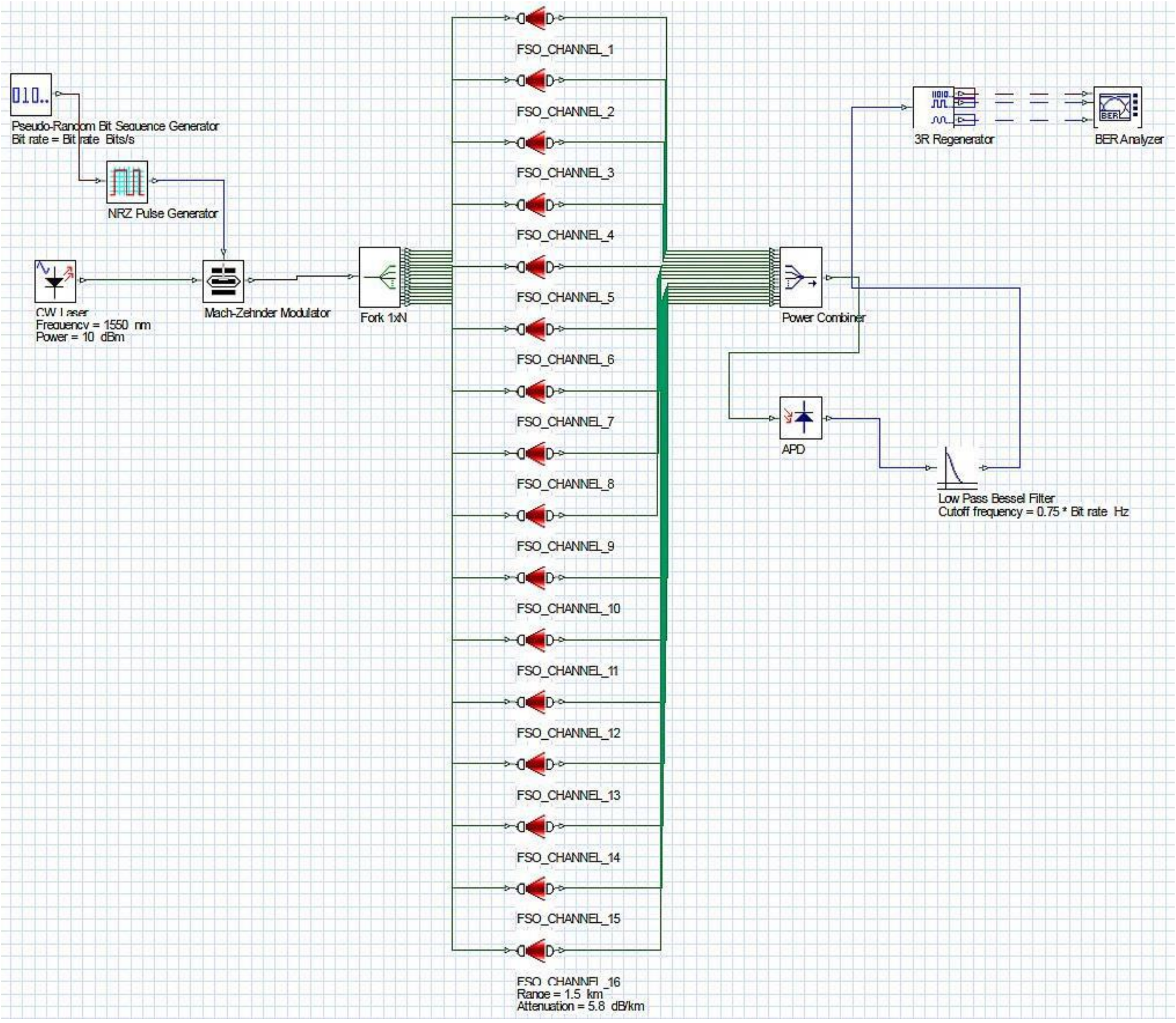


Figure 2: Simulation Layout of 16×16 massive MIMO FSO System

5. RESULT ANALYSIS

The proposed system was analyzed in various weather conditions. The diversity order selected for the simulation was 16. A Continuous Wave (CW) Laser is used as the optical source. Four different weather conditions have been used in simulation. These are clear weather, haze, moderate rain and heavy rain. The 16 FSO channels have been implemented with equal attenuation values in each weather condition for this simulation.

The performance of the 16×16 FSO system is analyzed at a 10 Gbps transmission rate at first. From the min. Log of BER vs Source Power graph in Figure 3, it is observed that the model yields very good results at this data rate. In case of heavy rain, at 1 km distance, the min. log of BER obtained is 3.19×10^{-119} by applying 0 dBm source power. In case of heavy rain, a BER of 3.19×10^{-119} is obtained at 1 km distance by applying a source power of 0 dBm.

The min. log of BER vs source power graph at 10 Gbps transmission rate in different weather conditions for 2 km distance is shown in Figure 4. The BER at 2 km distance is observed to increase noticeably. It is 3.14×10^{-14} in case of heavy rain by applying a source power of 10 dBm.

The results from Figure 1 and Figure 2 show that the performance of the 16×16 system under all weather conditions at 10 Gbps is quite satisfactory. Hence, it is possible to achieve higher data rate with this system for a significant transmission range. So, further analysis was conducted to obtain optimum parameters of the proposed massive MIMO FSO system.

For this purpose, simulation was conducted to obtain the highest data rate for an optimum distance for a 16×16 system by considering a constant bit error rate (BER) of $10 - 10$. The graphical results can be seen in Figure 5. From the graph, a data rate of 40 Gbps was taken to be optimum. It was observed that under clear weather the optimum distance was found to be much higher compared to other weather conditions. For clear weather the maximum distance was 8.2 km for the optimum data rate of 40 Gbps. The similar analysis was also done for 8×8 system. In this case, the distance was 6.32 km for clear weather.

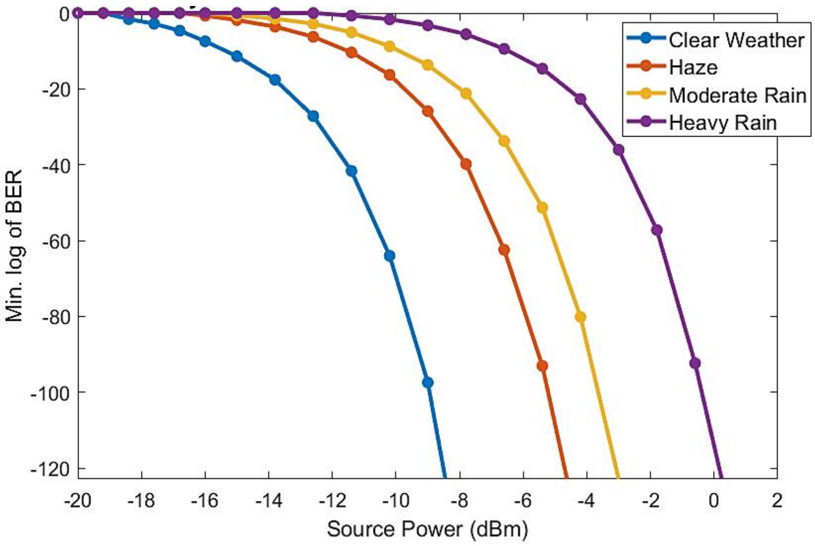


Figure 3: Min. log of Bit Error Rate vs. Source Power (dBm) graph for 16 × 16 system at 1 km in different weather conditions

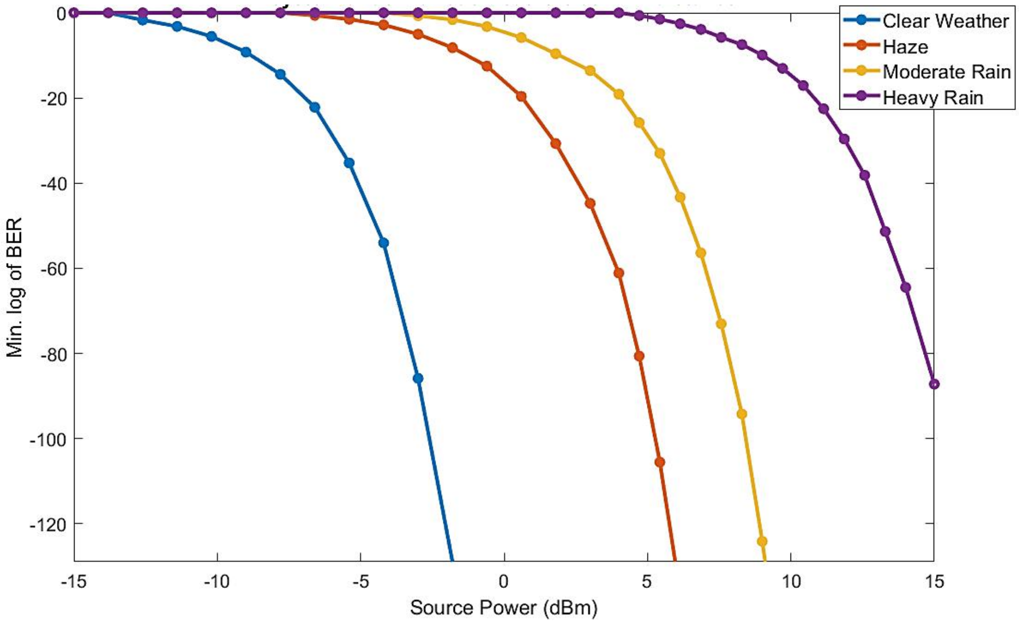


Figure 4: Min. log of Bit Error Rate vs. Source Power (dBm) graph for 16 × 16 massive MIMO FSO system at a distance of 2 km in different weather conditions

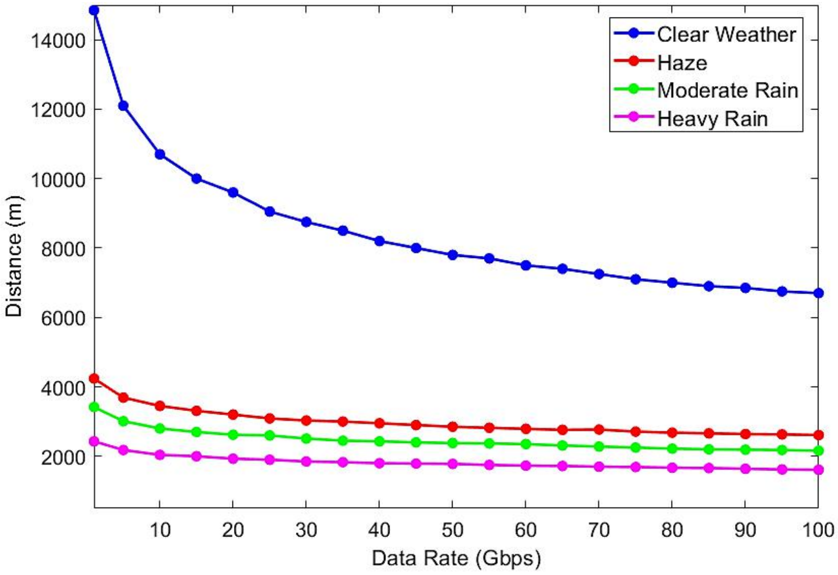


Figure 5: Distance vs data rate graph of 16 × 16 massive MIMO FSO system for a BER of $10e^{-10}$

When turbulent weather conditions were considered, the transmission range reduced significantly. However, the distance was still significant for these weather conditions. The distance was found to be 2.97 km in haze for 16×16 system, whereas it was 2.53 km for 8×8 system. In case of 8×8 system, in moderate rain and heavy rain, the transmission ranges obtained were 2.11 km and 1.6 km, which increased to 2.43 km and 1.79 km for 16×16 system. Thus, for turbulent weather conditions, the transmission range of the 16×16 system gets increased by about $200 - 300$ m on average compared to that of the 8×8 system.

Here, the simulation is carried out at a constant source power of 10 dBm. The optimum system parameters obtained from above analysis are listed in Table 3. The performance analysis of the 16×16 system with these optimum parameters is done with power penalty and receiver sensitivity plots. The plots are compared with that of 8×8 system for same simulation parameters.

Table 3
Optimum System Parameters

Attenuation (dB/km^{-1})	**Weather**	**BER**	**Data Rate (Gbps)**	**Optimum Distance (16 × 16 Massive MIMO FSO System) (km)**	**Optimum Distance (8 × 8 Massive MIMO FSO System) (km)**
0.43	Clear Weather	10^{-10}	40	8.2	6.32
4.2	Haze			2.97	2.53
5.8	Moderate Rain			2.43	2.11
9.2	Heavy Rain			1.79	1.6

Figure 6 shows the power penalty plot of 8×8 MIMO system in 4 different weather conditions. The values used in this plot are for a distance of 1.79 km and at the optimum data rate of 40 Gbps. From the power penalty plot of 8×8 massive MIMO FSO system we see that, to attain a BER of 10^{-10}, source power of -3.5 dBm is needed for clear weather. For heavy rain, the power requirement becomes 13 dBm.

From the power penalty plot of 16×16 FSO system shown in Figure7, it can be observed that for clear weather the source power needed to obtain a BER of 10^{-10} is -6.5 dBm. For haze it is around 0 dBm and for heavy rain the required source power is 10 dBm. Hence we can see that in case of same weather the power requirement reduces by 3 dBm if the antenna number is doubled. That is, when antenna number is doubled, the requirement of source power becomes half. Now, the analysis is done with received power vs. distance plots. Figure 8 shows the received power vs distance curve for 8×8 MIMO FSO system. From the curve it is seen that the optimum distance for each of 4 weather conditions is obtained when the received power is -25 dBm. As the distance increased, the received power decreased. That is, the performance will degrade for larger distance. From the received power vs. distance curve for 16×16 FSO system shown in Figure 9, it is visible that when the received power is -22 dBm, the optimum distance is obtained for all 4 weather conditions considered here. It is observed that, if the antenna number is doubled, the system will yield similar performance even if the received power becomes half.

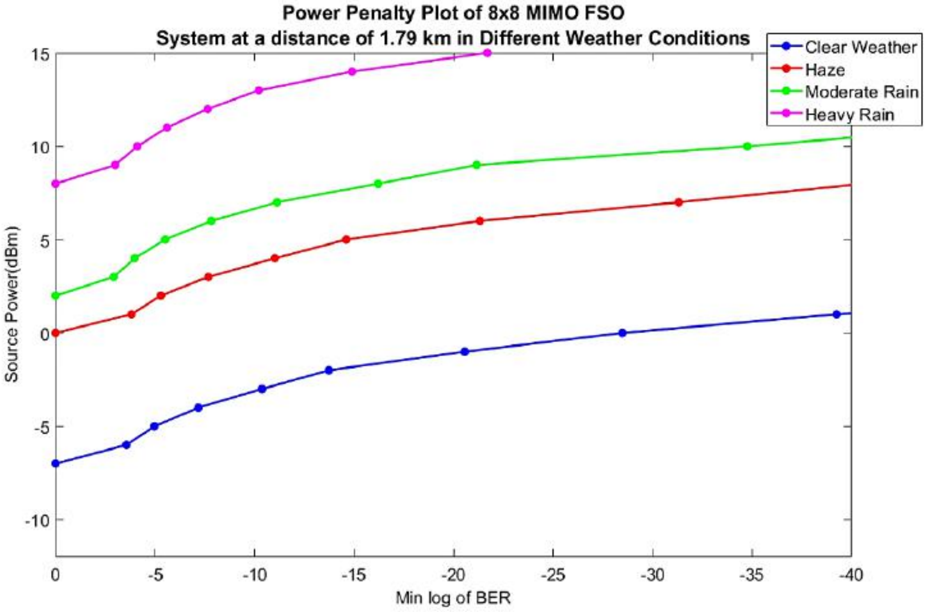


Figure 6: Power penalty plot of $\mathbf{8 \times 8}$ massive MIMO FSO system in different weather conditions at a distance of $\mathbf{1.79}$ km.

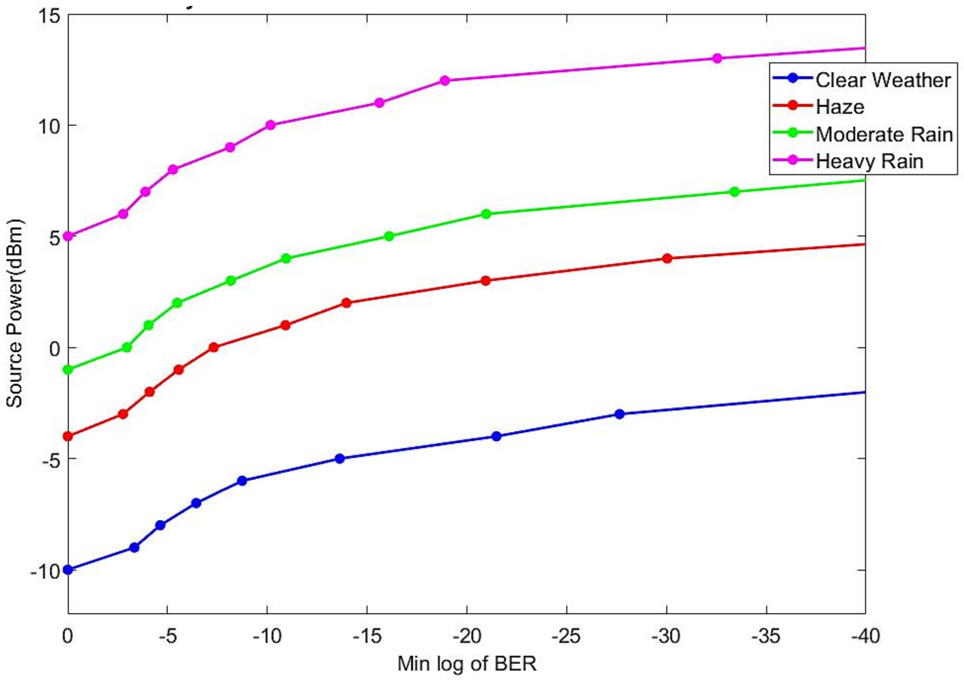


Figure 7: Power penalty plot of 16×16 massive MIMO FSO system in different weather conditions at a distance of 1.79 km.

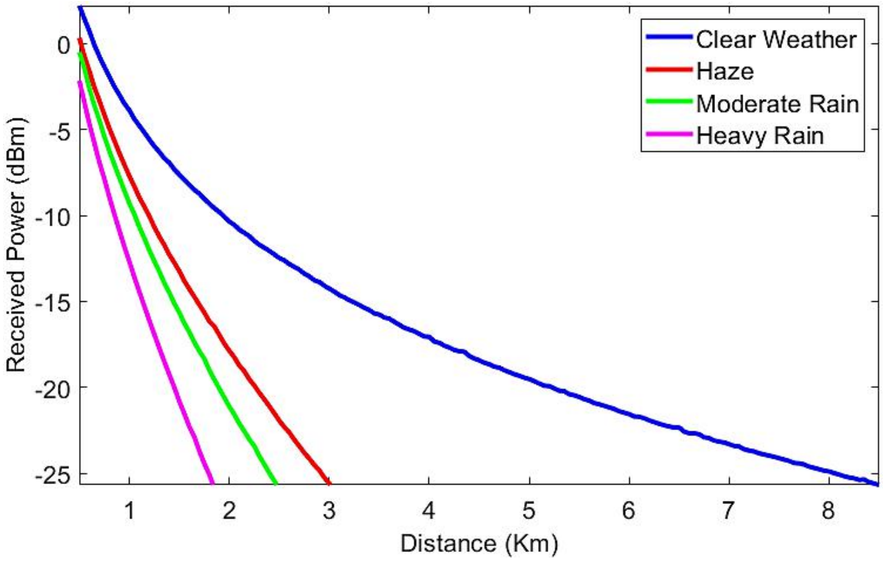


Figure 8: Received power vs distance curve for 8×8 MIMO FSO system

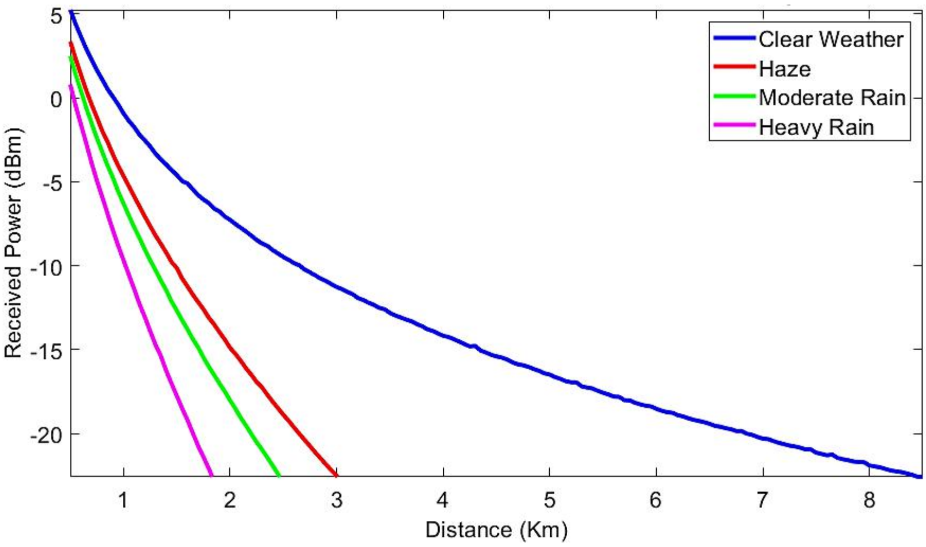
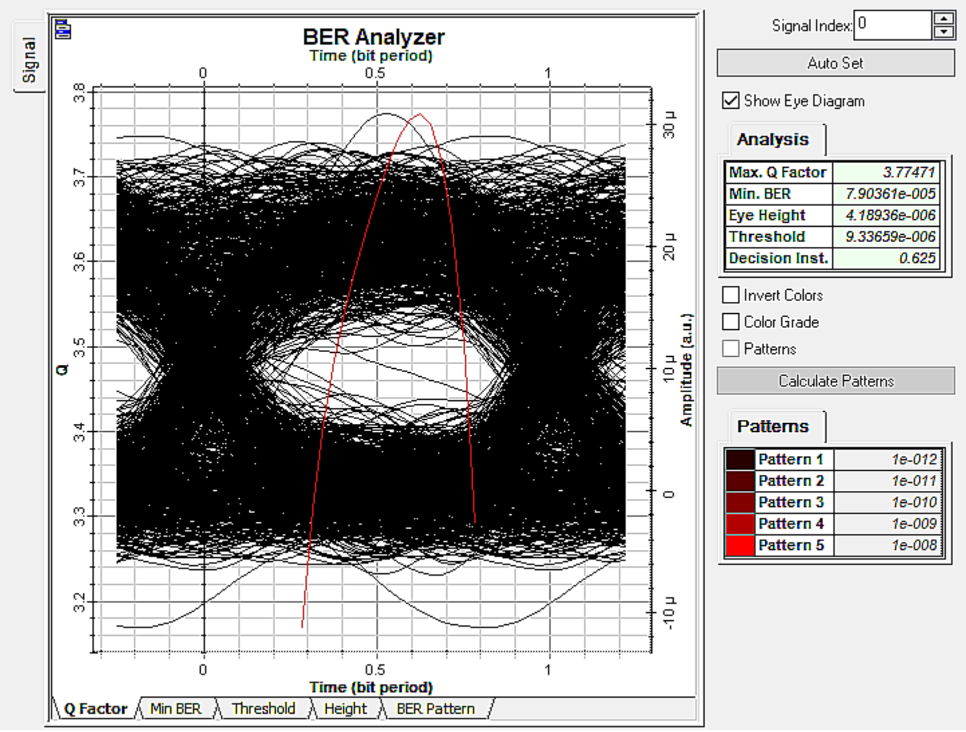


Figure 9: Received power vs distance curve for 16×16 massive MIMO FSO system

Now, the presence of noise in the system is analyzed by observing the eye diagram. For 8×8 MIMO system, the performance is poor at a distance of 1.79 km in heavy rain. From the eye diagram in Figure 10, the min BER is seen to be 7.9×10^{-5}. However, the performance significantly improves for 16×16 system. The performance improves for the 16×16 system as it has more redundant paths than that of the 8×8 system. Signal can move through these multiple redundant paths during inclement weather and thus the probability of error in the transmitted bits is reduced.

Figure 11 shows the eye diagram of 16×16 FSO system. From the eye diagram of the 16×16 system the min BER is found to be $1 \times 10 - 11$. The quality factor also becomes double in 16×16 system compared to that of 8×8 system.



Signal Index: 0

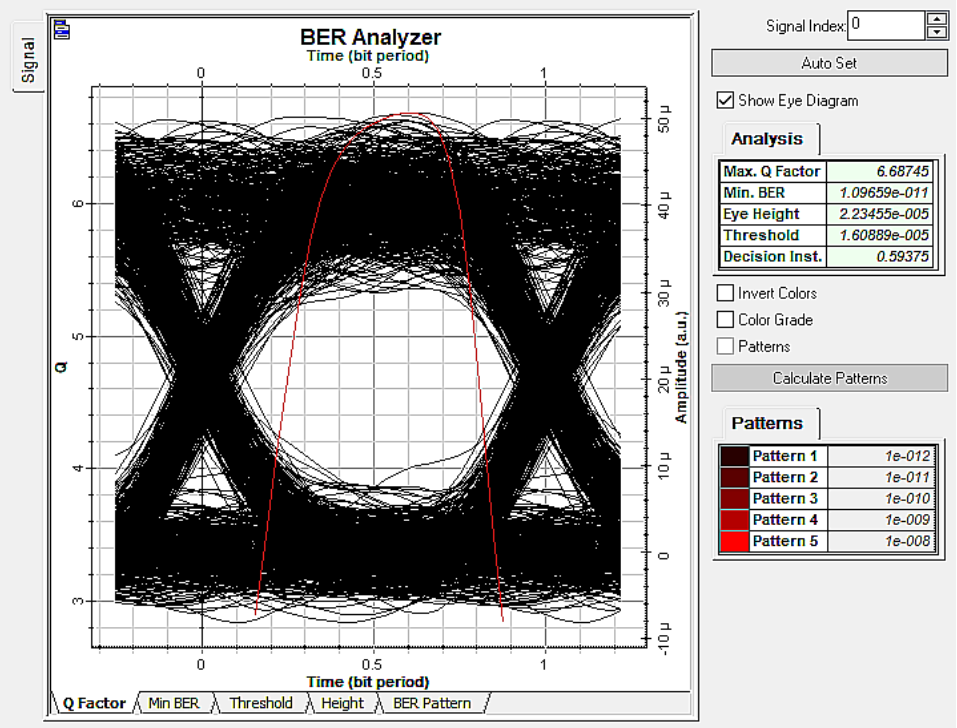
☑ Show Eye Diagram

Max. Q Factor	3.77471
Min. BER	7.90361e-005
Eye Height	4.18936e-006
Threshold	9.33659e-006
Decision Inst.	0.625

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Figure 10: Eye Diagram of 8×8 MIMO FSO system in heavy rain at a distance of 1.79 km



Signal Index: 0

☑ Show Eye Diagram

Max. Q Factor	6.68745
Min. BER	1.09659e-011
Eye Height	2.23455e-005
Threshold	1.60889e-005
Decision Inst.	0.59375

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Figure 11: Eye Diagram of 16 × 16 massive MIMO FSO system in heavy rain at a distance of 1.79 km

6. CONCLUSIONS

In this work, the performance of a massive MIMO FSO system in various turbulent weather conditions is analysed and the optimum parameters in these conditions are obtained. The optimum transmission rate for the system is found to be 40 Gbps. The simulation is done with a $16x16$ array of antennas. More number of antennas could have been used which could give better results. However, the antenna number is selected to be 16 for both transmitter and receiver by considering cost-efficiency. In this proposed system, the Gamma- Gamma distribution model is used to characterize the atmospheric turbulence.

The performance of the system was analyzed in terms of BER, quality factor, source power, and receiver sensitivity. The performance has been graphically shown by power penalty and receiver sensitivity plots. In case of haze, a date rate of 40 Gbps is obtained with 16×16 antennas at a min BER of 10^{-10} for a transmission range of 2.97 km. For 8×8 it has been reduced to 2.53 km.

In case of moderate rain and heavy rain, similar performance is obtained at a transmission range of 2.43 km and 1.79 km, whereas the range is found to be 2.11 km and 1.6 km for 8×8 array of antennas. The proposed 16×16 system gives a satisfactory performance in turbulent weather conditions. It can serve the purpose of achieving a good transmission range at a higher data rate by overcoming the hindrance of atmospheric turbulence quite well. A noteworthy observation from the power penalty graph is that to maintain a constant BER, the source power requirement reduces to half when the number of antennas is made twice.

The receiver sensitivity also gets enhanced for the 16×16 system. In heavy rain, the receiver sensitivity is around 1 dBm for 16×16 system, while it is 2.5 dBm for 8×8 system. Another important point is that the source in this model is used in the infrared region. The performance might be enhanced by using a visible light source as the frequency range is higher in this case. However, due to issues related to health safety, it is permitted to use very low source power (up to 1 mW only) when visible light source is employed.

With such low source power, it is not possible to transmit data up to a considerable distance. So, further research is needed to devise a massive MIMO FSO system using a visible light source that may provide significant transmission performance. In addition to this, different modulation schemes and higher order modulation techniques might be employed to design a more robust massive MIMO FSO system.

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