On performance improvement and range extension of free space optical system with MIMO techniques

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In this paper 2×2 multiple input multiple output (MIMO) and 4×4 MIMO architectures for the FSO link have been presented and compared with conventional FSO link. The performance has been analysed in terms of the Q-factor and BER. The parameter values and environmental conditions are kept the same for all system configurations. The key objective of this work is to use MIMO technology to improve the system performance in free-space optical communication (FSO). MIMO takes advantage of the receiver's spatial diversity by receiving several independent copies of the same signal at the receiver. In this work, the particular focus is on designing suitable MIMO FSO systems and analyzing the performance of the free space optic system. Only 4×4 MIMO configurations yield acceptable Q-factors (>6) and BER(< 10^{-9}) up to the 670 m range. Whereas the 2×2 MIMO system is capable of providing acceptable BER and Q-factor up to 630 m range. Both the MIMO techniques provide a significant range extension than the FSO system without MIMO where a maximum allowed range of 580 m is observed.

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1. Introduction

Free space optical communication (FSO) is a promising innovation that is considered as another option innovation to the radio frequency (RF) Communication system. In FSO the carrier is light and due to the high-frequency carrier, the data-carrying capacity of the link increases manifolds as compared to RF systems. Free Space Optical (FSO) Communication has evolved to meet the increasing demand for high-speed communication over long distances [1]. Free Space Optics (FSO) communications, also known as Free Space Photonics (FSP) or Optical Wireless, FSO is an optical communication technique that wirelessly transmits data by propagating light in free space (air, outer space, vacuum, or something similar). FSO can transmit data, audio, and video at a high data rate, enabling optical communication without the use of optic fibre cable or the purchase of spectrum licences. Typically, FSO works between the wavelength bands of 780 and 1600 nm [2]. FSO system has three stages: a transmitter that transfers optical signal through the atmosphere according to Beer-Lamberts law, a free space transmitting channel that contains turbulent eddies (cloud, rain, dust, fumes, temperature fluctuations, fog, and aerosol), and a receiver that processes the signal obtained. The use of lasers is similar to optical communications over fibre-optic cables, except for the transmitting medium. Since light travels quicker through the air than through glass, FSO can be considered as optical communication system working at the speed of light. Radio relay link line-of-sight (LOS) communication systems are being replaced by FSO communication. Its data transmission technology uses lasers to move information in free space from one point to another. FSO have numerous merits, like high information rate, simple organization, Low bit error rates (BER), low estimation cost and permit free frequency spectrum, high-security and installation of FSO system is quick and easy. It uses an invisible and eye-safe signal, also provide Immunity from electromagnetic interference. FSO is used for point to point LOS link communication.

Moreover, regardless of their significant merits, there are some demerits, that free-space optical (FSO) communication systems get degraded by atmospheric turbulence, absorption, scattering, diffraction, and misalignment. Additionally, it has many challenging issues, like building–sway, weather conditions such as rain, fog, sparkle, scintillation. This results in a reduction of practical capacities moreover; the main challenge is the variation of optical intensity. Indeed, even in the clear weather condition, scintillation is there, which is categorized into atmospheric turbulence this results in the fluctuation of intensity of the received signal and this deteriorates the performance of the system. Multiple input multiple-output (MIMO) is a practical technique for transmitting and receiving several data signals over the same radio channel at the same time by using multipath propagation.

To improve the system performance of FSO, multiple-input multiple-output (MIMO) technology is a potential solution that can be introduced. This would improve the data capacity by using spatial multiplexing by increasing the number of transmitting and/or receiving antennas. Multiple transmitters and receivers (MIMO) can be used in various weather conditions to boost the efficiency of the communication system (FSO) decreasing BER and improving transmission throughput. The key objective of this work is to use MIMO technology in FSO to solve the problems in free-space optical communication (FSO).

In this work, the particular focus is on designing the MIMO FSO systems to analyse the performance of (MIMO) configurations in free-space optical communication. In the present work, the OptiSystem software is being used for simulating the MIMO FSO link. The results for the MIMO FSO case are compared as a result of a free space optical link with a single input and single output free space optical link (SISO-FSO). The performance evaluation of the 2×2 MIMO and 4×4 MIMO-FSO system is carried out. The performance improvement with the implementation of MIMO FSO over the FSO link will be presented. MIMO takes advantage of the receiver's spatial diversity by receiving several independent copies of the same signal at the receiver, hence the performance will be analysed by the received power, the bit error rate (BER) and Q- factor. From the measured data, the system efficiency will be calculated, which is the main factor for quality and estimation for the reliability and availability of the FSO link.

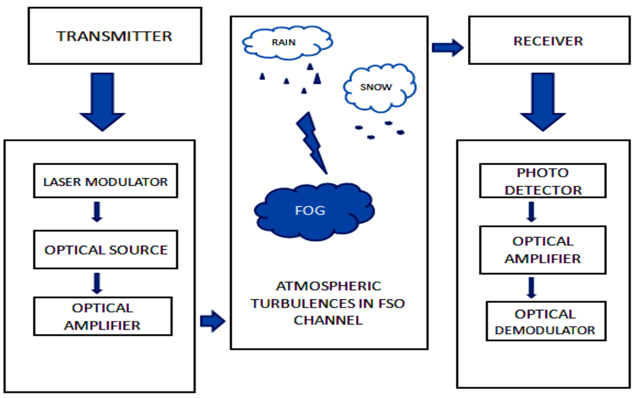


Fig. 1. Block Diagram of Free Space Optical Communication (FSO)

Fig. 1 illustrates how FSO works, there are three segments initially there is a transmitter, FSO channel and receiver. At the transmitter side, the data is transmitted through a laser modulator which comprises optical transporters for example LASER/LED. Generally, we use the laser at the transmitter side due to different potential benefits over the LED. Data via free-space is detected by the receiver observed by a photo-detector and the data is forwarded to the destination by filtration, amplification and demodulation of the data [3].

2. Literature Review

In this section an overview of the literature related to FSO and MIMO is presented. Mingboniu proposed a coherent multiple-input multiple-output architecture for optical communication (OWCs) to reduce atmospheric turbulence effects. They demonstrated the error rate performance of MIMO FOR various turbulence conditions and also compared to the performance of a coherent SISO link. It was also observed that coherent MIMO technology can effectively mitigate atmospheric turbulence with both maximal ratio combining (MRC) and equal gain combining (EGC) Diversity techniques, and can outperform coherent SISO systems significantly" [4]. Analysis of the performance of the FSO communication system is studied by Mansour et al. (2017) in which they defined many challenges and limits of the FSO system. In a similar way, the models of the channel in the FSO system have been checked and classified by Miglani and Malhotra (2017), Yang and Cheng (2016), and Anbarasi et al. (2017) according to channel turbulence level. A. Kadhim et al. (2017) has presented a (SISO over MIMO) FSO communication channel that was simulated and compared. in which they analyzed the design of MIMO FSO link for different weather conditions, where they evaluated power loss for link due to various weather conditions by using Optisystem software and they compared Q-factor, received power, and bit error rate (BER) for different system attributes. The authors conclude on the basis of their result that MIMO improves the performance of the FSO system; therefore, the power received is also improved [5]. The performance of WDM-MIMO in the free-space optical system under atmospheric turbulence is analyzed by A. Ahmed et al. (2019) [6]. They proposed four FSO models i.e. FSO-WDM, FSO-MIMO, and FSO-WDM-MIMO in the turbulent atmosphere and they concluded that in the case of haze weather conditions (FSO-MIMO) provided much improved results than the other three models and similarly FSO-WDM-MIMO has the greatest values compared to FSO-MIMO for higher range value in same weather conditions. A. Kashani et al. (2015) [7] analyzed the bit error rate (BER) performance of single-input multiple-output (SIMO), multiple-input single-output (MISO) and multiple-input multiple-output (MIMO) FSO systems where they consist intensity modulation/direct (IM/DD) detection with on-off keying (OOK) over gamma-gamma turbulence channel they shown the spatial diversity improved the system performance and carry incredible performance gain over SISO system. Similarly, the performance improvement of FSO system using the MIMO technique was investigated by Arjun Dubey et al. They analyzed MIMO-FSO and SISO-FSO communication systems with Non-Return to Zero (NRZ) modulation and Avalanche Photodiode (APD) to assess the BER performance for different atmospheric turbulences. They demonstrated a stimulation setup of 1 km communication link with NRZ line code, 1550 nm wavelength and APD receiver for various atmospheric conditions [8]. Ali Khalighi et al. described outdoor terrestrial OWC link which operates in the near IR band, they also compared modulation schemes that are genrally used in FSO systems. Out of these presenetd schemes, some are shown in Table 1 [9].

Table 1. Comparison of modulation schemes [9]

Modulation Scheme	Observations
OOK [10]	Dynamic threshold is at required receiver side
PPM [10][11]	Most select in terms of energy efficiency
MPPM [12]	Lower PAPR and more effective than PPM bandwidth
PWM [11]	Requires less peak power, greater spectral efficiency, and greater ISI resistant than PPM
PPMPWM [11]	Efficiency of power and bandwidth between PPM and PWM
DPIM [13][10]	No need to symbol synchronization, more bandwidth efficient than PPM and PWM
DPPM [11]	Symbol synchronization easier and bandwidth efficiency improved than MPPM
OPPM [14]	Efficient than PPM bandwidth
PAM (Multilevel) [10]	Higher bandwidth efficiency than PPM, need dynamic receiver threshold
SIM [15]	High capacity, effective deployment, low power efficiency

The outage probability (OP) and the average bit-error-rate (BER) of multiple-input multiple-output (MIMO) free-space optical (FSO) system with maximal ratio combining (MRC) diversity technique over Gamma–Gamma (GG) fading channels with generalized pointing errors modelled by the Beckmann distribution is studied by Yulong Fu et al. They stated a probability of closed-form high signal -to -noise ratio (SNR) density function (PDF) for MRC scheme which is derived by inverse Laplace transform in term of the h by inverse Laplace transformation process [16]. Robert W et al. proposed the analog–to–digital converters (ADCs) a significant part of the total consumption in a massive MIMO base station. They focus our attention on the analysis of the spectral efficiency of single-carrier also OFDM transmission in a massive MIMO system that uses one–bit ADCs [17]. The 5G system communication based on free-space optics is implemented and its system output is evaluated with various influencing factors such as link range, beam divergence is analyzed by M Sumathi et al. They compared the previous model with the proposed modified model with the use of maximum quality factor and various optical filters have been built with the modified model these experiments have also been linked with the numerical equation of the transfer function of different filters [18]. They proved that the maximum quality factor could be improved by using Gaussian optical filters. To combat turbulence-induced fading, a polar-coded multiple-input multiple-output (MIMO) free-space optical communication (FSO) was proposed by Jiafei Fanget et al. [19]. In this polar-coded MIMO FSO system, spatially correlated fading dominated the MIMO FSO system. Further, they examine the ergodic capacity of the gamma-gamma modelled MIMO FSO turbulence channel with and without spatially correlated fading. They proved that the polar-coded multiple optical sources scheme is durable to the spatially correlated turbulence by using ergodic capacity and Monte Carlo simulation. According to the literature, various atmospheric turbulence degrades FSO system performance, and numerous elements such as scintillation alter the intensity of data signal. As a result, a new technology that overcomes the limitations of FSO is required, and it must be investigated in the near future in order to maximise the benefits of a wireless optical link. As a result, we presented an FSO MIMO configuration in this work to address some of the FSO system issues.

3. System description

The Optisystem V.13 simulator has been used to simulate the proposed schematic FSO models. In this section, the block diagram representation for the various proposed schematics is discussed. The research has been carried out on three different models: the free space optical single-input-single-output (FSO-SISO) system, the free space optical using 2×2 MIMO system, the free space optical using 4×4 MIMO system. Fig. 2 shows a schematic diagram of the free space optics system. The diagram consists of three major components: a transmitter system, a receiver system, and a transmission channel. Four modules comprise the transmitter system. The PRBS (Pseudo-Random Binary Sequence) generator is the first module. The Non-Return-to-Zero (NRZ) encoder is the second module, which encrypts data. The optical transmitter is the third module (laser generator).

The receiver side comprises an avalanche photodiode (APD), optical amplifiers, a filter (Law Pass Bessel Filter) to filter out unwanted high-frequency signals, and a 3R regenerator to evaluate the electrical signal. The receivers are direct sensing instruments that monitor the collected optical field's instantaneous power as it enters the receivers.

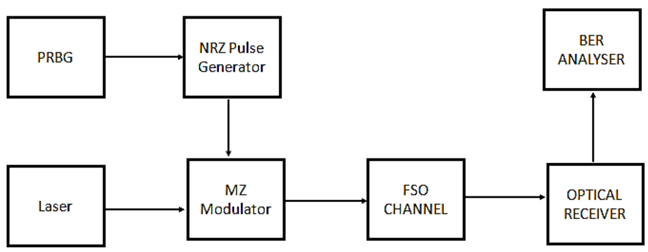


Fig. 2. Schematic diagram of free space optics

A pseudo-random bit generator generates logical signals, such as 1010, and sends them to the NRZ pulse generator. The NRZ pulse generator's job is to convert a logical signal into an electrical signal, which is then passed on to the Mach Zender Modulator. This modulator takes two inputs: an electrical signal from the NRZ pulse generator and a carrier signal from a continuous wave laser. Because the system is based on free-space optics, the major role of this modulator is to convert electrical signals into optical signals. This modulator now sends the optical signal along with the carrier signal to the photodetector through the FSO channel. The received optical signal is then converted to electrical form and passed to the LPF by the photo-detector. The signal has now been filtered to remove any unwanted signals from the electrical signal that is sought. The output signal's errors and power can be measured using a BER analyzer and an electrical power meter, respectfully [16].

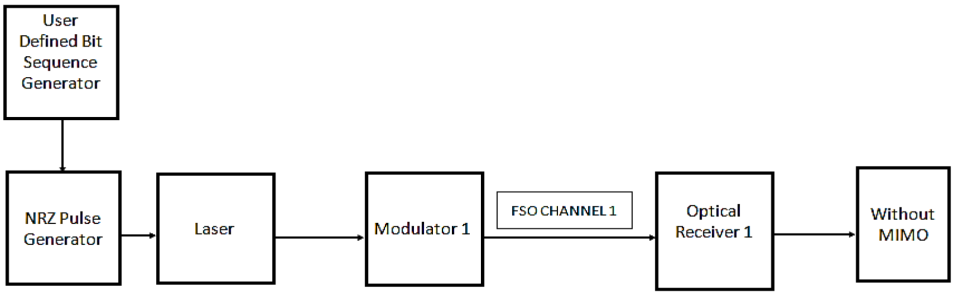


Fig. 3. Simulation layout of FSO system

For creating the MIMO FSO system the bits which are to be transmitted are modulated on two lasers of the same carrier wavelength and are transmitted individually through the FSO links. The same information travels through 2 separate paths, which provides special diversity. The individually received signals at the receiver side are added together to create a 2×2 MIMO receiver as shown in Fig. 4. The bit error rate is calculated by comparing received bits to the sent bits. A similar approach is used to create the setup for the 4×4 MIMO FSO which is shown in Fig. 5.

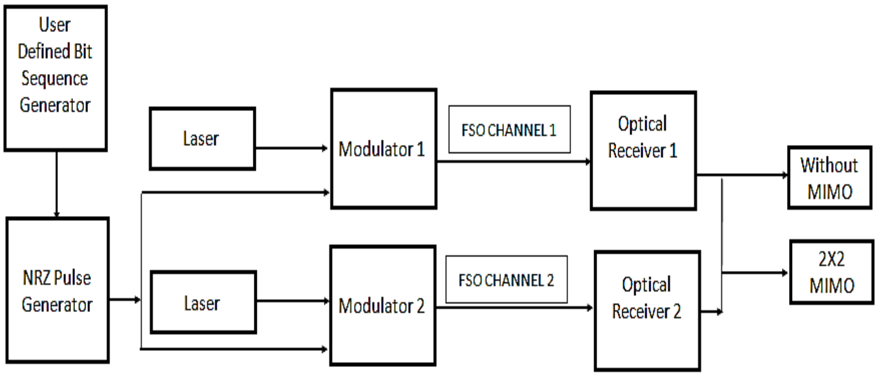


Fig. 4. Simulation layout of (FSO 2×2 MIMO) system

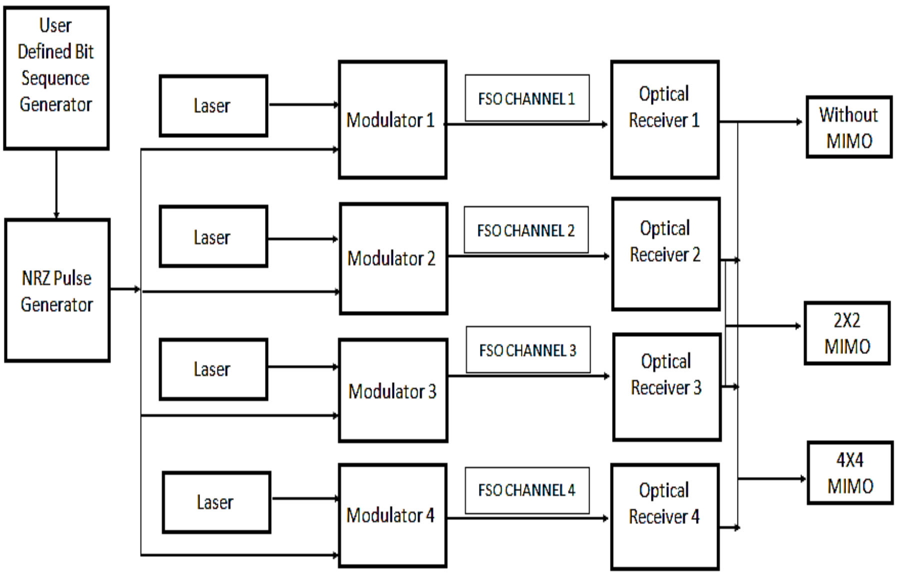


Fig. 5. Simulation layout of (FSO 4×4 MIMO) system

Instead of 2TX/2RX, we use 4TX/4RX. MIMO takes advantage of spatial variation by receiving multiple individual copies of the same signal at the receiver, increasing the signal-to-noise ratio. Via spatial diversity, MIMO technology not only increases data rate but also improves device reliability Fig. 5 depicts the 4TX/4RX configuration.

4. Simulation results and performance analysis

In free-space optical communication, the most commonly used wavelength ranges are from 850 to 1550 nm. In this study, we focus on the 1550 nm wavelength since it can handle high data rates while also reducing the solar background. The effects of Max Q factor and Min BER for FSO-SISO, FSO 2×2 MIMO, FSO 4×4 MIMO and a table of parameters are presented in this portion. Table 2 shows the values of the different parameters which are used in Optisystem setups.

Table 2. Values of the different parameters used in optisystem setups

Parameters	Values
Wavelength	1550 nm
Laser Power	5dB
Sequence length	128bits
Sample per bit	64
Transmitter aperture	5 cm
Receiver aperture	20 cm
Bit rate	10×10^9 bits/s
Signal format	NRZ
Attenuation	25 dB/km

Fig. 6 shows the relation between range and Q – factor. The system Q factor should be at least 6 for acceptable transmission. It is observed from the figure that by using 2×2 MIMO configuration, the max Q-factor obtained is 30 at 450 m, while without MIMO configuration, the max Q-factor obtained is 20 and similarly the max Q-factor obtained is 44 for 4×4 MIMO configuration which is the highest Q-factor obtained as compared to other configurations. At the 650 m range only 4×4 MIMO configuration provide acceptable Q-factor whereas 2×2 MIMO and conventional FSO configuration, provide Q-factor below 6 which is not acceptable. It could be observed that the 4×4 MIMO FSO system has the highest Q factor as compared to the conventional and 2×2 MIMO systems. Hence MIMO technique enhances the system performance

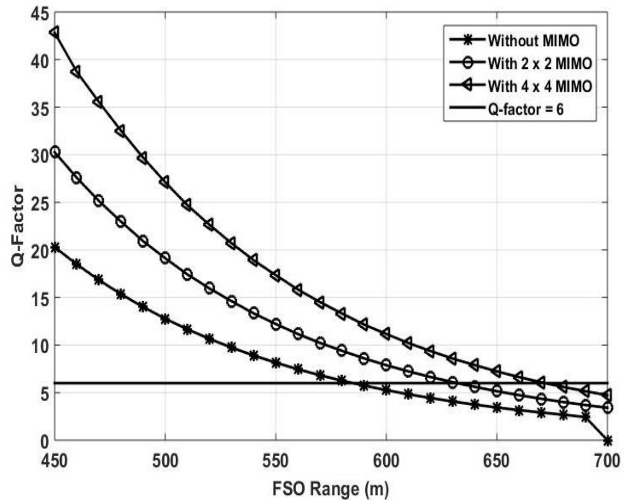


Fig. 6. Graphical comparison of without MIMO, 2×2 MIMO FSO & 4×4 MIMO FSO with respect to Q-factor vs. Range

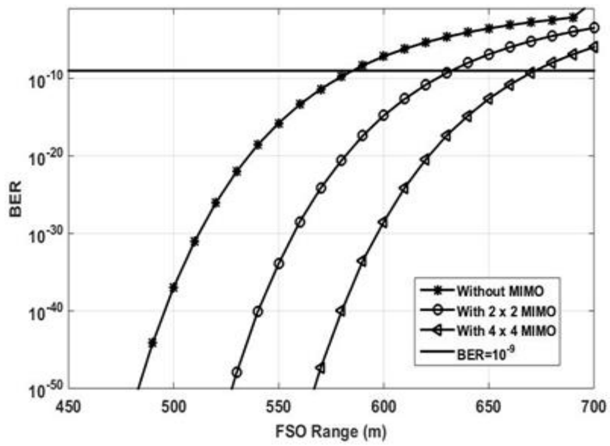
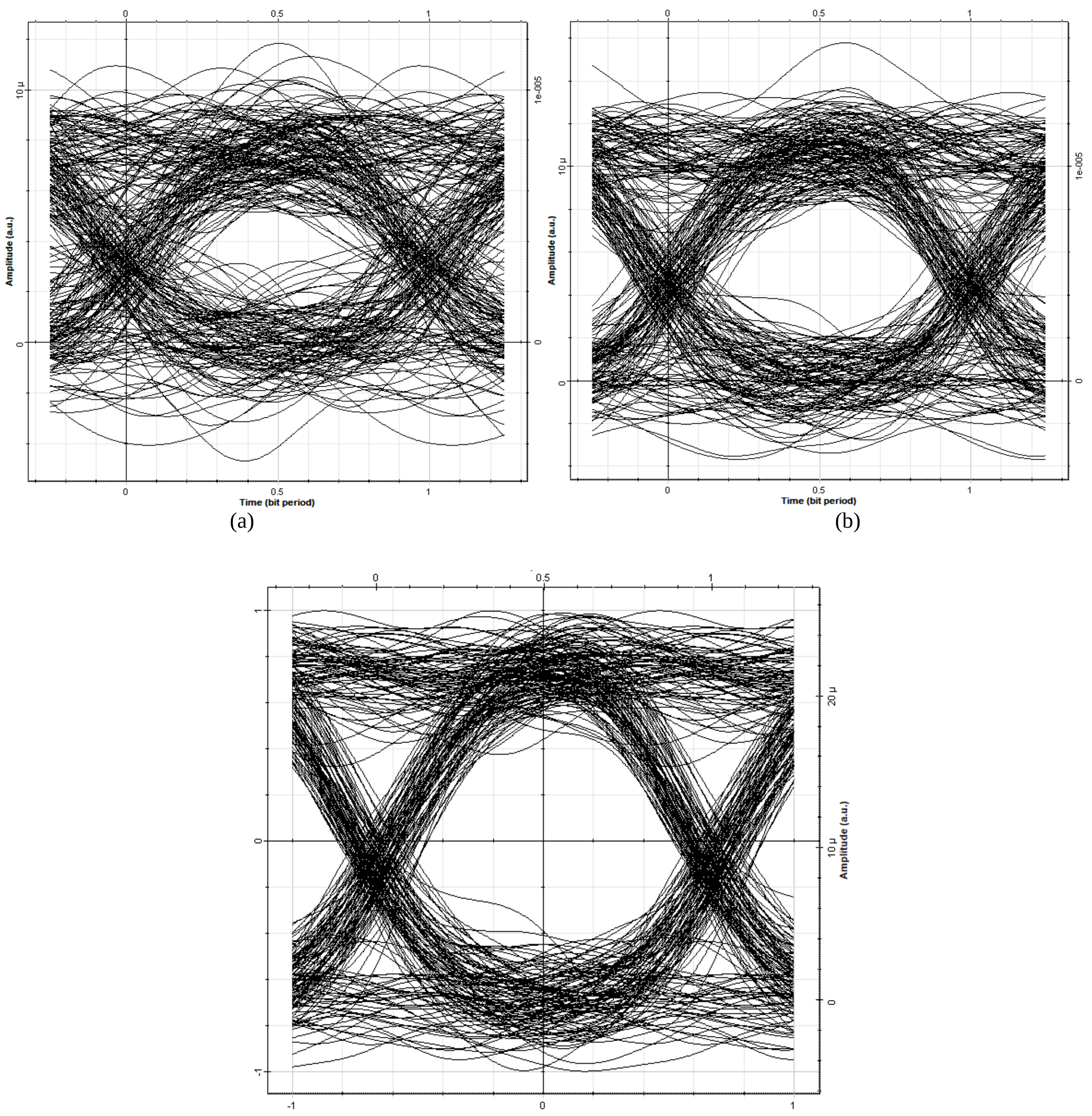


Fig. 7. Graphical comparison of without MIMO, 2×2 MIMO FSO & 4×4 MIMO FSO with respect to Range vs. BER

Fig. 7 depicts the relation between range and BER. For acceptable transmission, the system BER should be lower than 10^{-9}. Similar to the case of the Q-factor, it is observed from the figure that the BER performance improves as the number of antennas increase. At the 650 m range, only 4×4 MIMO configuration provide acceptable BER where 2×2 MIMO and without MIMO configuration, provide Q-factor below 6 which is not acceptable. The 4×4 MIMO FSO provides a maximum link length of 670 m whereas for 2×2 MIMO FSO the maximum allowed link length is 630 m. The convention FSO without MIMO is only capable of providing acceptable Q-factor and BER up to a link length of 580 m. Therefore the 2×2 MIMO FSO and 4×4 MIMO FSO provide significant link length extension over the conventional FSO link without MIMO. The eye diagrams for the FSO without MIMO, 2×2 MIMO FSO and 4×4 MIMO FSO have been shown in Figs. 8 (a), 8(b) and 8 (c), respectively. It is clear that the eye-opening is best in the case of 4×4 MIMO FSO. Whereas the eye in the case of FSO is worst as compared to the MIMO FSO systems.



(a) (b)

(c)

Fig. 8. Eye diagrams at the 680m range for (a) FSO without MIMO (b) 2×2 MIMO (c) 4×4 MIMO

5. Conclusion

According to the findings, MIMO techniques were utilized to improve the system's efficiency. In this situation, the best design was achieved by using a free-space optical system with 4×4 MIMO with a wavelength of 1550 nm. At 450 m range, the maximum Q-factor obtained for without MIMO is 20, while the maximum Q-factor obtained with a 4×4 MIMO system is 44. Only 4×4 MIMO configurations provide acceptable Q-factors and BER at the 650 m range. However, 2×2 MIMO and without MIMO configurations provides Q-factors of less than 6, which is unacceptable. The 4×4 MIMO FSO system provides the highest Q factor as compared to the 2×2 MIMO system and FSO system without MIMO. As a result, the MIMO approach improves the system's performance. From the results and observations, the 4×4 multiple input multiple output free-space optical (4×4 MIMO FSO) system provides significantly lower bit errors than those observed in the case of FSO without MIMO and 2×2 MIMO FSO. The maximum reach lengths of 680 m, 580 m and 530 m have been observed for the 4×4 MIMO

FSO, 2×2 MIMO FSO and convention FSO system, respectively.

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