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Performance Analysis of Double-MIMO Free Space Optical System under Atmospheric Turbulence

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ABSTRACT

Over the last few years, free space optical communication (FSO) has emerged as a viable alternative to radio frequency communication. It provides a promising high-speed point-to-point communication solution. However, atmospheric absorption, scattering and turbulence degrade wireless optical communication significantly, lowering device efficiency. The attenuation of signals due to the above atmospheric reasons is another major factor that affects device efficiency. The atmospheric turbulence conditions are observed implemented into different models of FSO systems, such as Single Input Single Output (SISO), Multiple Input Multiple Output (MIMO), Wavelength Division Multiplexing MIMO (WDM-MIMO) and proposed model Double Multiple Input Multiple Output (DMIMO) using the Gamma-Gamma model for a variety of reasons. The OptiSystem 7.0 software was used to run simulations to study how various weather conditions (clear, haze and fog) affected the performance of the channel. Simulation results show that implementing Double Multiple Input Multiple Output (DMIMO) techniques for FSO systems provides high quality factor for various ranges while still achieving accurate transmitted data at the receiver side. In the presence of atmospheric turbulence conditions such as clear air, haze and fog, performance improvements signal power levels, quality factor and link distance range have been demonstrated.

Keywords: atmospheric turbulence, free space optical communication, Gamma-Gamma modelling, multiple-input multiple-output, on-off keying

1. INTRODUCTION

Free Space Optics (FSO) is an optical wireless communication technology that sends data between two points by using light. Optical communications, which use visible and infrared wavelengths to transmit high-speed data optically wirelessly across the atmosphere, is thought to be more powerful technology [1], [2]. In the field of wireless networking, FSO communications has emerged as a game-changing technology. The enormous increase in the amount of data transfer across the world, as well as the resulting increase in bandwidth requirements, has given rise to this technology. Optical fibre is without a doubt the most dependable mode of optical communication. However, the cost of laying fibre is typically prohibitively high because to the digging, delays, and other costs [3]. FSO's main characteristics, such as rapid data transmission, faster implementation, cost-effective infrastructure, and data rates of tens of gigabytes per second, make it a viable short-range radio frequency (RF) link alternative [4], [5]. The underlying mechanism of FSO transmission is identical to fibre optic communication, except that instead of using a directed optical fibre, the modulated data is transferred through an unguided channel [6].

Despite their numerous benefits, they have a number of significant drawbacks that limit their obstacles; geometrical losses such as beam spreading attenuation and signal power loss;

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widespread adoption. Physical obstructions such as flying objects, buildings, and natural absorption of photon power from the signal by water molecules in the atmosphere; and atmospheric turbulence and attenuation are among the most common. Atmospheric turbulence is one of the most concerning of these [7]–[9]. The free-space medium is particularly sensitive to scattering, attenuation and turbulence for long-distance communication with a link range exceeding 1km. Fading (or scintillation), which is caused by variations in the refractive index caused by inhomogenieties in temperature and pressure changes, is a significant impairment that severely degrades the FSO link performance. Link distance and weather conditions such as temperature and light, heat, fog, snow, smoke, haze, and rain can all affect the quality and output [10]–[12]. Figure 1 depicts the impact of restrictions on the atmosphere. These problems, particularly scintillation or turbulence, must be addressed in order to optimize system performance. As a result, the principles of MIMO and double carrier MIMO must be established in order to manage transmission under both heavy and weak atmospheric turbulence.

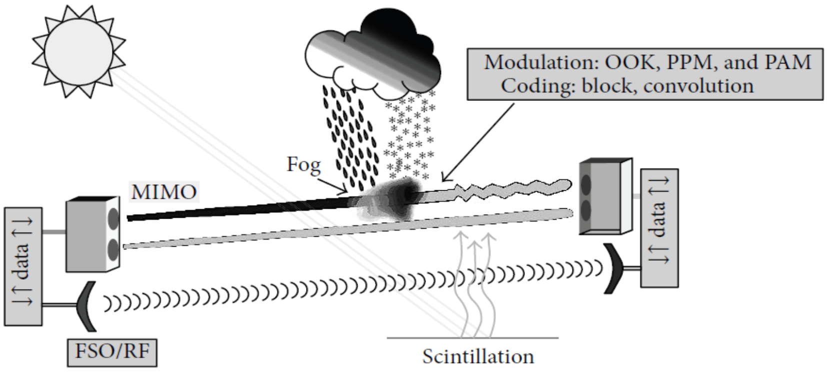

Figure 1. Effects of the atmosphere on the FSO system [7]

In this paper, we analyze the performance of FS0-Multiple Input Multiple Output (MIMO) and Double MIMO (DMIMO) systems with Non Return to Zero (NRZ) and PIN photodiode on the receiver side which is then connected to the generator, hence the performance is analyzed in terms of received signal power, bit error rate (BER) and quality factor under various weather conditions. Also, we compare the results with Wavelength Division Multiplexing (WDM) FSO-MIMO and Single Input Single Output (SISO) techniques. The remaining part of the paper is organized as follows. The mathematical model is presented in Section 2. The simulation and the observations are made in Section 3. Section 4 includes discussion along with concluded remarks.

2. MATERIAL AND METHODS

2.1 Free Space Optical (FSO) system

For information to be transmitted from one location to another, free-space optical communication requires a line-of-sight link between the transmitter and receiver. The information signal from the source is modulated on the optical carrier, which is then permitted to propagate toward the receiver over the atmospheric channel or free space rather than guided optical fibres [13], [14].

A laser beam is used in free space optics to transmit very high bandwidth data from a source to a destination over the free space atmospheric channel. As indicated in Figure 2, the FSO system comprises of three primary functional elements: transmitter-receiver and atmospheric channel. The data signal is modulated by a modulator using the most popular method, intensity modulation, and the electrical signal is transformed into an optical signal using an optical source such as an LED or LASER at the transmitter. It propagates to the receiver across free space and transmits data at rapid rates. Light sources used in optical communication must have the required wavelength, line width, modulation bandwidth, and numerical aperture [15], [16].

Because the FSO communication channel uses the atmosphere as its propagating medium, it is influenced by unpredictably changing weather conditions such as cloud, snow, fog, rain, and so on. The received signal is attenuated and deteriorated as a result of these effects, which have no fixed features. One of the limiting variables in the performance of the FSO system is the channel [17], [18].

The transmitted beam is received by the receiver lens and transformed to an electrical source by a photo detector and pre amplifier circuit on the receiving side. To obtain the transmitted data, a demodulator demodulates the electrical signal [19].

2.2 Atmospheric Turbulence Model

The absorption of solar radiation by the earth's surface causes the air surrounding it to become warmer and less dense, causing temperature fluctuations. Turbulent inhomogeneities can be visualized as discrete cells or eddies of differing temperatures that act as refractive prisms of different sizes. Using the magnitude of index of refraction variance and inhomogeneities, atmospheric turbulence is classified into regimes. These regimes are categorized into three stages based on the distance travelled by optical radiation through the atmosphere: weak, moderate, strong and saturation. Signal fading and system efficiency degrade as a result of this turbulence [20], [21].

The statistical channel model is measured as follows:

$$y = sx + n = {}^{\eta}Ix + n \tag{1}$$

where y is the signal at the receiver, $s = {}^{\eta}I$ is the instantaneous intensity gain, and ${}^{\eta}$ is the effective photocurrent conversion ratio of the receiver. I is the normalized irradiance, x is modulated signal and n is the AWGN with zero mean and variance $N_0/2$ [22].

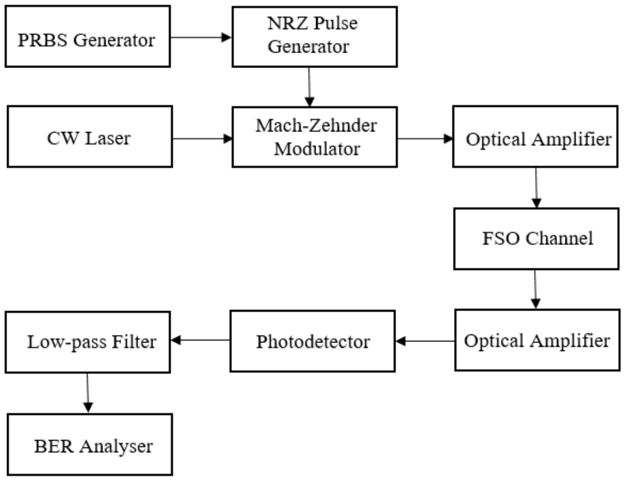

Figure 2. Block Diagram of FSO system

2.3 Gamma-Gamma Turbulence Model

The Gamma-Gamma model is known to have weak to strong turbulence, with the PDF of its intensity I being the product of two gamma random variables, suggesting variations from large and small turbulence. X and Y represent the two random variables. I=XY is the acquired intensity I. The PDF of I is provided by [22], [23],

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

where α is the number of large eddies, β is the number of small eddies, I the irradiance, $\Gamma(.)$ is the Gamma function and $K(\alpha, \beta)$ is Bessel function of second order. α and β given by equation [13], [24].

$$\alpha = \left\{exp\left(\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{12/5}\right)^{7/6}}\right) - 1\right\}^{-1}, \ \beta = \left\{exp\left[\frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{5/6}}\right] - 1\right\}^{-1} \tag{3}$$

The parameter σ_R^2 is the Rytov variance, assuming plane wave propagation it is given by,

$$\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} L^{\frac{11}{6}} \tag{4}$$

where L is the link length, $k = 2\pi/\lambda$ is the optical wave number and C_n^2 is the altitude-dependent index of the refractive structure parameter determining the turbulence strength. Typically C_n^2 varies from 10^{-17} to 10^{-12} according to the strength of atmospheric turbulence. To simplify, σ_R is used as a metric of turbulence strength which is combination of distance, wavelength and parameter C_n^2 [23], [25].

2.4 MIMO Wireless Channel

MIMO technology is the most commonly used wireless communication technology because it improves data throughput while also increasing link range without increasing bandwidth or transmitted power. It transmits the necessary power through the antennas to achieve array gain, which improves spectral efficiency. The reliability of the link is enhanced, and the fading effect is minimized at the same time. For these benefits, MIMO technology has become an integral part of today's wireless systems. The Mathematical expression for a MIMO channel is as follows [26]:

$$y = Hx + n \tag{5}$$

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

2.5 System Design Model

FSO channel is designed in OptiSytem in the presence of atmospheric disturbances. Two units of MIMO channel are used to boost the link efficiency of the FSO. The wavelength range for FSO is from 850nm to 1550nm. Rayleigh scattering causes attenuation that is inversely proportional to wavelength, so the transmitted wavelength is chosen to be 1550nm. To achieve the lowest scattering attenuation, the longest wavelength of 1550nm is chosen. Increased bit rate optical signals are a better alternative for higher output and lower bit error rate [27], [28]. Although no particles are thought to be in the path of light, fog and haze particles are seen. To compare the performance of SISO, MIMO, WDM-MIMO and DMIMO systems in a simplified manner, the total transmitted power is presumed to be the same.

2.5.1 Transmitter

It is composed of four components. The first is pseudo-random bit sequence generator (PRBS). This generator portrays the data or knowledge that must be transmitted. After PRBS the output signal is transferred to an NRZ pulse generator, which generates the coded signals. The 0.05 bit NRZ generated pulse's fall and rise edges. The output light signal is modulated by optical modulator. A continuous wave (CW) laser with a power level of 10dBm is assumed to be the optical source. SISO, 2X2 MIMO, WDM-MIMO and 2x2 DMIMO are used in this model.

2.5.2 Optical Wireless Channel

The FSO channel is varied in OptiSystem software between an optical transmitter and optical receiver with an 8cm optical antenna and 2.5cm optical antenna. The transmitter and receiver gain assumptions are 0dB. The receiving and transmitting antennas are considered to be ideal, with no pointing errors and a 100 percent optical efficiency.

2.5.3 Receiver

A photodiode, a low pass filter, a visualizer and a generator make up the receiver. The photodetector used in this work which is PIN photodiode has responsivity of 1A/W and dark current of 10nA. The received signal is then limited in bandwidth by passing it through low pass Bessel filter with cutoff frequency of 75% of the bit rate. For BER evaluation, the 3R regenerator is used to regenerate a modulated electrical signal identical to that generated by the transmitter as well as an electrical signal with the same original bit series. The generator's output is related to the eye diagram analyser, which provides the minimum BER, eye height, maximum Q-factor and threshold.

2.6 FSO Systems

2.6.1 SISO FSO Systems

The transmitter, FSO channel, and receiver are the components of an FSO system. Laser source of 1550nm, Non-Return to Zero (NRZ) pulse generator, Pseudo Random Bit Sequence (PRBS) generator and Mach-Zehnder (MZ) modulator are the elements included in transmitter. The PIN photodetector receives optical signals from the FSO channel.

2.6.2 MIMO FSO Systems

Two different MIMO systems can do optimal designing in FSO. FSO system increases communication efficiency by using two transmitters and two receivers. The use of multiple transmitters and receivers improves communication efficiency. The types of MIMO systems are based on the number of transmitters and receivers. If there are two transceivers, it is known as 2x2 MIMO and when there are four transceivers, it is known as 4x4 MIMO. 2x2 MIMO system is represented in Figure 3.

2.6.3 WDM-MIMO FSO Systems

This schematic depicts the combined effect of a WDM transmitter and a 2x2 MIMO channel link. The features of the WDM transmitter and the channel attributes are comparable to those of the previous models addressed in this study. This schematic is represented as a block diagram in Figure 4. A WDM CW Laser transmitter with 16 channels and a 2x2 FSO-MIMO channel are also included in this scheme. The transmitter's bit rate is 155MHz, with a power level of 10dBm. It should be emphasised that this study used NRZ coders and a Gamma-Gamma scintillation model. There are three parts of the schematic: the transmitter side, the channel and the receiver side. The transmitter is made up of a CW laser, an NRZ coder, a MZ modulator and PRBS generator. The channel having different attenuations for different weather conditions such as clear air, haze, light fog and moderate fog.

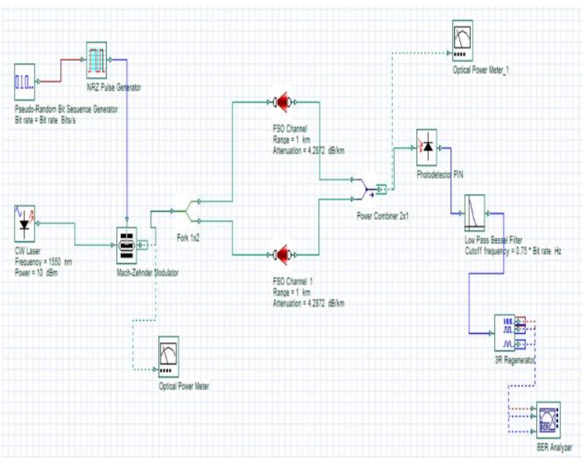

Figure 3. 2X2 MIMO FSO System

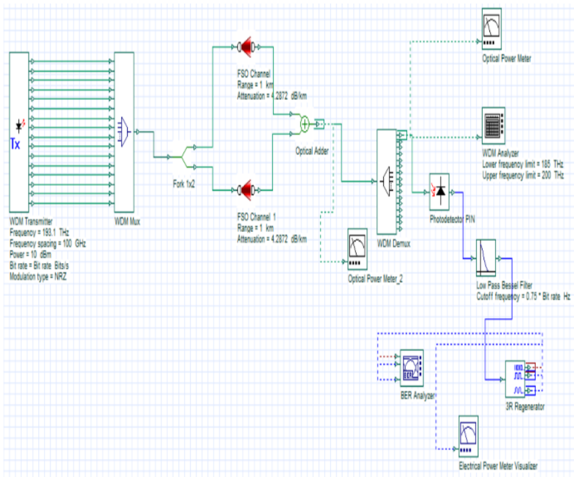

Figure 4. WDM-MIMO FSO System

2.6.4 DMIMO FSO Systems

The transmitter, FSO channel and receiver are the three basic components of any FSO system.

The transmitter consists of a laser source (650nm, 850nm and 1550nm) 1550nm chosen for this work, PRBS generator and NRZ pulse generator and a MZ modulator. PIN photodetector receives optical signals from the FSO channel. The optical power tests the power received in both dB and Watts and the BER analyser automatically calculates the BER value, Q-factor and display eye diagram in this simulation.

In Figure 5 shown simulation layout of DMIMO system with double the number 2x2 transceivers. 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 the previous component connected to it. The fork produces several laser beams, which are combined by the power combiner. At the receiver end, power is combined from the FSO channel and fed to the optical receiver. In this simulation, two visualizers were used: an optical power meter and a BER analyser. In this layout, double MZ modulator is used as the double carrier to enhance the performance efficiency of the FSO system.

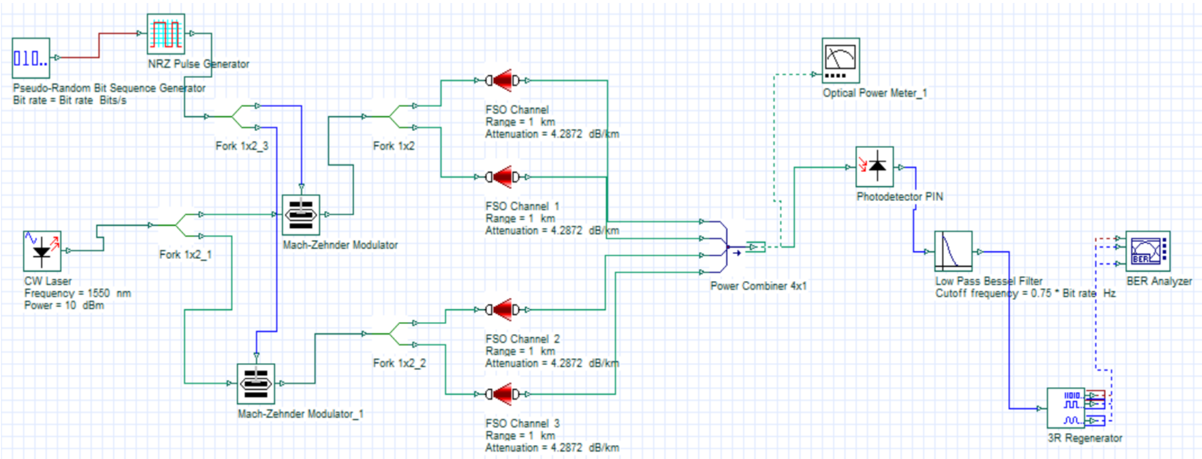

Figure 5. DMIMO FSO System

3. RESULTS AND DISCUSSION

Based on the above FSO models, analysis is done on different types of models with the aim to enhance the performance of the FSO systems. The performance of the FSO systems are measured based on the bit error rate (BER), Q-factor and signal power received. Each FSO systems are analysed under different atmospheric turbulence, namely clear air, light fog, haze and moderate fog. Data rate of 155MHz with constant optical power 10dBm applied in analysing the FSO models performances. The performance simulation of the communication link at range of 0km to 5km with NRZ line code and 1550nm wavelength and PIN photodetector as receiver is done. The model includes an optical spectrum analyser, BER analyser and optical power meter for determining the system BER and received and transmitted signal power levels.

3.1 Studying the performance of proposed schematics under attenuation of 4.2872dB/km

3.1.1 Q-factor as parameter

Figure 6 shows the Q factor against propagation range for the four FSO systems considered under turbulent atmosphere having an attenuation at constant 4.2872dBm/km. It has been observed that the Q factor to range curve for DMIMO FSO system has the highest values at lower values of range up to higher range. The trend then followed secondly by WDM-MIMO FSO system. The FSO system that has lowest value of Q factor at lower values of range and decrease down moving to the higher values of range is SISO FSO system. At range of 1km, 91.1501, 201.285, 388.811 and 1268.84 achieved by SISO, MIMO, WDM-MIMO and DMIMO FSO systems respectively under constant attenuation of 4.2872dBm/km.

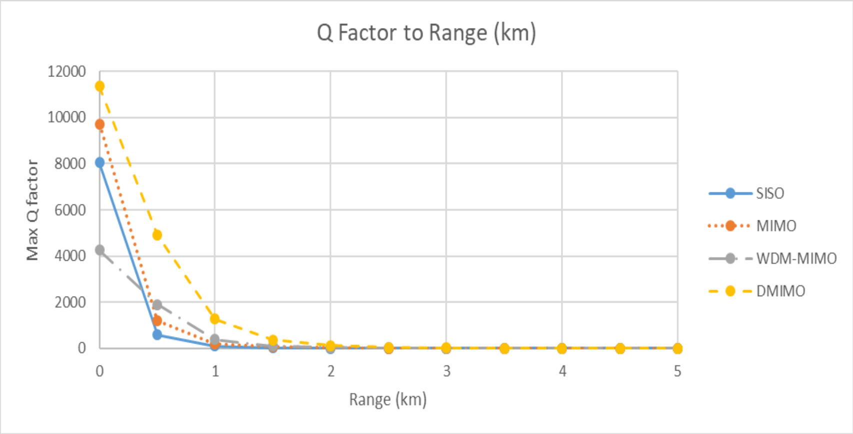

Figure 6. Q-factor to Range plot under atmospheric turbulence

3.2 Studying the performance of proposed schematics under different atmospheric conditions

3.2.1 Q-factor as parameter

The results obtained while considering Q factor for the comparison of performance are shown in Figure 7-10.

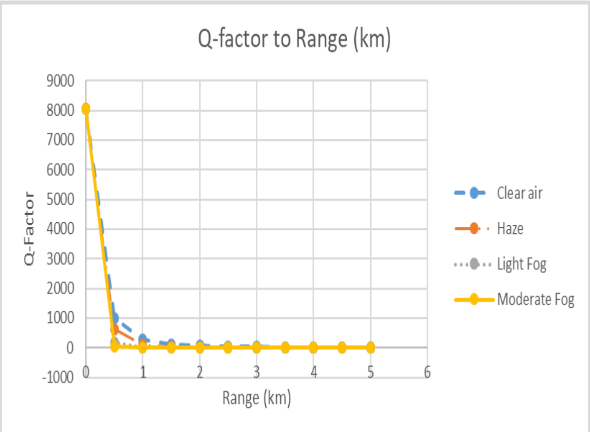

Figure 7. Q-factor to Range plot of SISO under different atmospheric conditions

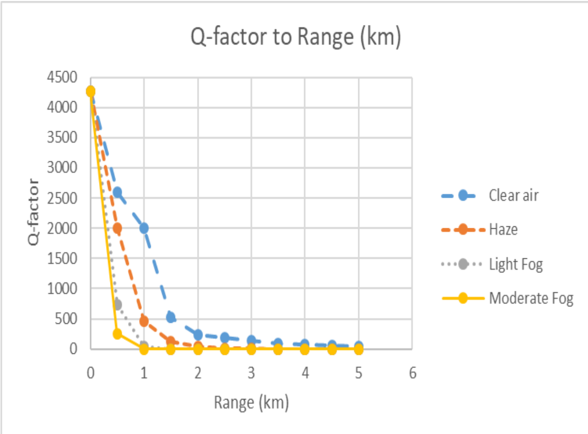

Figure 8. Q-factor to Range of WDM-MIMO FSO under different atmospheric conditions

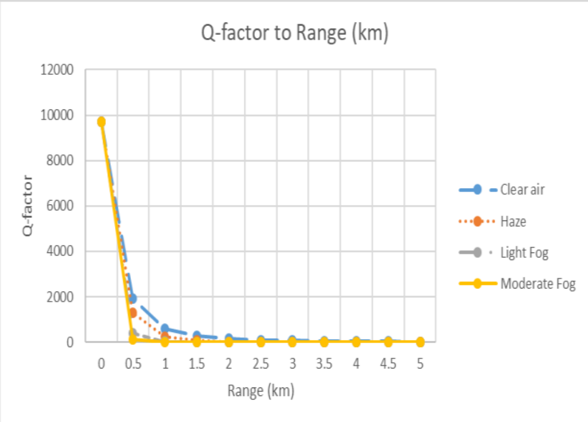

Figure 9. Q-factor to Range plot of MIMO FSO under under different atmospheric conditions

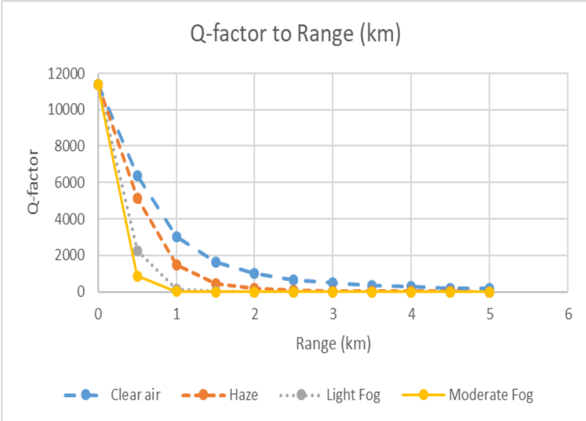

Figure 10. Q-factor to Range of DMIMO FSO system under different atmospheric conditions

Figure 7-10 shows the Q-factor to range plot of SISO, MIMO, WDM-MIMO and DMIMO FSO systems under different atmospheric conditions. Clear air with high visibility has an attenuation constant of 0.1408dBm (V=23km), haze has an attenuation constant of 4.2872dBm (V=2km), light fog has an attenuation constant of 15.5633dBm (V=0.8km) and moderate fog has an attenuation constant of 25.5291dBm (V=0.6km) [29]. An analytical comparison between the four models shows that DMIMO system has the largest value of Q-factor compares to SISO, MIMO and WDM-MIMO at lower range to higher values of range. At 1km of range, under clear air condition 274.087, 586.092, 2001.57 and 3016.35 are achieved by SISO, MIMO, WDM-MIMO and DMIMO respectively. Meanwhile under strong turbulence (25.5291dBm/km) at 1km, each models of FSO systems namely SISO, MIMO, WDM-MIMO and DMIMO achieved 0, 0, 3.66667 and 14.5377 correspondingly. It could be deduced that WDM-MIMO and DMIMO systems could be used for communication ranges of 0 km to 5 km even in the presence of haze.

3.2.2 Signal power as parameter for DMIMO and MIMO

Figure 11 shows the signal power to range plot of MIMO and DMIMO systems under clear air condition. An analytical comparison shows that DMIMO has the highest received signal power starting from larger values at lower values of range and decreasing down to lower values towards higher values of range. At 0.5km under clear air condition, DMIMO can achieved up to 4.420dBm while MIMO achieved -4.611dBm. As shown in Figure 11, up to 5km of range, DMIMO provided a better received signal power compares to MIMO.

Figure 12 shows the signal power to range plot of MIMO and DMIMO systems under moderate fog condition. An analytical comparison shows that DMIMO has the highest received signal power starting from larger values of 18.893dBm at lower values of range and decreasing down to lower values towards higher values of range. At 1km under moderate fog condition, DMIMO can achieved up to -26.850dBm while MIMO achieved -35.881dBm. As shown in Figure 12, up to 5km of range, DMIMO provided a better received signal power compares to MIMO.

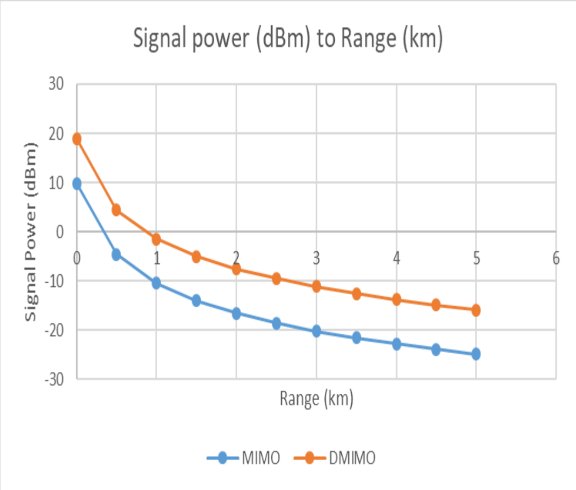

Figure 11. Signal power to range plot of DMIMO and MIMO system under clear air

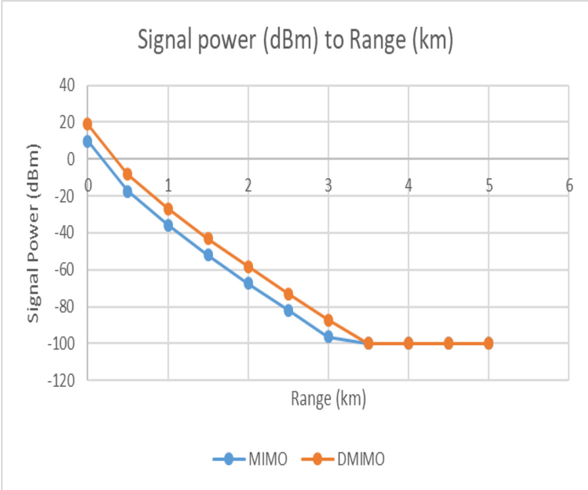

Figure 12. Signal power to range plot of MIMO and DMIMO system under moderate fog condition

4. CONCLUSION

In this paper, we compare the performances between four different systems, which is SISO, WDM-MIMO, MIMO and DMIMO FSO system. The achievable performance improvements, including signal power level and quality factor (Q-factor) are presented. Based on the findings and observations, we can infer that in haze weather conditions, the proposed system Double Multiple Input Multiple Output (DMIMO) FSO systems perform significantly better than SISO, Wavelength Division Multiplexing MIMO (WDM-MIMO) and MIMO FSO systems. At lower values of ranges until 5km, WDM-MIMO FSO system has the second highest Q factors after DMIMO FSO system under four different weather condition namely clear air, haze, light fog and moderate fog. DMIMO FSO system outperform the other FSO system in this paper by achieving quality factor of 13.8828 at 3.5km under haze weather condition. SISO FSO and MIMO FSO system achieved quality factor of 0 and 3.49651 for WDM-MIMO FSO at 3.5km under the same condition of weather. As a result, using DMIMO in FSO system improves performance. The presented findings would be a useful approach for maximizing channel capability of FSO links under a variety of atmospheric turbulence conditions.

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