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Performance Investigation of MIMO Based CO-OFDM FSO Communication Link for BPSK, QPSK and 16-QAM under the Influence of Reed Solomon Codes

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Highlights:

- Performance of BPSK, QPSK and 16-QAM was investigated.
- In terms of error correction, 16-QAM was found best.
- PSK is superior to 16-QAM in terms of peak to average power ratio (PAPR), with a compromise in BER.
- Geometric losses decrease with rising link length with least losses achieved by 16-QAM.
- Lower SNR was required for 16-QAM than for BPSK and QPSK.

Abstract. The MIMO based CO-OFDM FSO communication system is emerging as a promising approach to meet the future bandwidth requirements for seamless communication. The atmosphere being the propagation medium is a major hindrance in wide-scale acceptability of FSO technology. For seamless and error-free transmission and reception of data, a novel concept of MIMO integrated with RS code is proposed in this paper. The system performance of an RS 64 (RS (255,127)) coded MIMO-based CO-OFDM FSO communication link was investigated using BPSK, QPSK and 16-QAM under the combined effects of geometric losses, path losses and atmospheric attenuations at a hitherto un-investigated data rate of 40 Gbps and a link distance of 5 km. The modified gamma-gamma distribution was used for modeling a moderately turbulent channel. With link length varying over a range of 1 to 5 km, error correction was maximum in 16-QAM as compared to BPSK and QPSK, with 150 to 167 corrected errors. In terms of PAPR, PSK was more apt than QAM, but with a compromise in BER. The geometric losses were reduced with link length due to an increase in error correction capability for all three modulation cases, with the least losses occurring in 16-QAM. At the target bit error rate (BER), the signal to noise ratio (SNR) required for BPSK and QPSK was higher by 3.98 dB and 6.14 dB compared to 16-QAM.

Keywords: *BER; CO-OFDM; FSO; MIMO; Modified Gamma-Gamma; RS codes; SNR*.

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1 Introduction

The existing data networks are no longer able to sustain the growing traffic demands due to increased spectrum congestion and have led service providers to go for other alternatives. FSO communication is the most viable solution, providing the best possible connectivity bottleneck compared to RF technology, optical fiber cables and other means. It is similar to optical fiber networks, with the additional benefit of being wireless [1,2]. FSO thus enjoys the best of both worlds, being optical in nature and wireless in transmission and reception. Since the atmosphere is used as the medium of propagation, it becomes a limiting factor for effective communication. Due to photon absorption and scattering, meteorological processes like rain, fog, clouds, snow, dust, haze, smoke, etc. may result in signal attenuation [3]. Also, temperature and pressure inhomogenities cause variations in refractive index, which results in atmospheric turbulences [4,5]. There have been several techniques for mitigating atmospheric turbulences over time, which include spatial diversity, hybrid RF/FSO, aperture averaging, MIMO, modulation and coding, etc. [6-9]. By employing the MIMO concept, FSO communication performance can be enhanced. Due to spatial multiplexing and multiple antennas at both ends, the capacity gain can be increased [10]. At higher data rates, the effect of inter-symbol interference (ISI) arises, due to which the MIMO system capacity degrades. OFDM offers the best possible solution for mitigating ISI- and turbulence-induced fading. To meet the requirements of future broadband wireless communication, the MIMO concept can be used in combination with OFDM. Prabu, *et al.* [11] analyzed MIMO FSO systems using the BPSK Subcarrier Intensity Modulation (BPSK-SIM) signaling technique. In addition to OFDM, they investigated the forward error correction (FEC) technique in order to combat link impairment. RS codes are possibly the most commonly used codes in all forms of transmission and data storage for FEC. By adding redundancy to the user information, this channel coding technique helps to reduce flawed detection of data at the receiver. It has enormous power and utility with numerous applications in compact disc players, error control for feedback systems, computer memory and deep-space telecommunications [12].

Chronopoulos, *et al.* [13] have demonstrated the effectiveness of coded OFDM links with noise effects in order to achieve higher data rates. Djordjevic, *et al.* [14] investigated the performance of OFDM FSO links with BPSK and OOK using Low Density Parity Check (LDPC) codes and achieved a coding gain of more than 20 dB in comparison to 14 dB for OOK under turbulent conditions. With the increase in turbulent conditions, the performance reduced significantly. In order to improve the performance in terms of longer ranges and higher data rates, other researchers have proposed several OFDM-based FSO links [15-17]. Kakati, *et al.* [18] used coherent detection at the FSO receiver in conjunction with digital signal processing at a distance of 1 km for a data rate of 120 Gbps.

Mane & Belsare [19] proposed an RS coded method to improve the effectiveness of the Space-Time Block Coded (STBC) MIMO system concatenated with M-ary Phase Shift Keying (MPSK) and M-ary QAM for reducing the BER in Rayleigh, Rician and Nakagami channels. In contrast to uncoded systems this coded technique offers a lower BER, with 63% to 98% improvement in Rayleigh as compared to the other two channels.

Sanghvi, *et al.* [20] evaluated the effect of RS (7, 3) code in an Additive White Gaussian Noise (AWGN) channel for FSK, PSK and QAM. The use of RS code reduced the error rate, with QAM performing superior to the other modulation schemes used. Kaur, *et al.* [21] investigated the BER performance of BPSK, QPSK and 16-QAM in OFDM using RS (255, 85), RS (255, 128) and RS (255, 170) in an AWGN channel. The BER probability improved by choosing a smaller code rate encoder with BPSK superior to QPSK and 16-QAM. Kapoor, *et al.* [22] conducted a performance comparison of Gaussian Minimum Shift Keying (GMSK) modulation for uncoded and RS-coded AWGN channels with code word lengths 255, 127, 63, 31 at a data rate of 1 Mbps. RS (63, k) proved to be the best combination among coded as well as uncoded systems. The authors also suggested GMSK over PSK, DPSK, QPSK and FSK for moderate values of *n*. Miglani, *et al.* [23] compared the BER performance of an OFDM-based FSO link using coherent BPSK and QPSK under impact of RS codes and found BPSK superior to QPSK and OOK under channel conditions. Kumar & Payal [24] evaluated the impact of RS (255, k), k = 239, 223, 191, 127 on the performance of an FSO communication link in the presence of geometric losses and turbulent conditions at a data rate of 25 Gbps. RS (255, 127) performed optimally in terms of BER with powerful error correction capability and large coding gain, with geometric losses reducing with increasing link distance.

In the present work, a novel concept of MIMO integrated with RS code was developed. Using modified gamma-gamma distribution with moderate turbulences and combined effects of geometric losses, path losses and atmospheric attenuations, the error performance was investigated for an RS 64 coded MIMO based CO-OFDM FSO communication link at a previously un-investigated data rate of 40 Gbps. The rest of this paper is structured as follows: Section 2 contains the proposed link design. Section 3 describes the implemented simulation layout. The results are explained in detail in Section 4, followed by the conclusion in Section 5.

2 Proposed Link Design

The combination of CO-OFDM with MIMO results in increased spectrum efficiency and ease of integration. Figure 1 depicts the proposed design of an RS 64 coded MIMO-based CO-OFDM FSO communication link.

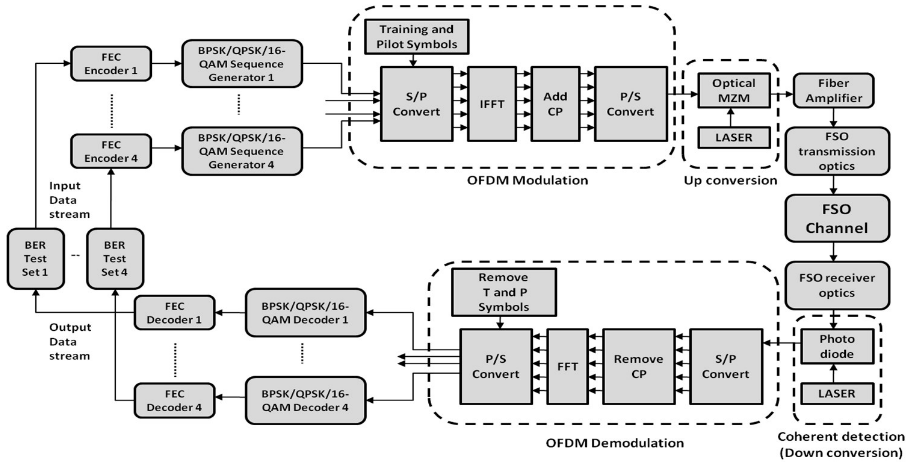


Figure 1 Proposed schematic comprising of transmitter and receiver of an RS coded MIMO-based CO-OFDM FSO communication link using modulation schemes (BPSK, QPSK and 16-QAM).

The input data streams are first encoded using the RS code (255,127), followed by modulation (BPSK, QPSK or 16-QAM) one by one. After that, it undergoes OFDM modulation where the data stream gets divided into several parallel sub streams. The training and pilot pulses offer synchronization between transmitter and receiver. This coherence enables more effectual original signal recovery compared to direct detection OFDM systems. OFDM symbols with *n* orthogonal subcarriers are generated by the IFFT block. For a MIMO-based CO-OFDM system with M subcarriers, M_t transmit antennas and M_r receive antennas, the signal in the frequency domain is represented as $\{X_i[l]\}_{l=0}^{M-1}$, where l is the frequency index. If M IFFT points from the *i*-th transmitting antenna are considered, the discrete time baseband OFDM signal is expressed by Eq. (1) [25].

$$x_i[n] = \frac{1}{\sqrt{M}} \sum_{l=0}^{M-1} X_i[l]\, e^{j2\pi\frac{ln}{LM}},, n = 0, 1, . . ., LM-1 \tag{1}$$

where *n* is the discrete time index and L is the oversampling rate. PAPR is defined as the ratio of maximum instantaneous power to average power. It is expressed as:

$$PAPR(x_i[n]) \triangleq \frac{\underset{0\le n\le M-1}{max}|x_i[n]|^2}{\frac{1}{M}\sum_{l=0}^{M-1}|x_i[n]|^2} \tag{2}$$

In a MIMO-based CO-OFDM system it is defined as the maximum of all M_t PAPR values evaluated in each MIMO path, expressed as:

$$PAPR(MIMO) = \underset{1 \le i \le M_t}{max} PAPR(x_i[n]) \tag{3}$$

PAPR is measured using a complementary cumulative distribution function (CCDF), expressed as:

$$CCDF = probability\{PAPR_{OFDM} \geq PAPR_T\} \tag{4}$$

which gives a measure of the probability of a PAPR of the OFDM signal that exceeds a given threshold. The cyclic prefix (CP) is generally added to combat dispersion that devastates orthogonality among the subcarriers. To mitigate the effects of chromatic dispersion and enhance system performance, equalization is necessary. Finally, the resultant signal is converted to a serial stream, digital-to-analog converted and sent for up conversion to be done using a Mach-Zehnder modulator (MZM) and a laser-light source. The Erbium Doped Fiber Amplifier (EDFA) is used for signal strengthening due to its numerous advantages, before propagating through free space.

Being a fiber amplifier, it requires less pump power and has polarization-insensitive gain characteristics. Fiber amplifiers are easier to couple due to negligible splicing loss and inter-channel crosstalk for multiple transmission inputs. The light signal is transmitted using collimating lenses, arranged to make sure that the beam propagates with least wander through the atmospheric channel.

The receiver executes exactly the reverse process of the transmitter. The optical signal from the FSO channel is collected by the receiver optics, followed by coherent detection using an APD photodiode and a laser as local oscillator. The gain of APD, resulting in high SNR, makes it appropriate for use in long-haul communications as a high speed receiver and in applications incorporating high bandwidth and bit rates, where high cost is unavoidable. Communication systems with APD generally produce a higher Q-factor than PIN at multiplication factor (MF) 3. This is the threshold point where shot noise greatly affects its performance, so it becomes necessary to choose the optimum MF for the best APD gain figure. APD with MF greater than 8 starts to deteriorate the performance of the system, granting superiority to PIN. Then OFDM demodulation takes place, followed by BPSK/QPSK/16-QAM sequence decoding and FEC decoding. Finally, the BER test set is used to record the results.

3 Simulation Setup

The proposed RS coded MIMO-based CO-OFDM FSO communication link was designed and analyzed using OptiSystem 16.1 Simulator, as shown in Figure 2. To investigate the system's performance, RS 64 (RS (255,127)) code with code rate ½ was used. An FSO channel with moderate turbulences was considered. Based on our previous work on remodeling refractive index structure parameter C_n^2, the modified gamma-gamma distribution was used for the moderately turbulent channel. In this distribution, the parameter C_n^2 of the existing lognormal and gamma-gamma model was remodeled with the inclusion of a rainfall parameter for implementation of FSO links in mountainous regions. This results in increased losses in the lognormal and gamma-gamma model and provides accurate calculation of link losses for engineering a fail-safe and reliable FSO link [26]. In addition to this, the FSO communication channel was evaluated under the combined effects of geometric losses, path losses and atmospheric attenuations.

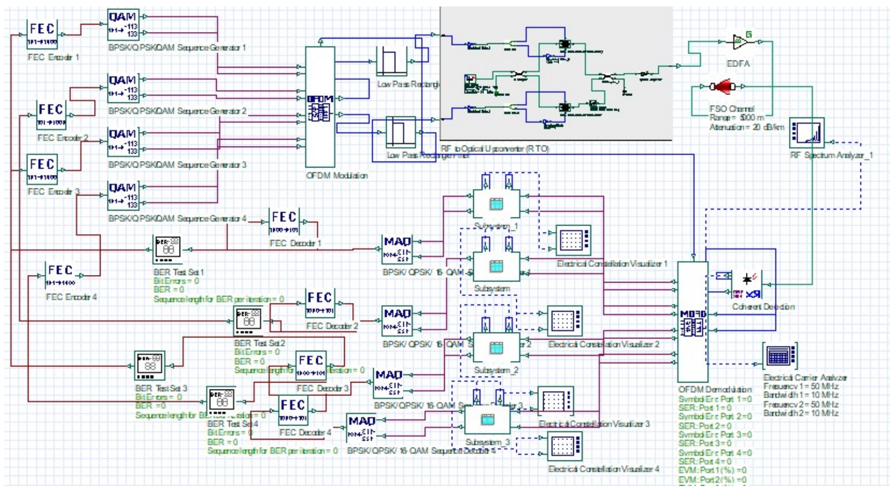


Figure 2 Simulation design of RS coded MIMO-based CO-OFDM FSO communication link using modulations schemes (BPSK, QPSK and 16-QAM) in Optisystem Simulator 16.1.

The data sequence is transmitted at a previously un-investigated higher data rate of 40 Gbps for propagation through the FSO channel. First, the data for four inputs is encoded using the RS 64 code, followed by M-ary phase shifting using BPSK, QPSK and 16-QAM. The sequence generated is then OFDM modulated having 128 subcarriers, with 20 subcarriers per input located at 25-44, 45-64, 65-84 and 85-104 for up conversion. The output optical signal is then amplified using EDFA before propagation through the FSO channel using suitable transmission optics. The value of C_n^2 for a line of sight FSO channel obtained using the modified gamma-gamma distribution is 1.36 x $10^{-15}m^{-2/3}$.

The atmospheric attenuation and additional losses (due to internal factors) considered in the designed simulation layout were 20 dB/km and 5 dB respectively. Thus, for an FSO link with a transmission range of 1 km to 5 km, attenuation of 25dB to 125dB are encountered. The sequence was coherently homodyne detected, followed by OFDM demodulation and BPSK, QPSK and 16-

QAM decoded outputs. For recovery of actual user data, an RS 64 decoder was used and error analysis was done using the BER test set. The values of the parameters for the components used in the simulation design for transmitter, FSO channel and receiver are given in Tables 1, 2 and 3 respectively.

Table 1 Transmitter parameters.

Parameters	Values
FEC encoder	RS 64 (n = 255, k = 127)
Modulation used for comparison	BPSK (bits/symbol = 1), QPSK (b/s = 2), 16-QAM (b/s = 4)
Bit rate	40 Gbps
Number of users	4
Subcarriers	128
Number of subcarriers per port	20 (25-44, 45-64, 65-84, 85-104)
Average OFDM power	15 dBm
Clipping ratio (CR)	1
Low pass rectangle filter cutoff frequency	0.75X symbol rate
MZM extinction ratio	60dB
Laser and wavelength	Continuous wave (CW) (193.1 THz)
Laser power	10 dBm
EDFA gain	30 dB

Table 2 FSO channel parameters.

Parameters	Values
Range	1-5 km
Atmospheric attenuation	20 dB/km
Additional losses	5 dB
Turbulence model	Modified Gamma-Gamma
Turbulence strength (C_n^2)	Moderate (1.36 x $10^{-15}m^{-2/3}$)
Transmitter and receiver aperture diameter	5 and 20 cm
Geometric losses	-60dB
Divergence angle	2 mrad

Table 3 Receiver parameters.

Parameters	Values
Detection type	Coherent
Local oscillator frequency	193.1 THz
Photo detector and gain	APD (3)
Number of prefix points	10
Number of training symbols	10
Number of pilot symbols	12 (25-104)

4 Results and Discussion

The designed RS coded MIMO-based CO-OFDM FSO communication link was evaluated for efficient throughput, optimum error detection and correction, higher data rate and longer transmission reach. For an investigation into error performance, three different modulations (BPSK, QPSK and 16-QAM) were used. The FSO link length was varied from 1 km to 5 km at a data rate of 40 Gbps for evaluating the following performance metrics: (i) number of errors corrected, (ii) peak average to power ratio (PAPR), and (iii) variation in geometric losses. Further, the BER performance was investigated for the mentioned modulation formats in the designed link at a link length of 5 km. Figure 3 illustrates the number of errors corrected in the MIMO BPSK, QPSK and 16-QAM based CO-OFDM FSO communication link using RS (255, 127) with code rate ½.

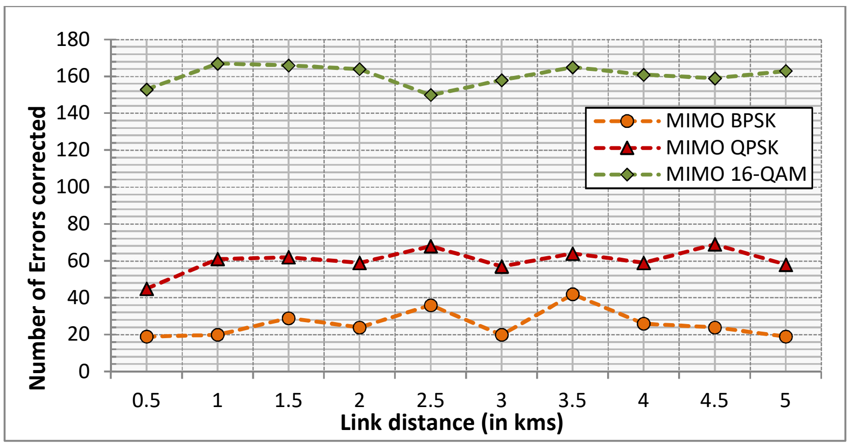


Figure 3 Errors corrected versus FSO link length for modulation schemes (BPSK, QPSK and 16-QAM) in a MIMO-based CO-OFDM FSO communication link using RS 64.

Here, the error performance of the RS (255, 127) coded MIMO-based CO-OFDM FSO link was evaluated for the modulation schemes BPSK, QPSK and 16-QAM. From Figure 3 it can be seen that the number of errors corrected was higher for the 16-QAM than for the BPSK and QPSK MIMO-based CO-OFDM FSO links. With BPSK, QPSK and 16-QAM, the possible number of errors corrected in the considered link range was 19 to 42, 45 to 69 and 150 to 167 respectively. This entirely depends on the number of detected blocks with errors, which varies. When a single bit is in error in every symbol, the worst case arises, and when all symbols are in error it is the best case, as it becomes easier for the decoder to correct the erroneous symbols.

The presence of multiple independently modulated subcarriers in an OFDM system can result in a large peak value of the system in comparison to the average value of the whole system. The implementation of an OFDM-based link at higher data rates with an increased number of subcarriers leads to a high PAPR. This is the major difficulty with OFDM. However, employing FEC in OFDM enables the evasion of errors in transmission.

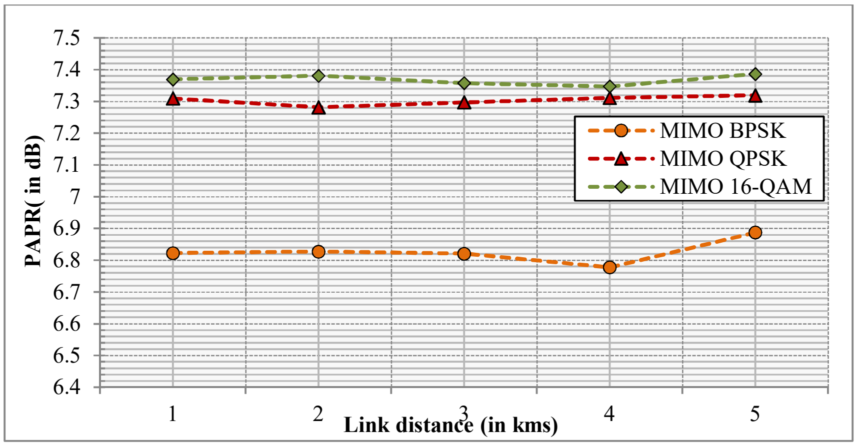


Figure 4 PAPR versus FSO link length for modulation schemes (BPSK, QPSK and 16-QAM) in a MIMO-based CO-OFDM FSO communication link using RS 64.

The PAPR versus link length graph for the MIMO-based CO-OFDM FSO communication link using RS 64 code for BPSK, QPSK and 16-QAM is depicted in Figure 4. From the graphical illustrations, PSK is more appropriate than QAM, with lower PAPR values. This depends on the clipping ratio (CR), which is defined as the ratio of amplitude, A, to the root mean squared value of the unclipped OFDM symbol, σ. With low CR, i.e. a larger amount of clipping, QAM has less PAPR than PSK. For moderate CR, PSK results in less PAPR than QAM. We chose a moderate amount of CR, which resulted in PSK being more suitable than QAM with a low PAPR. The higher the amount of clipping, the higher the BER. Thus, there is a need for system trade-off. Hence, PAPR was reduced with a little sacrifice of BER. With BPSK, QPSK and 16-QAM, PAPR of (6.82, 6.88), (7.31, 7.32) and (7.37, 7.38) dB respectively were attained with link length (1, 5) km. However, less PAPR, BPSK and QPSK caused higher BER than 16-QAM.

As far as FSO links are concerned, there are two types of losses that are responsible for link degradation. One type of loss arises due to internal parameters that are associated with the FSO design itself, such as divergence angle, wavelength, link length, aperture diameter at the transmitter and receiver. Some of these parameters are accountable for geometric losses. The other losses relate to the atmospheric conditions. Figure 5 illustrates the geometric losses in the RS 64 coded MIMO-based CO-OFDM FSO communication layout as a function of FSO link range for the three considered modulation schemes.

For simple FSO links, the geometric losses are proportional to link distance. For a link distance increasing from 1 to 5 km, the geometric losses of a simple FSO link increase from -60dB to -34dB. Meanwhile, by employing RS coding in our designed layout, the error correction capability increased, which contributes to communication quality improvement regardless of the existing conditions. With an increase in link distance from 1 km to 5 km, the path losses were reduced from -80 to -93.97dB, -80.12 to -94.42dB and -80.98 to -95.59dB for BPSK, QPSK and 16-QAM respectively. In general, the RS coded designed FSO layout was found to be more suitable in terms of error correction.

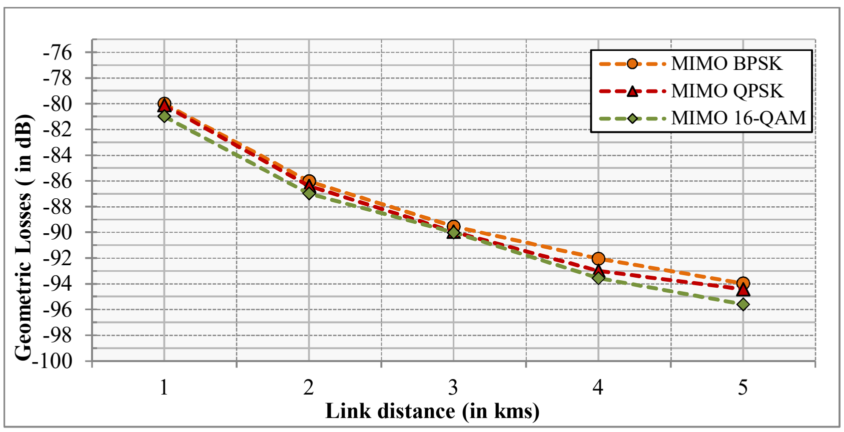


Figure 5 Geometric losses with FSO link length for modulation schemes (BPSK, QPSK and 16-QAM) in a MIMO-based CO-OFDM FSO communication link using RS 64.

Figure 6 provides a graphical illustration of SNR with FSO link length. The SNR lies within (29.15, 27.49), (30.12, 29.65) and (26.97, 23.51) dB for BPSK, QPSK and 16-QAM respectively, with the link length of FSO varying within (1, 5) km. This means that the higher the number of bits encoded per symbol, more the link is immune to induced uncertainties and the greater the reduction in occupied optical bandwidth.

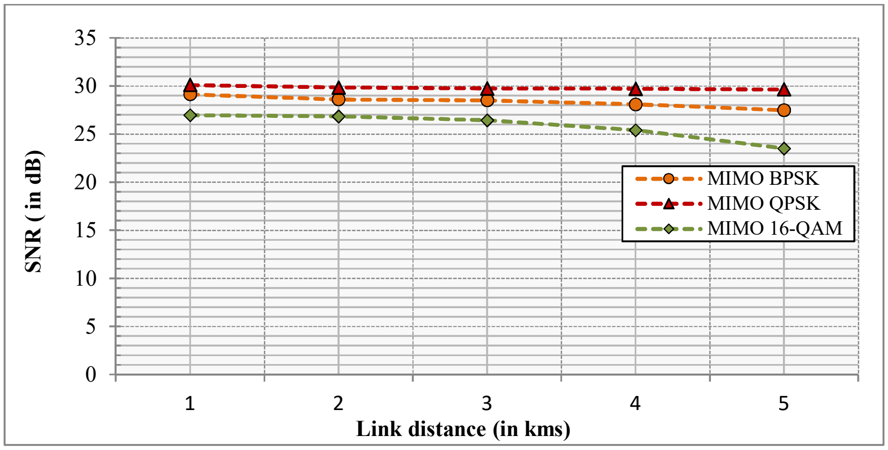


Figure 6 SNR with FSO link length for modulation schemes (BPSK, QPSK and 16-QAM) in a MIMO-based CO-OFDM FSO communication link using RS 64.

Figure 7 depicts the BER performance of an RS 64 coded MIMO-based CO-OFDM FSO communication link for BPSK, QPSK and 16-QAM. These BER curves were plotted at an FSO link length of 5 km under moderate turbulence conditions. It may be observed that at a BER of 10^{-4}, the SNR required for BPSK was 27.49 dB, for QPSK it was 29.65 dB and for 16-QAM it was 23.51 dB. Thus, at a link length of 5 km and moderate turbulences at the target BER, the SNR required for BPSK and QPSK rose by 3.98 dB and 6.14 dB compared to 16-QAM. As 16-QAM corrected more errors, the BER became lower, but there is a system trade-off between PAPR and BER.

Figure 8 illustrates the constellation diagrams for BPSK, QPSK and 16-QAM modulated RS 64 coded MIMO-based CO-OFDM FSO links for a moderately turbulent environment with a link distance of 5 km. QPSK in comparison to BPSK stayed at the same data rate and half of the bandwidth with almost same BER.

In 16-QAM, one symbol corresponds to 4 bits. The constellation points are gray coded, which means a single bit change. BER is computed based on the probability that any one point in the constellation could be forced to cross a threshold into another state's place in the constellation. When this happens, either at one or more points, the error bits are received. Thus, if a measured point is wrongly assigned to a neighboring point due to noise, the BER is kept to a minimum, i.e. one wrong bit. The center constellation points depict attenuations present during propagation.

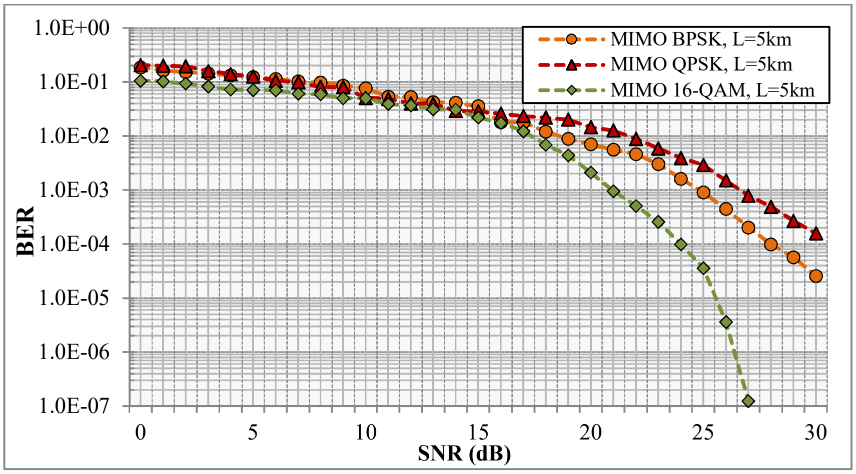


Figure 7 BER performance of BPSK, QPSK and 16-QAM modulated MIMO-based CO-OFDM FSO links using RS 64.

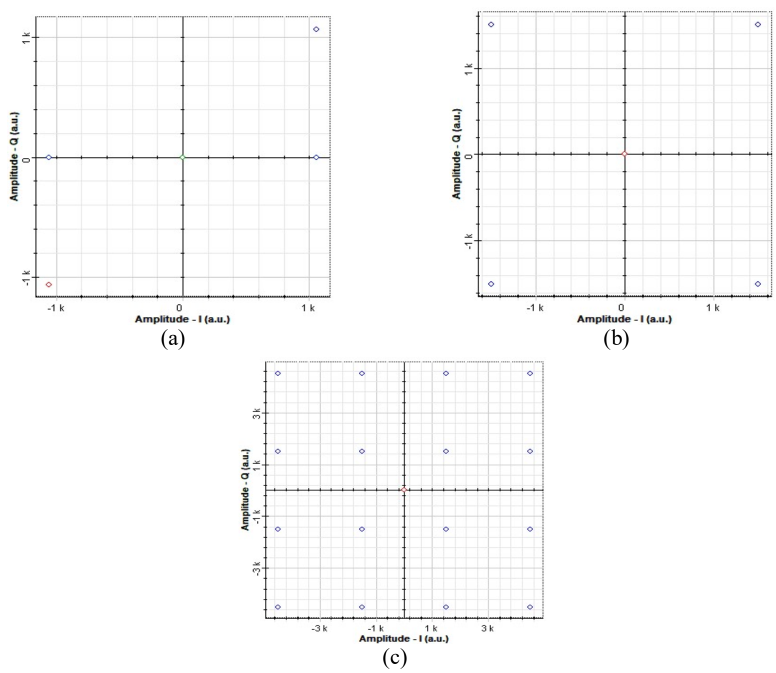
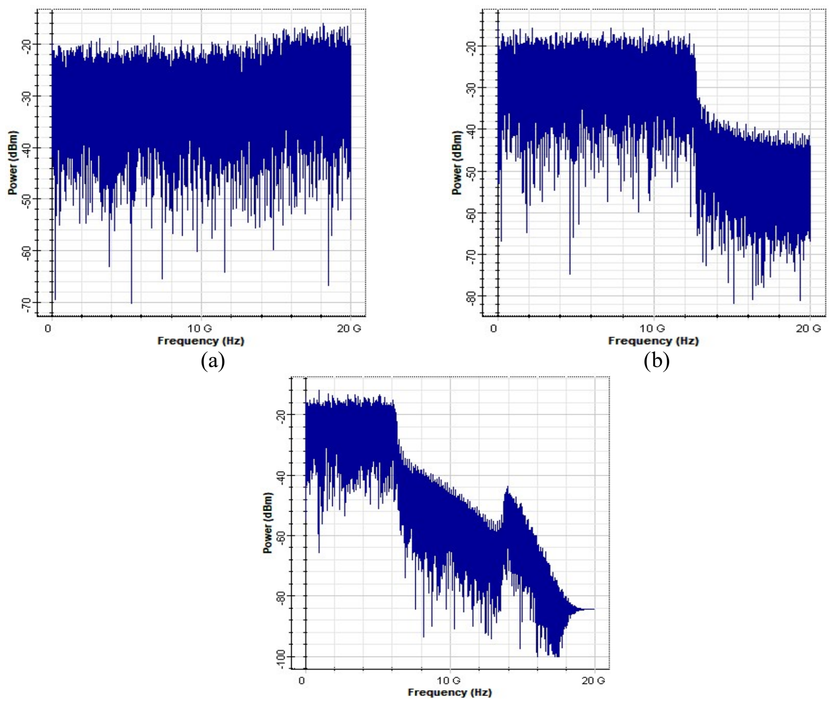


Figure 8 Constellation diagrams of RS 64 coded MIMO-based CO-OFDM FSO link for moderate turbulent environment at L = 5 km for (a) BPSK (b) QPSK and (c) 16-QAM.

The spectral analysis after OFDM modulation for BPSK, QPSK and 16-QAM modulated RS 64 coded MIMO-based CO-OFDM FSO links for a moderately turbulent environment is depicted in Figure 9.



(a) (b) (c)

Figure 9 Spectrum analysis of proposed link after OFDM demodulation for (a) BPSK (b) QPSK and (c) 16-QAM.

The spectrums were centered at 10 GHz, with power ranging within (-72.85, -13.27) dBm for BPSK, (-85.13, -11.20) dBm for QPSK and (-104.45, -7.56) dBm for 16-QAM respectively. The spectrum of BPSK shows that the power variation was almost linear and lay between -47 dBm to -20 dBm, with varying frequency. Meanwhile for QPSK, up to 10 GHz, the variation of power was almost constant and lay between -42 dBm and -20 dBm. As the frequency was increased up to 20 GHz, the power variation ranged between -60 dBm and -40 dBm. From the spectrum analysis of 16-QAM it can be seen that with variation in frequency, the power varied in three steps: around 12 dBm to 7 GHz, 10 dBm to 14GHz, and 8 dBm to 20 GHz. Thus, a narrower power width can be seen in 16-QAM, which signifies that the amplifier had lower power variation, which can make designing the amplifier more complex if it becomes higher.

5 Conclusion

In this present work we propose a novel concept of MIMO integrated with RS codes for mitigating the declining performance of FSO communication due to atmospheric propagation. The RS 64 (RS (255,127)) code was employed for investigating the performance of a MIMO-based CO-OFDM FSO communication link for the BPSK, QPSK and 16-QAM modulation schemes. The combined effects of geometric losses, path losses and atmospheric attenuations were taken into consideration at a hitherto un-investigated data rate of 40 Gbps and a link distance of 5 km. The simulation results revealed that in terms of error correction, 16-QAM outperformed the other two modulations. Meanwhile in terms of PAPR, PSK is more appropriate than 16-QAM but with a compromise in BER.

The geometric losses were found to reduce with an increase in link length due to an increase in error correction capability for all three modulation schemes, with least losses ranging between -80.98 and -95.59dB for 16-QAM. The BER performance curves indicate that at a target BER of 10^{-4}, the SNR required for 16-QAM was less by 3.98 dB and 6.14 dB in contrast to BPSK and QPSK. This novel robust and efficient coded modulation system, called RS coded MIMO-based CO-OFDM FSO, is a very promising concept for future FSO systems. It can be used for enterprise connectivity, storage area networks, last mile access, video surveillance and monitoring, fiber back up and outdoor wireless access applications. This research work can be extended by using different channel encoding/decoding schemes, spatial diversity techniques and aperture averaging in combination with coherent detection to aid future FSO systems.

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