Performance enhancement of multi channel multi beam FSO communication link with the application of Reed Solomon codes

Suresh Kumar1 · Deepak Sharma2 · Arora Payal1

Received: 30 June 2022 / Accepted: 24 August 2022 / Published online: 16 September 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
The rising user needs for high speed applications and services have necessitated the requirement of a communication link that can provide the data rate comparable to optical fiber. Free Space Optical (FSO) Communication is an admired means of communication from past few years. To achieve seamless and error free transmission at high speed for heterogeneous multimedia applications at desired bit rates, novel advancements in optical communication technology are being explored along with FSO. However, several constraints such as atmospheric turbulence, uneven terrain, dynamic climatic conditions cause several nonlinearities which limit the connectivity. In this work, a multi channel multi beam FSO communication system by incorporating Reed Solomon (RS) Codes has been proposed at 30 Gbps. The Modified Gamma-Gamma model is being applied for channel turbulences. The application of Forward Error Correction (FEC) coding in the designed system offers ease of error detection and correction with improved performance at higher data rate for implementation over longer link lengths. The system performance has been evaluated for (i) Number of errors corrected, (ii) Bit Error Rate (BER), (iii) Received power, (iv) Geometric path losses and (v) Signal to Noise Ratio (SNR). At an acceptable BER of $10^{-9}$, the RS (255, 127, 129) encoded Four channel Four beam FSO communication link is effectively implemented for a distance of 3500 m with $-32.5$ dBm received low optical power and 25 dB SNR.

Keywords BER · FSO · Reed Solomon (RS) codes · Multi beam · Multi-channel
1 Introduction

The high speed multimedia applications and progressing field of information and communication demand high bandwidth requirements which cannot be fulfilled by existing data networks due to increase in spectrum congestion, price and complexity. This has engrossed service providers to look for other alternate.

The transmission capability of point to point full duplex communication is improved using laser beam for propagation having medium as free space (Riza et al. 2012, Rahman et al. 2012).

The use of unlicensed frequency band in FSO and several inherent advantages such as secured data transmission at higher rate, efficient bandwidth utilization at lower powers have attracted the communication and networking (Payal and Kumar 2020; Malik and Singh 2015; Kumar and Payal 2021).

Despite having these significant applications and advantages, there are several inherent constraints in ensuring impairment free communication. These impairments are caused due to several atmospheric disturbances causing scattering, absorption and turbulences and are region specific weather dependent.

In a single-beam FSO communication system, the low received power, implementation up to smaller distance and scalability features are minimized by using Wavelength division multiplexing (WDM).The light signal travelling via free space is affected by scintillation and turbulent atmosphere. This causes broadening of light beam that reduces the coupling efficiency of receiver thereby reducing SNR and increasing error probability.

A reliable FSO system design requires a smaller BER. This can be carried out with the use of efficient coding technique in which the added extra bits contribute in correction of errors that occurred during data transfer (Kumar and Payal 2020). By employing these techniques, data quality is maintained with unchanging SNR with reduction in transmitted power and hardware costs. The correction code using FEC offers greater significance for single channel as well as multiple channel WDM system to ensure error free data reception.

In (Sanghvi et al. 2011), authors have measured the impact of RS code (7, 3) over an Additive White Gaussian Channel (AWGN) channel using 8-FSK, 8-PSK and 8-QAM schemes. Simulative results show that the RS code gives improved error rate for QAM scheme and provide better Symbol Error Rate (SER). An analytical study of relationship has been done between Channel symbol error probability and BER for several n = 31, t—error correcting RS codes over an AWGN channel. It has been determined that the error performance of the channel improves with increase in symbol error correcting capability, t from 1 to 4 (Sonar and Mudholkar 2016).

In (Kaur et al. 2018) BER performance has been investigated in RS coded OFDM system using BPSK, QPSK and 16-QAM. Three different RS codes of fixed code length of 255, varying data bits − 85, 128 and 170 and code rates in AWGN channel are examined. By choosing the smallest rate encoder, the BER probability gets improved and BPSK performs superior to the other two techniques. Also in (Migliani and Malhotra 2019), BER parameter for RS coded OFDM based FSO system applying coherent BPSK and QPSK has been evaluated. The link length and atmospheric adversities affect the error performance of the link. The use of FEC offers significantly improved error performance compared to IM/DD OOK system. Further, the performance of Dual-Polarization (DP) 16-QAM based FSO communication system is analyzed with the help of RS (255,127) under the weak and moderate turbulence with fog, rain and haze affected condition. To achieve the target BER under strong turbulences, the requirement of SNR increases. The RS code enabled
FSO link rectifies errors with improvement in link performance and coding gain of around 7.7 dB in clear weather compared to conventional link (Patel and Mandloi 2021).

The FSO link using single beam suffers from wave front distortion, beam broadening and beam wander. The temperature gradient due to variable solar heating also hampers the performance causing refractive index instability thereby reducing channel capability by increasing BER. As, the single beam FSO communication system itself doesn’t cope up with the atmospheric turbulences therefore, for improved performances FSO communication system using multiple beams is being explored.

The authors have designed a WDM FSO system for mitigation of scintillation effects using one and multiple beams. The transmission distance enhanced by 3 km using multiple beams (Grover et al. 2017). The authors have evaluated the performance of designed hybrid WDM with multiple beam FSO communication system considering Delhi weather conditions at 5 and 10 Gbps. In heavy rainy weather, the link was found to be working effectively for 3.3 km (Srivastava et al. 2019). The performance of Multi beam FSO link has been evaluated considering effect of Malaysian haze weather. It was observed that the attenuation was reduced with successful transmission up to 1.5 km (Rathore et al. 2020).

In (Arora et al. 2022), the authors have proposed a Spectrum Slicing (SS) WDM system with Pre and Post Amplification to mitigate the effects of atmospheric attenuation in FSO communication. The performance of the designed system is compared with a traditional SS-WDM model and is found efficient in terms of Q-Factor and BER during all seasons.

In (Almogahed et al. 2022), a decision feedback equalizer (DFE) has been proposed with minimum mean square error (MMSE) in mode division multiplexing (MDM) for the FSO system to minimize the effects of atmospheric turbulences. The performance is analyzed in terms of BER and Eye diagrams and on comparison with the traditional model it is found that DFE improves the outdoor FSO system immunity to distortion in different weather conditions while maintaining high throughput and desired low BER.

However, despite several advantages, the design of a higher data rate long range communication link while mitigating several nonlinearities remains a challenging task. The integration of Multi beam FSO with RS codes can be a novel idea in improving the performance of designed FSO communication link. This work presents the performance investigation of four channel multi beam FSO communication system using RS codes. The paper has been organized in four sections. Section 2 provides the block diagram explanation succeeded by simulation and results discussed in Sect. 3. Section 4 concludes the paper.

2 Block diagram of proposed RS encoded four channel multi beam FSO communication link

In this proposed work, the authors have designed a RS encoded Four channel Multi beam FSO communication system using Optisystem Simulator V 18.

Figure 1 shows the Block diagram of transmitter section of RS encoded Four Channel Multi-beam FSO communication system. The binary information sequence is FEC encoded to generate $n$ symbol codeword by adding parity symbols to $k$ data symbols, each with $s$ bits expressed as:

$$RS(\text{code word, parity symbols, minimum distance } ) = (n = 2^r − 1, k = 2^r − 1 − 2t, d_{\text{min}} = 2^r − 2t)$$

(1)
The laser output and the encoded sequence is externally modulated using Mach Zehnder Modulator (MZM). The modulated signals from four different channels are first WDM multiplexed to achieve optimum capacity. The power splitter here splits the signal having multiple beams and thereafter, transmits it over the turbulent FSO link.

The received multiple beams are power combined and Erbium Doped Fiber Amplifier (EDFA) amplified before being WDM de-multiplexed and provided at optical receivers. Each optical receiver comprises of Avalanche Photo Diode (APD) detector followed by electrical demodulation and then FEC decoder is used to regenerate the original information source at the receiving end as shown in Fig. 2.

### 3 Simulation layout and results

Figure 3 shows the proposed designed layout of RS encoded Four channel Multi beam FSO communication system. The design is simulated considering geometric losses and moderate atmospheric turbulences with attenuation of 5 dB/km. The bit rate used for designed layout is 30 Gbps.

For channel turbulences, the modified Gamma-Gamma distribution has been used in which $C_n^2$ is remodeled with inclusion of rainfall parameter for implementation of FSO link in mountainous and high density areas. The overall link reliability is improved and this results in more accurate calculation of link losses. This signifies that even if worst conditions arise, the link will remain working and fail safe which otherwise would have resulted in link failure with the conventional model (Kumar and Arora 2019). The values of parameters for various components considered during simulation are enumerated in Table 1.

The RS code having code length of 255 and data bits 191 and 127 are investigated for number of errors corrected with varying FSO link distance up to 4000 m as shown in Fig. 4.
For code length 255 and data bits 191 i.e. RS 32, the number of errors corrected lie within 38 to 99 with link distance. The errors corrected range within 190 to 444 for RS 64 i.e. RS (255, 127,129). The rise and fall shows that the errors are of varying nature. Also this depends entirely on the detected number of errors per block.

As and when one erroneous bit per symbol is received, it is the worst case and when all the erroneous bits are received, this becomes the best possible case because it is much easier to correct these bulk errors for the decoder. Due to more error correction capability, the RS (255, 127, 129) is used at each source and detector to evaluate the performance of

---

**Fig. 2** Receiver section of proposed FEC encoded four channel Multi beam FSO communication system

**Fig. 3** Designed simulation layout of RS encoded four channel multi beam FSO communication system
designed Four channel Multi beam FSO communication system. Figure 5 represents BER as a function of distance for one and multiple beams.

The graph depicts that at a same BER, the FSO system using four beams has a longer reach than one beam FSO system.

At a standard BER of $10^{-9}$, the one beam FSO system can effectively reach up to distance of 2910 m which gets enhanced using four beams up to 3500 m even under turbulent atmosphere with same atmospheric and geometric conditions.

### Table 1 Simulation parameters

| Parameters              | Values                                      |
|-------------------------|---------------------------------------------|
| Bit rate                | 30 Gbps                                     |
| Wavelengths             | 1550 nm, 1550.8 nm, 1551.6 nm...             |
| RS index n              | 255                                         |
| RS index k              | 191, 127                                    |
| Transmission range      | 500–4000 m                                  |
| Additional attenuation  | 5 dB/km                                     |
| Angle of divergence     | 2 mrad                                      |
| Aperture diameter       | 5 and 20 cm                                 |
| Turbulence strength     | $1.36 \times 10^{-15} m^{-2/3}$             |
| Amplifier gain          | 30 dB                                       |
| Amplifier noise figure  | 4 dB                                        |
| APD gain                | 3                                           |
| APD responsivity        | 1 A/W                                       |

![Fig. 4 Number of errors corrected versus FSO link distance](image)

**Fig. 4** Number of errors corrected versus FSO link distance
The received power for BER using one beam and four beams is shown in Fig. 6.

It is clear from the graphical results that using more beams increases the receiver sensitivity. The FSO system using four beams can detect power at lower values than one beam FSO system. At a BER of $10^{-17}$, the four beam FSO receiver can detect low power up to $-31$ dBm while one beam has less sensitivity up to $-28$ dBm. The graphical values of Fig. 6 are tabulated in Table 2.

There are two major losses that primarily affect the performance of FSO communication system—atmospheric and geometric losses. In general, the geometric losses are in proportion to link distance. But as the distance increases, the beam spreads and it broadens bigger...
than the receiver aperture size. This results in beam divergence/ geometric loss. With the use of RS codes, the capability of error correction increases. This results in enhanced communication quality. The geometric losses with FSO link distance are shown in Fig. 7.

With the combined use of RS codes and multiple beams in FSO communication system, the geometric losses get improved. The geometric losses reduce from $-8.65$ to $-27.15$ dB using one beam and $-14.4$ to $-32.08$ dB using four beams in FSO communication system.

The variation of SNR with FSO link distance is shown in Fig. 8.

The SNR of FSO communication system using one beam varies from 92 to 13 dB with FSO link distance varying from 500 to 4000 m. It is observed that with increase in number of beams, due to reduction in error rate the SNR improves by 10–14 dB. At longer link distances of 3500 and 4000 m, the difference between SNR reduces due

| Received power (in dBm) | BER | One beam | Four beams |
|------------------------|-----|----------|------------|
| $-34$                  | $2.76E-04$ | $1.00E-07$   |
| $-32$                  | $4.68E-06$ | $1.29E-12$   |
| $-30$                  | $8.78E-11$ | $1.91E-20$   |
| $-28$                  | $1.04E-18$ | $4.98E-33$   |
| $-26$                  | $7.86E-27$ | $6.17E-41$   |
| $-24$                  | $1.07E-38$ | $5.50E-49$   |
| $-22$                  | $1.17E-45$ | $2.19E-56$   |
| $-20$                  | $2.39E-55$ | $1.39E-65$   |

Fig. 7 Geometric losses versus FSO link distance
to increased nonlinearities. The graphical results of Figs. 5, 7 and 8 are tabulated in Table 3.

It can be observed that the overall performance is improved by integrating multiple beams with RS codes in comparison to single beam FSO communication system. Using multiple beams, the system can be implemented up to a distance of 3500 m with improvement in BER by $10^{-3}$, SNR by 5 dB and reduction in geometric losses by 3 dB.

For a transmission distance of 500 m to 3500 m, the proposed RS coded four channel multi beam FSO communication system shows a considerable improvement of 12.4 to 26.53% in SNR over single beam respectively. Further, a considerable improvement of 13.57% is achieved in geometric loss for a transmission distance of 3500 m in multi beam FSO over single beam.

### Table 3 BER, SNR and geometric losses as a function of link distance for one beam and four beams using RS codes

| Link distance (m) | One beam | | | Four beams | | |
|------------------|----------|----------------|-------------|----------------|-------------|
|                  | BER      | BER            | SNR (dB)    | SNR (dB)       | Geometric losses (dB) |
| 500              | 2.39E-53 | 1.39E-65       | 91.7        | 103.12         | 19.68        |
| 1000             | 1.17E-45 | 2.19E-56       | 80          | 94.41          | 14.21        |
| 1500             | 1.07E-38 | 5.50E-49       | 69.87       | 80.52          | 17.25        |
| 2000             | 7.86E-30 | 6.17E-41       | 63.25       | 73.12          | 20.26        |
| 2500             | 1.04E-20 | 4.98E-32       | 45.45       | 55.22          | 22.56        |
| 3000             | 8.78E-10 | 1.91E-17       | 32.27       | 45.72          | 23.15        |
| 3500             | 4.68E-06 | 1.29E-09       | 19.68       | 24.8           | 25.16        |

Fig. 8 SNR versus FSO link distance
4 Conclusion

The performance of RS encoded multi channel multi beam FSO communication system has been analyzed at 30 Gbps in presence of geometric and atmospheric losses and turbulences. The combined relevance of RS codes and multiple beams provide significant improvement by enhancing link distance with reduced geometric losses and power. The RS encoded four channel four beam FSO communication has been evaluated for successful implementation up to a link distance of 3500 m with acceptable BER of $10^{-9}$ and at a received low optical power of $-32.5$ dBm and SNR of 25 dB. Compared with single beam, the designed RS coded Multichannel multi beam FSO shows significant improvement in performance.

Author contributions All authors contributed to the study conception and design. Data collection and analysis were performed by SK and D. The first draft of the manuscript was written by P. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interests The authors have no relevant financial or non-financial interests to disclose.

References

Almogahed, A., Amphawan, A., Mohammed, F., Alawadhi, A.: Performance improvement of mode division multiplexing free space optical communication system through various atmospheric conditions with a decision feedback equalizer. Cogent Eng. 9(1), 1–25 (2022). https://doi.org/10.1080/23311916.2022.2034268
Arora, D., Saini, H.S., Bhatia, V., Kaur, J.: Enhanced spectrum slicing: wavelength division multiplexing approach for mitigating atmospheric attenuation in optical communication. Opt. Quantum Electron. 54, 258 (2022). https://doi.org/10.1007/s11082-022-03544-8
Grover, M., Singh, P., Kaur, P.: Mitigation of Scintillation Effects in WDM FSO System using Multibeam Technique. J. Telecommun. Inf. Technol 2, 69–74 (2017). https://doi.org/10.26636/joit.2017.111917
Kaur S, Singh N, Kaur G, Singh J.: Performance Comparison of BPSK, QPSK and 16-QAM Modulation Schemes in OFDM System using Reed Solomon Codes. In: International Conference on Recent Innovations in Electrical, Electronics and Communication Engineering (ICRIEECE), Bhubaneswar, India, 530–533 (2018)
Kumar, S., Payal: Enhancing performance of coherent optical OFDM FSO communication link using cascaded EDFA. Wirel. Pers. Commun. 120, 1109–1123 (2021). https://doi.org/10.1007/s11277-021-08506-z
Kumar, S., Arora, P.: Modeling C2n by Inclusion of Rainfall Parameter and Validate Modified Log Normal and Gamma-Gamma Model on FSO Communication Link. J. Opt. Commun. Aop 1–7 (2019). https://doi.org/10.1515/joc-2019-0247
Kumar, S., Payal.: Impact of Reed Solomon forward error correction code in enhancing performance of free space optical communication link. In: Proc. SPIE 11506, Laser Communication and Propagation through the Atmosphere and Oceans IX, p. 1150605 (2020). https://doi.org/10.1117/12.2567835
Malik, A., Singh, P.: Free space optics: current applications and future challenges. Int. J. Opt. 1–17 (2015). https://doi.org/10.1155/2015/945483
Miglani, R., Malhotra, J.S.: Investigation on R-S coded coherent OFDM free space optical (CO-OFDM-FSO) communication link over gamma–gamma channel. Wirel. Pers. Commun. 109, 415–435 (2019)

Patel, D.K., Mandloi, D.S.: Data reliability enhancement using RS coded DP-16-QAM based FSO system under different weather condition. Opt. Quantum Electron. 53, 1–19 (2021). https://doi.org/10.1007/s11082-021-02989-7

Payal, Kumar, S.: Free-space optics: a shifting paradigm in Optical communication systems in difficult terrains. In: Luhach. A., Kosa, J., Poonia, R., Gao, X.Z., Singh D. (eds) First International Conference on Sustainable Technologies for Computational Intelligence. Advances in Intelligent Systems and Computing, vol. 1045. Springer, Singapore (2020)

Rahman, T., Iqbal, S., Islam, M.M.: Modeling and performance analysis of free space optical communication system. In: International Conference on Informatics, Electronics & Vision (ICIEV), pp 211–218 (2012)

Rathore, G., Madhu, C., Dhindsa, A.: Mitigation of haze effects on free space optical communication using multibeam technique. In: Choudhury, S., Mishra, R., Mishra, R., Kumar, A. (eds.) Intelligent Communication, Control and Devices. Advances in Intelligent Systems and Computing, vol. 989. Springer, Singapore (2020). ISBN:978–981–13–8617–6. https://doi.org/10.1007/978-981-13-8618-3_19

Riza, N.A., Marraccini, P.J.: Power smart in-door optical wireless link applications. In: International Wireless Communications and Mobile Computing Conference (IWCNC), pp. 327–332 (2012)

Sanghvi, A.S., Mishra, N.B., Waghmode, R., Talele, K.T.: Performance of reed-solomon codes in AWGN channel. Int. J. Electron. Commun. 4(3), 259–266 (2011)

Sonar, N.S., Mudholkar, R.R.: Analytical study of reed-solomon error probability. Int. J. Eng. Stud. 8(2), 297–304 (2016)

Srivastava, D., Kaur, G., Singh, P.: Design of novel hybrid WDM/multiple-beam FSO system to improve the link length in rainy season. J. Opt. 48, 184–188 (2019). https://doi.org/10.1007/s12596-019-00534-0

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.