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Analysis of OAM Modes and OFDM Modulation for Outdoor Conditions

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Abstract. Signals transporting orbital angular momentum (OAM) have gained significant interest due to their unique structure and capability for increasing the channel capacity. OAM beams are orthogonal and can be multiplexed to increase link capacity in different scenarios. The collective combination of radio OAM modes and OFDM modulations in outdoor conditions has not been extensively explored. This paper depicts an analysis of multiple OAM modes transmitted as narrowband subcarriers using orthogonal frequency division multiplexing (OFDM) modulation with outdoor free space optical channel measurements based on OAM modes. OAM-OFDM simulations were conducted to investigate the performance of QPSK, 16QAM, and 64QAM baseband modulation and demodulation mechanisms, with code rates ½ and ¾ respectively. Four outdoor OAM free space optical channel characteristics parameters were applied. The throughput, bit error rate (BER), and packet error rate (PER) were evaluated. The results show that OAM +4 Mode outperforms other OAM modes in terms of BER and PER. In terms of the throughput, 64 QAM at code rate ¾ outperforms other coding schemes and code rates, for all OAM modes.

Keywords: Drone; Free space optics; Orbital Angular Momentum (OAM); Structured waves; Orthogonal Frequency Division Multiplexing (OFDM)

1. Introduction

5G communications drive the connectivity of people and devices and are gradually infiltrating various industries, supporting the thrust toward a digital society and smart living (Biffl *et al.*, 2023). This enables cyber-physical systems, real-time data access, shared data between various services, and intelligent data insights (Lynn and Wood, 2023). This requires high-bandwidth communications for outdoor conditions, such as between buildings and open public spaces.

In relation to this, structured waves have been deployed in various wireless communications environments due to their orthogonality and ability to be combined with other multiplexing schemes for capacity improvement (He, Shen, and Forbes, 2022). However, the behavior of a simulation model for outdoor conditions is constantly unpredictable as there are various factors affecting the signal transmissions, such as transceiver misalignment and weather conditions (Weng and Vuong, 2022). One of the

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concerning questions related to outdoor conditions for structured waves is the lack of details from current papers on measured channel characteristics and how this affects the transmission performance (Zeleke *et al.*, 2023). This paper bridges the gap in this regards by applying outdoor drone-based free space optical channel measurements based on structured OAM fields to assess the reliability of an OAM-OFDM system using various coding mechanisms for free space optical communications.

The paper has the subsequent structure. Section 2 summarises recent work on orbital angular momentum modes and orthogonal frequency division multiplexing methods. Section 3 discusses the motivation for research and research objectives. Section 4 provides the system model and testing method. Meanwhile, Section 5 presents the results and discussion. The work is concluded in Section 6.

2. Related Works

For this section, information retrieved from several related literature sources will be highlighted. Further explanations regarding structured waves, orbital angular momentum multiplexing, and orthogonal frequency division multiplexing modulation will be provided for a better understanding of how techniques can synergize to accomplish the objectives of this project. Structured waves carrying spatial modes such as Laguerre-Gaussian (LG) modes and the orbital angular momentum (OAM) (a subset of LG modes) have pervasive applications in wireless communications systems (He, Shen, and Forbes, 2022; Wang *et al.*, 2012). However, the transmission distance of spatial modes will be gravely decreased due to beam divergence, transceiver misalignment, and weather conditions (Weng and Vuong, 2022; Su *et al.*, 2022).

OAM can be applied in low-frequency radio domains without receiving any restrictions from the optical frequency range (Edfors and Johansson, 2012). Several demonstrations of structured waves include various spatial modes as follows. In (Raza *et al.*, 2023), LG00 and LG01 modes were multiplexed to increase the system bandwidth using intensity modulation. In (Cui, Cai, and Zhang, 2022), 2-hop free space optics (FSO) transmission was established using LP01 and OAM+1 modes, facilitated by a few modes' fiber relays at 1550nm. In (Badavath *et al.*, 2023), 3-bit depth grayscale images are transmitted on three LG beams through FSO and retrieved using a convolutional neural network on speckle distributions. In (Zhu *et al.*, 2023), two OAM groups (OAM + 2, +3, +4 and OAM-2, -3, -4) were used for multiplexing separate data streams through an FSO system for non-line-of-sight transmission, assuming atmospheric turbulence, using discrete multi-tone signals. The same research group also demonstrated in (Wang *et al.*, 2021), three OAM mode groups (OAM-1,0,1, OAM+2, +3, +4, OAM+5, +6, +7) for transmitting 3 data streams generated using SLM phase patterns, where three distinct OAM modes were used for diversity per channel.

Apart from the SLM, mode diversity has also been shown using photonic crystal fibers for multiplexing spatial modes through radio-over FSO communications (Amphawan *et al.*, 2021; 2020; Chaudhary and Amphawan, 2018a; 2018b). Structured modes have also been used for drone-based FSO communications for mode diversity (Amphawan *et al.*, 2022). In (Amphawan *et al.*, 2022), OAM modes were used in conjunction with diagonal permutation shift codes to increase the transmission data rates (Armghan *et al.*, 2023; El-Mottaleb *et al.*, 2022). Despite these works, there is a lack number of channel measurements to assess the reliability of OAM-OFDM system using various coding mechanisms for optical communications. By providing continuous research and development in this area, it will ensure a promising future for wireless communication advancements.

Meanwhile, orthogonal frequency division multiplexing, generally referred to as OFDM, is a multicarrier channel modulation technology in which signals are communicated when bandpass signals are digitally modulated (Zeleke *et al.*, 2023). It is a modulation format that is extensively applied in many latest wireless networking channels, notably local area networks (LAN), mobile communication technologies, digital broadcasting, and others (Wang *et al.*, 2012). Referring to the figure below, an OFDM signal has several modulated carriers that are closely packed and can be separated by the receiver using a filter. Hence, OFDM has undeniably gained a crucial value in wireless technology because of the multipath effects that are a result of the combination of elevated data capacity, high spectral efficiency, and its supreme resilience towards interference (Su *et al.*, 2022).

He, Shen, and Forbes (2022) conducted research on 6G channel models for various application scenarios. Their study primarily focuses on the generation and degradation of waves, antenna design for orbital angular momentum (OAM), and the potential applications of OAM in wireless communication. The research involves measurements of millimeter-wave frequency bands in electromagnetic radio propagation settings for the OAM channel. The outcome shows that the OAM channel demonstrates multiplexing gain, divergence of beams and misalignment, and reflection degradation. However, the channel modeling for the propagation of OAM waves is currently still an open issue, which requires further studies for different frequency bands and under different scenarios. Researchers in (Weng and Vuong, 2022) developed research on radio communication using orbital angular momentum. This research applies the technique of using OAM radio electromagnetic signals to generate multiple channels through the conventional MIMO communication approach. Both researchers identified the conditions where radio waves are generated with OAM features and compared them with the characteristics of traditional communication with the help of the MIMO antenna system. Correspondingly, the research concluded that there is conceptually no improvement gained to radio communication technology through the exploitation of OAM as it will be used instantaneously based on the availability of the array configurations and propagation conditions.

Authors (Edfors and Johansson, 2012) presented an orthogonal division multiplexing (HODM) hybrid scheme that implements the use of OAM and OFDM methods with hopes of attaining maximum throughput in wireless communication systems of sparse multipath propagating conditions. This application is proven reliable based on several existing academic journal articles from other authors, which evidently show that OAM is suitable with the OFDM modulation technique as OFDM is equally important to achieve extremely large capacity as well as beneficial in anti-multipath for wireless channel networks (Badavath *et al.*, 2023; Raza *et al.*, 2023). The feature of this modulation technique enables the inter-symbol interference (ISI) to be completely canceled out in wireless channel transmissions. Through the developed HODM scheme by the authors of this article, it is verified that there is a considerable increment in the throughput of sparse multipath conditions according to their numerical and theoretical outcomes.

(Sa'd, Saad, and Abd-Wahab, 2020) proposed two algorithms in embedding Side-Information (SI) in data-based blind Selected Mapping (SLM) in order to produce better bit error rate (BER) and SI error rate (SIER) performance in terms of binary codes. The proposed algorithms prove that there was an increase of performance by up to 1 dB at

Eb/N0 = 3 dB as well as able to generate multiple set of codes with same performance. Meanwhile, (Dahawi *et al.*, 2019) has proposed a converged fiber-wireless (FiWi) including OFDM and passive optical network (OFDM-PON). This proposed technique has achieved high spectral efficiency as well as reducing the complexity at the transceiver side. Apart from that, (Juwono, Triprasetyo and Gunawan, 2013) introduced and analyzed the use of low-density parity check code for clipping to reduce the Peak-to-Average Power Ratio (PAPR) that actually will degrade the overall performance of the system. Based on the proposed technique, classical clipping yields the best results in PAPR reduction and error probability in the system.

According to the article by Zhu *et al.* (2023), the HODM scheme is also proposed to employ the joint use of OAM and OFDM, aiming to produce a significant increase in the spectrum efficiency and, at the same time, ensuring no extra time or resources are needed. The methodology suggested by the authors was to develop the 2D-IFFT and 2D-FFT algorithm, which modulates the transmitted signal and demodulates the received signal, respectively. Other than that, the authors also initiated an optimal power allocation scheme, which helps in the maximization of spectrum efficiency to the HODM scheme, and numerical result proves the reliability of the proposed schemes and methods. Even so, the authors' efforts remain futile as the aim to obtain maximum spectrum efficiency through the combined use of OAM modes and OFDM modulation in radio wireless channels is still a taxing problem to researchers. Nevertheless, the outcome of the proposed technique by the authors has shown that their developed HODM scheme managed to outperform the traditional OFDM technique and, thus, provided much increment to the spectrum efficiency in radio vortex communications.

In the article (Wang *et al.*, 2021), the authors developed a crosstalk model and capacity model deriving it from the proposed OAM-OFDM wireless networking channel, considering atmospheric turbulence conditions which affect the capacity of the system. Moreover, when compared to the traditional OAM wireless channel, the throughput performance of the recommended OAM-OFDM model has improved tremendously by an average of 751%. This proves that the authors succeeded in managing the implications of atmospheric turbulence while simultaneously boosting the throughput of the introduced system. However, the results of the analysis concluded the BER of the OAM-OFDM wireless communication system is much higher compared to the one from the conventional OAM wireless transmission model. Hence, it has become a future to develop a new model to solve the stated issue.

The authors of the article (Chaudhary and Amphawan, 2018b) demonstrated OFDM-MIMO transmission channel to achieve high spectral efficiency. The software and hardware design of photonic crystal fibers is dependent on the channel characteristics, which may be unpredictable. To address this, the performance of an OFDM-MIMO system is tested and analyzed using real outdoor measurements from a drone-based free space optical system with structured fields (Amphawan *et al.*, 2022). Having apriori information on channel propagation characteristics allows more realistic OFDM-MIMO system testing and analysis in terms of BER, PER, throughput average throughput. This would leads to reduced expenditure for the design of hardware for structured fields.

3. Methodology

3.1. System Model

This section describes the system model and testing methods for the OFDM-OAM model for outdoor conditions. A block diagram of the system model is given in Figure 1. The dotted red lines depict various parts for OFDM modulation.

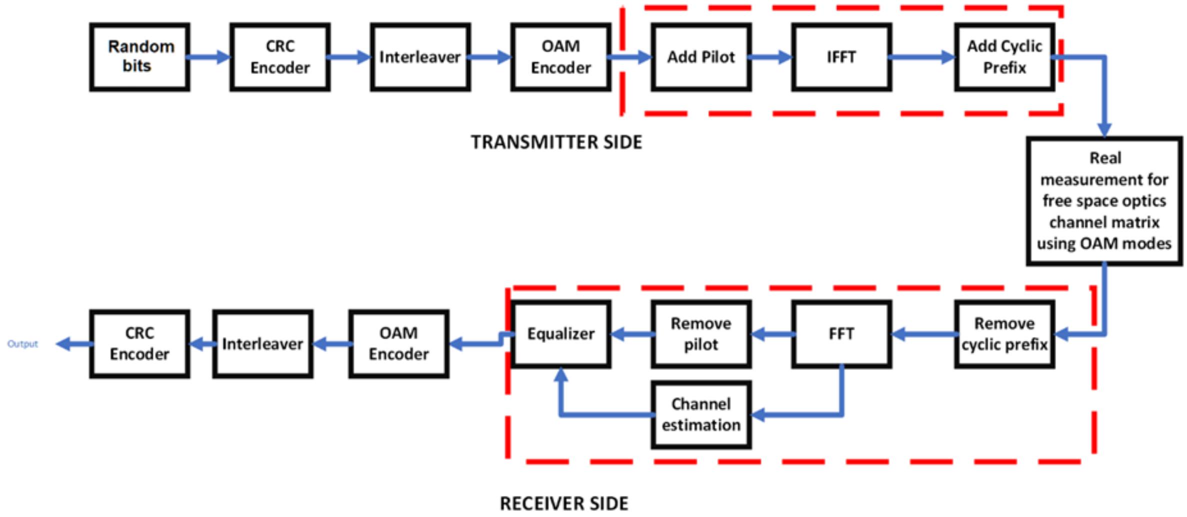

Figure 1 Block diagram for free space optical system using outdoor measurements based on OAM modes**.** The dotted red lines depict various parts for OFDM modulation.

Input data bit are generated randomly based on the Bernoulli distribution. This is followed by cyclic redundancy check (CRC) for error detection, then interleaving, to form the baseband signal. The baseband signal is then OFDM modulated to reduce multipath fading. The absolute bandwidth of the channel signal is modulated into a series of subcarriers which have a data rate of R/N bps for data transmitted at R bps and has a bandwidth of Nfb. Following that assumption, the bit length of each subcarrier of the frequency is N/R (Amphawan *et al.*, 2020). Apart from that, the transmission of data bits through the OFDM modulator and demodulator also conducts the attachment and removal of the Cyclic Prefix (CP), also known as Guard Interval. The mechanism functions as a guard band between successive symbols to prevent inter-symbol interference (ISI), which is a distortion of signal when two subsequent symbols interfere with each other. The use of CP in OFDM modulation is vital as it enables the OFDM signal to operate in a reliable manner.

The OFDM signal is then propagated through various types of OAM fields on the same frequency. For this project, outcomes of the simulation will be compared among the OAM modes, OAM+1 and OAM+4, in relation to the bit error rates (BER), packet error rates (PER), and throughput. The Monte Carlo approach is applied to the processing of the physical layer based on OAM outdoor parameter impulse responses, in which BER and PER are calculated for an average number of 2,000 samples. The OAM outdoor impulses resembles a log-normal distribution. White Gaussian noise is then added to the OAM signals. The received signal is simplified in Equation 1 as:

$$r(t) = x(t) + n(t), \tag{1}$$

in which $n(t)$ stands for Gaussian noise, having a mean value of 0, variance representing the power of noise, and $x(t)$ denoting the signal that is transmitted.

The Error Rate Calculation functions to analyze the bits of input data coming from the transmitter (T_x) with the bits of input data coming from the receiver. It computes the error rate as runtime statistical data, obtaining the BER and PER through Equation 2, given by:

$$PER = \frac{No.of\ packets\ with\ errors\ after\ FEC}{total\ no.of\ packets\ received}. \quad (2)$$

Following this, Forward Error Correction (FEC) enhances the physical layer output by providing additional redundant bits into a bit stream to assist the detection and correction of transmission error at the decoder. The application of FEC simplifies the transmission without having to request for a retransmission of a packet.

3.2. Measurement and Testing

Table 1 shows six types of modulation and coding schemes (MCS) applied on the OAM channels. The OAM channels are assigned different values of phase shift keying (PSK) and quadrature amplitude modulation (QAM) under code rates ½ and ¾. A log-normal distribution channel is assumed for the simulation, based on outdoor OAM channel measuremets. The simulation is conducted on the MATLAB platform.

Bit rates applied in this simulation are tested on each MCS mode and OAM channel. The results of PER, BER, spatial multiplexing throughput, average throughput and maximum throughput will be shown in graphs comparing the values between different modes, in the next section. The SNR value represents the quality of the signal. Spatial multiplexing throughput is the measure of the number of processed signals or bitstreams that are sent separately in a fixed period to improve the signal channel performance rate. The average throughput is calculated by obtaining the mean throughput value. Maximum throughput is the highest value of throughput produced from all the MCS modes.

Throughout the analysis of this simulation, the samples are collected 2000 times for each simulation process. The channel bandwidth used in this simulation is 20 MHz, a packet size of 54 bytes and a FFT size specified to 2048.

Table 1 Modulation and coding scheme (MCS) for simulation

Mode	Modulation Scheme	Code Rate	Bit Rate (Mbps)
1	QPSK	½	*8.4*
2	QPSK	¾	*12.6*
3	16 QAM	½	*16.8*
4	16 QAM	¾	*25.2*
5	64 QAM	½	*25.21*
6	64 QAM	¾	*37.8*

4. Results and Discussion

The system will be tested based on the transmission of distinct OAM modes, which are OAM Mode 1 to OAM Mode 4. The results will be analyzed based on the graphs created from the outcomes of the simulation, which will compare the OAM modes with regards to the BER, PER, and throughput. The throughput calculations are analyzed in terms of spatial multiplexing throughput, average throughput, and maximum throughput. The average throughput is computed by multiplying the data rate with the residual PER, and it is measured in bits per second (bps), given in Equation 3, where R is the bit rates of each MCS mode:

$$Throughput \approx R\,(1 - PERphy) \quad (3)$$

Throughout the paper, a packet size of 64 bytes is consistently used, and each simulation considers 2000 samples for all testing unless otherwise specified. If the Signal-to-Noise Ratio (SNR) drops to a negative value, the link will be deemed out of service. The following subsection analyzes the performance of each OAM mode.

4.1. Mode OAM+1

As shown in Figure 2, the PER value of signals for MCS modes 2 to 5 decrease following an increase in the value of SNR. Given that a PER transmission objective of 10% is frequently anticipated, it can be shown that signals will be out of service when the SNR is below 0dB. Mode 1 shows only one plot point when the SNR value of approximately 10dB is implemented, which proves its robustness as a signal under Mode1 outdoor parameters. For Mode 6, it is illustrated that the signal experienced 6 packet errors throughout the impulse response transmission through the Mode 1 channel. Hence, the signal of OFDM Mode 6 is weaker as compared to the other transmitted signals as it experiences a high value of packet error. Hence, it has been demonstrated that the OFDM Mode 1 signal is stronger compared to other signals during the transmission in channel Mode 1.

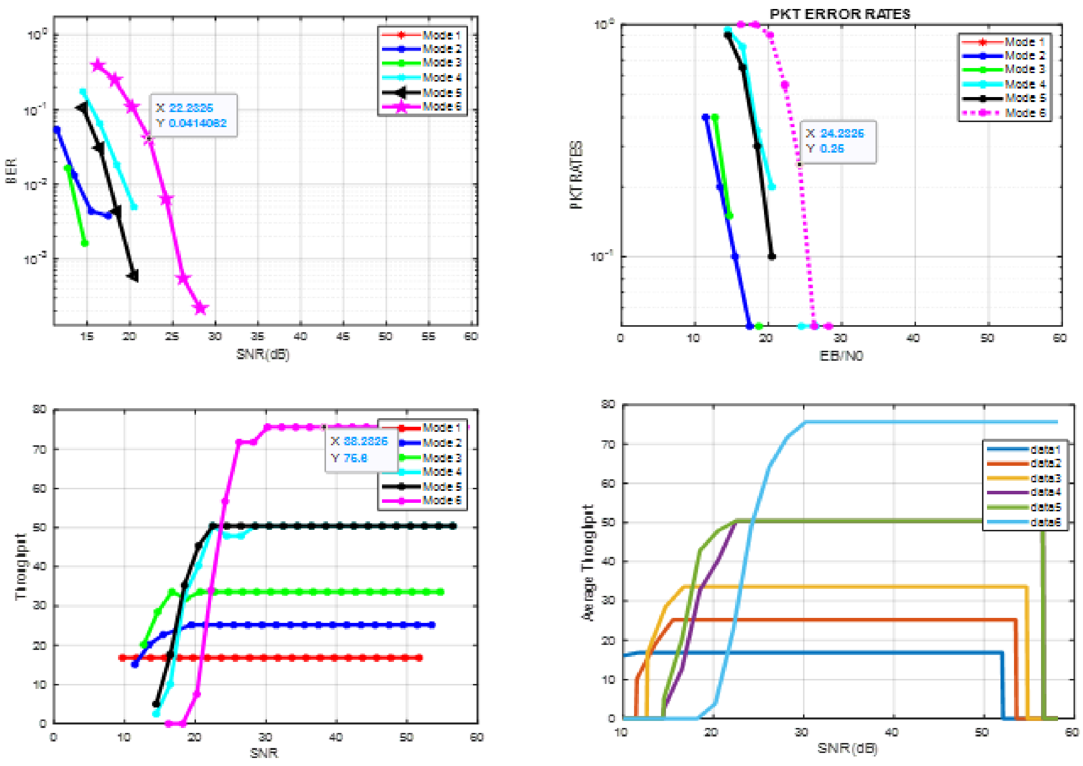

Figure 2 Figure 2 PER, BER, throughput and average for different bit rates in OAM +1 Mode

The plotted lines show the BER value in Figure 2. The BER for Modes 2 to 5 decrease following the increase in the value of SNR. However, the BER for Mode 2 shows an unexpected spike towards the end when an SNR of approximately 18dB is applied. This is possibly due to external factors affecting the signal transmitted in the channel, namely jitters. Jitter may cause a slight fluctuation in the wave pattern of the signal with regards to the time domain, thus leading to the deviation of signal timing from its original time of appearance.

Apart from the slight spike in Mode 2, other OFDM modes exhibit similar results to the analysis of PER in channel Mode 1. Hence, the graph of BER over SNR for Mode 2 has shown that the Mode 1 signal transmitted through OFDM modulation techniques face the least errors and smooth transmission despite the high interference.

For the throughput graph in Figure 2, results show that at low SNR, Mode 1 signal exhibits the best spatial multiplexing throughput performance. However, at high SNR values, we observe that MCS Mode 6 exceeds Mode 1 and provides the highest throughput value, while Mode 1 gives the most stable throughput value.

In the average throughput graph in Figure 2, it is observed that the average throughput of signal for Mode 1 is the most stable among others. Despite the low SNR value causing high interference to the signal, Mode 1 signal can still maintain its throughput, which proves it is a strong signal. As for signals from Modes 2 to 6, these signals are weaker and easily affected by the interference caused by the signal transmitted, specifically the signal for Mode 6. Though some disturbance may arise from outdoor parameters, Mode 1 signal initially experiences some effects from the low SNR value.

4.2. Mode OAM+4

From Figure 3, MCS Mode 6 experienced the highest packet errors. This shows that this signal is much weaker even though there is only a small amount of interference is applied. Apart from that, Modes 2 to 5 experience a stable decrease in PER, which shows that the lower the interference, the lower the PER and the stronger the signal from respective modes. MCS Mode 1 has stronger and more robust tolerance towards interference as it only faces one packet error throughout the simulation.

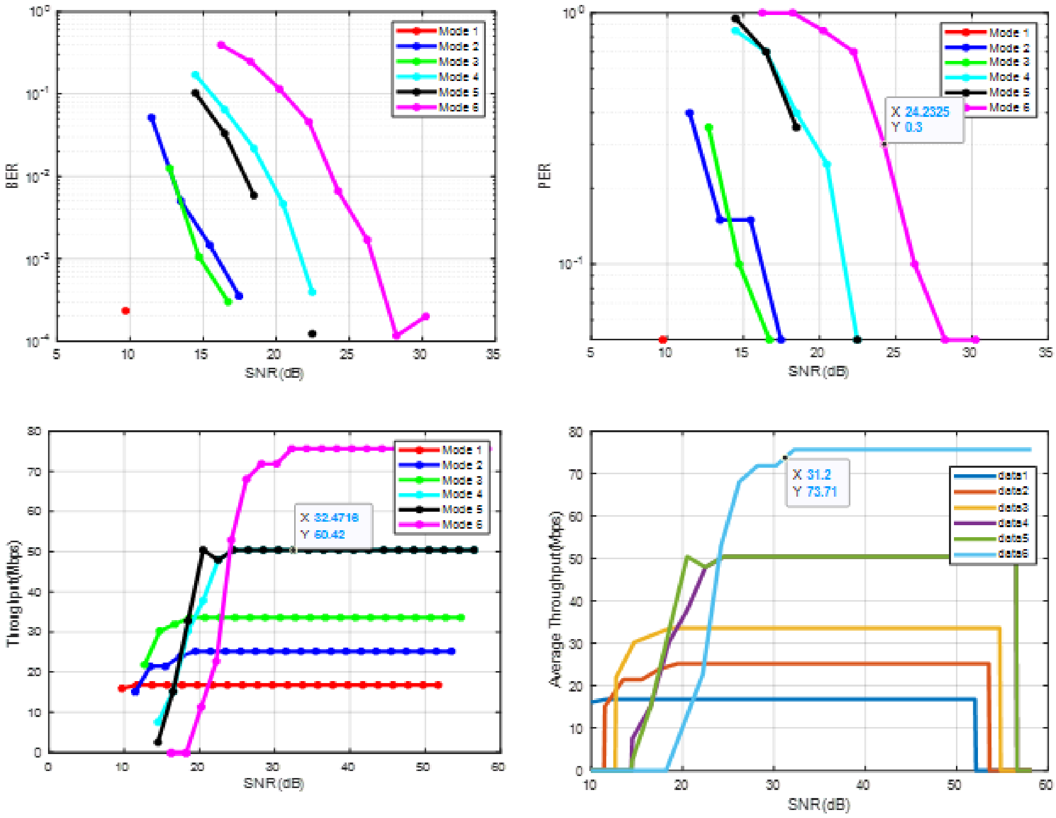

Figure 3 PER, BER, throughput and average for different bit rates in OAM+4

MCS Mode 1 signal shows the weakest signal strength as it is easily affected by interference caused by the stronger noise. However, a signal of Modes 2 to 5 experiences more bit error due to the interference to the signals. At high SNR values, we observe that MCS Mode 6 exceeds MCS Mode 1 in throughput. Even so, the signal from Mode 6 is weaker at lower SNR values, and has a lower value of throughput. MCS Modes 2 to 5 signals have weaker resistance towards interference, thus affecting their throughput performances. Despite other signal modes exceeding the Mode 1 signal in high SNR, Mode 1 is still relatively the strongest signal as it manages to produce an almost perfect constant horizontal line even when a low SNR value is implemented. In terms of the average throughput, we can observe that there is a slight increase in the average throughput at SNR

10dB. Unlike the previous figures on average throughput, the signal from MCS Mode 1 does not show a horizontal straight line throughout the implementation of SNR interference to the transmission. This may be due to the differences in outdoor parameters on OAM+4, which causes more interference or disturbance to the signal transmission.

However, at low SNR values, Gaussian noise becomes stronger and starts affecting the transmission of signals in the channel. This causes the slope in the lines of the graphs. On the other hand, whenever the SNR value becomes a negative value, the signal transmitted will be nullified. This is because as the value reaches the noise floor, the signal becomes unsteady and fluctuates inconsistently.

From the results, it is apparent that OFDM-modulated signals produce distinct results under various outdoor parameters and MCS schemes. Through the integration of OAM modes with OFDM modulation and coding schemes, the research deduces the optimal outdoor parameter mode that produces the strongest and most stable signal with the help of various MCS as listed in Table 1 for this simulation. The suggested mode, which would serve as a benchmark for future wireless communication systems in outdoor conditions, is OAM+4. The outcome is proposed based on the comparison between various outdoor modes in terms of their PER, BER, and throughput values. Based on the graphs obtained, signals transmitted in OAM+4 demonstrated more stability, strength, and consistency despite the variation in the values of SNR.

5. Conclusions

Although OAM multiplexing has garnered recognition in the field of wireless communications, the combination between OAM multiplexing and OFDM modulation and multi-symbol coding has yet to be attentively discussed in free space optical communications, particularly for outdoor conditions. To address the gap, an OFDM-OAM radio communications model is simulated for outdoor conditions through channel impulse responses under outdoor conditions. The BER, PER and throughput performance for OAM+1, OAM+2, OAM+3 and OAM+4 demonstrated that OFDM-OAM is viable for outdoor communications, with 64 QAM at code rate ¾ achieving the best performance. The OFDM-OAM system would be valuable for applications requiring high-bandwidth communications between buildings. The input bits for the system is based on a Bernoulli distribution with real OAM-FSO propagation under outdoor conditions. Future research will look into the integration of bit streams from cyber-physical systems for real-time communications in open public spaces.

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