Performance evaluation of PDM/SAC-OCDMA-FSO communication system using DPS code under fog, dust and rain

Somia A. Abd El-Mottaleb1 · Ahmed Métwalli2 · Tarek A. ElDallal2 · Mostafa Hassib2 · Heba A. Fayed2 · Moustafa H. Aly2

Received: 13 July 2022 / Accepted: 30 August 2022 © The Author(s) 2022

Abstract
A new hybrid polarization division multiplexing (PDM) spectral amplitude coding optical code division multiple access (SAC-OCDMA) is proposed for free space optical (FSO) for capacity enhancement. Two polarization signals are utilized; one is x-polarization and carries three different channels at 0° azimuthal angle while the other is y-polarization at 90° azimuthal angle, and carries the same three channels. Each channel is assigned with a diagonal permutation shift (DPS) code and carries 10 Gbps. The suggested system is simulated, and its performance is evaluated in terms of maximum allowable number of users, propagation range, bit error rate (BER), Q-factor, and received power for the different channels under various fog, dust storm, and rain scenarios. The reported results indicate that the system can support a signal travelling up to 2, 0.9, and 1.3 km, respectively, under light fog (LF), light dust (LD), and light rain (LR). As the level of these weather conditions is increased from light to moderate, the FSO link length decreases to 1.3, 0.25, and 1.8 km under medium fog (MF), medium dust (MD), and medium rain (MR), respectively. Furthermore, the shortest propagation range is achieved as the level of weather conditions becomes heavy, where the FSO link range becomes 1, 0.095, and 1.1 km under heavy fog (HF), heavy dust (HD), and heavy rain (HR), respectively. All these ranges are considered at BER ≤ 10⁻³ and a received power ≤ −27 dBm with 60 Gbps overall data transmission. This new hybrid FSO system is suggested to be implemented in desert areas that affects by dust storms and in 5G wireless transmission communications.

Keywords Polarization division multiplexing (PDM) · Spectral amplitude coding optical code division multiple access (SAC-OCDMA) · Free space optics (FSO) · Diagonal permutation shift (DPS) · Fog, dust, and rain weather conditions
1 Introduction

The need for high bandwidth has expeditiously increased for the future generation of communication networks. Free-Space Optical (FSO) communication is very promising, as it offers less expenses and more flexibility in designing optical networks at high speed. It also can emerge radio frequency (RF) communication as it provides a solution to the last-mile distribution of high bandwidth networks with a higher data rates, immunity to RF interference, secure communication links, and unlicensed spectrum (Majumdar 2019; Chaudhary et al. 2014; Amphawan et al. 2015; Chaudhary et al. 2014). It can be an alternative solution in areas where the traditional optical fiber wired communication systems is hardly installed and can be applied in hospitals and in healthcare (Yang et al. 2020; Amphawan et al. 2015; Zhang et al. 2021a, b).

The FSO communication is a wireless transmission of data through modulated optical beam directed via the atmosphere or vacuum as a communication channel between transceivers with a line of sight (LOS) (Kanno et al. 2011). On the other hand, the effect of the atmospheric conditions is considered an enormous challenge to FSO communication links, such as fog which affects the FSO links and causes a signal attenuation (Chaudhary et al. 2020; Sharma et al. 2021).

Optical Code Division Multiple Access (OCDMA) is based on binary 1 and 0, where 1 represents the presence of light, which supports considerable users to share the same medium asynchronously and simultaneously without any interruption (Wang et al. 2009). Spectral Amplitude Coding (SAC) is selected among many coding techniques that can be implemented in OCDMA due to less cost. In SAC-OCDMA, each user is assigned a unique code sequence that serves as its address providing security to each user during their accessing time on the same transmission channel. Many codes are used with SAC-OCDMA. Some have zero cross correlation like random diagonal (Chaudhary et al. 2020), multi diagonal (Mostafa et al. 2017) and others have unity cross correlation like enhanced double weight (EDW) (Abd El-Mottaleb et al. 2018) and diagonal permutation shift code (DPS) (Ahmed et al. 2017, 2022). Although, code construction of zero cross correlation code is easy but their implementation in a real experiment is difficult.

Comparisons between different OCDMA codes are carried out in (Mrabet et al. 2021). The authors used these codes with optical fiber communication systems only, not in optical wireless communication.

However, unity cross correlation codes suffer from multiple access interference (MAI) caused by various noises that lead to performance degradation. This undesired effect of MAI can be resolved by using detection techniques at the receiver, such as single photodiode detection (SPD) technique (Abd El-Mottaleb et al. 2018).

Recently, researchers integrated multiplexing techniques with OCDMA to enhance the capacity of the optical communication system. A hybrid space division multiplexing (SDM) with OCDMA using balanced incomplete block chain code (BIBC) was proposed in the FSO/passive optical network by Farghal (2019). Atmospheric turbulence was considered while atmospheric attenuation due to different weather conditions was not considered. Conducted results showed successful transmission of eight channels with an overall capacity of $8 \times 0.5 = 4$ Gbps.

Multiple polarization signals are combined in polarization division multiplexing (PDM) to generate a new parallel polarization state. PDM also improves transmission capacity by allowing distinct signals to be carried at the same wavelength in an orthogonal condition (Zhou et al. 2017; Goossens et al. 2017; Upadhyay et al. 2019).
Chaudhary et al. (2019), a hybrid PDM/SAC-OCDMA was proposed but with RD codes for inter-satellite communication. Chaudhary et al. (2020), the performance of hybrid PDM with SAC-OCDMA in the FSO system was solely tested for random diagonal (RD) code using direct detection approach and under different fog weather conditions only. Although the results showed enhancement in transmission capacity as its overall capacity was 50 Gbps, the implementation of this code in a real experiment was difficult due to its code property that has zero cross correlation.

In this paper, a hybrid PDM/SAC-OCDMA based FSO communication system is used for transmitting three different channels, on x-polarization signals and on y-polarization to increase transmission capacity. A DPS code with SPD detection scheme is used. The performance is investigated under various weather conditions: fog {light (LF), medium (MF) and heavy (HF)}, dust storm {low (LD), medium (MD), and heavy (HD)}, and rain {low (LR), medium (MR), and heavy (HR)}. The system performance is evaluated in terms of maximum allowable number of users, maximum propagation link, minimum bit error rate (BER), Q-factor and received power.

The remainder of the paper is organized as follows. SAC-OCDMA code construction and property are explained in Sect. 2. Performance analysis of our proposed model is illustrated in Sect. 3. Section 4 describes the schematic diagram of PDM/SAC-OCDMA-FSO system, followed by results and discussion in Sect. 5. Finally, Sect. 6 is devoted to the main conclusions.

### 2 Code properties and code construction

#### 2.1 Code properties

A DPS code is proposed to our FSO model, and its code property is given in Table 1 (Ahmed et al. 2017).

#### 2.2 Code construction

The DPS code is driven from prime code sequences that are based on Galois field GF \( (w) = \{0, 1, \ldots, w-1\} \), where \( w \) is any prime number greater than 2 (Ahmed et al. 2017). Four process are used for making DPS code which are sequent diagonal, permutation, shifting and joining.

In the diagonal process, primary diagonal \( (d_{x,y}) \) sequences of integer number are constructed according to Ahmed et al. (2017)

\[
d_{x,y} = (x \cdot y) \mod w
\]

where \( x \) and \( y \) represent the location of each element over GF and \( \mod \) is the modulo operation.

| Parameter                  | Value                                                                                           |
|----------------------------|-------------------------------------------------------------------------------------------------|
| Code weight \((w)\)        | Can be any prime number greater than 2, so, we choose \( w=3 \)                                 |
| Code Length \((L)\)        | \( L = U + w = w^2 + w \), where \( U \) is the number of channels                             |
| Cross correlation \((\lambda_{cc})\) | \( \lambda_{cc} = \text{unity between any two code sequences} \)                              |
Based on $d_{x,y}$, the construction of generator sequence, $D_w$, is Ahmed et al. (2017)

$$D_w = \{d_{0,0}d_{1,1}d_{2,2} \cdots d_{w-1,w-1}\} \quad (2)$$

For any value of $w$, the following diagonal sequences are fixed as Ahmed et al. (2017)

$$d_{0,0} = 0, \quad d_{1,1} = 1,$$

$$d_{w-1,w-1} = (w-1) \cdot (w-1) \mod P = (w^2 - 2w + 1) \mod (w) = 1 \quad (3)$$

Then, the value of $D_w$ at $w=3$ can be written as

$$D_3 = \begin{bmatrix} 0 & 1 & 1 \end{bmatrix} \quad (4)$$

Now, the permutation process can be done and by first constructing a basic matrix, $B^0_w$, having $D_w$ in the first row. Then, in the next rows, making permutation of $D_w$ one time to get a $w \times w$ zero-diagonal symmetric matrix without repeating any row as follows Ahmed et al. (2017)

$$B^0_w = \begin{bmatrix}
    d_{0,0} & d_{1,1} & d_{2,2} & \cdots & d_{w-1,w-1} \\
    d_{w-1,w-1} & d_{0,0} & d_{1,1} & \cdots & d_{w-2,w-2} \\
    d_{w-2,w-2} & d_{w-1,w-1} & d_{0,0} & \cdots & d_{w-3,w-3} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    d_{1,1} & d_{2,2} & d_{3,3} & \cdots & d_{0,0}
\end{bmatrix} \quad (5)$$

So, $B^0_w$ at $w=3$, can be written as Ahmed et al. (2022)

$$B^0_3 = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \quad (6)$$

Here, a shifting process can be applied through constructing $(w-1)$ shifted matrices, $B^H_w$, by adding $H$ to each element of the matrix $B^0_w$, where $H = 1, 2, 3, \ldots, w-1$ as follows

$$B^1_3 = \begin{bmatrix} 1 & 2 & 2 \\ 2 & 1 & 2 \\ 2 & 2 & 1 \end{bmatrix} \quad (7)$$

$$B^2_3 = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix}$$

Finally, the matrix $K$ is obtained in a joining process through joining $B^H_w$ in each sequence, then an extra column of matrix $m_w$ is added to each corresponding $B^H_w$ as Kanno et al. (2011) and Ahmed et al. (2017)

$$K = \begin{bmatrix}
    \left[ B^0_w \right] & \cdots & \left[ m_w \right] \\
    \left[ B^1_w \right] & \cdots & \left[ m_w \right] \\
    \vdots & \cdots & \vdots \\
    \left[ B^{w-1}_w \right] & \cdots & \left[ m_w \right]
\end{bmatrix} \quad (8)$$
where \( m_w \) is a \( w \times 1 \) matrix containing the elements \( \{0, 1, 2, \ldots, w - 1\} \) in an arbitrary order. The matrix \( K \) size is \( w^2 \times (w - 1) \) and its elements are \( K_{x,y} \) where \( x = 0, 1, 2, \ldots, w^2 - 1, \) and \( y = 0, 1, 2, \ldots, w \).

As an example, for \( w = 3 \), the DPS code is shown in Table 2 (Ahmed et al. 2022).

According to Table 1, channel 1 will have the code word 10010010100. So, it will have wavelengths \( \lambda_1, \lambda_5, \lambda_8, \lambda_{10} \) corresponding to the number of “1s” bit that will carry its information. While for channels 2 and 3, their code words are 010100010010 and 010010100001, respectively, and their corresponding wavelengths are \( \lambda_2, \lambda_4, \lambda_8, \lambda_{11} \) and \( \lambda_2, \lambda_5, \lambda_7, \lambda_{12} \), respectively.

### 3 Performance analysis

The received power for FSO link is Singh and Malhotra (2019)

\[
S_{rx} = S_t x \left( \frac{d_{rx}}{d_{tx} + \theta F} \right)^2 10^{-\frac{\alpha_f}{10}}
\]

where \( S_{rx} \) and \( d_{rx} \) are the received power and received aperture angle, respectively. \( S_t \) and \( d_{tx} \) represent the transmitted power and transmitted aperture angle, respectively. \( \theta \), \( F \) and \( \alpha_f \), respectively, are the beam divergence angle, FSO range and attenuation due to weather conditions.

The fog attenuation, \( \alpha_f \), in dB/km is expressed as Kim et al. (2001)

\[
\alpha_f = \frac{3.912}{V} \left( \frac{\lambda}{550nm} \right)^{-z}
\]

where \( V \) and \( \lambda \), respectively, are the visibility in km and the wavelength in nm while \( z \) is the size distribution of the scattering particle that can be determined according to Kim model as Singh et al. (2022a, b)

| \( x \) | \( K_{x,y} \) | \( y = 0, 1, 2, 3 \) | DPS code |
|---|---|---|---|
| 0 | 0110 | 100 | 010 | 010 | 100 |
| 1 | 1011 | 010 | 100 | 010 | 010 |
| 2 | 1102 | 010 | 010 | 100 | 001 |
| 3 | 1220 | 010 | 001 | 001 | 100 |
| 4 | 2121 | 001 | 100 | 001 | 010 |
| 5 | 2212 | 001 | 001 | 010 | 001 |
| 6 | 2000 | 001 | 100 | 100 | 100 |
| 7 | 0201 | 100 | 001 | 100 | 010 |
| 8 | 0022 | 100 | 100 | 001 | 001 |
As dust storms affect the FSO channel and cause attenuation, the dust storm attenuation, $\alpha_D$, in dB/km, is expressed as Singh et al. (2022a, b)

$$\alpha_D = 52 \times V^{-1.05}$$

Also, the different rain conditions cause attenuation that causes degradation in the received signal power and can be expressed as Muhammad et al. (2005)

$$\alpha_R = \beta R^\gamma$$

where $\beta$ (dB/km), $R$ (mm/hr), $\gamma$ and $q$, respectively, indicate the rain attenuation, the rain rate, a coefficient that depends on frequency, and a coefficient that depends on ambient temperature. At the $R = 100$ mm/hr, $\gamma = 1.076$ and $q = 0.67$, yielding $\alpha_R$ of $\sim 18.3$ dB/km (Mohammed et al. 2013).

At PD, the power spectral density (PSD), $P(v)$, is Al-Khafaji et al. (2013)

$$P(v) = \frac{S_{rx}}{B_{op}} \sum_{i=1}^{U} d_{U} \left( \sum_{i=1}^{L} H_a(i) \cdot H_b(i) - \sum_{i=1}^{L} (H_a(i) \cdot H_b(i)(H_a(i)) \right) \left\{ u \left[ \frac{B_{op}}{L} \right] \right\}$$

where $B_{op}$ and $u\left[ \frac{B_{op}}{L} \right]$, respectively, represents optical bandwidth and unit step function. $H_a(i)$ and $H_b(i)$ represent the ith element of the element of a and b code sequence.

The DPS code property when SPD detection is used as

$$\sum_{i=1}^{L} H_a(i).H_b(i) - \sum_{i=1}^{L} (H_a(i)\cdot H_b(i)(H_a(i)) = \left\{ \begin{array}{ll} w_{PD}, & \text{for } a = b \\ 0, & \text{for } a \neq b \end{array} \right.$$ 

where $w_{PD}$ is the number of “1’s” that reach PD and is equal to $w + 1$.

The average received optical power, $P_u$, by the PD for the desired channel with SPD detection is Abd El-Mottaleb et al. (2021)

$$P_u = \Re \int_{0}^{\infty} P(v)dv = \frac{S_{rx} B_{op}}{L} w_{PD}$$

where $\Re$ is the PD responsivity.

The shot noise, $Sh_N$, can be expressed as Ahmed et al. (2022)

$$Sh_N = 2e B_e \Re S_{rx} B_{op}$$

where $e$ is electron charge and $B_{electric}$ is electrical bandwidth.

The phase induced intensity noise (PIIN) noise power, $PN_N$, is Ahmed et al. (2022)
Thermal noise, $Th_N$, can be expressed as Abd El-Mottaleb et al. (2021)

$$Th_N = \frac{4k_B T_n}{R_L}$$  \hspace{1cm} (19)

where $k_B$ is Boltzmann constant, $T_n$ is the receiver noise absolute temperature, and $R_L$ is the receiver load resistance.

The SNR is expressed as Abd El-Mottaleb et al. (2021), Moghaddasi et al. (2015), 2017 and Kakati and Arya (2019a, 2019b)

$$SNR = \frac{(P_u)^2}{\frac{S_{rx}^2 B_e B_{op} w_{PD}}{L} + \frac{2e B_e R_S B_{op}}{L} w_{PD} + \frac{4k_B T_n B_e}{R_L}}$$  \hspace{1cm} (20)

Using Gaussian approximation, the BER can be expressed as a function of SNR as Abd El-Mottaleb et al. (2021) and Al-Khafaji et al. (2013)

$$BER = 0.5erfc\left(\frac{\sqrt{SNR}}{2}\right)$$  \hspace{1cm} (21)

Also, the BER can be expressed in term of Q-factor as Ahmed et al. (2022):

$$BER = 0.5erfc\left(\frac{Q}{\sqrt{2}}\right)$$  \hspace{1cm} (22)

### 4 Proposed PDM/SAC-OCDMA-FSO model

Figure 1 shows the schematic diagram for six users of a PDM/SAC-OCDMA-FSO system. Channel 1 will assign 100010010100 DPS code according to Table 1. So, the transmitter consists of continuous wave (CW) source for generating optical signals and also delivers azimuthal angle of 0° and 90° for x and y polarizations. Channels 1 and 4 have the same code but one is transmitted on x-polarization while the other on y-polarization and the same applies for the other channels. The information signal, that is 10 Gbps, is then generated from the pseudo random bit generator (PRBG) and the non-return to zero (NRZ) modulator. Further, Mach–Zehnder modulator (MZM) is used for encoding the information signal onto optical signals. Then, the three channels from x-polarization are combined together through an ideal multiplexer (MUX) and the same sequence is done for the other channels from y-polarization. Both signals that transmitted on x-polarization and y-polarization are combined through PDM before transmitting to the FSO channel.

At the receiver, the six channels are split using the PDM splitter into x-polarization and y-polarization. For channel 1, as an example, its receiver consists of a single branch that has a decoder, a subtractive decoder, a low pass filter (LPF), and a BER analyzer (Ahmed et al. 2022). In the decoder, the SPD detection technique is used to detect the right code (desired information), which is 100010010100. The decoder consists of four fiber Bragg gratings
having the same spectral width as the encoder, while a subtractive decoder has an interference bit with channel 2, which is the eighth bit as channel 2 has the code 010100010010. So, after subtracting the subtractive decoder from the decoder, the desired channel (channel 1) is detected. Then, the output passes through the photodiode (PD) for optical/electrical conversion. Finally, the received signal passes to the LPF for rejecting unwanted noise, and the BER is visualized to evaluate the performance of the signal. The same sequence is done at the receiver of the other channels, either on x-polarization or y-polarization, but according to their assigned codes.

The recommended PDM/SAC-OCDMA-FSO system is evaluated and simulated using Optisystem software version 19 with the parameters mentioned in Table 3 (Kakati and Arya 2019a, 2019b; Imtiaz and Ahmad 2014; Zhang et al. 2021a, b).

5 Simulation results

In this section, the obtained results are displayed and discussed for our proposed model PDM/SAC-OCDMA-FSO system using DPS code with the given parameters in Table 2. The performance of the model is evaluated under different fog conditions: LF, MF and HF in terms of maximum allowable number of users and propagation range, Q-factor, BER, and optimum received power.

Figure 2 shows BER versus number of users for SAC-OCDMA-FSO system code at different bit rates, under LF condition and at propagation range 1.5 km. As noticed, when the number of users increases, the BER increases and as the bit rates increases, the number of users that the system can support decreases. At BER $\sim 10^{-6}$, the maximum allowable number of users that the system can support is 50 at 2.5 Gbps, 25 at 5 Gbps and 11 at 10 Gbps.

Figure 3 shows BER versus FSO propagation range under LF, MF and HF for channels 1 and 3 on x-polarization and channels 4 and 6 on y-polarization. These
Performance evaluation of PDM/SAC-OCDMA-FSO communication…

Table 3 Simulation parameters (Al-Khafaji et al. 2013; Kakati and Arya 2019a, 2019b; Imtiaz and Ahmad, 2014; Zhang et al. 2021a, b)

| Symbol | Parameter | Value |
|--------|-----------|-------|
| $S_t$ (dBm) | PRBG sequence length | 1024 bits |
| $L_t$ (dBm) | Transmitter source power | 15 |
| $R_b$ (GHz) | Laser linewidth | 10 MHz |
| $R_b$ (Hz) | Bit rate per user | 10 |
| $B_e$ (Hz) | Electrical bandwidth | $0.75 \times \text{Bit rate}$ |
| $d_t$ (cm) | Transmitter aperture diameter | 10 |
| $d_r$ (cm) | Receiver aperture diameter | 20 |
| $\alpha_f$ (dB/km) | LF | 9 |
| | MF | 16 |
| | HF | 22 |
| $\alpha_f$ (dB/km) | LD | 25.11 |
| | MD | 107.66 |
| | HD | 297.38 |
| $\alpha_R$ (dB/km) | LR | 6.27 |
| | MR | 9.64 |
| | HR | 19.28 |
| $\mathcal{R}$ (A/W) | Photodiode responsivity | 1 |
| | Thermal noise power density | $10^{-22}$ W/Hz |
| $T_{n}$ (K) | Receiver noise temperature | 300 |
| $R_L$ | Receiver load resistance | 1030 $\Omega$ |

Fig. 2 BER versus number of users at different bit rates

Specific channels are chosen for simplicity as these channels give the highest and lowest performance. Fog is atmospheric phenomenon that causes water particles to stay in the atmosphere. So, it affects the LOS link between transmitter and receiver and causes degradation to the performance of FSO transmission system. As the level of fog increases from light to heavy, the propagation link range decreases as declared in Fig. 3. The maximum FSO range achieved for channels 1 and 4 is 2 km, and for
channels 3 and 6 it is 1.8 km under LF condition with BER value $<10^{-6}$. When the level of fog slightly increases and becomes MF, these ranges are decreased to 1.3 km for channels 1 and 4, and to 1.2 km, for channels 3 and 4. Furthermore, increasing the fog level until becoming heavy leads to minimum propagation distance; 1 km (channels 1 and 4) and 0.92 km (channels 3 and 6). Table 4 summarizes the simulation results of the BER for the different channels at propagation ranges 2 km under LF, 1.3 km under MF and 1 km under HF.

The Q-factor versus FSO propagation range is displayed in Fig. 4 under LF, MF and HF for different channels. As the fog level rises from light to heavy, both the propagation range and the Q-factor decrease. Figure 4. As an example, the maximum range and Q-factor, respectively, for channel 1 is 2 km and 4.5 under LF, 1.3 km and 4.3 under MF, and 1 km and 4.7 under HF, respectively.

Table 5 summarizes the simulation results of the Q-factor for the different channels at propagation ranges of 2 km under LF, 1.3 km under MF and 1 km under HF.

Figure 5 shows the received power versus FSO propagation range under LF, MF and HF for channels 1 and 3 on x-polarization and channels 4 and 6 on y-polarization. As the propagation range increases, the received power decreases. The LF achieves the highest received power as Fig. 5 depicts. Channel 1 has the highest received power under different weather conditions while channel 6 has the lowest. The received power for channel 1 is $-26.123$ dBm at 2 km under LF, $-26.293$ dBm at 1.3 km under MF and $-26.015$ dBm at 1 km under HF. As for channel 6, the received powers at the same ranges (2 km
under LF, 1.3 km under MF and 1 km under HF), are $-27.852$ dBm, $-28.001$ dBm and $-27.777$ dBm, respectively. Table 6 summarizes the simulation results of the received power for the different channels at the mentioned propagation ranges.

| Weather condition (range) | Channel | PDM Type   | BER      |
|---------------------------|---------|------------|----------|
| LF (2 km)                 | Channel 1 | x-polarization | $2.61 \times 10^{-6}$ |
|                           | Channel 3 |            | $6.6 \times 10^{-4}$ |
|                           | Channel 4 | y-polarization | $9.8 \times 10^{-7}$ |
|                           | Channel 6 |            | $2.94 \times 10^{-3}$ |
| MF (1.3 km)               | Channel 1 | x-polarization | $8 \times 10^{-6}$ |
|                           | Channel 3 |            | $8.8 \times 10^{-4}$ |
|                           | Channel 4 | y-polarization | $6.61 \times 10^{-6}$ |
|                           | Channel 6 |            | $7.46 \times 10^{-3}$ |
| HF (1 km)                 | Channel 1 | x-polarization | $1.19 \times 10^{-6}$ |
|                           | Channel 3 |            | $4.58 \times 10^{-4}$ |
|                           | Channel 4 | y-polarization | $5.36 \times 10^{-7}$ |
|                           | Channel 6 |            | $5.9 \times 10^{-4}$ |

**Fig. 4** Q-factor versus range for PDM/SAC-OCDMA and DPS under **a** LF, **b** MF and **c** HF.
Table 5 Q-factor values for different ranges

| Weather condition (range) | Channel | PDM Type | Q-factor    |
|---------------------------|---------|----------|-------------|
| LF (2 km)                 | Channel 1 x-polarization | 4.55489 |
|                           | Channel 3 |          | 3.20954     |
|                           | Channel 4 y-polarization | 4.75585 |
|                           | Channel 6 |          | 2.75328     |
| MF (1.3 km)               | Channel 1 x-polarization | 4.31289 |
|                           | Channel 3 |          | 3.12522     |
|                           | Channel 4 y-polarization | 4.35432 |
|                           | Channel 6 |          | 3.17506     |
| HF (1 km)                 | Channel 1 x-polarization | 4.71564 |
|                           | Channel 3 |          | 3.31394     |
|                           | Channel 4 y-polarization | 4.87658 |
|                           | Channel 6 |          | 3.23541     |

Fig. 5 Received power versus range for PDM/SAC-OCDMA using DPS under a LF, b MF and c HF

Figure 6 displays the BER versus propagation range under LD, MD and HD for channels 1 and 3 with the x-polarization and channels 4 and 6 with y-polarization. Dust introduces aerosols into the atmospheric channel. Therefore, it affects the LOS link between transmitter and receiver and causes degradation to the performance of FSO transmission.
system. As the level of dust increases from light to heavy, the propagation link range decreases as declared in Fig. 6. The maximum FSO range achieved for channels 1 and 4 is 0.9 km, and for channels 3 and 6 it is 0.85 km under LD condition with BER value < 10^{-6}. When the level of dust slightly increases and becomes MD, these ranges are decreased to
0.25 km for channels 1 and 4, and to 0.23 km for channels 3 and 4. Further increasing the dust level until becoming heavy leads to minimum propagation distances; 0.095 km (channels 1 and 4) and 0.09 km (channels 3 and 6). Table 7 summarizes the simulation results of the BER for the different channels at propagation ranges 0.9 km under LD, 0.25 km under MD and 0.095 km under HD.

The Q-factor versus FSO propagation range is displayed in Fig. 7 under LD, MD and HD for different channels. As the dust level rises from light to heavy, both the propagation range and the Q-factor decrease. As an example, the maximum range and Q-factor, respectively, for channel 1 are 0.9 km and 4.4 under LD, 0.25 km and 4.8 under MD, and 0.095 km and 5.3 under HD, respectively.

Table 8 summarizes the simulation results of the Q-factor for the different channels at propagation ranges of 0.9 km under LD, 0.25 km under MD and 0.095 km under HD.

Figure 8 shows the received power versus FSO propagation range under LD, MD and HD for channels 1 and 3 with x-polarization and channels 4 and 6 with y-polarization. As the propagation range increases, the received power decreases. The LD achieves the highest received power as Fig. 8 depicts. Channel 1 has the highest received power under different weather conditions while channel 6 has the lowest one. Table 9 summarizes the simulation results of the received power for the different channels at the mentioned propagation ranges.

Figure 9 shows the BER versus FSO propagation range under LR, MR and HR for channels 1 and 3 with x-polarization and channels 4 and 6 with y-polarization. The difference between rain and fog is the density and size of water particles in the atmospheric channel. Attenuation of the optical beam due to the rain is lower as compared to the fog. Rain affects the LOS link between transmitter and receiver and causes degradation to the performance of FSO transmission system. As the scale of rain increases from light to heavy, the propagation link range decreases as declared in Fig. 9. The maximum FSO range achieved for channels 1 and 4 is 2.4 km, and for channels 3 and 6 it is 2.3 km under LR condition with BER value < 10^{-6}. When the level of rain slightly increases and becomes MR, these ranges are decreased to 1.8 km for channels 1 and 4, and to 1.7 km for channels 3 and 4. Furthermore, increasing the rain level until becoming heavy leads to minimum propagation distance; 1.1 km (channels 1 and 4) and 1.05 km (channels 3

| Table 7 BER for different ranges under dust conditions |
|-------------------------------------------------------|
| Weather condition (range) | Channel | PDM Type | BER         |
|---------------------------|---------|----------|-------------|
| LD (0.9 km)               | Channel 1 | x-polarization | 5.07 × 10^{-6} |
|                           | Channel 3 | x-polarization | 6.21 × 10^{-4} |
|                           | Channel 4 | y-polarization | 7.64 × 10^{-7} |
|                           | Channel 6 |            | 5.73 × 10^{-3} |
| MD (0.25 km)              | Channel 1 | x-polarization | 5.65 × 10^{-6} |
|                           | Channel 3 | x-polarization | 2.84 × 10^{-4} |
|                           | Channel 4 | y-polarization | 2.27 × 10^{-4} |
|                           | Channel 6 |            | 3.25 × 10^{-4} |
| HD (0.095 km)             | Channel 1 | x-polarization | 5.54 × 10^{-8} |
|                           | Channel 3 |            | 1.37 × 10^{-3} |
|                           | Channel 4 | y-polarization | 7.15 × 10^{-8} |
|                           | Channel 6 |            | 1.46 × 10^{-3} |
Table 8  Q-factor for different ranges under dust conditions

| Weather condition (range) | Channel   | PDM Type   | Q-factor |
|---------------------------|-----------|------------|----------|
| LD (0.9 km)               | Channel 1 | x-polarization | 4.4128 |
|                           | Channel 3 |              | 3.22783 |
|                           | Channel 4 | y-polarization | 4.8065 |
|                           | Channel 6 |              | 3.2506 |
| MD (0.25 km)              | Channel 1 | x-polarization | 4.86674 |
|                           | Channel 3 |              | 3.44484 |
|                           | Channel 4 | y-polarization | 5.04266 |
|                           | Channel 6 |              | 3.40708 |
| HD (0.095 km)             | Channel 1 | x-polarization | 5.30722 |
|                           | Channel 3 |              | 3.63726 |
|                           | Channel 4 | y-polarization | 5.26019 |
|                           | Channel 6 |              | 3.62043 |

and 6). Table 10 summarizes the simulation results of the BER for the different channels at propagation ranges 2.4 km under LR, 1.8 km under MR and 1.1 km under HR.

The Q-factor versus FSO propagation range is displayed in Fig. 10 under LR, MR and HR for different channels. As level of rain rises from light to heavy, both the propagation range and the Q-factor decrease. Table 11 summarizes the Q-factor for the
different channels at propagation ranges of 2.4 km under LR, 1.8 km under MR and 1.1 km under HR.

Figure 11 shows the received power versus FSO propagation range under LR, MR and HR for channels 1 and 3 with x-polarization and channels 4 and 6 with y-polarization.
As the propagation range increases, the received power decreases. Table 12 summarizes the simulation results of the received power for the different channels and ranges.

Table 13 performs a comparison between our work and previously published related work.

---

**Table 10** BER for different ranges under rain conditions

| Weather condition (range) | Channel | PDM Type | BER values |
|---------------------------|---------|----------|------------|
| LR (2.4 km)               | Channel 1 | x-polarization | $1.25 \times 10^{-11}$ |
|                           | Channel 3 | x-polarization | $3.52 \times 10^{-6}$ |
|                           | Channel 4 | y-polarization | $1.396 \times 10^{-10}$ |
|                           | Channel 6 |            | $1.59 \times 10^{-6}$ |
| MR (1.8 km)               | Channel 1 | x-polarization | $2.95 \times 10^{-9}$ |
|                           | Channel 3 |            | $1 \times 10^{-5}$ |
|                           | Channel 4 | y-polarization | $2.98 \times 10^{-9}$ |
|                           | Channel 6 |            | $1.5 \times 10^{-5}$ |
| HR (1.1 km)               | Channel 1 | x-polarization | $3.55 \times 10^{-7}$ |
|                           | Channel 3 |            | $1.9 \times 10^{-4}$ |
|                           | Channel 4 | y-polarization | $8.18 \times 10^{-7}$ |
|                           | Channel 6 |            | $3.2 \times 10^{-4}$ |

---

Fig. 9 BER versus range for PDM/SAC-OCDMA using DPS under a LR, b MR and c HR
Fig. 10 Q-factor versus range for PDM/SAC-OCDMA and DPS under a LR, b MR and c HR

Table 11 Q-factor for different ranges under rain conditions

| Weather condition (range) | Channel | PDM Type    | Q-factor |
|---------------------------|---------|-------------|----------|
| LR (2.4 km)               | Channel 1 | x-polarization | 6.67     |
|                           | Channel 3 |              | 4.49     |
|                           | Channel 4 | y-polarization | 6.3      |
|                           | Channel 6 |              | 4.65     |
| MR (1.8 km)               | Channel 1 | x-polarization | 5.81     |
|                           | Channel 3 |              | 4.26     |
|                           | Channel 4 | y-polarization | 5.81     |
|                           | Channel 6 |              | 4.17     |
| HR (1.1 km)               | Channel 1 | x-polarization | 4.95     |
|                           | Channel 3 |              | 3.54     |
|                           | Channel 4 | y-polarization | 4.79     |
|                           | Channel 6 |              | 3.41     |
Fig. 11  Received power versus range for PDM/SAC-OCDMA using DPS under a LR, b MR and c HR

Table 12  Received power for different ranges under rain conditions

| Weather condition (range) | Channel | PDM Type       | Received power (dBm) |
|---------------------------|---------|----------------|----------------------|
| LR (2.4 km)               | Channel 1 | x-polarization | −24.398              |
|                           | Channel 3 |                | −26.104              |
|                           | Channel 4 | y-polarization | −24.406              |
|                           | Channel 6 |                | −26.11               |
| MR (1.8 km)               | Channel 1 | x-polarization | −24.825              |
|                           | Channel 3 |                | −26.519              |
|                           | Channel 4 | y-polarization | −24.803              |
|                           | Channel 6 |                | −26.504              |
| HR (1.1 km)               | Channel 1 | x-polarization | −25.81               |
|                           | Channel 3 |                | −27.507              |
|                           | Channel 4 | y-polarization | −25.76               |
|                           | Channel 6 |                | −27.46               |
| Reference                  | System                                           | Capacity | Weather condition | FSO range (km) | Received power (dBm) |
|----------------------------|--------------------------------------------------|----------|-------------------|----------------|----------------------|
| Chaudhary et al. (2020)    | PDM/OCDMA using RD code                          | 50 Gbps  | LF                | 1.05           | NA                   |
|                            |                                                  |          | MF                | 0.75           | NA                   |
|                            |                                                  |          | HF                | 0.625          | NA                   |
| Zhang et al. (2021a, b)    | MDM based FSO system with NRZ                    | 20 Gbps  | LF                | 2.7            | NA                   |
|                            |                                                  |          | MF                | 1.7            | NA                   |
|                            |                                                  |          | HF                | 1.3            | NA                   |
| Singh et al. (2022a, b)    | NRZ-OAM based FSO                                | 40 Gbps  | LF                | 0.48           | NA                   |
|                            |                                                  |          | MF                | 0.375          | NA                   |
|                            |                                                  |          | HF                | 0.32           | NA                   |
|                            |                                                  |          | LR                | 0.51           | NA                   |
|                            |                                                  |          | MR                | 0.45           | NA                   |
|                            |                                                  |          | HR                | 0.35           | NA                   |
|                            |                                                  |          | LD                | 0.31           | NA                   |
|                            |                                                  |          | MD                | 0.13           | NA                   |
|                            |                                                  |          | HD                | 0.064          | NA                   |
| Present work               | PDM/SAC-OCDMA based FSO using DPS code           | 60 Gbps  | LF                | 2              | −27                  |
|                            |                                                  |          | MF                | 1.3            | −27                  |
|                            |                                                  |          | HF                | 1              | −27                  |
|                            |                                                  |          | LR                | 2.4            | −26.5                |
|                            |                                                  |          | MR                | 1.8            | −26.5                |
|                            |                                                  |          | HR                | 1.1            | −27                  |
|                            |                                                  |          | LD                | 0.9            | −27.8                |
|                            |                                                  |          | MD                | 0.25           | −25.7                |
|                            |                                                  |          | HD                | 0.095          | −25.4                |
6 Conclusion

A hybrid PDM/SAC-OCDMA based FSO communication system with DPS code is proposed. Three different channels, each carrying 10 Gbps, are transmitted on two different polarization directions signals, x at azimuthal angle 0° and y at azimuthal angle of 90°. The system performance is studied in terms of maximum allowable number of users, different propagation ranges, Q-factor, BER, and received power under different fog weather conditions: LF, MF and HF. The simulation results assure that as the level of fog increases, the propagation link length decreases and the received power decreases. Accordingly, the LF weather condition achieves the longest propagation distance with the highest received power. In the proposed model, the signal travels up to 2 km with a Q-factor of 4 and a received power of −27 dBm under LF. At the same value for Q-factor and received power, the propagation range is decreased to 1.3 km and 1 km, under MF and HF, respectively. Additionally, the impact of dust storms is also considered. The maximum achievable FSO link length is 0.9, 0.25, and 0.095 km, respectively, under LD, MD, and HD. Furthermore, the system performance under LR, MR and HR is performed and the results show that the signal can propagate up to 2.4 km under LR, 1.8 km under MR, and 1.1 km under HR. We recommend this work to be carried out in future 5G wireless transmission communications networks and in remote areas.

Authors’ contributions S.A.A., A.M., T.A.E, M.H., H.A.F., and M.H.A. have directly participated in the planning, execution, and analysis of this study. AHB drafted the manuscript. All authors have read and approved the final version of the manuscript.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors did not receive any funds to support this research.

Availability of data and materials The data used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval Not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.
References

Abd El-Mottaleb, S.A., Fayad, H.A., Abd El-Aziz, A., Metawee, M., Aly, M.H.: Enhanced spectral amplitude coding OCDMA system utilizing a single photodiode detection. Appl. Sci. 8(10), Article 1861 (2018)

Abd El-Mottaleb, S.A., Metwalli, A., Hassib, M., Alfikky, A.A., Fayad, H.A., Aly, M.H.: SAC-OCDMA-FSO communication system under different weather conditions: performance enhancement. Opt. Quantum Electron. 53(11), 616–633 (2021)

Ahmed, H.Y., Gharseldien, Z.M., Aljunid, S.A.: Performance analysis of diagonal permutation shifting (DPS) codes for SAC-OCDMA systems. J. Inf. Sci. Eng. 33, 433–448 (2017)

Ahmed, H.Y., Zeghid, M., Bouallegue, B., Chehri, A., Abd El-Mottaleb, S.A.: Reduction of complexity design of sac ocdma systems by utilizing diagonal permutation shift (DPS) codes with single photodiode (SPD) detection technique. Electronics 11(8), 1224–1240 (2022)

Al-Khafaji, H.M.R., Aljunid, S.A., Amphawan, A., Fadhil, H.A., Safar, A.M.: Reducing BER of spectral-amplitude coding optical code-division multiple-access systems by single photodiode detection technique. J. Eur. Opt. Soc. Rapid Publ. 8, 13022–13026 (2013)

Amphawan, A., Chaudhary, S.: Free-space optical mode division multiplexing for switching between millimeter-wave picocells. In: Proceeding SPIE, International Conference on Optical and Photonic Engineering (icOPEN), Singapore, Singapore, 14–16 April 2015, vol. 9524, pp. 1–6 (2015)

Amphawan, A., Chaudhary, S., Ne, T.-K.: Hermite–Gaussian mode division multiplexing for free-space optical interconnects. Adv. Sci. Lett. 21(10), 3050–3054 (2015)

Chaudhary, S., Amphawan, A.: The role and challenges of free-space optical systems. J. Opt. Commun. 35(4), 327–334 (2014)

Chaudhary, S., Amphawan, A., Nisar, K.: Realization of free space optics with OFDM under atmospheric turbulence. Optik 125(18), 5196–5198 (2014)

Chaudhary, S., Tang, X., Sharma, A., Lin, B., Wei, X., Parmar, A.: A cost-effective 100 Gbps SAC-OCDMA-PDM based inter-satellite communication link. Opt. Quantum Electron. 61, 148–157 (2019)

Chaudhary, S., Choudhary, S., Tang, X., Wei, X.: Empirical evaluation of high-speed cost-effective Ro- FSO system by incorporating OCDMA-PDM scheme under the presence of fog. J. Opt. Commun. 39, 1–4 (2020)

Farhgal, A.: On the performance of OCDMA/SDM PON based on FSO under atmospheric turbulence and pointing errors. Opt. Laser Technol. 114, 196–203 (2019)

Goossens, J.-W., Yousef, M.I., Jaouën, Y., Hafermann, H.: Polarization-division multiplexing based on the nonlinear Fourier transform. Opt. Express 25, 26437–26452 (2017)

Imtiaz, W.A., Ahmad, N.: Cardinality enhancement of SAC OCDMA systems using new diagonal double weight code. Int. J. Commun. Netw. Inf. Secur. 6(3), 226–232 (2014)

Kakati, D., Arya, S.C.: Performance of 120 Gbps single channel coherent DP-16-QAM in terrestrial FSO link under different weather conditions. Optik 125(18), 5196–5198 (2014)

Kakati, D., Arya, S.C.: Performance of grey-coded IQM-based optical modulation formats on high-speed long-haul optical communication link. IET Commun. 13(18), 2904–2912 (2019b)

Kanno, A., Inagaki, K., Morohashi, I., Sakamoto, T., Kuri, T., Hosako, I., Kawanishi, T., Yoshida, Y., Kitayama, K.: 40 Gb/s Wband (75–110 GHz) 16-QAM radio-over-fiber signal generation and its wireless transmission. Opt. Express 19, 56–63 (2011)

Kim, I.I., McArthur, B., Korevaar, E.J.: Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications. In: Proc. SPIE, Opt. Wirel. Commun. III, vol. 4214, pp. 26–37 (2001)

Majumdar, A.: Optical Wireless Communications for Broadband Global Internet Connectivity. Elsevier, Amsterdam (2019)

Moghadassi, M., Mamdooohi, G., Noor, A.S.M., Mahdi, M.A., Anas, S.B.A.: Development of SAC-OCDMA in FSO with multi-wavelength laser source. Opt. Commun. 356, 282–289 (2015)

Moghadassi, M., Seyedzadeh, S., Glesk, I., Lakshminarayana, G., Anas, S.B.A.: DW-ZCC code based on SAC-OCDMA deploying multi-wavelength laser source for wireless optical networks. Opt. Quantum Electron. 49(12), 393–406 (2017)

Mohammed, H.S., Aljunid, S.A., Fadhil, H.A., Abd, T.H.: A study on rain attenuation impact on hybrid SCM-SAC OCDMA-FSO system. In: Proceeding of 2013 IEEE Conference on Open Systems (ICOS), Kuching, Malaysia, 2–4 Dec. 2013, pp. 195–198 (2013)

Mostafa, S., Mohamed, A.E.-N.A., El-Samie, F.E.A., Rashed, A.N.Z.: Performance evaluation of SAC-OCDMA system in free space optics and optical fiber system based on different types of codes. Wirel. Pers. Commun. 96(2), 2843–2861 (2017)
Mrabet, H., Cherifi, A., Raddo, T., Dayoub, I., Haxha, S.: A comparative study of asynchronous and synchronous OCDMA systems. IEEE Syst. J. 15(3), 3642–3653 (2021)
Muhammad, S.S., Kohldorfer, P., Leitgeb, E.: Channel modeling for terrestrial free space optical links. In: Proceeding of 2005 7th International Conference Transparent Optical Networks, Barcelona, Spain, 7–7 July 2005, vol. 1, pp. 407–410 (2005)
Sharma, A., Kaur, S., Chaudhary, S.: Performance analysis of 320 Gbps DWDM-FSO system under the effect of different atmospheric conditions. Opt. Quantum Electron. 53, 239–247 (2021)
Singh, M., Malhotra, J.: Long-reach high-capacity hybrid MDM-OFDM-FSO transmission link under the effect of atmospheric turbulence. Wirel. Pers. Commun. 107(4), 1549–1571 (2019)
Singh, M., Aly, M.H., Abd El-Mottaleb, S.A.: Performance analysis of 6 × 10 Gbps PDM-SAC-OCDMA-based FSO transmission using EDW codes with SPD detection. Optik 264, 169415–169426 (2022a)
Singh, M., Atieh, A., Grover, A., Barukab, O.: Performance analysis of 40 Gb/s free space optics transmission based on orbital angular momentum multiplexed beams. Alex. Eng. J. (AEJ) 61(7), 5203–5212 (2022b)
Upadhyay, K.K., Srivastava, S., Shukla, N.K., Chaudhary, S.: High-speed 120 Gbps AMI-WDM-PDM free space optical transmission system. J. Opt. Commun. 40(4), 429–433 (2019)
Wang, Z., Chowdhury, A., Prucnal, P.R.: Optical CDMA code wavelength conversion using PPLN to improve transmission security. IEEE Photon. Technol. Lett. 21, 383–385 (2009)
Yang, L., Guo, W., Ansari, I.S.: Mixed dual-hop FSO-RF communication systems through reconfigurable intelligent surface. IEEE Commun. Lett. 24(7), 1558–1562 (2020)
Zhang, C., Liang, P., Nebhen, J., Chaudhary, S., Sharma, A., Malhotra, J., Sharma, B.: Performance analysis of mode division multiplexing-based free space optical systems for healthcare infrastructure’s. Opt. Quantum Electron. 53(11), 635–648 (2021a)
Zhang, C., Liang, P., Nebhen, J., Chaudhary, S., Sharma, A., Malhotra, J., Sharma, B.: Performance analysis of mode division multiplexing-based free space optical systems for healthcare infrastructure’s. Opt. Quantum Electron. 53, 635–648 (2021b)
Zhou, X., Huo, J., Zhong, K., Long, K., Lü, C.: Polarization division multiplexing system with direct decision for short reach optical communications. J. Beijing Univ. Posts Telecommun. 40(2), 21–28 (2017)

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