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Improving FSO Link Performance using PolSK Modulation

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Free Space Optical (FSO) communication systems are based on the use of infrared light to transmit information at high speed through the atmospheric channel. Their performance is therefore affected by the characteristics of the atmospheric channel. One of the most widely used methods of compensating for the effects of atmospheric factors is modulation.
The main aim of this research is to demonstrate the improvement in FSO link performance using PolSK modulation in a subtropical environment such as Côte d'Ivoire. The performance indicators considered are bit error rate, channel capacity, outage probability and energy efficiency. The mathematical expression of the evolution of each of these indicators as a function of the atmospheric parameters of our environment was

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determined using the gamma-gamma model. A numerical evaluation of the results obtained was carried out using Matlab software.
The results show that PolSK modulation offers the best results in terms of BER reduction, with a BER of the order of 10^{-11} for an SNR of $50dB$, compared with BERs of 10^{-4} and 10^{-2} for BPSK and OOK modulations respectively. We obtain a probability of interruption of the order of 10^{-3} for PolSK modulation compared with 10^{-2} for BPSK modulation and 10^{-1} for OOK modulation. As for the channel capacity, we obtain the same value $(4.1458bit/s)$ for PolSK and BPSK modulation compared with $3.8181bit/s$ for OOK modulation. BPSK modulation, on the other hand, stands out for its excellent energy efficiency.

Keywords: Atmospheric turbulence; BER; BPSK; channel capacity; FSO; gamma-gamma; modulation; OOK; PolSK; outage probability; SNR

2010 Mathematics Subject Classification: 53C25, 83C05, 57N16

1 INTRODUCTION

Since the Covid 19 crisis, requirements in terms of bandwidth, capacity and network security have greatly increased. Interconnection systems are finding it increasingly difficult to meet these needs, while keeping deployment costs low. Despite its ability to meet expectations in terms of bandwidth and capacity, optical fibre is still fairly expensive and difficult to deploy, while the development of radio frequency systems is increasingly limited by the scarcity of frequencies [1]. To overcome these limitations whilst improving the quality of service offered by the latest generation of mobile network technologies, such as 5G, research is increasingly focusing on ways of combining the performance of optical fiber with the mobility of radio frequency (RF) systems in a single system [2]. To this end, Free Space Optical (FSO) communication has emerged as a promising communications technology, offering high data rates and low latency to meet the growing needs of our digital society [3]. Indeed, in [4] the authors show that the integration of FSO systems into 5th generation networks aims to improve the performance, capacity and efficiency of communication networks, enabling advanced services and applications. Unlike fiber optic communications, FSO systems don't need physical support to transmit optical signals, eliminating the need for physical cables and combining the data rates offered by optical transmission with the mobility of radio frequency systems. This makes it ideal for a wide range of applications, including high-speed connectivity in urban areas, inter-satellite data links, communication in hostile environments and much more [2]. However, despite its undeniable advantages, FSO technology is subject to a number of challenges that stand in the way of its full realization. These include atmospheric turbulences that can cause beam divergence, a reduction in the optical power emitted and an increase in noise. This turbulence is mainly due to the presence in the atmospheric channel of meteorological factors such as raindrops, fog particles, heat islands, etc [3]. In order to guarantee the availability of the link while maintaining optimum quality of service, it is essential to anticipate and compensate the consequences induced by the properties of the atmospheric channel on the light beam [3]. Various techniques have been developed by researchers to achieve this objective. These include adaptive optics, aperture averaging, diversity techniques, artificial intelligence and modulation [5]. Recent developments in the field of optical processors are also helping to improve the performance of free-space optical communication systems, in particular through better detection of optical beams and more efficient management of signal modulation [6, 7]. Modulation is an intrinsic part of FSO system design and has many advantages for improving system performance, that is why a lot of research is turning to it for system robustness. In [8], the researchers show how BPSK (Phase Shift Keying) modulation improves the robustness of the system to channel noise, with an increase in signal noise ratio (SNR) of the order of 3 dB. In [9], the authors study the optimal communication link for the FSO link, and show that modulation improves the propagation distance of the link and reduces the bit error rate (BER). In [10], the authors analyze the impact of different modulation techniques on FSO link performance and the results show that they improve system performance in terms of energy efficiency, throughput increasing and system capacity. In [11] the authors have analyzed the performance of OOK modulation in Hybrid fiber/ FSO networks, and propose a method for improving it. They show that the proposed system offers an improvement in link SNR of the order of 2 dB. In the study carried out in [12] the authors proceeded to characterize the subtropical environment like Côte d'Ivoire in the context of free-space optical communication. They found that the town of Man is a moderately turbulent environment and that the link there had an availability of around 80%.

In this study, we will try to show the impact of polarization shift keying (PolSK) modulation scheme on improving FSO link performance in a subtropical environment such as Côte d'Ivoire in terms of energy efficiency, error reduction, channel capacity and outage probability. In section 2, we describe FSO systems. Then, in Section 3, we introduce the modulation techniques used to improve FSO link performance with a focus on PolSK modulation. In Section 4, we compare the performance of the different types of modulation we studied in the FSO context. Finally, Section 5 presents the conclusions of our study.

2 FREE SPACE OPTICAL COMMUNICATION

2.1 System Overview

A free-space optical communication system is a data transmission system that uses light signals, usually in the form of laser beams, to transmit information through space without the need for physical medium such as cables [13, 14]. It relies on the modulation of light to carry data and is often used for high-speed, low-latency, high-security transmissions. Light travels at an extremely high speed, enabling high data rates of up to 100 Gbps and low latency [2, 13]. These systems are commonly used for applications requiring high bandwidth, such as high-speed data transmission [2, 14]. Light signals are difficult to intercept without being detected, which increases the security of free-space optical communications [2, 15]. Fig. 1. shows the key stages in the operation of these systems.

Element (1) represents the beginning of the process of generating light using specific light sources, usually lasers, which emit intense beams of coherent light [2, 15]. Then in(2) the light signals are modulated to carry data. Modulation involves the variation of intensity, frequency or phase of the light beam according to the data to be transmitted [2, 15]. This modulation creates variations in the light signal, which are interpreted as 0 and 1, thus representing the data. Once modulated, in (3) the light signals are transmitted through air or space, towards the remote receiver. Transmission through free space means that the signals travel without the need of cables or physical supports to guide them [2, 15]. Element (4) represents the receiving device, an optical receiver that picks up light signals using components such as photodetectors. These devices convert light variations into electrical signals. Once the light signals have been captured, in (5) they are demodulated to extract the data [2, 15]. The receiver converts the light intensity variations into digital data, according to the demodulation scheme used. Finally, at (6) the extracted data is then processed by electronic equipment for use into the intended applications, such as voice communications, file transfers, navigation, etc [2, 15].

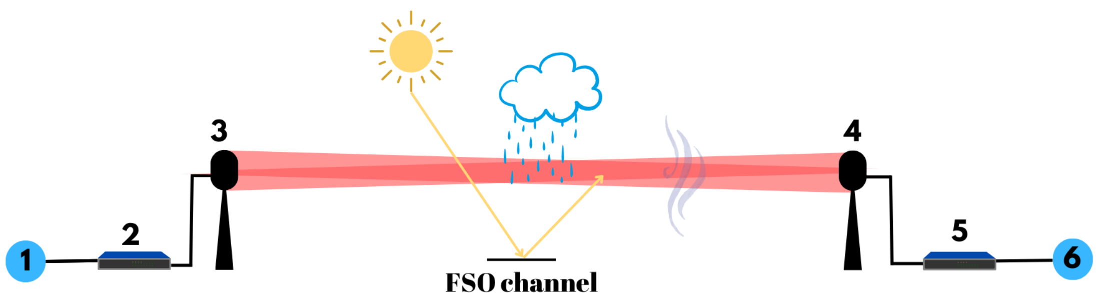

Fig. 1. The process of operation of optical systems in free space

2.2 The Atmospheric Channel

The atmospheric channel, in the context of free-space optical communication, refers to the atmospheric environment through which light signals travel during free-space optical transmission [2, 15]. This atmospheric environment can have a significant impact on the quality of free-space optical transmission due to a number of phenomena and effects [16]. Here are some important aspects of the atmospheric channel :

- **Atmospheric attenuation** is one of the most notable characteristics of the atmospheric channel. The Earth's atmosphere absorbs and scatters light at different wavelengths, which can reduce the intensity of the optical signal in transit [16, 17]. Atmospheric attenuation is influenced by the wavelength of the light used, the absorption and scattering of light by air particles, molecules and other elements in the atmosphere that can cause a decrease in optical signal intensity [16,17].
- **Scintillation** is an optical phenomenon in which the brightness of the light signal varies due to local fluctuations in the air's refractive index. This creates fluctuations in light intensity along the transmission path [16,17]. Scintillation can lead to rapid fluctuations in light intensity, which can disrupt communication through the introduction of additional noise [16,17].
- **Diffraction**, when light passes through the atmosphere, it undergoes diffraction phenomena, which means that the light bends around obstacles and variations in the refractive index in the air [16,17]. This can cause the light beam to diverge, limiting the range of optical transmissions.
- **Réfraction** mainly due to changes in temperature, pressure and atmospheric humidity, which lead to variations in the refractive index along the atmospheric channel, it can cause a change in the trajectory of the optical beam and lead to pointing errors [16,17].
- **Absorption** is a physical phenomenon that is mainly due to raindrops in the atmosphere, which can absorb light and cause non selective scattering, resulting in a significant loss of signal during showers of rain [16,17].
- **Atmospheric conditions**, suspended particles such as dust and smoke, as well as variations in air density, can also influence the propagation of the optical signal [16,17].

Atmospheric channel characterization and modeling are essential for the design of free-space optical communication systems [16, 17]. Engineers and researchers are working on techniques to compensate for these atmospheric effects, such as adaptive optics, spatial and temporal diversity techniques, aperture averaging, artificial intelligence including the use of advanced error correction systems and beam tracking techniques to maintain the quality of optical communication despite the challenges posed by the atmospheric channel [16,17].

2.3 Characterization of the Atmospheric Channel

The atmospheric channel can be characterized using various parameters and measurements that describe its properties and variations [18]. The evolution of these parameters is described by different probability distribution models.The most commonly used model in the FSO context for week and moderate turbulence environnement like Cote d'ivoire is the Gamma-gamma model [12,17]. This model can be used to accurately determine the nature of turbulence in a low, medium or high turbulence environment [12, 17]. Gamma-gamma model is commonly used to describe the statistics of the atmospheric channel in free-space optical communications (FSO) [12, 19]. It is mainly used to model scintillation, which is a rapid variation of light beam intensity due to fluctuations in the air's refractive index [19]. The gamma-gamma model is based on the gamma-gamma distribution, a probability distribution that is often used to describe the light intensity distribution of the optical signal on reception [16,19]. This distribution is characterized by two main parameters :

- **Shape parameter (α)**, the shape parameter determines the shape of the distribution and influences the degree of scintillation. The higher the value of α, is the less scintillation, and its expression is given by equation 1 [16,19],

$$\alpha = \left(exp\left(\frac{0.49\sigma_l^2}{(1 + 1.11\sigma_l^{12/5})^{7/6}} \right) - 1 \right)^{-1} \quad (2.1)$$

- **Scale parameter (β)**, the scale parameter is related to the average light intensity. It indicates how high or low the average light intensity is. Its expression is given by equation 2 [16,19],

$$\beta = \left(exp\left(\frac{0.51\sigma_l^2}{(1+0.69\sigma_l^{12/5})^{5/6}} \right) - 1 \right)^{-1} \quad (2.2)$$

This model is widely used to evaluate the performance of FSO systems and to design more robust free-space optical communication systems [16,17,19]. It predicts the probability of signal degradation as a function of atmospheric conditions and system parameters, which is essential for planning and optimizing FSO links. The global expression of the Gamma-gamma distribution is given by equation 3 [16,19],

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}), I > 0 \quad (2.3)$$

This model can also be used to predict the probability of signal degradation as a function of atmospheric conditions and system parameters, which is essential for planning and optimizing FSO links.

3 MODULATION TECHNIQUES USED IN THE FSO CONTEXT

Modulation in free-space optical communication is an essential method of transmitting data in the form of light signals over FSO (Free-Space Optical Communication) links. Modulation involves varying one or more characteristics of an optical signal, such as its amplitude, frequency, phase or polarization states, to represent digital information [20]. Any optical communication signal requires a carrier signal, which is usually a coherent light wave, such as a laser or light-emitting diode (LED) [20,21]. This carrier signal is essential for transmitting data across free space. Digital data, such as bits, are modulated onto the carrier signal by modifying one or more characteristics of the light signal. Common modulation methods in free-space optical communication include Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Polarization Shift Keying (PolSK) [16–18]. Once the information has been modulated onto the carrier signal, the modulated optical signal is transmitted across free space to the remote receiver. This can be a point-to-point transmission or a transmission to a network of receivers [21]. At the receiving end, the optical signal is picked up by an optical receiver, which detects variations in the signal characteristics (amplitude, phase or polarization state) to extract the modulated data. Demodulation converts the modulated signals into understandable digital data [16–18]. The modulation technique used in free-space optical communications offers great flexibility for the transmission of high-speed data over long distances 19. Modulation methods can be tailored to suit system requirements, link quality, desired transmission capacity and local atmospheric conditions. More complex modulation, such as coherent modulation, is often used for high data rate FSO systems, while simpler modulations such as ASK can be adapted for lower data rates and shorter distances [21,22].

3.1 On Off Keying (OOK) Modulation

This is an intensity modulation technique used in telecommunications, particularly optical communications, to transmit digital data [16]. It is sometimes referred to "all or nothing" modulation because it uses two separate amplitude levels to represent the data bits, usually "1" and "0". In OOK modulation, an optical or electrical signal is modulated to transmit digital data [11]. When the signal have an amplitude level above the defined threshold, it represents a "1" (the "on" or "marked" state), and when the signal have an amplitude level below this threshold, it represents a "0" (the "off" or "unmarked" state). The advantage of OOK modulation is its simplicity. However, its main limitation is its low spectral efficiency, which means that it is not ideal for high data rates [16,18]. For FSO communication systems, the power required for good transmission may be expressed like a function of the signal-to-noise ratio (SNR) according to the following expression [16–18] :

$$Pr = \frac{1}{R}\sqrt{\sigma_N^2 SNR} \quad (3.1)$$

where R is the photodetector responsivety. For this type of modulation, the expression for the instantaneous SNR is given by [16–18],

$$SNR(I) = \frac{(PrR)^2}{\sigma_N^2} I \quad (3.2)$$

3.2 BPSK (Phase Shift Keying) Modulation

It is a technique commonly used in free-space optical communication to transmit data by changing the phase of the carrier signal [16]. In BPSK, different phase states are used to represent the data bits. The phase of the optical carrier is modulated according to the bit sequence of the data [16, 20]. For example, a phase shift of 0 degrees (or no phase change) may represent a ”0” bit, while a phase shift of π may represent a ”1” bit. In more complex BPSK modulation schemes, multiple phases are used to represent multiple bits [20]. In addition, it makes efficient use of bandwidth, as it does not require additional bandwidth to transmit multiple bits per symbol [18]. This makes it suitable for high-speed optical communication systems. However, BPSK modulation is sensitive to phase errors, which means that even small variations in the phase of the signal can cause demodulation errors [16,23]. This can be particularly problematic in environments where the phase of the signal can be disturbed, such as in moving wireless communications [16, 23]. To evaluate the performance of this type of modulation, it is important to know the expression of its instantaneous signal-to-noise ratio, which is given by equation 6 [16,23] ,

$$SNR(I) = \frac{(\eta I)^2}{N_0}\mu \qquad (3.3)$$

where μ is the average signal-to-noise ratio, and N_0 is the power of the noise spectral density.

3.3 Polarization Shift Keying (PolSK) modulation

Polarization Shift Keying (PolSK) is a modulation technique used in free-space optical communications to transmit data by changing the polarization state of light. Unlike other optical modulation techniques that modulate characteristics such as the amplitude or phase of the light, PolSK changes the orientation of the polarisation state of light to represent the data. It is an advanced modulation that exploits the polarisation of light for communication [16]. The polarization state of light is modulated according to the bit sequence of the data. For example, a particular polarisation orientation may represent a ”0” bit, while a different polarization orientation may represent a ”1” bit [16, 24]. PolSK modulation has the advantage of being relatively resistant to atmospheric turbulence, as changes in the polarization state of light are less sensitive to atmospheric effects such as dispersion and scintillation [16, 24]. It is particularly suitable for free-space optical communication over long distances, where atmospheric conditions can vary considerably [25]. Our work will focus on this scheme. The advantages of robustness against atmospheric disturbances mean that PolSK modulation is increasingly used in free-space optical communication applications, including satellite communication and other long-range terrestrial links.

3.3.1 System Operating Principle

With PolSK modulation, information is transferred by alternating the polarisation of the optical beam as it propagates between two orthogonal linear polarisation states (vertical and horizontal) [16,25]. Fig. 2. presents PolSK block diagram.

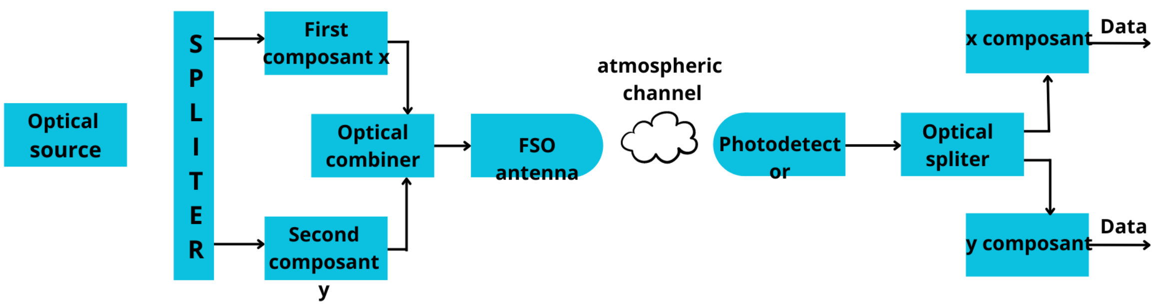

Fig. 2. Polsk Block diagram

Typically, the PolSK modulator consists of two sections: first, a splitter, followed by a waveguide-based wavelength-dependent phase shift. The divider of length "d" has a propagation matrix M_p which is defined by equation 7 [16,25],

$$M_p = \begin{pmatrix} coskd & -sinkd \\ sinkd & coskd \end{pmatrix} \tag{3.4}$$

where k is a coefficient. A phase shift $\Delta\phi$ is then introduced between the two components of the polarized beam according to the following equation 8 [16,25],

$$\Delta\phi = \frac{2\pi n_1}{\lambda} Lp - \frac{2\pi n_2}{\lambda}(Lp + \Delta Lp), \tag{3.5}$$

where n_1 et n_2 the refractive index in Lp and $Lp + \Delta$. the phase shifter propagation matrix is given by [16,25],

$$M_{\Delta\phi} = \begin{pmatrix} exp(j\Delta\phi/2) & 0 \\ 0 & exp(j\Delta\phi/2) \end{pmatrix} \tag{3.6}$$

The optical field obtained in each direction of polarisation is given by equation 10 [16,25],

$$M \begin{pmatrix} \overrightarrow{E_h} \\ \overrightarrow{E_v} \end{pmatrix} = M \begin{pmatrix} \overrightarrow{E_0}(t) \\ 0 \end{pmatrix} \tag{3.7}$$

where M is defined as [16,25]

$$M = M_{\Delta\phi} \times M_p = \begin{pmatrix} exp(j\Delta\phi/2)coskd & -exp(j\Delta\phi/2)sinkd \\ exp(-j\Delta\phi/2)sinkd & exp(-j\Delta\phi/2)coskd \end{pmatrix} \tag{3.8}$$

Demodulation and detection are carried out by analyzing the SOP (State of Polarization) [16,25]. This is done by using an optical lens to focus the received optical beam on the photodetector, and then the received signal $E_r(t)$ can be treated in both cases as consisting of two orthogonal ASK (Amplitude Shift Keying) signals, which are associated with the orthogonal components of the transmitted optical field. The local oscillator $E_{lo}(t)$ is linearly polarized at an angle of $\frac{\pi}{4}$ with respect to the receiver's reference optical field. The $E_r(t)$ and E_{lo} fields are given by [16,25]:

$$Er(t) = \sqrt{P_r} e^{i(\omega_r t + \phi_r(t))}[(1 - m(t)).x + m(t).y] \tag{3.9}$$

$$E_{lo} = \sqrt{P_{lo}} e^{i(\omega_{lo} t + \phi_{lo}(t))}[x + y] \tag{3.10}$$

where P_r and P_{lo} are the received signal and local oscillator signal powers respectively. ω_r, $\phi_r(t)$ and ω_{lo}, $\phi_{lo}(t)$ are the angular frequencies and phase noises for the received and local oscillator fields, and $m(t)$ is the message signal. The received E_r field is combined with the E_{lo} field by a directional coupler with transfer matrix Sc, with Sc described by equation 3.8 [16,25],

$$S = \begin{pmatrix} \alpha_c & \sqrt{1 - \alpha_c^2} \\ -\sqrt{1 - \alpha_c^2} & \alpha_c \end{pmatrix} \tag{3.11}$$

where α_c is the power splitting ratio. The resulting field is then transmitted to a polarized beam splitter, which separates its horizontal and vertical components. The expressions for the horizontal and vertical fields are given in equation 3.9 [16,25],

$$E_x(t) = \left(\alpha_c \sqrt{\frac{P_r}{2}} [1 - m(t)] e^{i(\omega_r t + \phi_r(t))} + \sqrt{\frac{(1 - \alpha_c^2) P_{lo}}{2}} e^{i(\omega_{lo} t + \phi_{lo}(t))} \right) \overrightarrow{x} \tag{3.12}$$

$$E_x(t) = \left(\alpha_c \sqrt{\frac{P_r}{2}} m(t) e^{i(\omega_r t + \phi_r(t))} + \sqrt{\frac{(1 - \alpha_c^2) P_{lo}}{2}} e^{i(\omega_{lo} t + \phi_{lo}(t))} \right) \overrightarrow{y} \tag{3.13}$$

Assuming that one electron is generated for each photon detected, the signals from two similar optical receivers pass through ideal bandpass filters (BPFs) with a one-sided bandwidth W equal to 2Rb, where Rb represents the data rate. The outputs of this filter are defined as follows [16,25]:

$$c_x = R\alpha_c \sqrt{(1 - \alpha_c^2) P_r P_{lo}} [1 - m(t)] cos(\omega_{IF} t + \phi_t(t)) + n_x(t) \tag{3.14}$$

$$c_y = R\alpha_c\sqrt{(1-\alpha_c^2)P_rP_{lo}}m(t)cos(\omega_{IF}t + \phi_t(t)) + n_x(t) \tag{3.15}$$

where R is the photodiode responsivity, $\omega_{IF} = \omega_r - \omega_{lo}$ and $\phi_t(t) = \phi_r(t) - \phi_{lo}(t)$ are the intermediate angular frequency (IF) and the IF phase noise, respectively. n_x and n_y are AWG noise with zero mean and variance $\sigma_n^2 = WN_0$.

3.3.2 Stockes Parameters

In free-space optical communication, the polarisation states of the beam can be described by the Stokes parameters. There are four main Stokes parameters, generally noted as S_0, S_1, S_2 and S_3 [16]. S_0 represents the total intensity of the light, i.e. the total luminous power carried by the beam, S_1 is the difference in intensity between the horizontally ($S_1 = +ve$) and vertically ($S_1 = -ve$) polarized components, S_2 indicates preference for SOP $+45$ (S_2 positive) or -45, and S_3 is the preference for right and left circular polarization. their expressions are given in equation 3.13 [16],

$$\begin{aligned} S_0 = |c_x(t)|^2 + |c_y(t)|^2 = \frac{R^2\alpha_c^2(1-\alpha_c^2)P_rP_lo}{2} + n_0(t), \\ S_1 = |c_x(t)|^2 - |c_y(t)|^2 = \frac{R^2\alpha_c^2(1-\alpha_c^2)P_rP_lo}{2}[1-2m(t)] + n_0(t), \\ S_2 = 2|c_x(t)|^2 \times |c_y(t)|^2 cos(0) = 0 + n_2(t), \\ S_2 = 2|c_x(t)|^2 \times |c_y(t)|^2 sin(0) = 0 + n_2(t). \end{aligned} \tag{3.16}$$

3.4 Bit eror rate (BER)

The bit error rate (BER) depends on a number of factors, including signal quality, system configuration, transmission channel properties and the detection technique used. To calculate the BER, you need to consider these elements in your specific system [16,24]. BER is generally calculated by comparing the number of bit errors (bits incorrectly received) with the total number of bits transmitted. For more complex modulation systems, the BER calculation can be influenced by parameters such as the modulation constellation, the SNR (Signal-to-Noise Ratio), and the characteristics of the demodulator [16, 25]. The general formula for calculating BER for modulation is as follows [16,24,25]:

$$Pe = \frac{1}{2}P(e|0) + \frac{1}{2}P(e|1), \tag{3.17}$$

For the O0K, BPSK and PolSK modulations, the BER in the absence of atmospheric turbulence is given by equation 21 [16,24,25],

$$\begin{aligned} Pe_{OOK} = P_{OOK}(e|0) = P_{OOK}(e|1) = \frac{1}{2}erfc\left(\frac{\sqrt{\gamma(I)}}{2\sqrt{2}}\right), \\ Pe_{BPSK} = P_{BPSK}(e|0) = P_{BPSK}(e|1) = \frac{1}{2}erfc\left(\sqrt{\gamma(I)}\right), \\ \mathrm{Pe}_{PolSK} = \mathrm{P}_{PolSK}(e|0) = P_{PolSK}(e|1) = \tfrac{1}{2}erfc\left(\tfrac{\sqrt{\gamma(I)}}{\sqrt{2}}\right), \end{aligned} \tag{3.18}$$

where $\gamma(I)$ is SNR for irradiance I. In the presence of atmospheric turbulence, the BER expression becomes [16,24,25]:

$$Pec = \int_0^\infty Pe \cdot p(I)\,\mathrm{d}I, \tag{3.19}$$

By replacing Pe and $p(I)$ by their values, we obtain for each of our modulations [16, 24, 25]:

$$\begin{aligned}
Pec_{-OOK} &= \int_0^{\infty} \frac{1}{2} erfc\left(\frac{\sqrt{\gamma(I)}}{2\sqrt{2}}\right) \cdot \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})\,\mathrm{d}I \\
Pec_{-BPSK} &= \int_0^{\infty} \frac{1}{2} erfc\left(\sqrt{\gamma(I)}\right) \cdot \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})\,\mathrm{d}I \\
Pec_{-PolSK} &= \int_0^{\infty} \frac{1}{2} erfc\left(\frac{\sqrt{\gamma(I)}}{\sqrt{2}}\right) \cdot \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I})\,\mathrm{d}I
\end{aligned} \tag{3.20}$$

to make it easier to solve equation (23), we replace the complementary error function erfc and the modified Bessel function of the second kind by their Meijer G transforms [26, 27]. With

$$erfc(\sqrt(x)) = \frac{1}{\sqrt{x}} G_{2,0}^{1,2}\left(x \middle| \begin{array}{c} 1 \\ 0, 1/2 \end{array}\right). \tag{3.21}$$

and

$$K_v = \frac{1}{2} G_{0,2}^{2,0}\left(\frac{x^2}{4} \middle| \begin{array}{c} - \\ (v-2), -(v-2) \end{array}\right) \tag{3.22}$$

Equation 22 becomes [16, 24] :

$$Pec = \frac{1}{2\sqrt{x}} \frac{(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} \int_0^{\infty} I^{\frac{\alpha+\beta}{2}-1} G_{2,0}^{1,2}\left(x \middle| \begin{array}{c} 1 \\ 0, 1/2 \end{array}\right) G_{0,2}^{2,0}\left(\frac{x^2}{4} \middle| \begin{array}{c} - \\ (v-2), -(v-2) \end{array}\right) \mathrm{d}I \tag{3.23}$$

Based on the MeijerG function product integral calculation formula described in [28], the results of solving the integral (26) for OOK, BPSK, and PolSK modulations are given by equations (27), (28), and (29) respectively [16, 24, 25] :

$$Pec_{-OOK} = \frac{2^{\alpha+\beta-3}}{\pi^{3/2}} G_{5,2}^{2,4}\left(\left(\frac{2}{\alpha\beta}\right)^2 \gamma_{-OOK} \middle| \begin{array}{c} \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, \frac{1-\beta}{2}, \frac{2-\beta}{2}, 1 \\ 0, \frac{1}{2} \end{array}\right) \tag{3.24}$$

$$Pec_{-BPSK} = \frac{1}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} G_{3,2}^{2,2}\left(\frac{\gamma_{-BPSK}}{\alpha\beta} \middle| \begin{array}{c} 1-\beta, 1-\alpha, 1 \\ 0, \frac{1}{2} \end{array}\right) \tag{3.25}$$

$$Pec_{-PolSK} = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} \left(\frac{\gamma_{-PolSK}}{2}\right)^{-\frac{\alpha+\beta}{2}} G_{2,3}^{2,2}\left(\frac{2(\alpha\beta)}{\gamma_{-PolSK}} \middle| \begin{array}{c} 1-\frac{\alpha+\beta}{2}, \frac{1}{2}-\frac{\alpha+\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2} \end{array}\right) \tag{3.26}$$

. With $\gamma_{-PolSK} = \frac{R^2 P_{Lo} I}{\sigma^2}$.

3.5 Outage Probability

Outage probability is a concept commonly used in wireless communication systems to assess the reliability and performance of the communication link. It represents the probability that the system will fail to achieve a certain specified level of performance [9, 10]. In the context of optical wireless communications, the outage probability is often associated with the probability that the received signal strength falls below a certain threshold, resulting in a loss of communication or a degradation in signal quality [9, 16]. The threshold is usually defined in terms of the minimum acceptable signal strength required for reliable communication. The general expression for the outage probability is given by the equation 30 [16, 29] :

$$P_{out} = Pr\left(I < \sqrt{\frac{\gamma_{Th}}{\gamma_0}}\right) = Pr\left(I < \frac{1}{\sqrt{\gamma_n}}\right) \tag{3.27}$$

γ_0 the signal-to-noise ratio received in the absence of turbulence, and $\gamma_n = \frac{\gamma_{Th}}{\gamma_0}$ standardized electrical SNR in the absence of atmospheric turbulence. The expression for the interruption probability can be obtained from the

CDF of the PDF of I, as described in equation 31 [29, 30] ,

$$P_{out} = \int_0^{\frac{1}{\sqrt{\gamma_{Th}}}} p(I)\,\mathrm{d}I = F_I\left(\frac{1}{\sqrt{\gamma_{Th}}}\right) \tag{3.28}$$

The expression of F_I as a function of the MeijerG function is given by equation 32 [29, 30] :

$$F_I = \frac{1}{\Gamma(\alpha)\Gamma(\beta)}(BI)^{\frac{\alpha+\beta}{2}} G_{2,1}^{1,3}\left(BI\middle|\begin{array}{c} 1-\frac{\alpha+\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2}\end{array}\right) \tag{3.29}$$

, with $B = \frac{\alpha\beta}{I_k}$ and $I_k = 1$ for our system without diversity. By replacing I by its expression, the expressions of the outage probabilities for the OOK, BPSK, and PolSK modulations are given by equations (33), (34), and (35) respectively [29, 30].

$$P_{out-OOK} = \frac{1}{\Gamma(\alpha)\Gamma(\beta)}\left(\alpha\beta\sqrt{\frac{\gamma_{ook}}{\overline{\gamma_{ook}}}}\right)^{\frac{\alpha+\beta}{2}} G_{2,1}^{1,3}\left(\alpha\beta\sqrt{\frac{\gamma_{ook}}{\overline{\gamma_{ook}}}}\middle|\begin{array}{c} 1-\frac{\alpha+\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2}\end{array}\right) \tag{3.30}$$

,

$$P_{out-BPSK} = \frac{1}{\Gamma(\alpha)\Gamma(\beta)}\left(\alpha\beta\sqrt{\frac{\gamma_{BPSK}}{\overline{\gamma_{BPSK}}}}\right)^{\frac{\alpha+\beta}{2}} G_{2,1}^{1,3}\left(\alpha\beta\sqrt{\frac{\gamma_{-BPSK}}{\overline{\gamma_{-BPSK}}}}\middle|\begin{array}{c} 1-\frac{\alpha+\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2}\end{array}\right) \tag{3.31}$$

,

$$P_{out-PolSK} = \frac{1}{\Gamma(\alpha)\Gamma(\beta)}\left(\alpha\beta\frac{\gamma_{PolSK}}{\overline{\gamma_{PolSK}}}\right)^{\frac{\alpha+\beta}{2}} G_{2,1}^{1,3}\left(\alpha\beta\frac{\gamma_{-PolSK}}{\overline{\gamma_{-PolSK}}}\middle|\begin{array}{c} 1-\frac{\alpha+\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2}\end{array}\right) \tag{3.32}$$

, Where $\overline{\gamma_{ook}}$, $\overline{\gamma_{-BPSK}}$, and $\overline{\gamma_{-PolSK}}$ are the expressions for the average signal-to-noise ratios.

3.6 Channel capacity

Channel capacity is a fundamental concept in information theory and communication. It represents the maximum amount of information that can be reliably transmitted through a given communication channel under certain conditions [16, 31]. Channel capacity depends on various factors, including the physical properties of the channel and constraints imposed by noise and interference. The channel capacity (C) is determined by the Shannon-Hartley theorem, its expression is given by [16, 31] :

$$C = B \times log_2(1+\gamma). \tag{3.33}$$

The expression for the channel capacity as a function of atmospheric parameters is given by [16, 31] :

$$< C >= \int_0^{\infty} B \times log_2(1+\gamma)p(I)\,\mathrm{d}I \tag{3.34}$$

Or $log_2(x) = \frac{ln(x)}{ln(2)}$ and the expression of $ln(1+x)$ as a Meijer functionG is given by equation 38 :

$$ln(1+x) = G_{2,2}^{1,2}\left(x\middle|\begin{array}{c} 1,1 \\ 1,0\end{array}\right). \tag{3.35}$$

By replacing (38) in (37) and applying the integral product formula of two MeijerG functions [25], we obtain the channel capacity expressions for an FSO system operating with OOK, BPSK, and PolSK modulations described by equations (39), (40), and (41) respectively [16, 31]:

$$< C_{OOK} >= \frac{B \times 2^{\alpha+\beta-2}}{\pi ln(2)\Gamma(\alpha)\Gamma(\beta)} G_{1,6}^{6,2}\left(\frac{16\gamma_{-OOK}}{(\alpha\beta)^2}\middle|\begin{array}{c} 1,1,\frac{1-\alpha}{2},\frac{2-\alpha}{2},\frac{1-\beta}{2},\frac{2-\beta}{2} \\ 1,0\end{array}\right), \tag{3.36}$$

$$< C_{BPSK} >= \frac{B \times (\alpha\beta)^{\frac{\alpha+\beta}{2}}}{ln(2)\Gamma(\alpha)\Gamma(\beta)} \times (\gamma_{-BPSK})^{-\frac{\alpha+\beta}{2}} G_{4,1}^{2,4}\left(\frac{\alpha\beta}{\gamma_{-BPSK}}\middle|\begin{array}{c} -\frac{\alpha-\beta}{2}, 1+\frac{\alpha-\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2}, -\frac{\alpha+\beta}{2}\end{array}\right), \tag{3.37}$$

$$< C_{PolSK} >= \frac{B \times (\alpha\beta)^{\frac{\alpha+\beta}{2}}}{ln(2)\Gamma(\alpha)\Gamma(\beta)} \times \left(\frac{\gamma_{-PolSK}}{2}\right)^{-\frac{\alpha+\beta}{2}} G_{4,1}^{2,4}\left(\frac{2\alpha\beta}{\gamma_{-PolSK}}\middle|\begin{array}{c} -\frac{\alpha-\beta}{2}, 1+\frac{\alpha-\beta}{2} \\ \frac{\alpha-\beta}{2}, -\frac{\alpha-\beta}{2}, -\frac{\alpha+\beta}{2}, -\frac{\alpha+\beta}{2}\end{array}\right). \tag{3.38}$$

4 RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Test environnement

The considered environment test is represented by Côte d'Ivoire, because of its diverse geography, Côte d'Ivoire has specific climatic variations. The coastal regions, including Abidjan, are wetter with higher rainfall and hight scintillation level, while the northern regions are drier and experience higher temperatures [12, 32]. The mountainous areas in the western part of the country, such as Man, have a cooler climate due to their elevation, with lower temperatures than in the coastal areas. The chosen environment is Man, a previous study carried out by [32] revealed that this is the environment where the FSO link suffers the most attenuation due to atmospheric parameters with BER levels of the order of 10^{-2} for values of $SNR = 50db$. In this study, we examine the improvement in link performance induced by the use of modulation techniques especially Polarization shift Keying. To do this, meteorological data from Man was collected on the historical weather platform $1001[33, 34]$, and used to carry out a numerical evaluation of the performance levels achieved by the FSO link for different modulation schemes using Matlab software.

4.1.2 Bit error rate

In this section we compare the bit error rate (BER) achieved by the system operating with PolSK modulation to that achieved when operating with OOK, and BPSK modulations in the presence of atmospheric turbulence caused by weather conditions in our test environment.

The BER values are shown in Fig. 3. Fig. 3. shows a comparison of the BER versus SNR obtained for an FSO system operating with OOK, BPSK, and PolSK modulation schemes under the atmospheric conditions of Man. It shows that the BER values for a system operating with OOK modulation are higher than those obtained using BPSK and PolSK modulation. Of the three types of modulation analyzed, PolSK modulation gives the best results in terms of error reduction. PolSK modulation offers better link reliability than OOK, and BPSK modulations. In fact, for an SNR value of 50 dB at Man, a system operating with PolSK modulation obtains a BER value of the order of 10^{-11}, whereas a system operating with OOK modulation obtains a BER of the order of 10^{-2} and a system operating with BPSK modulation obtains a BER of the order of 10^{-4}. This difference can be explained by the greater resistance of polarisation to the atmospheric characteristics of the environment. Polarisation allows the link to better resist phase noise and refraction phenomena induced by variations in the refractive index during propagation of the optical signal in the atmosphere [16, 35]. However, for an efficient system, it is important to find an optimum compromise between the power required and the acceptable BER [16]. In modulation power requirement refers to the power needed to modulate a signal, usually expressed in watts. This depends on the type of modulation used, such as amplitude, phase, or polarization [16,36]. By modifying these characteristics, we influence the power required to transmit information efficiently. The expression for the power required can be written as a function of BER as [16,18] :

$$\begin{aligned} 2\sqrt{2}erfc^{-1}(2Pe) &= \sqrt{\gamma_{-OOK}}, \\ erfc^{-1}(2Pe) &= \sqrt{\gamma_{-BPSK}}, \\ \sqrt{2}erfc^{-1}(2Pe) &= \sqrt{\gamma_{-PolSK}}, \end{aligned} \quad (4.1)$$

When we relate the three previous equations, we obtain [16,18] :

$$\begin{aligned} \frac{\gamma_{BPSK}}{\gamma_{OOK}} &= \frac{1}{2\sqrt{2}}, \\ \frac{\gamma_{PolSK}}{\gamma_{OOK}} &= \frac{1}{2}, \\ \frac{\gamma_{BPSK}}{\gamma_{PolSK}} &= \frac{1}{\sqrt{2}}, \end{aligned} \quad (4.2)$$

Theoretically, equation (43) shows us that BPSK modulation provides a higher power efficiency than OOK and PolSK modulation. Indeed for the same BER value, it seems BPSK modulation requires less power than OOK and PolSK modulation.

Fig. 4. shows the evolution of the power required as a function of the BER. Fig. 4. confirms the results presented above, it shows that in terms of power efficiency, BPSK modulation gives the best results. For example for a BER of 0.3, BPSK modulation requires $0.37\ W$, whereas OOK and PolSK modulation require $1.04\ W$ and $0.52\ W$ respectively. This is mainly due to the fact that in BPSK modulation the system can operate at peak power (the information can be encoded at maximum transmission power).

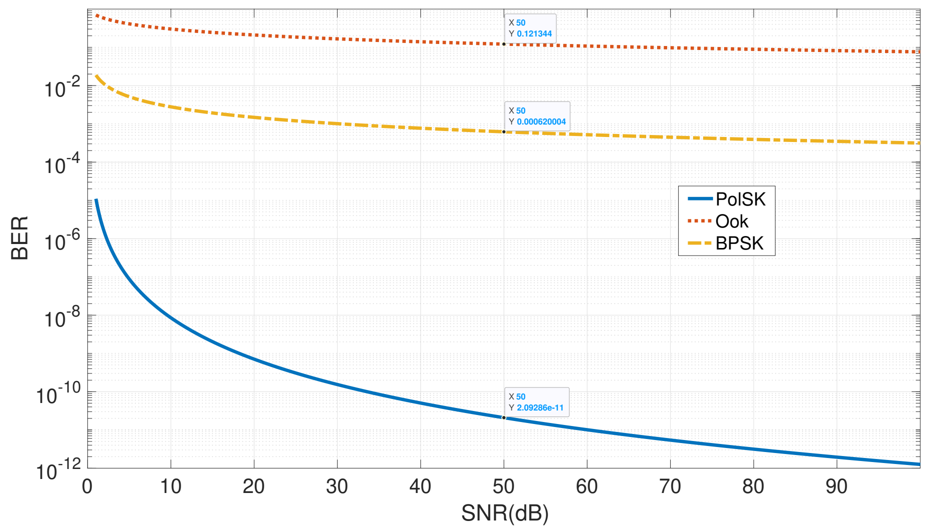

Fig. 3. OOK and PolSK BER comparison

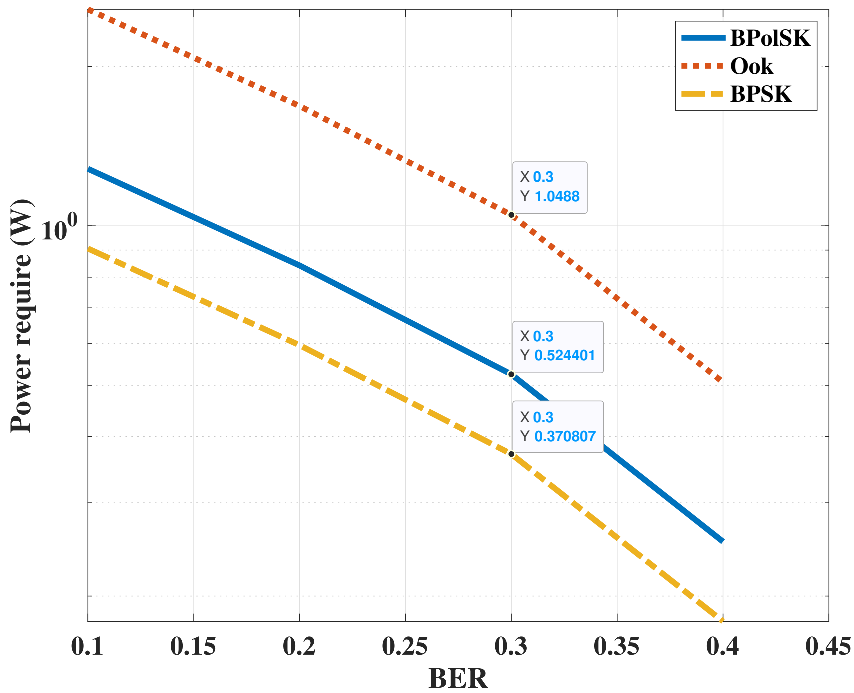

Fig. 4. Evolution of the power required as a function of the BER

4.1.3 Outage probability

In this section, we compare the impact in terms of reducing the probability of outage of each of our modulations in our environments. Analysis of the probability of interruption is crucial to the planning, optimisation and management of communication networks [16, 29] . It ensures efficient use of resources, adequate quality of service and an improved overall user experience.

Fig. 5. shows the evolution of the probability of interruption as a function of the SNR for the OOK, BPSK and PolSK modulations. We can see that PolSK modulation offers the best performance in terms of reducing the probability of interruption for our system. This shows that the probability of interruption improves as the signal-to-noise ratio increases. Indeed, Figure 5 shows that for a signal-to-noise ratio of $20\ dB$, the probability of interruption of the system when operating with PolSK modulation is 0.00394, whereas it is 0.02439 when considering BPSK modulation and 0.1461 when considering OOK modulation. This is mainly due to the fact that the nature of the polarisation of the light wave is very little influenced by the effects of atmospheric parameters, unlike amplitude and phase, which are particularly affected by absorption and phase noise phenomena [3, 16, 18].

4.1.4 Channel capacity

In this section, we compare the impact in terms of increased channel capacity of each of our modulations in our environments. In the age of connected systems (IOT), analysis of channel capacity in telecommunications is a fundamental aspect of ensuring high-performance, reliable networks capable of meeting growing communication needs [2, 3, 18] . Modulation plays a crucial role in the efficient exploitation of channel capacity by adapting signals to the characteristics of the communication channel [3, 16, 18]. Wise choices of modulation techniques can achieve higher data rates, reduce the impact of noise, and optimise the transmission of information.

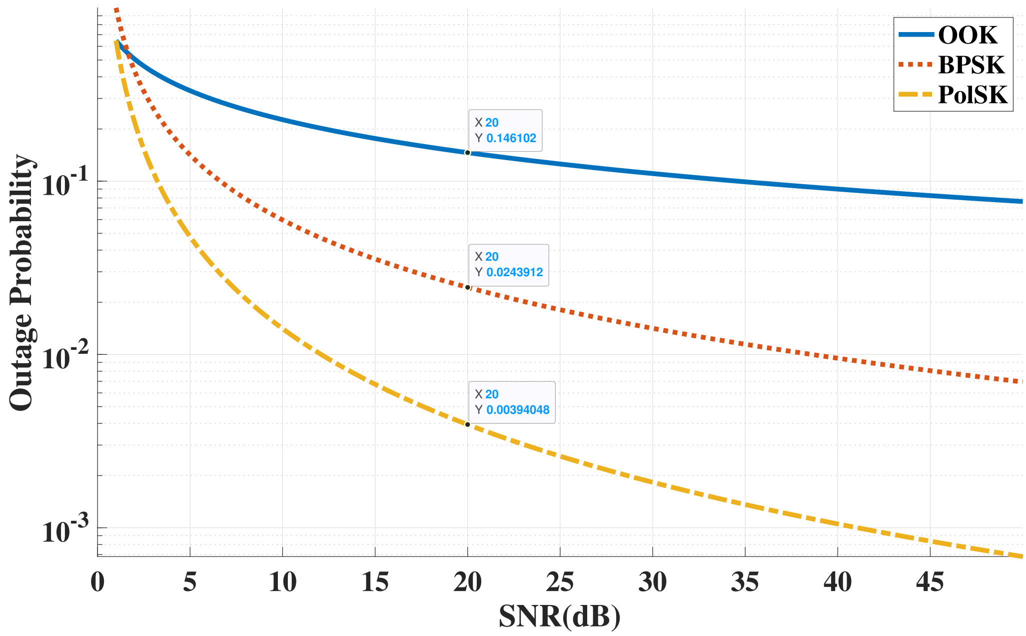

Fig. 5. OOK, BPSK and PolSK outage probability comparison

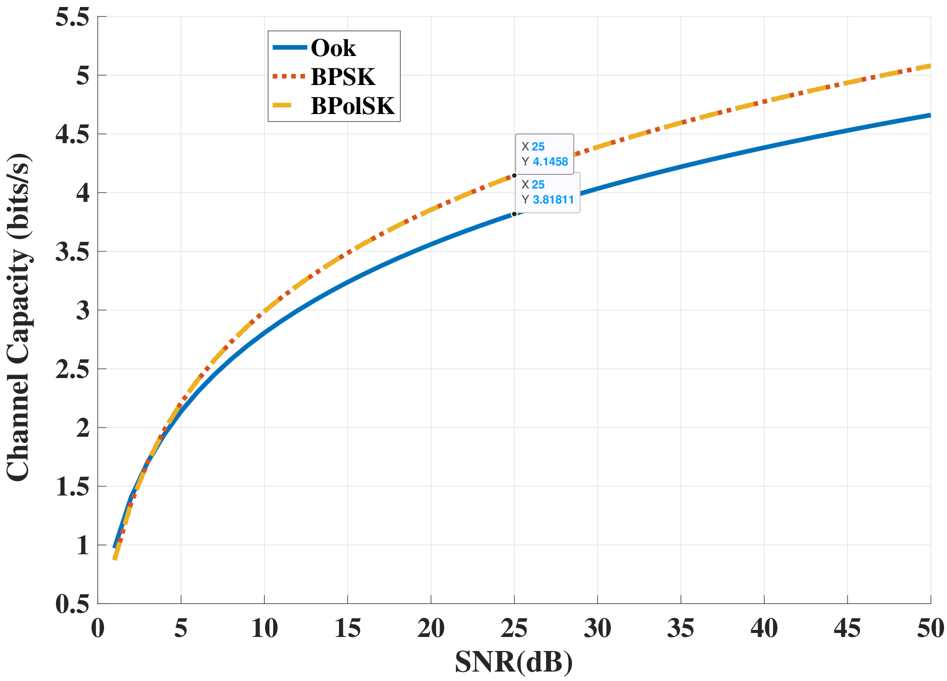

Fig. 6. Comparison of the channel capacity offered by OOK, BPSK and PolSK modulations

Fig. 6. shows that BPSK and PolSK modulations give the best results in terms of channel capacity, and perform better than OOK modulation in terms of increasing channel capacity. For an SNR value of 25 dB, BPSK and PolSK modulations provide a channel capacity of 4.1458 $bits/s$, while OOK modulation provides a channel capacity of 3.81811 $bits/s$.

4.2 Discussion

Analysis of system performance shows that, despite a slight increase in the power required, PolSK modulation maintains higher levels of performance in terms of bit error rate (BER), channel capacity and outage probability than the other modulations considered. And the choice of a specific modulation in an FSO communication system requires careful evaluation of various factors, such as error robustness, detection complexity and susceptibility to interference $1001[3, 16]$. Although PolSK modulation requires slightly more power, it is preferred because of the significant advantages it offers in other critical areas of performance. With regard to the analysis of the impact of PolSK modulation on FSO link performance, our results seem to converge with those already available in the literature. In [35], the authors show that FSO link performance is improved by the use of PolSK modulation. They show that PolSK modulation contributes significantly to improving the BER of the system. The authors of [37] focused on the impact of modulation in improving link performance in India environnement, they show that BPSK modulation offers better results in terms of energy efficiency. We are also observing the same trend in the Man environment. In [36] the authors analyze the impact of modulation on performance in terms of channel capacity on the FSO link. It was found that modulation improves link capacity and reduces the probability of system outages. However, in this study, the authors' analyses focused on the different variants of BPSK modulation and did not consider PolSK modulation which, according to our study and those of K. Prabu, S. Cheepalli, and D.S. Kumar, in [38], presents results similar to those of BPSK modulation in terms of channel capacity improvement and results superior to those of BPSK modulation in terms of outage probability reduction. These results can be explained by the robustness of the polarisation with respect to the channel parameters. Unlike amplitude and phase modulation schemes, which are strongly affected by background and phase noise, polarization state shift keying modulation schemes are very robust to these factors [16,39]. In fact, atmospheric scintillation and the presence of particles in the atmosphere have little influence on the evolution of the polarisation state of a wave [16], which means that the nature of the transmitted signal is not compromised and decoding errors at reception are avoided, hence the improvement in BER. In this way, PolSK modulation can be used to facilitate the transmission of the information signal over a communication channel to overcome challenges such as noise, interference and signal attenuation.

The main advantage of modulation is its ability to be combined with other techniques for improving the performance of free-space optical communication systems [3, 16, 39]. Recent studies have proposed the use of multiplexing to improve the performance of optical communication systems, particularly in terms of capacity [40]. However, before several signals can be combined for transmission, each signal must be modulated to prepare it for transmission on the communication medium. PolsK modulation could be used to boost performance using multiplexing systems such as Orbital Angular Momentum (OAM) multiplexing, which is becoming increasingly widespread [40–42].

5 CONCLUSION

At a time when bandwidth requirements are rising sharply, it is more than essential to find ways of improving the performance of the transmission systems currently used to meet consumer needs. FSO technology is no exception and various techniques are being developed to solve this problem, particularly in the field of modulation. The aim of this article is to present the impact of PolSK modulation on improving the performance of FSO links in a subtropical environment such as Côte d'Ivoire. To do this, we analyzed the impact of different types of modulation (OOK, BPSK, PolSK) on system performance. We have shown that PolSK modulation considerably increases the system's resistance in the presence of atmospheric turbulence, resulting in a reduction in BER (10^{-11}) compared with OOK (10^{-2}) and BPSK (10^{-4}) modulations, which are widely used in commercial systems. It also offers a better reduction in the probability of interruption of the order of 10^{-3} compared with OOK (10^{-2}) and BPSK (10^{-1}) modulation formats for an SNR of $20dB$. In terms of channel capacity improvement, PolSK modulation offers the same results as BPSK modulation at 4.1458 bit/s and is superior to those offered by OOK modulation ($3.8181bit/s$) for an SNR of 25 dB. Finally, in terms of energy efficiency, BPSK modulation offers the best results. In order to help improve the performance of free-space optical communication systems, the next stage of our work will involve combining PolSK modulation with WDM multiplexing based on the use of single-source solitonic microcombs [38].

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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