JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **15** No 3, 03021(6pp) (2023)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **15** № 3, 03021(6cc) (2023)

Comparative Study of the Performance of Different Modulations in FSO Communication over a Turbulent Channel with Pointing Error

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(Received 20 May 2023; revised manuscript received 18 June 2023; published online 30 June 2023)

Free Space Optical (FSO) communication is a method of transmitting data using modulated light waves through free space, such as air or vacuum, instead of using traditional wired or fiber-optic cables. FSO systems typically use lasers or light-emitting diodes (LEDs) as light sources to transmit data, and photodiodes or other light detectors to receive the data. In this paper, we investigate the error performance of a Free Space Optical system using various modulation techniques under different intensity fluctuation conditions. Our analysis takes into account the combined effects of atmospheric turbulence-induced fading and misalignment fading on the propagating signal. We derive novel closed-form expressions for the statistics of the random attenuation of the propagation channel for each modulation scheme used. Additionally, we perform a comparative study of bit-error rate (BER) performance for all modulation techniques considered in this work. We present numerical results to evaluate the error performance of all modulation schemes used in FSO systems with the presence of atmospheric turbulence and/or misalignment. Furthermore, we compare the OOK, PPM, DPSK, and BSPK modulation techniques to determine the best modulation that achieves the minimum BER for a given signal-to-noise ratio value equal to 30 dB in different scenarios.

Keywords: Free-Space Optics (FSO), OOK, BPSK, DPSK, PPM, Atmospheric turbulence, Pointing error.

DOI: 10.21272/jnep.15(3).03021 PACS number: 84.40.Ba

1. INTRODUCTION

The number of mobile users has been rising quickly, and the switch to the 5G cellular network is predicted to cause traffic to increase by a factor of seven [1], and the evolution of the idea of the Internet of Things [2], which is one of the most well-known names that has recently reached new heights and established a standard IoT [3]. A communication system can increase the transmitted data by using free space optics (FSO), which can enable high-speed, high-bandwidth over short distances, often up several kilometers. This communication technology uses optical signals to transmit data through atmosphere between two points. It is an alternative to traditional wireless technologies such as Wi-Fi, Bluetooth. FSO operates in the infrared and visible light spectrum and requires a line-of-sight (LOS) between the transmitter and receiver. FSO communication can be used to establish high-speed links between bas station in 5G cellular networks [4]. According to various predictions, the number of connected devices could reach between 20 and 30 billion by 2025, with some estimates even higher [5]. The integration of 5G features in IoT using FSO links can enhance the coverage area and performance of IoT [6].

The quality and reliability of FSO communication systems can be significantly degraded by atmospheric turbulence, which results in a loss of power. This issue is more present when there is a pointing error and the transmitter and receiver are far apart [7]. This impairment, due to atmospheric turbulence and misalignment, degrades the performance of FSO communication systems by increasing the bit error rate [8].

There are various modulation techniques that can be used in optical wireless communication. These techniques are often compared in terms of the average received optical power required to achieve a desired bit error rate (BER) at a specific data rate. The On-Off Keying (OOK) is frequently regarded as the simplest and most widely applied technique. It does, however, have several drawbacks, particularly when pointing errors and atmospheric turbulence are present. In order to enhance system performance, OOK also needs an adjustable threshold, which might complicate system design and introduce new requirements [9]. On the other hand, the phase modulation techniques BPSK and DPSK offer better performance compared to OOK in the presence of turbulence and pointing error. BPSK is the simplest form of phase shift keying (PSK), and it is the most robust of all PSKs as it requires the highest level of noise or distortion to disrupt its signal [10]. DPSK refers to a modulation technique that alters the phase of the carrier signal to convey data, and it can help alleviate the impact of scintillation to some degree [11].

This paper is organized as; after this introduction, the rest of this document is organized as follows: In Section two, we present the channel model. In Section three, we describe a mathematical model of atmospheric turbulence. In Section four, we present the pointing error model. In Section five, we derive the statistical model of

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combined turbulence and pointing error. In Section six, we derive the mathematical model of the bit error rate for each modulation technique used in this work. In Section seven, we analyze and discuss the simulated results. Finally, we conclude this paper in the eighth section.

2. CHANNEL MODEL

The transmitted signal propagates in the atmospheric channel. The channel model can be modeled as[12] :

$$y = x\eta h + n \tag{1}$$

where y is the received signal, x is the transmitted signal, η is the effective photoelectric conversion ratio, h is the received optical irradiance, and n is the additive white Gaussian noise with zero mean.

3. ATMOSPHERIC TURBULENCE

Scintillation effects are caused by atmospheric turbulence, and they can be described by many statistical models. The log normal distribution is widely accepted for low turbulence [13]. The Gamma-Gamma probability density function under certain approximations can describe the three regimes of turbulence namely weak, moderate and strong turbulence. In this work we have chosen the gamma-gamma turbulence model because it effectively describes the strength of any atmospheric turbulence. Its probability density can be well modeled as [14]:

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_a}\right) \quad h_a > 0 \tag{2}$$

With h_a is the normalized signal intensity, $\Gamma(.)$ is the gamma function, $K_{\alpha-\beta}$ is the modified Bessel function of second order, and α, β are the parameters that describe the strength of the atmospheric turbulence with α and β can be directly related to atmospheric conditions their mathematical expressions are:

$$\alpha = \left(exp\left(\frac{0.49\sigma_R^2}{\left(1 + 1.11\sigma_R^{12/5}\right)^{7/6}} \right) - 1 \right)^{-1} \tag{3}$$

$$\beta = \left(exp\left(\frac{0.51\sigma_R^2}{\left(1 + 0.69\sigma_R^{12/5}\right)^{5/6}} \right) - 1 \right)^{-1} \tag{4}$$

Where σ_R^2 is a parameter of the Rytov variance, it is a measure of the strength of turbulence fluctuations.

4. POINTING ERROR MODEL

The probability density of h_p can be modeled using the assumptions and methodology described in reference[15]. Specifically, if we assume a Gaussian optical beam of width w_z on the plane of the receiver having a circular aperture of radius r, and away from the transmitter by a distance z. The fraction of the collected power, due to geometric propagation with radial displacement α of the receiver from its origin, can be approximated by[15]:

$$h_p(\alpha) = A_0 exp\left(-\frac{2\alpha^2}{w_{z_{eq}}^2}\right) \tag{5}$$

Where $w_{z_{eq}}^2 = w_z^2\sqrt{\pi}erf(v)/2vexp(-v^2)$, $v = \sqrt{\pi}r/\sqrt{2}w_z$, $A0=[erf(v)]^2$, *erf(.)* is the error function. Considering that the elevation and horizontal displacement are identical and independent Gaussian processes, the radial displacement α follows the Rayleigh distribution, and the probability density of h_p is expressed as:

$$f_{h_p}((h_p) =) = \frac{\gamma^2}{A_0^{\gamma^2}} h_p^{\gamma^2-1} \qquad 0 \le h_p \le A_0 \tag{1}$$

Where $\gamma = \frac{w_{z_{eq}}}{2\sigma_s}$ represents the ratio of the equivalent beam radius at the receiver to the jitter variance at the receiver.

5. COMBINED ATTENUATION STATISTIC

Using the previous probability densities for turbulence and misalignment, the probability density of $h = h_l h_a h_p$ can be expressed in terms of [15]:

$$f_h(h) = \int f_{h/_{h_a}}\left({}^{h}/_{h_a}\right) f_{h_a}(h_a)dh_a \tag{2}$$

Where $f_{h/_{h_a}}\left(\frac{h}{h_a}\right)$ is the conditional probability given that the atmospheric communication channel is turbulent [14].

$$f_h(h) = \frac{\gamma^2\alpha\beta}{A_0 h_l \Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0}\left[\alpha\beta\frac{h}{A_0 h_l}\middle|\begin{matrix}\gamma^2\\ \gamma^2-1, \alpha-1, \beta-1\end{matrix}\right] \tag{3}$$

6. CHANNEL CHARACTERIZATION

6.1 Bit Error Rate of Modulations

The conditional BER values for different modulation techniques are given below [16]:

$$P(e|h)_{RZ-OOK} = \frac{1}{2}\, erfc\left(\sqrt{\left(\frac{\eta^2}{N_0}\right)\frac{h^2}{4}}\right) \tag{4}$$

$$P(e|h)_{NRZ-OOK} = \frac{1}{2}\, erfc\left(\sqrt{\left(\frac{\eta^2}{N_0}\right)\frac{h^2}{8}}\right) \tag{5}$$

$$P(e|h)_{BPSK} = \frac{1}{2}\, erfc\left(\sqrt{\frac{\eta A}{2qB}h}\right) \tag{6}$$

$$P(e|h)_{DPSK} = \frac{1}{2}\, erfc\left(\sqrt{\frac{\eta_e A T_s}{2h\upsilon_P v}h}\right) \tag{7}$$

$$P(e|h)_{PPM} = \frac{1}{2}\, erfc\left(\sqrt{\left(\frac{\eta^2}{N_0}\right)\frac{h^2}{8}L\frac{ln(L)}{ln(2)}}\right) \tag{8}$$

6.2 Atmospheric Turbulence Effect Only

In the case that only atmospheric turbulence occurs, then $h = h_a > 0$. Employing equation 21 [18], the average BER will be given by:

$$\begin{aligned} P(e) &= \int_0^\infty P(e|h_a) f_{h_a}(h_a) dh_a \\ &= M G_{5,2}^{2,4}\left[B\middle|\begin{matrix}\frac{1-\alpha}{2}, \frac{2-\alpha}{2}, \frac{1-\beta}{2}, \frac{2-\beta}{2}, 1\\ 0, \frac{1}{2}\end{matrix}\right] \end{aligned} \tag{9}$$

Where $M = \frac{2^{\alpha+\beta-3}}{\pi^{\frac{3}{2}}\Gamma(\alpha)\Gamma(\beta)}$ and B is expressed as $= \frac{4\,\mu}{(\alpha\beta)^2}$, $B = \frac{2\,\mu}{(\alpha\beta)^2}$ and $B = \frac{L\ln(L)\mu}{(\alpha\beta)^2\ln(2)}$ for RZ-OOK, NRZ-OOK and PPM respectively.

Employing equation 07.34.21.0011.01[19], the average BER will be given by:

$$P(e)_{\text{BPSK}} = \frac{1}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} G_{3,2}^{2,2}\left[\frac{\mu}{\alpha\beta}\middle|\begin{matrix}1-\alpha, 1-\beta, 1\\ 0, \frac{1}{2}\end{matrix}\right] \tag{10}$$

$$P(e)_{\text{DPSK}} = \frac{1}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} G_{3,2}^{2,2}\left[\frac{\mu}{2\alpha\beta}\middle|\begin{matrix}1-\alpha, 1-\beta, 1\\ 0, \frac{1}{2}\end{matrix}\right] \tag{11}$$

6.3 Pointing Error Effect Only

In the case where only pointing error occurs, afterwards $0 \le h = h_p \le A_0$. Using equation 26 [18], the average BER is given by:

$$P(e) = \int_0^{A_0} P(e|h_p)\, f_{h_p}(h_p)\, dh_p = KG_{2,3}^{2,1}\left[B\middle|\begin{matrix}1-\frac{\gamma^2}{2}, 1\\ 0, \frac{1}{2}, -\frac{\gamma^2}{2}\end{matrix}\right] \tag{12}$$

Where B is expressed as $B = \frac{\gamma^2+2}{4\gamma^2}\mu$, $B = \frac{\gamma^2+2}{8\gamma^2}\mu$ and $B = \left(\frac{\gamma^2+2}{16\gamma^2}\mu\right)L\frac{ln(L)}{ln(2)}$ with $K = \frac{\gamma^2}{4\sqrt{\pi}}$ for RZ-OOK, NRZ-OOK and PPM respectively. Also $B = \frac{\gamma^2+2}{\gamma^2}\mu$ $B = \frac{\gamma^2+2}{2\gamma^2}\mu$ with $K = \frac{\gamma^2}{2\sqrt{\pi}}$ for BPSK and DPSK respectively.

6.4 Combined Attenuation

The bit error rate of the FSO link for the combination of the two effects will be expressed as:

$$P(e) = \int_0^{\infty} P(e|h) f_h(h) dh \tag{13}$$

We use equation 21[18]

$$P(e) = \mathrm{A}\mathrm{G}_{7,4}^{2,6}\left[C\middle|\begin{matrix}\frac{1-\gamma^2}{2}, \frac{2-\gamma^2}{2}, \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, \frac{1-\beta}{2}, \frac{2-\beta}{2}, 1\\ 0, \frac{1}{2}, \frac{-\gamma^2}{2}, \frac{1-\gamma^2}{2}\end{matrix}\right] \tag{14}$$

Where C is expressed as $= \frac{4\,\mu(\gamma^2+2)}{\gamma^2(\alpha\beta)^2}\Big|$, $C = \frac{2\,\mu(\gamma^2+2)}{\gamma^2(\alpha\beta)^2}$ and $C = \frac{\mu L\frac{\ln(L)}{\ln(2)}(\gamma^2+2)}{\gamma^2(\alpha\beta)^2}$ for RZ-OOK, NRZ-OOK and PPM respectively, and $A = \frac{2^{\alpha+\beta-4}\gamma^2}{\pi^{\frac{3}{2}}\Gamma(\alpha)\Gamma(\beta)}$.

We use equation [20]

$$P(e) = EG_{4,3}^{2,3}\left[D\middle|\begin{matrix}-\gamma^2+1, -\alpha+1, -\beta+1, 1\\ 0, \frac{1}{2}, -\gamma^2\end{matrix}\right] \tag{15}$$

Where D is expressed as $D = \frac{\mu(\gamma^2+1)}{\gamma^2\alpha\beta}$ and $D = \frac{\mu(\gamma^2+1)}{2\gamma^2\alpha\beta}$ for, BPSK and DPSK respectively, and $E = \frac{\gamma^2}{\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)}$.

7. SIMULATION RESULTS

We consider different values of the Rytov variance parameter to describe the strength of atmospheric turbulence. Additionally, we vary the normalized pulse width $\frac{W_z}{r}$ and take discrete values of the normalized jitter variance σ_s/r to account for the impact of pointing error. The evolution of average BER versus signal to noise ratio is presented in Fig.1, where we only assume the effect of moderate atmospheric turbulence ($\sigma_R{}^2 = 1$). It is evident that the average Bit Error Rate (BER) decreases as the Signal-to-Noise Ratio (SNR) increases for all modulation techniques. The curves in the figure show that BPSK modulation performs the best among them. With the most performant modulation, it is possible to achieve a reference BER of 10^{-9} when the signal-to-noise ratio (SNR) is 37 dB.

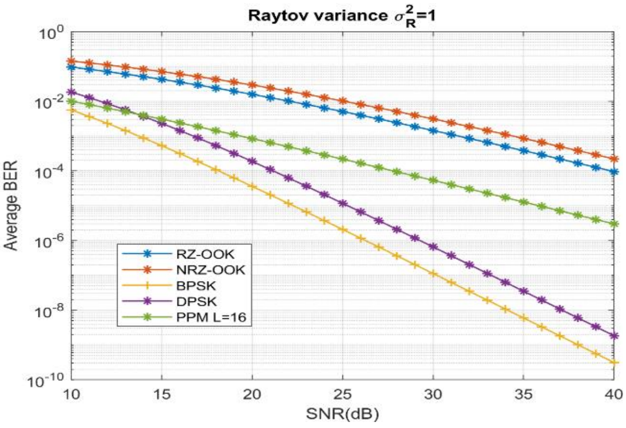

Fig. 1 – Average bit error rate (BER) versus SNR for a turbulent channel only

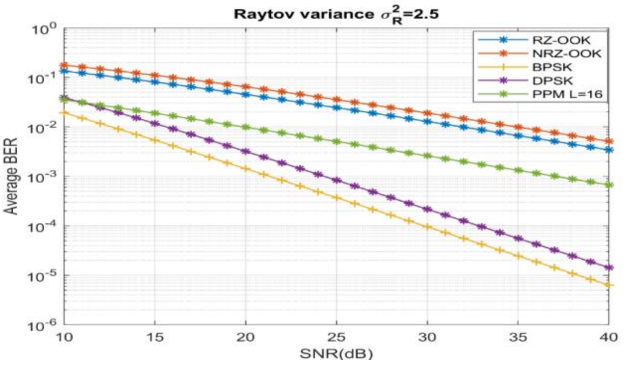

Fig. 2 – Average bit error rate (BER) versus SNR for a turbulent channel only

The Fig. 2 depicts the average BER versus SNR under the effect of strong atmospheric turbulence ($\sigma_R{}^2$ = 2,5). Based on the curves shown in Fig. 2, it is evident that the impact of strong turbulence is substantial. With the best modulation BPSK we achieve a BER of 10^{-5} at SNR = 37 dB. Comparing the results in Fig. 2 with those in Fig. 1, we can see that strong turbulence causes severe signal fading and bit error rate (BER) degradation, which can render the Free Space Optical (FSO) system practically unusable.

In addition to evaluating the performance of the FSO system, we specifically focus on analyzing the impact of misalignment fading while assuming the absence of turbulence effects and a fixed SNR of 30 dB. We assume that the normalized beamwidth, denoted by $\frac{W_z}{r}$, can take values from 1 to 6. The evolution of BER versus beamwidth for two values of normalized jitter. $\frac{\sigma_s}{r} = 2{,}5$ and $\frac{\sigma_s}{r} = 4{,}5$, are presented in Fig. 3 and Fig. 4, respectively.

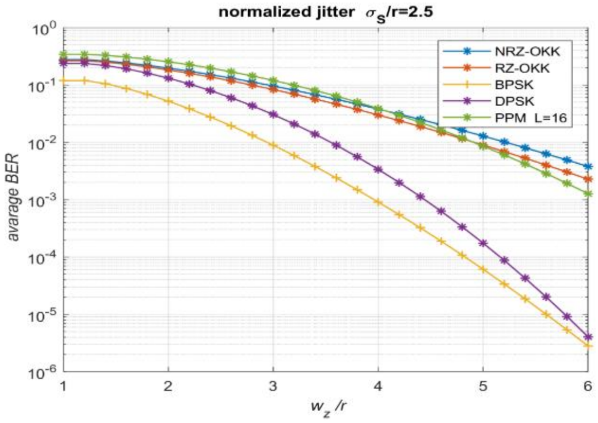

Fig. 3 – BER versus normalized beamwidth assuming pointing error effects only

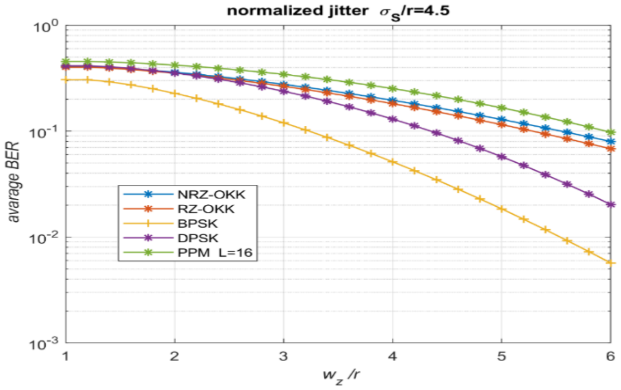

Fig. 4 – BER versus normalized beamwidth assuming pointing error effects only

According to the curves presented in two figures, we observe that the average BER increase as the beamwidth rises. We note that the BER is very important when the normalized jitter increases. For BPSK modulation, the values of BER are 10^{-5} and 10^{-2} for normalized jitter $\frac{\sigma_s}{r} = 2{,}5$ and beamwith $\frac{W_z}{r} = 5{,}7$, and normalized jitter $\frac{\sigma_s}{r} = 4{,}5$ and beamwith $\frac{W_z}{r} = 5{,}7$, respectively. The two figures show that the BPSK modulation exhibits better performance than other modulations.

Our next step is to evaluate the impact of the combined effects of atmospheric turbulence and pointing error. We maintain a constant value of SNR at 30 dB and vary the beamwidth from 1 to 6. The Fig.5 and Fig.6 depict the average BER in terms of normalized beamwidth for moderate turbulence $\sigma_R^2 = 1$ and normalized jitter equal to $\frac{\sigma_s}{r} = 2.5$. Based on the curves in those figures, we see that the combined atmospheric effect and misalignment degrade drastically the system performance.

For the best BPSK modulation and moderate turbulence, the minimum BER values are noted to be approximately 10^{-5} and 10^{-2} for normalized jitter equal to $\frac{\sigma_s}{r} = 2.5$ and $\frac{\sigma_s}{r} = 4.5$, respectively. This indicates that the transmission over an FSO link in these conditions may have a high error rate, and the receiver may face difficulty in successfully decoding the transmitted bit.

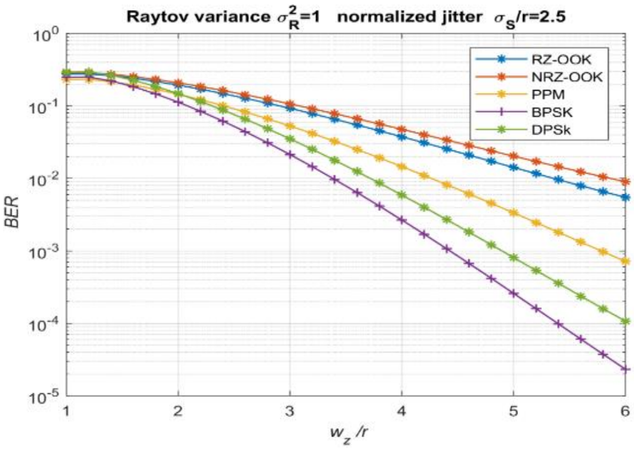

Fig. 5 – BER versus normalized beamwidth

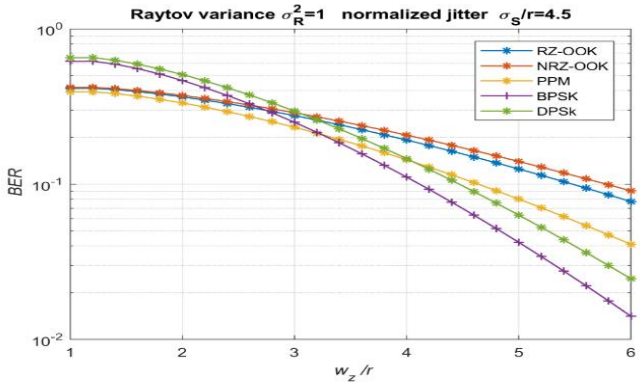

Fig. 6 – BER versus normalized beamwidth

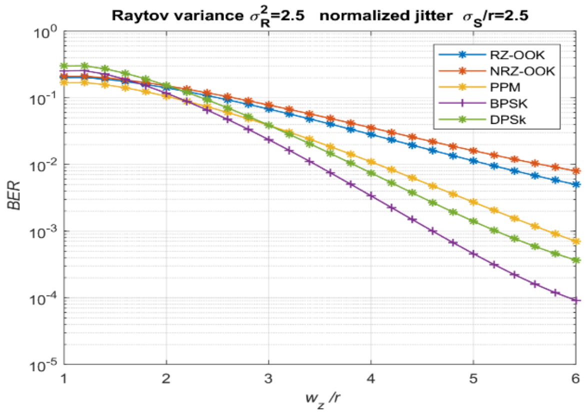

Fig.7- BER versus normalized beamwidth

Finally, we evaluate the FSO system using the modulation schemes of OOK, PPM, DBSK, and BPSK under strong turbulence conditions with two values of normalized jitter, $\frac{\sigma_s}{r} = 2{,}5$ and $\frac{\sigma_s}{r} = 4.5$, while maintaining a constant SNR of 30 dB.

The curves in Fig.7 and Fig.8 represent the evolution of BER versus normalized beamwidth. We can observe that the BER is significant and increases rapidly as the normalized jitter increases. The curves in the two figures show, as with the previous results, that the minimum BER achieved by the optimal modulation scheme is much lower than the reference BER of 10^{-9}.

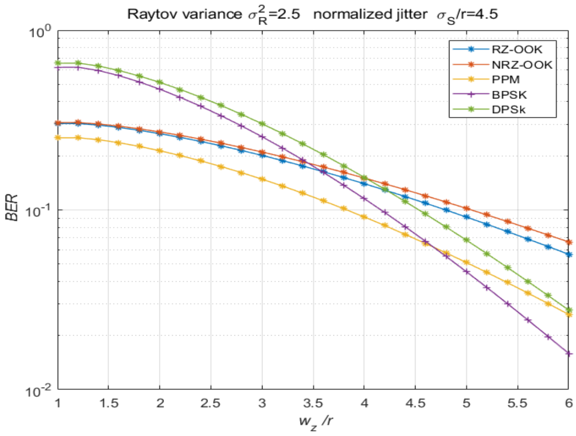

Fig. 8 – BER versus normalized beamwidth

It is noteworthy that the performance of the FSO system degrades significantly under strong turbulence and pointing errors.

8. CONCLUSIONS

We investigated the bit error rate (BER) performance of an FSO communication system using different modulation schemes. We derived BER expressions for each modulation scheme, taking into account the effects of atmospheric turbulence and pointing errors. The simulation results demonstrate that the bit error rate (BER) performance is influenced by numerous factors that are related to atmospheric turbulence and misalignment. These factors can include the strength of turbulence, normalized jitter, normalized beamwidth, and the transmitted power that affects the signal-to-noise ratio (SNR). The results show that the turbulence and point-ing error increase drastically the BER which render the FSO system practically unusable. By taking into ac-count the factors mentioned above, along with the possible application of techniques such as error control coding and transmit-receive diversity to enhance BER performance, this study may serve as a basis for fur-ther exploration of unresolved areas in the future.

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Порівняльне дослідження ефективності різних модуляцій у FSO: зв'язок по турбулентному каналу з помилкою вказівки

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Оптичний зв'язок у вільному просторі (FSO) — це метод передачі даних за допомогою модульованих світлових хвиль через вільний простір, наприклад, повітря чи вакуум, замість використання традиційних дротових або волоконно-оптичних кабелів. У системах FSO зазвичай використовують лазери або світлодіоди як джерела світла для передачі даних, а також фотодіоди або інші детектори світла для отримання даних. У статті досліджена ефективність помилок оптичної системи вільного простору з використанням різних методів модуляції за різних умов коливання інтенсивності. Аналіз, проведений в роботі, враховує комбінований вплив завмирання, спричиненого атмосферною турбулентністю, і завмирання зміщення на сигнал, що поширюється. Були отримані нові співвіношення закритої форми для статистики випадкового загасання каналу розповсюдження для кожної використаної схеми модуляції. Крім того, проведено порівняльне дослідження ефективності частоти бітових помилок (BER) для всіх методів модуляції. Наведені чисельні результати для оцінки ефективності похибок усіх схем модуляції, що використовуються в системах FSO з наявністю атмосферної турбулентності та/або неузгодженості. Крім того, ми порівнюємо методи модуляції OOK, PPM, DPSK і BSPK, щоб визначити найкращу модуляцію, яка забезпечує мінімальний BER для заданого значення співвідношення сигнал/шум, що дорівнює 30 дБ у різних сценаріях.

Ключові слова: Оптика вільного простору (FSO), Методи модуляції: OOK, BPSK, DPSK, PPM, Атмосферна турбулентність, Помилка наведення.