INVESTIGATING PERFORMANCE OF A MULTI-SUBCARRIER FREE SPACE OPTIC USING LOG-NORMAL CHANNEL MODEL

KHẢO SÁT HIỆU NĂNG CỦA HỆ THỐNG THÔNG TIN QUANG KHÔNG DÂY ĐA SÓNG MANG PHỤ SỬ DỤNG MÔ HÌNH KÊNH LOG-NORMAL

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Abstract - The paper builds a computational model of a multi-subcarrier free space optic, a variant of the Subcarrier Intensity Modulation Free Space Optic (SIM-FSO), establishes algorithmic flowcharts, writes a computational program to investigate the system performance under various modulation methods, air turbulence levels and different numbers of subcarriers and data rates. In order to achieve a BER value of 10^{-4}, FSO-SIM systems using BPSK, DPSK, 16-QAM, 64-QAM, 16-PSK and 64-PSK modulation techniques require SNR approximately values of 17 dB, 18 dB, 19.6 dB, 22.6 dB, 22.8 dB and 34.5 dB, respectively. When compared to other modulation techniques, DPSK performs better and comes very close to BPSK without requiring complex synchronous detection. The paper focuses on evaluating the performance of the SIM-FSO-DPSK system at various bitrates, subcarrier numbers, and with different diversity techniques to enhance transmission capacity and system performance.

Keywords – Performance; multi-subcarrier free space optic system; algorithm flowchart; air turbulence; diversity.

Tóm tắt - Bài báo xây dựng mô hình tính toán cho hệ thống thông tin quang không dây đa sóng mang phụ, một biến thể của hệ thống quang không dây điều chế cường độ sóng mang phụ, lập lưu đồ thuật toán và viết chương trình khảo sát hiệu năng với các phương pháp điều chế, mức độ nhiễu loạn không khí, số sóng mang phụ và tốc độ dữ liệu khác nhau. Kết quả cho thấy, để đạt BER = 10^{-4}, các hệ thống FSO-SIM dùng các kỹ thuật điều chế sóng mang phụ BPSK, DPSK, 16-QAM, 64-QAM, 16-PSK và 64-PSK yêu cầu các giá trị SNR lần lượt xấp xỉ 17 dB, 18 dB, 19,6 dB, 22,6 dB, 22,8 dB và 34,5 dB. Nhận thấy, DPSK cho hiệu năng tốt hơn so với các trường hợp sử dụng các định điều chế khác, gần bằng với BPSK nhưng không cần cấu trúc tách sóng đồng bộ phức tạp. Bài báo tập trung khảo sát hiệu năng của hệ thống SIM-FSO-DPSK theo tốc độ bít, số sóng mang phụ và các phương pháp phân tập khác nhau nhằm nâng cao dung lượng truyền dẫn và chất lượng hệ thống.

Từ khóa - Hiệu năng; hệ thống quang không dây đa sóng mang phụ; lưu đồ thuật toán; nhiễu loạn không khí; phân tập.

1. Introduction

Nowadays, as a result of the continuous increase in internet traffic and the rapid development of optical technologies, the modern telecommunications network architecture has experienced significant modifications. With their huge transmission capacity, current fiber-optic communication systems can connect many users and provide a wide range of services. Deploying such fiber-optic infrastructures is difficult, though, especially in areas with unusual geography or restricted infrastructure. Free-Space Optical (FSO) communication is considered as a necessary addition to current optical transmission systems. In recent years, FSO has become an attractive alternative for traditional broadband wireless connections due to its ultra high-speed transmission capability, no frequency license requirement, simple installation, relocation, or reconfiguration when network topology changes are needed [1–5].

Basically, FSO technology uses light transmission to send signals between two locations through free space. However, the atmosphere is not an ideal medium for communication. The light beam may suffer from deflection by air turbulence caused by changes in the refractive index along the transmission path caused by variations in air temperature and pressure. Furthermore, weather factors like wind, rain, and fluctuating light levels throughout the day may affect system performance, creating major challenges for FSO systems that aim to achieve user's demands for signal quality, high capacity, and long transmission distances [6–9]. Therefore, improving the quality of signal in FSO system while considering balancing power, capacity, and complexity of system has become an important goal for both research teams as well as service providers. To address these challenges, advanced signal modulation techniques and diversity schemes have been proposed for FSO systems to improve the reliability and efficiency of optical communication links.

To balance these above goals, multi-subcarrier modulation techniques combined with basic modulation methods have attracted a lot of attention in recent years [10–12]. However, in these studies, the authors mainly focus on

BPSK-SIM systems, where the BPSK modulation and demodulation methods require the recovery of the subcarrier at the receiver. This requires the synchronization of phase and frequency with the subcarrier at the transmitter (coherent detection) using a Phase-Locked Loop (PLL), which increases system complexity. In [13-15], the authors did not discuss the application of diversity techniques at the receiver to improve transmitted signal quality.

This paper compares and evaluates the performance of FSO-SIM systems after surveying their features using multi-subcarrier techniques with different modulation methods, including BPSK, DPSK, 16-QAM, 64-QAM, 16-PSK, and 64-PSK. We also examine the SIM-FSO-DPSK system at various bit rates, with varying numbers of subcarriers that improve transmission capacity, and with different diversity techniques to enhance overall system performance.

2. Diagram of an FSO system using multi-subcarrier modulation SIM technique

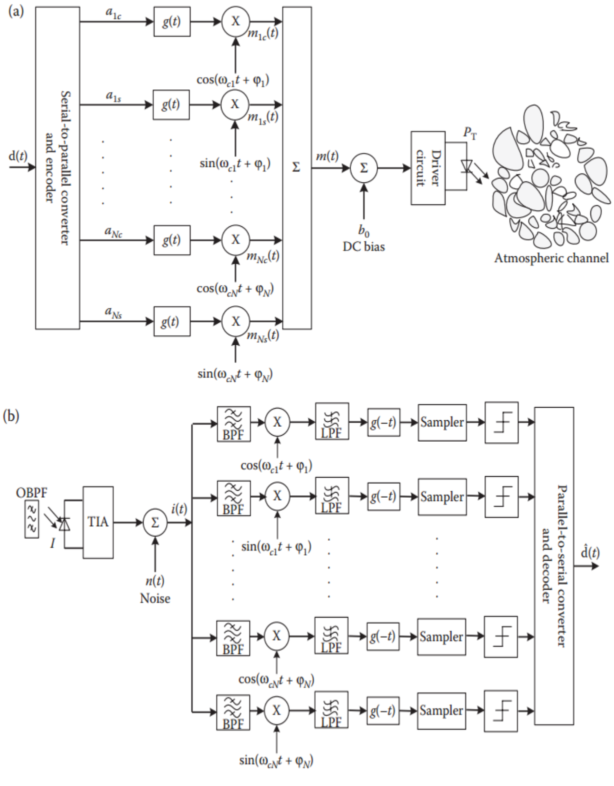

Figure 1. *Block diagram of the FSO-SIM system using N-subcarrier modulation technique. (a) block diagram of the transmitter section; (b) block diagram of the receiver section*

Figure 1 illustrates the block diagram of the FSO-SIM system with N subcarriers [16]. The source data (original data), $d(t)$, is first converted from serial to parallel and then encoded to distribute the data to the corresponding N subcarriers. At this stage, the data is modulated with the subcarriers to generate electrical signals $m_1(t)$, $m_2(t)$ ... $m_N(t)$, which are then combined into a single signal, $m(t)$. After that, the signal $m(t)$ is DC-biased before being fed into the driver circuit to modulate by laser and generate an optical signal with power P_T. Note that, when the signal travels through the FSO channel, it is affected by atmospheric turbulence and leads to random fluctuations in received optical signal intensity. With the intensity variations are characterized by the air turbulence intensity σ_l^2 (Rytov variance) [17], for weak turbulence conditions ($\sigma_l^2 < 1$), these fluctuations have a log-normal distribution. The overall performance of the system decreases as a result of fading and signal distortion. Both unknown fading effects caused by turbulence and deterministic path loss determine the received optical power P_R. After travelling through the air to an optical bandpass filter (OBPF) and into a TIA (Transimpedance Amplifier) optical receiver, the optical signal is converted back into $m(t)$with the addition of noise. The signal $m(t)$ is then passed through the bandpass filters (BPFs), which have central frequencies corresponding to the subcarrier frequencies used at the transmitter, to recover the individual signals $m_1(t)$, $m_2(t)$ ... $m_N(t)$. Finally, these signals are demodulated and digital signal processed to restore the data streams and reassemble the original source data, $d(t)$.

The scenario with N users, in which each user uses a subcarrier with a different frequency, is not shown in Figure 1. Similarly, before getting intensity modulation, each user's data is modulated with separate subcarriers.

The expression for $m(t)$ is given as follows:

$$m(t) = \sum_{i=1}^{N} m_i(t) \tag{1}$$

And each subcarrier is expressed by [16]

$$m_i(t) = g(t)a_{ic}\cos(\omega_{ci}t + \varphi_i) - g(t)a_{is}\sin(\omega_{ci}t + \varphi_i) \tag{2}$$

where $g(t)$ is the pulse-shaping function, and $[\omega_{ci}, \varphi_i]_{i=1}^{N}$ is the angular frequency and phase of each subcarrier. Note that each subcarrier can be modulated by any modulation method, such as: QAM, M-PSK, M-FSK, or M-ASK, etc... After that, the optical signal at the transmitter, with power P_T, is transmitted through free space to the TIA receiver, where it attenuates to a power P_R. Here, the receiver optical signal is converted to an electrical signal $i(t)$. By normalizing the receiver's area to 1 and representing the received power by the irradiance I, we have the received signal as below:

$$i(t) = RI[1 + \xi m(t)] + n(t) \tag{3}$$

where, the optical modulation index $\xi = |m(t)/i_B - i_{Th}|$.

Table 1. *Parameter values of the simulation system*

System parameters	Value
Bit rate	155 Mbps
Wavelength	$\lambda = 850$ nm
Modulation index	$\xi = 1$
Normalized carrier amplitude	$A = 1$
Filter bandwidth	$B_0 = 10^{-9}$m
Receiver opening angle	FOV = 0.6 rad
Number of subcariers	$N = 1 \div 10$
Length of LoS route	$d = 1$ km
Optical-electrical responsivity	$R = 0.95$ A/W
Load resistance of receiver	$R_L = 50\ \Omega$

After that, a bandpass filter (BPF), with a minimum bandwidth of $2R_B$, is used to select the coressponding subcarriers for demodulation, reduce the power of noise, and reduce any slowly varying components RI in the received signal. For a subcarrier with frequency ω_{ci}, the received signal is expressed as:

$$i(t) = I_{comp} + Q_{comp} \quad (4)$$

$$I_{comp} = RI\xi g(t)a_{ic}\cos(\omega_{ci}t + \varphi_i) + n_I(t) \quad (5)$$

$$Q_{comp} = -RI\xi g(t)a_{is}\sin(\omega_{ci}t + \varphi_i) + n_Q(t) \quad (6)$$

where, $n_I(t)$ and $n_Q(t)$ are AWGN noise with a mean of 0 and variance of σ^2.

3. Results and discussion

3.1. Performance comparison of the SIM-FSO system using different subcarrier modulation techniques

Figure 2 illustrates the flowchart for estimating the FSO-SIM system's BER of using different modulation methods. Meanwhile, Figure 3 presents the relationship between the bit error rate (BER) and the signal-to-noise ratio (SNR) for the FSO-SIM system at the wavelength of $\lambda = 850$ nm. The analysis considers various modulation techniques and assumes air turbulence intensity of $\sigma_l^2 = 0.2^2$.

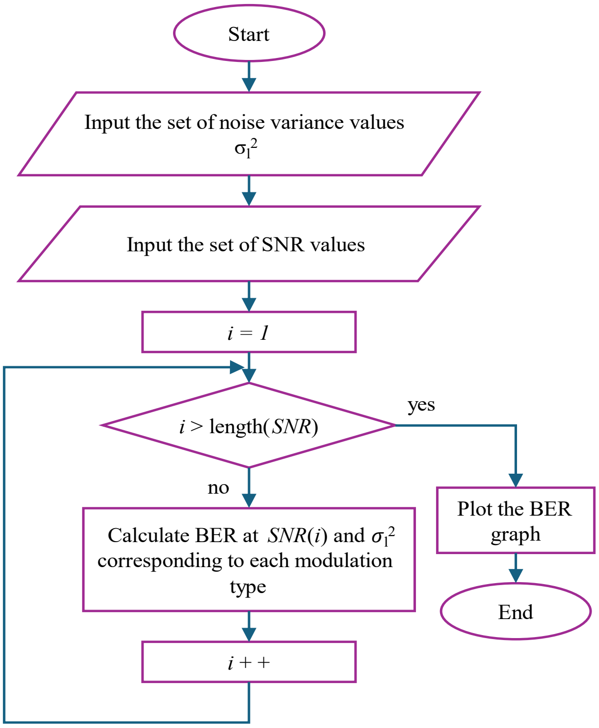

Figure 2. *Flowchart for determining the BER values of the SIM-FSO system using different modulation techniques*

The result demonstrates that the BPSK modulation gives better performance than other ones, regarding the required SNR to achieve the given BER. Specifically, to achieve BER of 10^{-4}, the FSO-SIM system using different subcarrier modulation techniques BPSK, DPSK, 16-QAM, 64-QAM, 16-PSK, and 64-PSK need growing SNR values of 17 dB, 18 dB, 19.6 dB, 22.6 dB, 22.8 dB, and 34.5 dB respectively. This suggests that the M-PSK and M-QAM modulation techniques, the greater phase states M require the higher SNR values demands to maintain a consistent BER - since the proximity of bit combinations increases, raising the system's error probability.

Consequently, increasing the phase states M improves the bit rate but reduces the overall system performance. Based on the result of these evaluations, selecting a modulation technique depends on specific applications and requires the balancing system requirements such as complexity, capacity, power efficiency, bandwidth, and cost.

Since BPSK and DPSK modulation offer higher signal quality than M-PSK and M-QAM, the paper focuses on evaluating the FSO-SIM system's performance using these modulation methods. Furthermore, system capacity will be increased by employing multiple SIM subcarriers.

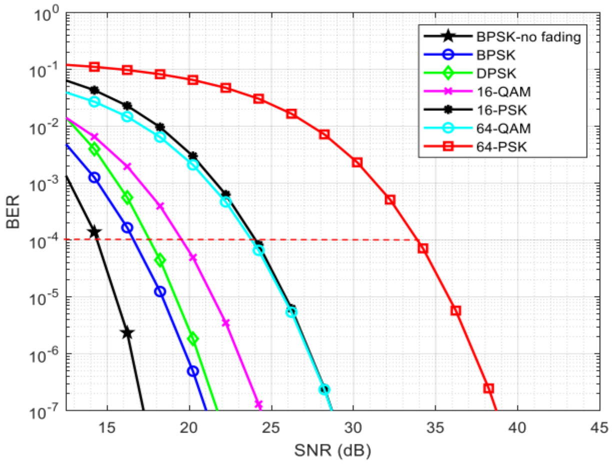

Figure 3. *BER graph of the FSO-SIM system using different modulation techniques with λ=850 nm và $\sigma_l^2 = 0.2^2$*

3.2. Performance comparison of the SIM-FSO system using BPSK and DPSK with different turbulence intensities

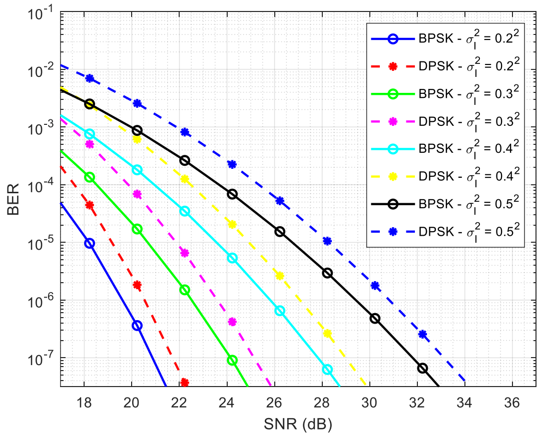

Figure 4. *BER graph of the SIM-FSO system using BPSK and DPSK modulation with different turbulence intensities*

Figure 4 illustrates the relationship between BER and SNR for the FSO-SIM system using BPSK and DPSK modulation techniques, with varying air turbulence intensities of $\sigma_l^2 = [0.2^2, 0.3^2, 0.4^2, 0.5^2]$. The BER is plotted based on $SNR = (RE[I])^2/\sigma^2$, where both R and I_0 are normalized to 1. Simulations are set up with different σ_l^2 values.

The results show that for any given σ_l^2, BPSK modulation technique always gives slightly better BER than the DPSK case does. For example, to achieve an equal BER, the required SNR for the DPSK demodulator is higher than that for BPSK, approximately 0.5 to 1 dB.

However, the DPSK method is simpler than BPSK one since it doesn't require coherent detection at the receiver. Which mean the subcarrier can be recovered without the need of Phase-Locked Loop (PLL). Therefore, to reduce system complexity, compared to earlier studies, the paper proposes evaluating system performance using the DPSK technique in the following sections.

3.3. Performance analysis of the SIM-FSO-DPSK system corresponding to different bit rates and number of subcarriers with various turbulence intensities

Figure 5 presents the algorithm flowchart for determining BER of the SIM-FSO-DPSK system at different bit rates R_b.

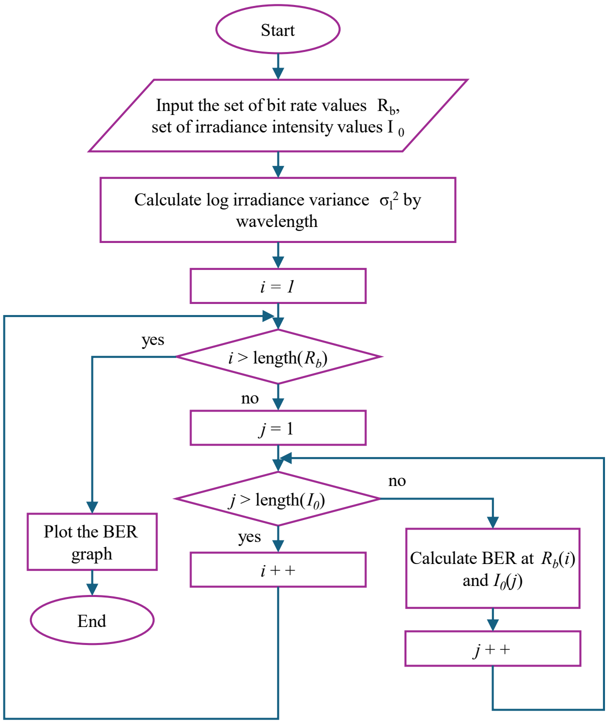

Figure 5. *Algorithm flowchart for determining the BER values of the SIM-FSO-DPSK system at different R_b*

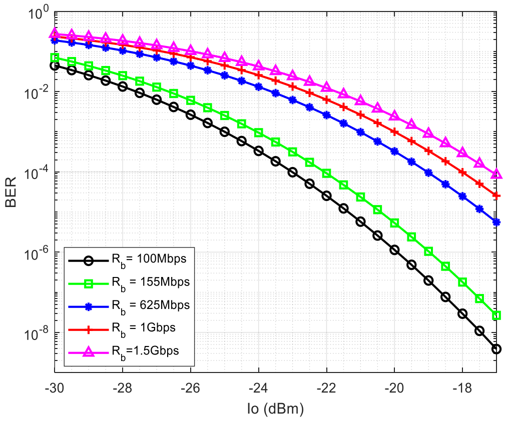

Figure 6. *BER graph of the FSO-SIM-DPSK system at different bit rates R_b and $\lambda = 850nm$*

Figure 6 illustrates the relationship between BER and radiation intensity I_0 at the ngreceiver for the SIM-FSO-DPSK system operating at wavelength of $\lambda = 850nm$. It has been observed that for a given I_0, system performance degrades (corresponding with BER increasing) as the data bit rate per channel increases from 100 Mbps, 155 Mbps, 625 Mbps, 1 Gbps, to 1.5 Gbps. As the bit rate increases, so does the receiver bandwidth ($B_E = 0.75\, R_b$), resulting in increasing noise power, which reduces SNR and raises BER.

Figure 7 shows the relationship between BER and SNR of the SIM-FSO-DPSK system with varying numbers of subcarriers $N = 1, 2, 4, 8$, assuming that all subcarriers have the same modulation index $\xi_{sc} = \xi/N$. It can be observed that, for a given BER value, the required SNR increases as the number of subcarriers rises. Specifically, to achieve a given BER of 10^{-3}, the required SNR values for SIM-FSO-DPSK systems using 1, 2, 4, and 8 subcarriers are approximately 16 dB, 22 dB, 28 dB, and 34 dB, respectively. And to achieve a BER of 10^{-4}, the required SNR values for these systems are approximately 18 dB, 24 dB, 30 dB, and 36 dB, respectively.

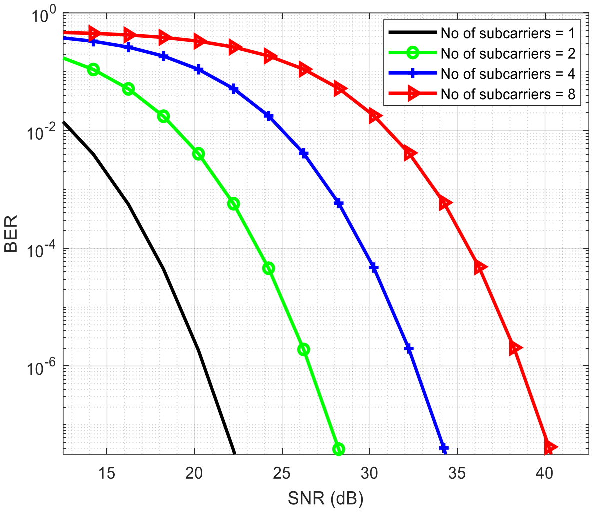

Figure 7. *BER graph of the system for different numbers of subcarriers*

This result can be explained as follows, as the SNR for each subcarrier is proportional to the square of the modulation index, according to the formula $SNR = (R\xi I_0)^2/2\sigma^2$. Therefore, an additional loss of approximately $20\, lg(N)\ [dB]$ occurs when the number of subcarriers increases.

At the same BER requirement, the SNR increases with the number of subcarriers according to:

$$SNR_{FSO-DPSK-SIM-N_{subcarrier}} = SNR_{FSO-DPSK-SIM-1\_subcarrier} + 20\, lg(N)\, [dB] \quad (7)$$

where, N is the number of subcarriers used in the FSO-SIM system.

3.4. SIM-FSO-DPSK system using SelC receive diversity technique

The SelC (Selection Combining) technique is suitable for DPSK modulation, where the subcarrier signal is asynchronously demodulated. Moreover, the SelC technique may reduce the receiver complexity compared to MRC and EGC as in earlier works, and the SNR of SelC is given by:

$$\gamma_{SelC}(I) = \frac{R^2A^2I_{\max}^2}{2N\sigma^2} \tag{8}$$

where, $I_{\max} = max(I_1, I_2, \dots I_N)$.

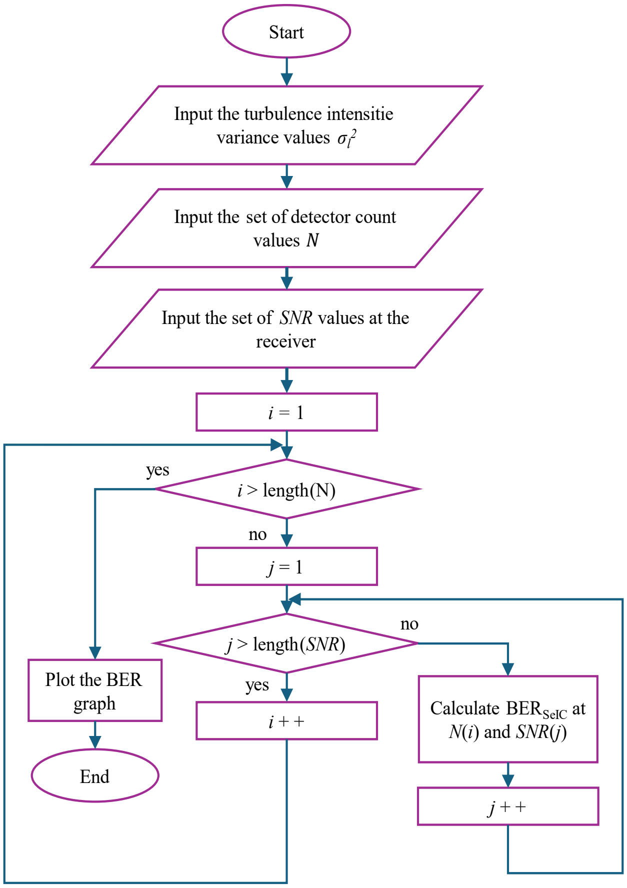

***Figure 8.** Flowchart for determining the BER values of the FSO-SIM-DPSK system using the SelC receive diversity technique*

Figure 8 shows an algorithm for calculating the BER in the SIM-FSO-DPSK system using the SelC diversity reception technique. Figure 9 illustrates the simulation results, demonstrating the relationship between BER and SNR in the SIM-FSO-DPSK system using SelC diversity reception with the number of optical PIN photodetectors in the receiver are set to N = 1, 2, 3, and 4 in the turbulent conditions with $\sigma_l^2 = 0.5^2$.

When $N = 1$, corresponding to SIM-FSO-DPSK system without diversity reception, where turbulence causes slow fading at the symbol rate R_{symbol} at which the system operates. Assuming that, the turbulence correlation time is much greater than the duration of two symbols, so that the receiver can perform DPSK demodulation easily.

When $N = 2, 3, 4$, this corresponds to a SIM-FSO-DPSK system employing SelC diversity reception. Here, N photodetectors (PIN) are located at appropriate distances to receive uncorrelated laser radiation while remaining within the laser beam width.

The results in Figure 9 show that the performance of the SIM-FSO-DPSK system improves when the number of photodetectors N increases from 2 to 4. For example, at a given SNR of 25 dB, the BER in the case of system without SelC diversity ($N = 1$) and with diversity using $N = 2, 3, 4$ photodetectors are approximately 1.1x10^{-4}, 1.2x10^{-5}, 9x10^{-6} and 8x10^{-6} respectively. However, once the number of photodetectors reaches a certain threshold, further increases only get a minimal performance gains, as shown by the nearly overlapping BER curves when N increases from 3 to 4. So, limiting the number of photodetectors at 4 may reduce system complexity and cost.

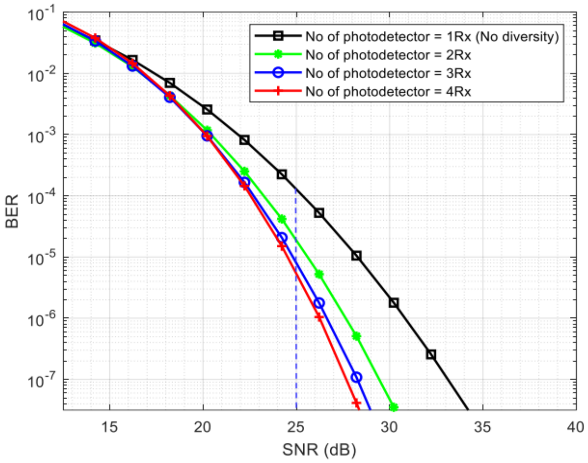

***Figure 9.** BER graph of the SIM-FSO-DPSK system using the SelC receive diversity technique*

4. Conclusions

Based on the computational model of a multi-subcarrier free space optic system (SIM-FSO), this paper has demonstrated algorithm flowcharts and written a Matlab program to evaluate the system's performance using various modulation techniques. From the simulation results, the paper has analyzed, compared, and evaluated the system's performance under various modulation methods, air turbulence levels, different numbers of subcarriers, and data rates. In this paper, to reduce the complexity of the receiver, we propose using DPSK modulation rather than BPSK method, as earlier studies with the need of PLL for subcarrier's synchronization. The work also deploys the SelC diversity technique, which can improve signal quality while slightly increasing the complexity or cost of the system. Considering the above results, the paper proposes the SIM-FSO-DPSK system as a solution to balance the demands of increased capacity, improved signal quality, reduced complexity, and lower system costs, which enhances the system's practical applicability and satisfy the growing information needs of users.

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