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The Impact of OFDM-IM System Parameters on the Performance of the SLM PAPR Reduction Technique

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A B S T R A C T

Orthogonal Frequency Division Multiplexing with Index Modulation (OFDM-IM) is an effective communication technology that utilizes subcarrier indices to transmit information in addition to the information traditionally modulated on active subcarriers. However, OFDM-IM suffers from high peak-to-average power ratio (PAPR), which can result in signal distortion and hence system performance degradation. One of the techniques used to alleviate the PAPR in OFDM-IM is the selected mapping (SLM) technique. The effectiveness of the SLM PAPR reduction technique is affected by OFDM-IM system parameters, such as the number of subcarriers and subcarrier activation ratio. This paper explores the impact of these OFDM-IM system parameters on the PAPR reduction performance of the SLM technique with different phase sequence settings. The obtained results provide an overview of the collective effect of both OFDM-IM and SLM parameters in different operation cases. The findings show that the amount of PAPR reduction is mainly affected by the number of subcarriers, and less affected by the subcarrier activation ratio. That is a greater PAPR reduction of up to 4.2 dB is achievable with relatively smaller number of subcarriers. The results show the limited effect of more complex phase vectors, hence suggesting simpler SLM parameter setting alternatives to achieve a target PAPR reduction performance. Finally, the results show the improvement in Bit Error Rate (BER) performance of OFDM-IM system employing the SLM with carefully selected PAPR reduction parameters.

1. Introduction

Orthogonal Frequency Division Multiplexing, with Index Modulation (OFDM-IM) is a communication technique that combines the concepts of both OFDM and index modulation. By dividing the band into subcarriers and assigning different index values to each subcarrier OFDM-IM achieves high spectral efficiency [1]. The performance of an OFDM-IM system depends on parameters, including the number of subcarriers, N, the subcarrier activation ratio, r, the chosen modulation scheme and the size of the constellation, M. These parameters directly impact aspects such, as data rate, spectral efficiency and the system ability to withstand channel noise and fading [2].

One of the difficulties, in OFDM systems lies in the difference between the maximum and average power levels of the transmitted signal [3]. This disparity, known as Peak to Average Power Ratio (PAPR) can result in distortions, spectral expansion and radiation outside the desired range. Amplifiers may experience distortions due to PAPR values resulting in a decline in performance and an increase, in bit error rate. Consequently, it becomes crucial to minimize PAPR for enhancing the effectiveness of the OFDM system [4]. Various methods have been created to address the issue of PAPR in OFDM systems such as clipping and filtering [5], selected mapping (SLM) [6], partial transmit sequences [7], tone reservation [8], peak insertion [9], iterative SLM [10], turbo SLM [11], compounding transform SLM [12], hybrid SLM [13].

The SLM technique is a popular method used to decrease PAPR, in OFDM systems. SLM involves using sets of phase sequences to create versions of the OFDM signal, which are then sent over the channel. Upon reception the appropriate phase sequence is chosen to reconstruct the signal. These phase sequences are carefully selected to minimize the PAPR of the transmitted signal while maintaining the systems data carrying capacity [14]. SLM offers the benefit of maintaining the independence of the subcarriers making it easier to design the receiver and lowering complexity when compared to methods, for reducing PAPR. Additionally, SLM can effectively lower PAPR with impact, on the bit error rate (BER) [15]. However, on the other hand, SLM requires additional overhead to transmit the phase sequences, which can reduce the spectral efficiency of the OFDM system [16].
The use of SLM technique in reducing the PAPR of OFDM-IM signals has been studied in several works. In [17], an SLM-based technique was proposed for OFDM-IM systems with multiple subcarriers. A new phase rotation sequences were used that take into account the index modulation and the amplitude modulation. Simulation results showed that the proposed technique achieved significant PAPR reduction compared to the conventional SLM technique.

Also, in [15] the permutation procedure of SLM was investigated to analyze the optimal condition for the phase sequence. The research concluded that the addition of permutation procedure is advantageous when the number of active subcarriers is much less than the total, N.

An optimized version of conventional SLM (OSLM) exploits the characteristics of IM by utilizing the number of activated subcarriers to achieve PAPR reduction was presented in [18]. The motivation behind it was the conclusion that if the constant value is equally divided then the average power would be reduced to zero in the first samples of frequency domain. Because high peak powers occur in the first time domain samples which lead to low average power in their corresponding first samples of frequency domain. On the other hand, this can cause high peaks in the other samples. Therefore, OSLM adjusts this reduction by changing the phase factor in proper way to achieve the least possible PAPR reduction in noncoherent OFDM-IM [18].

The multiple mapping rule presented in [19] is a new technique for PAPR reduction in only OFDM-IM because it makes use of the multiple mapping rules availability for IM. This technique is similar to the SLM scheme but while SLM uses phase sequences to generate the OFDM signals, IM multiple mapping rules use different multiple mapping for each group of subcarriers (cluster) to generate the OFDM-IM signals. Though it might seem as a desirable condition for the selection process, however it can increase the computational complexity of the overall system.
However, based on the works presented so far and many others mentioned in recent review papers, such as [6], it is observed that the effect of different OFDM-IM system parameters, such as the size of the OFDM block, N, the subcarrier activation ratio, r, and the modulation order, M, had not been thoroughly addressed. Therefore, understanding how these parameters affect the performance of PAPR reduction techniques, such as SLM, can help in optimizing the system parameters for better PAPR reduction performance.

The objectives of this work may be stated as follows: To investigate the effect of the number of subcarriers, subcarrier activation ratio and SLM parameters on the effectiveness of the SLM technique in terms of the achievable amount of

PAPR reduction and the improvement in BER performance of the OFDM-IM system.

To provide recommendations for practical implementation of the SLM technique in OFDM-IM systems based on the research findings.

The rest of the paper is organized as follows. The mathematical model of the OFDM-IM system is presented in section 2. The research methodology is given in section 3. The simulation results and discussion are presented in section 4. The effect of PAPR reduction on the BER is explored in section 5. Finally, section 6 concludes the paper.

2. System Model

The fundamental structure of the OFDM-IM system is depicted in Figure [1]. Initially, a quantity of m information bits is input into the system and is subsequently partitioned into g groups, each consisting of p bits (p= m / g). Next, the total number of subcarriers in the OFDM block, denoted as N, is partitioned into g subblocks, with each subblock containing n subcarriers (n= N / g). Within each subblock, only k subcarriers out of the total n subcarriers are activated to transmit modulated symbols, leaving the remaining (n-k) subcarriers inactive and set to zero. The creation of each OFDM-IM subblock comprises two components: an index selector and a symbol mapper. The first part employs p_1 bits to ascertain the indices of the active subcarriers, as defined in equation (1), while the second part utilizes p_2bits to modulate the symbols employing M-ary modulation schemes, as shown in the equation (3) [20,21].

$$p_{1=}\lfloor log_2\, C(n\ \ k)\rfloor \quad (1)$$

In equation (2), C(n,k) represents the binomial coefficient, denoting the count of all conceivable combinations (SAP).

$$p_{1=}\lfloor log_2\, C(n\ \ k)\rfloor \quad (2)$$

By examining equation (2), it becomes evident that when n= 4 and k= 2, there are six potential SAPs, as illustrated in Fig. 2. Nevertheless, only four of these combinations are chosen, while the other two are disregarded. This selection is based on the fact that p1= 4 bits, as determined by equation (1), and the count of possible SAPs corresponds to 2 raised to the power of p1.

$$p2 = k\ log2\ M \quad (3)$$

$$p = p1 + p2 = \lfloor \log_2 C(n,k)\rfloor\ \ k\ \log_2\ M \quad (4)$$

Where, M is constellation size p represents the aggregate number of information bits conveyed by each individual subblock. The result of the index selector, denoted as I for the lth subblock, is determined by equation (5), with l ranging from 1 to g.

$$I^l = \{i_1^l, \dots, i_k^l\} \quad (5)$$

Where $i_\gamma^l \in [1, \dots, n]forI = 1,2, \dots g,$, and $\gamma = 1,2, \dots, k$.

$$S^l = [S_1^l\ \dots,\ S_k^l] \quad (6)$$

Equation (6) shows the output for the same lth block from the index mapper.

Where, S_γ^l∈S for I=1,2,…..g, and γ=1,2,…..,kand S is the set of M-ary constellation symbols.

Following this procedure, I^(l)and S^l are supplied to the OFDM block generator in order to build the frequency domain OFDM signal, denoted as XF in equation (7).

$$X_F = [X(1), X(2), \dots, X(N)]^T \quad (7)$$

Where, $X_\beta \in \{0, S\}\ for\ \beta = 1, 2, \dots, N.$

Furthermore, as depicted in Fig. 1, the frequency domain signal undergoes conversion into its time domain equivalent X_Tthrough the application of the Inverse Fast Fourier Transform (IFFT), as shown in equation (8).

$$X_T = \frac{N}{\sqrt{K}}\ IFFT\ \{X_F\} \quad (8)$$

Where, $\frac{N}{\sqrt{K}}$is used for normalization.

Ultimately, a cyclic prefix is appended to the time domain signal, followed by the execution of the parallel-to-serial conversion process for transmission over the communication channel. On the receiver end, these actions are reversed and carried out in the opposite order [22]. The module, for tracking delays, in multipath helps the OFDM system accurately identify the channel sequence and as a result determine the length of the cyclic prefix [23]. Recent studies have explored advanced PAPR reduction techniques for SLM-based OFDM-IM systems. For instance, a combined Hadamard transformation and selective mapping approach was shown to effectively reduce PAPR under Rayleigh and AWGN channels [24]. Additionally, low-complexity strategies for AFDM and OCDM in 6G networks have been proposed, highlighting efficient trade-offs between computational complexity and PAPR reduction [25]. These works provide valuable insights for optimizing system performance while maintaining manageable complexity.extraction of key point and feature extraction, and optimal classification.

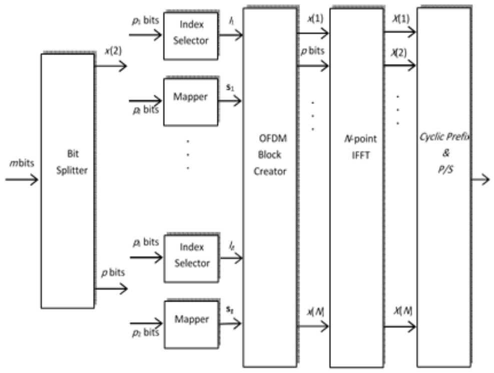

Fig. 1. Transmitter diagram of OFDM-IM.

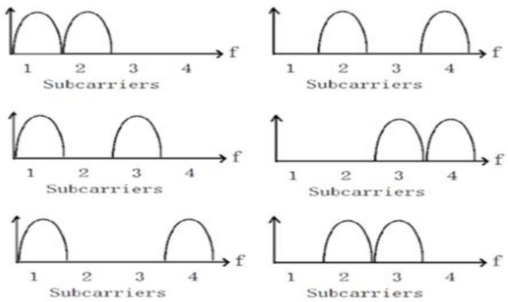

Fig. 2. Possible SAPs in OFDM-IM system (n=4 and k=2).

3. Methodology

The study is carried out by extensive computer simulations using MATLAB. The simulation model is created to simulate the OFDM-IM communication system described in section 2. The investigation focuses on the number of subcarriers (N), subcarrier activation ratio (r), and the SLM parameters. A frequency selective fading channel model is used to simulate realistic channel conditions.

The simulation experiments were conducted in MATLAB R2023a to assess the performance of the proposed system under various channel conditions. A 16-Quadrature Amplitude Modulation (16-QAM) scheme was used to achieve a balance between spectral efficiency and robustness against noise. Each simulation scenario was executed over 1,000 independent Monte Carlo runs with a fixed random seed (e.g., rng(2024, 'twister')) to ensure repeatability, transmitting 10^6 symbols per run using double-precision arithmetic for accuracy. The channel was modeled as a frequency-selective Rayleigh fading channel with an L = 5-tap FIR filter and an exponentially decaying power delay profile, while Additive White Gaussian Noise (AWGN) was added at SNR values ranging from 0 to 30 dB. The PAPR was calculated using the ratio of the maximum instantaneous power to the average power, and the BER was obtained by comparing transmitted and received bit sequences.

Different OFDM-IM and SLM parameter values are used to observe their impact on the PAPR reduction performance, which is measured in terms of the amount of PAPR reduction with respect to reference baseline system setup, the minimum achievable PAPR and the BER of the OFDM-IM system.

4. Simulation and Results

In order to explore the effects of OFDM-IM system parameters and those of the SLM technique on the PAPR reduction performance, the system has been simulated in MATLAB with the parameter values given in Tables 1 through 6.

Firstly, the effects of the number of subcarriers, N, and the subcarrier activation ratio, r, on the PAPRo of the OFDM-IM signal before applying the reduction scheme, are discussed. That is, when N increases, the PAPRo tends to increase. This is because each subcarrier contributes independently to the total power of the OFDM-IM signal. As a result, the peak power of the signal becomes more likely to reach high levels, leading to a higher PAPRo. Therefore, the choice of the number of subcarriers is often a trade-off between spectral efficiency and PAPRo. Increasing the number of subcarriers can improve spectral efficiency by allowing more data to be transmitted simultaneously. But on the other hand, it can increase PAPRo, which requires additional power back-off at the transmitter to avoid clipping or distortion.

The values for r (1/n, 1/2, 1-1/n) in Tables 1 through 6 were chosen to represent different cases in terms of the subcarrier activation ratio.

- 1/n represents the case of a single subcarrier being activated (k=1) within the subblock of n subcarriers. The minimum value of r.
- The second case represents the activation of 50% of the subcarriers in the subblock, k=n/2 and r=0.5.

The last case r=(1-1/n) represents the activation of all-but-one subcarriers in the subblock, k=n-1, which is the highest and most dense subcarrier activation ratio in OFDM-IM before it reached the theoretical maximum of all-activated subcarriers and turn back to an ordinary OFDM system.Next, for a given N and modulation order, M, the obtained results show that the effect of subcarrier activation ratio, r, on PAPRo is negligible. This is related to the principle of operation of OFDM-IM. The activation of subcarriers is determined by the information to be transmitted. The activation pattern is generally assumed to be random or semi-random, depending on the specific system design. This random or semi-random nature tends to distribute the energy across subcarriers relatively evenly, reducing the likelihood of creating a concentrated peak in the time-domain OFDM-IM signal.However, it is widely reported that the SLM technique is effective in mitigating the high PAPR issue in OFDM. The obtained results in this work show the performance of the SLM in

OFDM-IM system, and how it is influenced by various parameters, including N, r, Φ, and Z, as follows:

A. Number of Subcarriers: Increasing the number of subcarriers, N, generally provides more flexibility in SLM. More subcarriers lead to more choices when selecting candidate phases for phase rotation. This can lead to better PAPR reduction performance, as there are more options to optimize the signal's peak amplitudes. But unfortunately, this capability of the SLM is limited by the increased PAPRo as N increases. That is, for small N (such as 32), the SLM can reduce the signal PAPR from 8.7 dB to 4.5 dB achieving an amount of reduction of 4.2 dB. Whereas for larger N values (such as 1024), the SLM reduces the signal PAPR from 11.2 dB to 7.9 dB with a reduction of 3.3 dB. However, increasing N also leads to higher computational complexity and overhead, as the number of candidate phases to consider grows combinatorically.

B. Number of Phases per Subcarrier: The parameter Φ determines how many phase steering factors are available to modify the phase of a subcarrier. Basically, the more Φ, the more diversity in phase rotations, which can improve PAPR reduction. The values of Φ used in this study include {-1, +1}, {-1, +1, -j, +j}, and {1+j, 1-j, -1+j, -1-j}. However, practically, the simplest Φ of {-1, +1} seems to be sufficient, and more complicated Φ has no significant contribution to the PAPR reduction performance of the SLM, as shown in the presented results. Nevertheless, increasing Φ also increases the computational complexity, as it expands the search space for phase combinations.

C. Number of Candidate Signals:

The parameter Z determines the number of candidate signals that constitutes the search space from which the signal of the minimum PAPR is selected. This is also known as the number of SLM iterations. As can be observed from the presented results, running SLM for more iterations can lead to further PAPR reduction, but it also increases computational complexity.

Finally, the presented results give a quantitative evaluation to the performance of the SLM technique in OFDM-IM systems, in terms of the main parameters of both the OFDM-IM and SLM. Optimizing these parameters requires a trade-off between PAPR reduction and computational complexity. The results in this paper were obtained from testing the system for a wide variety of parameter values. Therefore they can be used as a basis for designers choose system parameters that balance PAPR reduction performance with computational cost and to find the best settings for a specific OFDM-IM system requirements and transmission scenario.

Table 1. PAPR reduction for N=32.

Φ	Z	r=1/n		r = 0.5		r =1-1/n	
		$PAPR_0$	PAPRr	$PAPR_0$	PAPRr	$PAPR_0$	PAPRr
Φ_1	20	8.7	5.2	8.9	5.2	9	5.5
	30		5.2		5		5
	40		5.2		5		5
	60		5.1		4.8		4.8
Φ_2	20		5.2		5.2		5.5
	30		5		5		5.2
	40		4.8		5		5
	60		4.5		4.8		4.8
Φ_3	20		5.2		5.2		5.4
	30		5		5		5
	40		4.8		4.9		5
	60		4.6		4.8		4.8

Table 2. PAPR reduction for N=64.

Φ	Z	r=1/n		r = 0.5		r =1-1/n	
		$PAPR_0$	PAPRr	$PAPR_0$	PAPRr	$PAPR_0$	PAPRr
Φ_1	20	9.4	6	9.4	6	9.5	6
	30		5.7		5.8		6
	40		5.7		5.8		5.8
	60		5.6		5.5		5.8
Φ_2	20		6		5.9		6
	30		5.8		5.8		6
	40		5.6		5.7		5.7
	60		5.2		5.5		5.6
Φ_3	20		6		6		6
	30		5.7		5.7		5.7
	40		5.6		5.6		5.8
	60		5.5		5.5		5.5

Table 3. PAPR reduction for N=128.

Φ	Z	r=1/n		r = 0.5		r =1-1/n	
		$PAPR_0$	PAPRr	$PAPR_0$	PAPRr	$PAPR_0$	PAPRr
Φ_1	20	9.8	6.6	9.9	6.6	10	6.8
	30		6.4		6.4		6.5
	40		6.4		6.4		6.4
	60		6.1		6.1		6.2
Φ_2	20		6.6		6.7		6.7
	30		6.6		6.7		6.6
	40		6.3		6.5		6.4
	60		6		6.3		6.2
Φ_3	20		6.8		6.6		6.6
	30		6.5		6.5		6.5
	40		6.3		6.4		6.5
	60		6		6		6.2

Table 4. PAPR reduction for N=256.

Φ	Z	r=1/n		r = 0.5		r =1-1/n	
		$PAPR_0$	PAPRr	$PAPR_0$	PAPRr	$PAPR_0$	PAPRr
Φ_1	20	10.2	7.2	10.2	7.2	10.4	7.4
	30		7		7		7.2
	40		6.9		7		7
	60		6.8		6.9		6.8
Φ_2	20		7.3		7.3		7.3
	30		7		7		7.15
	40		6.9		7		7
	60		6.8		6.9		6.9
Φ_3	20		7.4		7.2		7.2
	30		7		7		7
	40		6.9		7		7
	60		6.9		6.8		6.9

5. BER Performance

In an OFDM-IM system, the parameters N, r, Φ, and Z, which are associated with the SLM technique, primarily affect the PAPR characteristics of the transmitted signal. However, changes in PAPR can indirectly impact the BER performance of the system through various mechanisms. Therefore, this work considers the collective effect of these parameters represented by the achieved level of PAPR reduction. Because reducing PAPR can mitigate nonlinear distortion in the transmitter, which is a main source of errors in the system for given channel condition. PAPR reduction helps to prevent signal distortion or clipping in both the transmitter and high power amplifier. These nonlinear effects have the potential to cause errors and impact the performance of BER. SLM can also assist in decreasing, out of band emissions decreasing interference with neighboring channels. This can indirectly enhance BER by lowering the chances of errors caused by interference. Additionally by decreasing the likelihood of signal clipping or distortion from PAPR levels SLM can enhance the resilience of the transmitted signal against channel issues like multipath fading. This could result in error rates and an enhancement, in BER.

In this work, an OFDM-IM system appointing a SLM technique has been simulated in MATLAB for different parameter values. The BER performance is evaluated and compared with that of an ordinary OFDM-IM system that does not use PAPR reduction and the transmit signal is subjected to clipping and non-linearity of the power amplifier. A frequency-selective fading channel model is used, frequency-selective fading channel is a type of wireless communication channel where different frequency components of the transmitted signal experience varying levels of attenuation and phase shift due to multipath propagation. Figure 3 shows the BER performance of the OFDM-IM system under the case of short OFDM block (N=32) with the mentioned system parameter values. The use of the SLM technique, aims to mitigate the impact of high power peaks appearing in the transmitted signal. When PAPR reduction is not used, the effect of high power peaks become more noticeable at higher Signal-to-Noise Ratio (SNR) levels, where the system's performance becomes more susceptible to distortions caused by high peak power.

So, the role of the SLM technique is to enhance the BER performance at high SNR values to avoid the BER saturation that happens when SLM is not used. Figures 3 and 4 show the BER performance of these systems with the mentioned parameter values.

From Figs. 3 and 4, it can be observed that the compared systems have a close BER performance until a certain SNR value (45 dB and 35 dB, respectively).

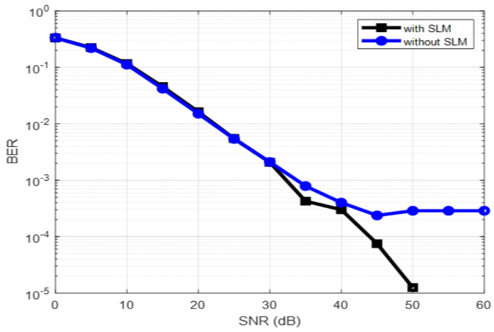

Fig. 3. BER performance, N=32, M=16, n=4, k=2, Φ ∈{-1, +1}, Z=60, $PAPR_o$=8.9 dB, $PAPR_{min}$=4.8 dB, SE=2.5 b/s/Hz.

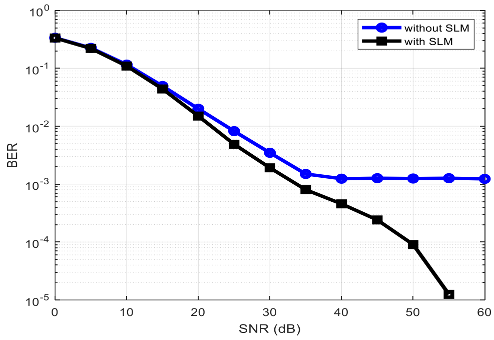

Fig. 4. BER performance, N=512, M=16, n=4, k=2, Φ ∈ {-1, +1}, Z=60, PAPRo=10.5 dB, PAPRmin=7.4 dB, SE=2.5 b/s/Hz.

After these SNR values, they show different behavior. The ordinary OFDM-IM system saturates at some BER value (3x10-4 and 1.2x10-3, respectively) even as the SNR increases. Whereas, this is not the case when the SLM technique is used, leading to continued BER improvement with increasing SNR. As compared with Figure 3, Figure 4 shows the increase in the effect of high peak power for larger N on the BER.

As mentioned before, SLM is a PAPR reduction technique that can help mitigate nonlinear distortion in the transmitter and power amplifiers. This, in turn, can indirectly improve SNR at the receiver. By reducing distortion and signal clipping, SLM can make the transmitted signal more robust, leading to better overall BER performance.

SLM often provides additional diversity in phase rotations (by using different phase sequences), allowing the receiver to recover the symbol information more accurately even at lower SNR levels.

6. Conclusion

This paper explores the impact of different OFDM-IM and SLM parameter values on the performance of the overall system. The collective and individual effects of the number of subcarriers and the subcarrier activation ratio together with

SLM parameters such as the number of candidate signals and phase sequence, on the PAPR reduction performance of the SLM technique have been investigated. Unlike prior SLM-OFDM-IM studies that concentrate on algorithmic developments, this work uniquely analyzes the effect of key system parameters on SLM performance, providing a new understanding of parameter optimization for effective PAPR reduction.

The results show that the effectiveness of SLM is better for shorter N, and as N increases, the amount of PAPR reduction becomes less. Moreover, among the used subcarrier phase steering vectors, the results show that the simplest phase vector {-1,+1} is still the most effective at different subcarrier activation ratios. This effectiveness relies on the use of larger number of candidate signals. However, this presents a trade-off between PAPR reduction performance and system complexity. Then, by careful selection of OFDM-IM and SLM parameters, a target performance can be achieved. It has been shown that the BER performance of the OFDM-IM system employing an optimized SLM can be significantly enhanced at high SNR values.

Therefore, obtained results provide a significant basis for system designers and researchers in this field to better understand the trade-offs and then select suitable parameter setups to better meet their specific application requirements.

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