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Research Article

Performance improvement of Intensity Modulation Direct Detection optical OFDM systems by optimizing SLM technique using Advanced Genetic Algorithm

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Abstract: This paper presents an improvement in the performance of an intensity modulation direct detection OFDM (IM/DD-OFDM) optical communication system by providing a 40 Gbps downstream signal. The system was simulated over a distance of 30 km using Single Mode Fiber (SMF). An advanced Genetic Algorithm based on Selected Mapping (AGA-SLM) was proposed and utilized as a new technique for reducing the Peak to Average Power Ratio (PAPR). This technique successfully reduces the PAPR of the original Orthogonal Frequency Division Multiplexing (OFDM) signal by half, leading to a decrease in hardware implementation costs and complexity, thus creating a more cost-effective optical communication system. The proposed AGA-SLM method enhances the proposed optical OFDM system by enhancing the Bit Error Rate (BER), power spectral density (PSD) performance, power savings, and reducing computational complexity. The proposed method demonstrates better simulation results than the classical partial transmit sequence (PTS) technique.

Keywords: IM/DD OFDM; PAPR; SLM; GA; PSD; PTS; BER

I. INTRODUCTION

In the optical communication systems, the Orthogonal Frequency Division Multiplexing (OFDM) technology is a commonly popular and attractive method to support high data rate transmission because it can reduce the effects of noise and interference [1]. OFDM systems can be implemented efficiently and effectively with modulators and demodulators based on the Fast Fourier Transform (IFFT) and its inverse. Additionally, the advantages of optical OFDM communication systems include immunity to chromatic dispersion and high spectral efficiency [2]. One important disadvantage of optical OFDM systems is the challenge of a high Peak-to-Average Power Ratio (PAPR). This challenge arises when an OFDM transmission combines several narrowband subcarriers with orthogonality. The signal's peak amplitude can vary between large and small values, with peak power exceeding average. High PAPR decreases system efficiency, leading to higher costs for power amplifiers. One of the most essential application issues for OFDM systems is determining the most effective technique for minimizing high PAPR [3]. Many reduction techniques have been suggested to minimize the PAPR values and enhance the Bit Error Rate (BER) performance system. Those methods are amplitude clipping, coding, clipping and filtering, Tone Injection (TI), Tone Reservation (TR), Selected Mapping (SLM), Active Constellation Extension (ACE), Partial Transmit Sequence (PTS), and interleaving [4-11]. These methods decrease PAPR but increase the power of the transmitted signal, data rate loss, BER, and other factors. The SLM technique is among the most prominent classical PAPR reduction algorithms, demonstrating significant PAPR reduction capability. The SLM technique efficiently reduces PAPR by multiplying Quadrate Amplitude Modulation (QAM) modulated data vectors with alternative phase factor combinations, selecting the signal with the lowest PAPR [12–13]. Alhalabi et al. [14] evaluated a bidirectional wavelength division multiplexing passive optical network (WDM-PON) employing intensity modulated/direct detection optical orthogonal frequency division multiplexing (IM/DD-OFDM).

In this paper, the advanced Genetic Algorithm based on the SLM (AGA-SLM) technique was proposed and successfully applied to the optical IM/DD-OFDM communication system to improve the PAPR performance. The following are research works on the PAPR problem in OFDM communication systems using various reduction methods [15–24]. In [15], an improved GASLM was applied to a universal filtered multicarrier (UFMC) to reduce the PAPR compared to the classical SLM. In [16], a Hadamard-based SLM using GA was applied to OFDM systems. In [17], a new SLM method with Conversion Matrices (CM) and GA, which required just one IFFT process, was introduced. In [18], the SLM technique with the Chaotic Biogeography Optimization (CBBO) algorithm was suggested to present a solution to reduce PAPR in the GFDM waveforms. In [19], The Vandermonde matrix was presented as a new phase sequence for the S-SLM scheme in OFDM systems, improving both PAPR reduction and complexity. In [20], A new PTS algorithm was proposed to tackle the issue, utilizing the centering phase sequences matrix (PTS-CPSM-Algo). In [21], A hybrid algorithm combining PTS and Adaptive Peak Power Reduction (APPR) techniques was proposed for a new PAPR reduction method. The author of this paper designed the proposed optical OFDM system in previous research to test its performance and the quality of transmission without using any PAPR reduction methods [22]. Taşpınar and Alhalabi [23] applied different swarm optimization algorithms based on PTS method to reduce the PAPR in optical CO-OFDM communication system. Alhalabi et al. [24] proposed DFOA-SLM method to minimize the PAPR in optical IM/DD OFDM communication systems. Additional researches focus on reducing the PAPR and improving the overall performance of optical-fiber communication systems. It investigates advanced modulation, signal-processing, and optimization techniques to mitigate nonlinear distortion, enhance power efficiency, reduce the bit-error rate, improve signal quality, and extend transmission distance. This work contributes to developing reliable, energy-efficient, and high-capacity optical networks for next-generation communication applications [25-32].

This work advances the field through the following original contributions:

1. This work discusses the application of the AGA-SLM method to minimize the PAPR in our proposed optical OFDM communication system.

2. The performance of the AGA-SLM method is compared to traditional SLM and the original optical OFDM signal in terms of PAPR minimization, Power Spectral Density (PSD), BER performance, and power savings.

3. The AGA-SLM method demonstrated superior performance compared to other PAPR reduction techniques, leading to improvements in the proposed optical OFDM system.

This paper is presented in the following manner: Section 2 offers an overview of the PAPR in the proposed optical OFDM system. Section 3 outlines the proposed AGA-SLM method within the optical OFDM system. Section 4 discusses the optimization of phase factors and the principle of application by the AGA-SLM method. Section 5 the simulation results. Finally, Section 6 gives a conclusion to this paper.

II. PAPR ANALYSIS IN AN OPTICAL OFDM COMMUNICATION SYSTEM

The block diagram of the optical OFDM communication system, which includes a transmitter, an optical channel, and a receiver, is illustrated in **Fig. 1**. Coded information bits are converted to symbols using PSK at the transmitter side. In most cases, OFDM utilizes complex-valued PSK modulation. After that, the modulated symbols are grouped into groups, every comprising N modulated symbols, represented as X. In an OFDM system, each modulated symbol $X(k)$ is sent on a specific sub-carrier with a center frequency, resulting in N sub-carriers. Each symbol is sent instantly on their separate subcarriers. By using formulates, this is equivalent to changing the sequence X into a new sequence x by using an N-point IFFT process, that is,

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi k}{N} n}. \tag{1}$$

X is a frequency domain signal in OFDM, while x represents a time domain signal. It is often referred to as an OFDM symbol. X includes a cyclic prefix (***CP***) and should have a longer transmission channel length than ***CP*** to prevent intersymbol interference. The IM/DD channel requires a non-negative and real transmitted signal due to the requirement of both non-negative and real light intensity.

Applying Hermitian symmetry to the frequency domain signal X yields a real-time domain signal, which is described below:

$$X(N-k) = X^*(k), k = 1,2,\ldots,N-1\,,$$

$$X(0) = X\left(\frac{N}{2}\right) = 0. \tag{2}$$

IFFT enables the identification of a pure positive and real-valued signal x, while OFDM signals are produced by adding sinusoidal functions in the time domain, allowing the peak power of some samples to be higher than the average power, known as PAPR:

$$\mathrm{PAPR(dB)} = 10\log_{10}\frac{\max|x(n)|^2}{E\{|x(n)|^2\}}. \quad (3)$$

E{.} represents the expected value. The complementary cumulative distribution function (CCDF) evaluates the probability that the PAPR value exceeds a specific threshold value to calculate the PAPR of transmitted samples, as written below:

$$P_r[\mathrm{PAPR}\ (x(n) \geq \mathrm{PAPR}_0)] = 1 - (1 - e^{-\mathrm{PAPR}_0})^N. \quad (4)$$

where ***$PAPR_0$*** represents the threshold value [33].

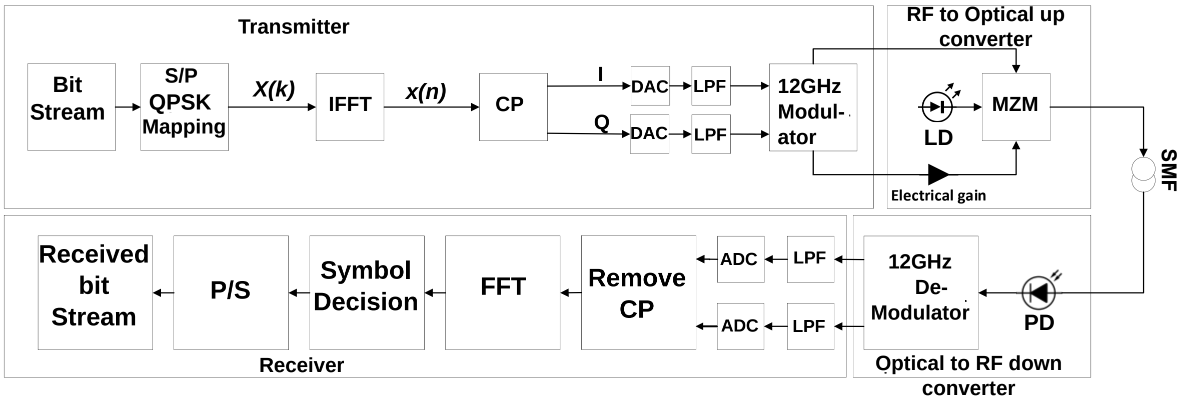


***Figure 1**. Block diagram of an optical IM/DD OFDM. S/P: Serial to parallel; IFFT: Inverse Fast Fourier Transform; CP: Cyclic Prefix; DAC: Digital to Analog Converter; LD: Laser diode; MZM: Mach-Zehnder modulator; SMF: Single Mode Fiber; LPF: Low Pass Filter; ADC: Analog to Digital Converter; FFT: Fast Fourier Transform; P/S: Parallel to Serial.*

III. PAPR REDUCTION BASED ON THE AGA-SLM METHOD IN THE OPTICAL TRANSMITTER

Fig. 2 illustrates the schematic diagram of the optical OFDM transmitter after integrating the AGA-SLM method.

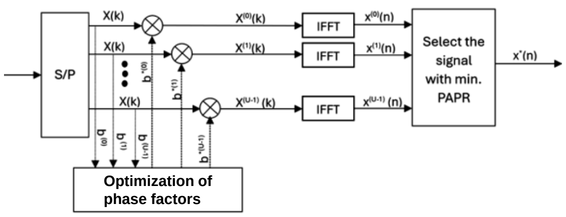


***Figure 2.** Block diagram of the transmitter based on AGA-SLM method.*

Firstly, the information bits are transformed into symbols by using any type of PSK modulation, and the PSK symbols are represented below:

$$X(k) = [X(0), \ldots, X(N-1)]. \quad (5)$$

After that, the vector of $\boldsymbol{X(k)}$ is multiplied by the optimized ***N*** length of different phase rotation factor vectors $\boldsymbol{b^{*(u)}(k) = [b^{*(0)}(0), ., b^{*(u)}(N-1)]}$ generated randomly, where $\boldsymbol{b^{*(u)}(k)} \in \{\boldsymbol{-1, 1}\}$, $\boldsymbol{u} = \boldsymbol{1, \ldots, U}$. The variable ***U*** represents the number of phase factor combinations that are randomly generated. Following the multiplication step, the optimized phase-rotated data sequence symbolized by $\boldsymbol{X^{(u)}(k)}$ is expressed as below:

$$X^{(u)}(k) = [X(0) \times b^{*(u)}(0), \ldots, X(N-1) \times b^{*(u)}(N-1)] = [X^{(u)}(0), , \ldots, X^{(u)}(N-1)]. \quad (6)$$

The IFFT operation is applied to the optimized phase-rotated data vector to obtain the following time domain signal:

$$x^{(u)}(n) = [x^{(u)}(0), \ldots, x^{(u)}(N-1)] = \mathrm{IFFT}\left(X^{(u)}(k)\right) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X(k).\, b^{*(u)}(k).\, e^{j\frac{2\pi k}{N}n}, 0 \leq n \leq N-1, u = 1, \ldots, U. \quad (7)$$

Then, the candidate OFDM signal with the minimized PAPR is selected to be sent.

$$x^*(n) = \min_{1\leq u\leq U}\{x^{(u)}(n)\}. \quad (8)$$

The receiver should find the data with the appropriate optimized phase rotation sequences $\boldsymbol{b^{*(v)}(k)}$ to recover the transmitted OFDM signals. The simple method involves transmitting the appropriate side information (SI) to the receiver for signal recovery.

IV. THE OPTIMIZATION PRINCIPLE OF THE AGA-SLM METHOD FOR THE PHASE FACTORS

The steps of the AGA-SLM algorithm to optimize the phase rotation vector are explained in the section below.

1. Initializing all the parameters of AGA-SLM, such as population size, crossover factor, mutation factor, number of generations, and the initial PAPR value.
2. Firstly, the population vectors are generated randomly, representing the phase rotation vector.
3. Evaluating the PAPR (fitness) values for every phase rotation vector in the population.
4. Updating the new PAPR value by comparing it with the old PAPR value.
5. Selecting the phase rotation vectors with the minimized PAPR of every generation as the best phase rotation vector and choosing these vectors to enter the next generation by applying tournament selection.
6. Crossing and mutating processes are applied to generate a new population.
7. Repeat steps 3 – 6 until the maximum generation number is reached. Choosing the optimum phase factors that provide the lowest PAPR.

The pseudo code of the related algorithm for MATLAB software is yielded as below:

- Initialize the population size, crossover, mutation ratio and the first PAPR value
- **for** i = 1 to max. generation
  for j = 1 to population size
  construct a rotation phase from the population size
  Evaluate the PAPR
  Compare the new PAPR with the previous PAPR and update it with the lower PAPR
  end

  Sort the phase factors based on the fitness values and using tournament selection

  Choose a subset of the sorted phase factors for the next generation

  Using crossover and mutation operations, create the remainder of the new generation.
- **end**

The flow chart of the AGA-SLM technique, which explains the above steps in detail, is shown in **Fig. 3**.

V. SIMULATION RESULTS

The proposed system uses OptiSystem and MATLAB software to simulate the optical system architecture and visualize results. The BER test set generates digital bits and compares sent and received bit streams. **Table 1** summarizes the basic Optisystem, OFDM modulator, Continues Wave (CW) laser, and PIN photodetector parameters. A cyclic prefix is added to avoid Intersymbol Interference (ISI) between OFDM symbols.

The PSK generator transforms generated bits into QPSK symbols, which are modulated into several orthogonal subcarriers in an OFDM modulator. However, the subcarriers and FFT point numbers are set to 80 and 128, respectively. The In-phase and Quadrature I-Q OFDM signals will be processed through a low pass filter with a cutoff frequency of 12.4 GHz. Quadrature modulators are utilized to increase the frequency of transmitted OFDM signals to 12 GHz. The transmitted RF electrical signal is transformed to the optical field using a Mach-Zehnder modulator (MZM).

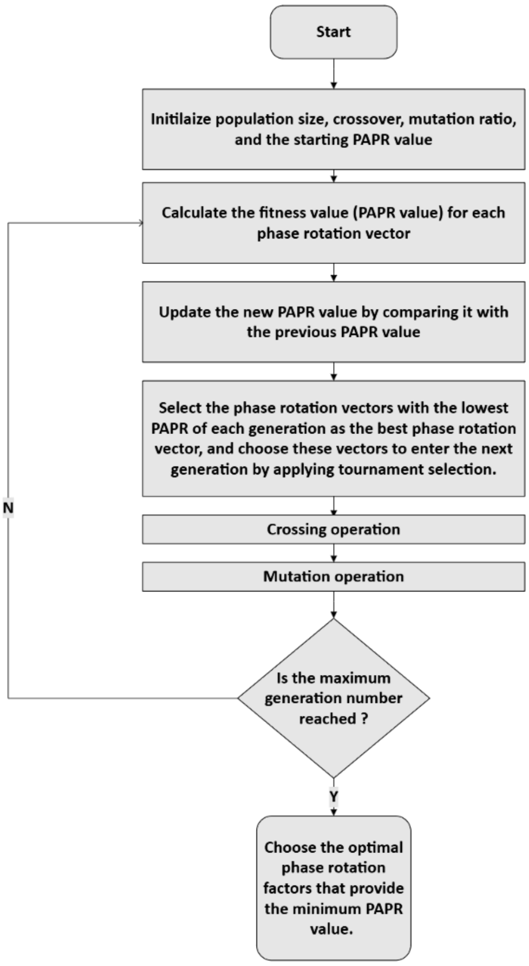


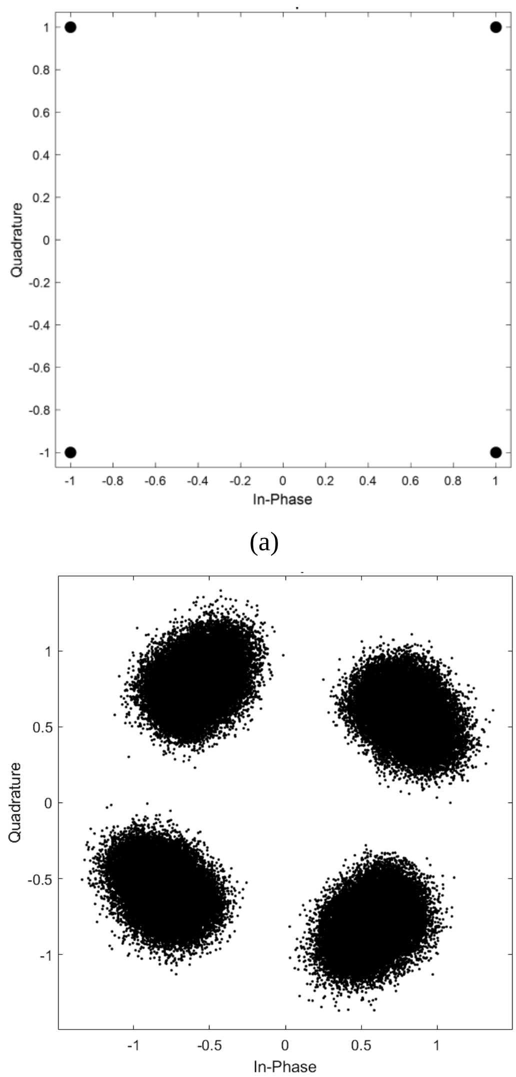
Figure 3. *AGA-SLM flow chart*

Following MZM, the optical signal is sent over (20+10×no. loops) of Single Mode Fiber (SMF). Dispersion Compensated Fiber (DCF) reduces the dispersion produced by the primary optical fiber and enhances transmission performance. The transmitted signal is amplified by another amplifier within the loop, compensating for any loss. The amplified optical signal is filtered using a Gaussian optical filter with the operating frequency of 193.1 THz and a bandwidth of 50 GHz. In the receiver block, the incoming optical signal is converted to the bandpass electrical signal by the PIN photodetector. The electrical signal that is received is again amplified by an electrical amplifier. The amplified bandpass electrical signal is demodulated and recovered by a quadrature demodulator to recover the baseband electrical signal. The OFDM modulator and demodulator must have identical parameters to recover the sent QPSK symbols accurately. After that, the PSK sequence detector converts the received symbols to bits per symbol. The BER test component is utilized to measure the BERs accurately. **Fig. 4** shows the transmitted and the received QPSK symbols, which take values as {1+j, 1-j, -1+j, -1-j} at a distance of 30 km and the BER = 10^{-5}. The received symbols are correctly recovered because of the short propagation length, as illustrated in **Fig. 4(b)**.

Table 1. *The overall simulation parameters.*

Component Name	***Variable name***	***Value***
Global System	Sequence Length	262144
	Samples per Bit	4
	Bit Rate	40 Gbps
	Number of samples	1048576
	Symbol Rate	$20e^9$ Symbols/s (4-QPSK)
OFDM modulator	FFT points	128
	Number of used subcarriers	80
	Cyclic prefix	5
CW laser	Operating frequency	193.1 THz
	Power	1 dBm
	Line width	10 KHz
PI N ph	Dark current	10 nA
	Responsivity type	InGaAs
	Shot noise distribution	Gaussian

(a)



(b)

Figure 4. *The constellation diagram of (a) transmitted and (b) received symbols.*

Fig. 5 illustrates the electrical OFDM spectrum of the optical system at 12 GHz for QPSK after the quadrature modulator and photodetector, respectively. The electrical OFDM signal has a bandwidth of 20 GHz, which is determined by the number of bits per symbol, as illustrated in **Fig. 5**. A quadrature modulator consists of three main parameters to be set up: gain, frequency, and bias. The bias is set to 2 to eliminate the negative values of the transmitted OFDM signal. In the optical OFDM systems, the transmitted OFDM signal should be non-negative and real due to the increasing bias of the quadrature modulator.

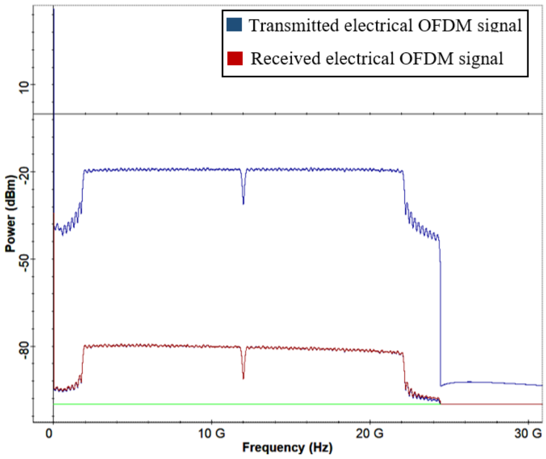


Figure 5. *Transmitted and received electrical OFDM signal.*

Fig. 6(a) shows the OFDM optical spectrum after the LiNb MZ Modulator, with fundamental values like 30 dB extinction ratio, 4V switching RF voltage, and 2V bias voltage. MZM converts the modulated bandpass electrical OFDM signal to the optical field after injecting a CW laser with an operating frequency of 193.1 THz. The optical OFDM signal is transmitted via an optical fiber with two fiber lengths and one optical amplifier. **Fig. 6(b)** illustrates the received optical OFDM spectrum before passing through the PIN photodetector. The Gaussian Optical Filter, which helps to reduce noise in the optical channel, is located between it and the receiver. The frequency of a Gaussian optical filter is 193.1 THz, and its bandwidth is 50 GHz.

In **Fig. 7**, an investigation of the AGA-SLM's ability to minimize the PAPR of the optical OFDM signal was carried out for different population sizes (***P***). Similarly, the crossover and mutation rates are 0.6 and 0.01, respectively. The number of generations was chosen to be 16. **Fig. 7** demonstrates that the PAPR of of original optical OFDM signal could be decreased significantly by increasing the value of ***P***. For instance, when the population size increases from 10 to 100, the reduced PAPR falls within a range of 5 to 6 dB at CCDF of 10^{-3}, as illustrated in **Fig. 7**.

In **Fig. 8**, an investigation of the AGA-SLM's ability to minimize the PAPR of the optical OFDM signal was carried out for different generation sizes (***G***). In contrast, the crossover, mutation rates, and population size are equal to 0.6, 0.01, and 10, respectively. **Fig. 8** shows that the PAPR of the original OFDM signal could be decreased significantly via increasing the value of ***G***. For instance, when the generation increases from 4 to 256, the reduced PAPR falls within a range of 4.5 to 7 dB at CCDF of 10^{-3}, as illustrated in **Fig. 8**.

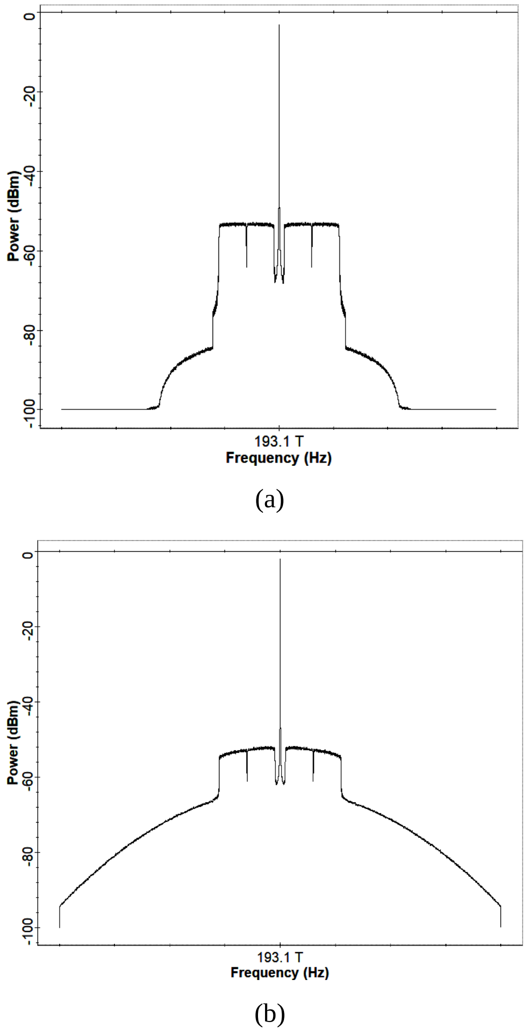


Figure 6. *The transmitted optical OFDM signal before (a) the optical channel and before (b) the PIN photo detector.*

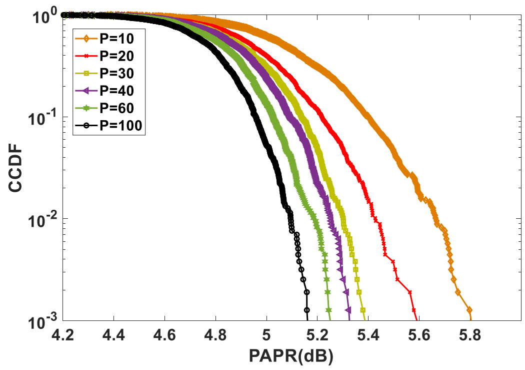


Figure 7. *PAPR performance of AGA-SLM for various population sizes.*

Fig. 9 compares the original OFDM, PTS, SLM, and AGA-SLM for reduced PAPR values. Referring to Fig. 9, when PTS is applied with several number of subblocks (**V**) equal to 4, 8, and 16, the minimized PAPR values are 8.8, 6.7, and 5.9 dB, respectively, at a CCDF of 10^{-3}. When SLM is used with number of search numbers (Number of phase factors) is 512, the minimized PAPR value is 5.5 dB at a CCDF = 10^{-3}. While AGA-SLM is used, the size of the population is 32, the size of the generation is 16, and the minimized PAPR value is 5.3 dB at a CCDF = 10^{-3}. The number of searches (***SN***) is determined to be 512 in total. After applying the AGA-SLM to the proposed optical OFDM communication system, the PAPR is decreased from 10.5 dB to 5.3 dB at a CCDF = 10^{-3}, leading to a 5.2 dB reduction. **Table 2** presents that the AGA-SLM method reduced the computational complexity and provided lower PAPR values for low population sizes.

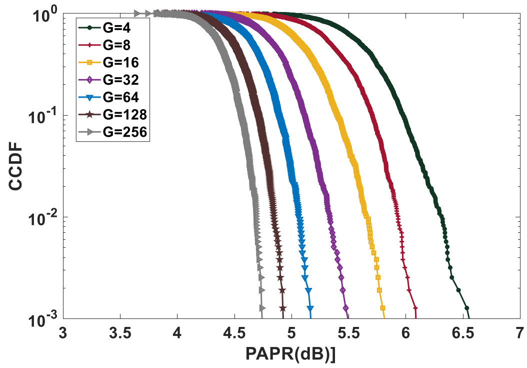


Figure 8. *PAPR performance of AGA-SLM for different generation sizes.*

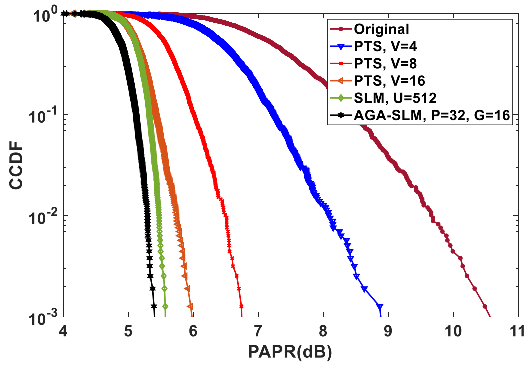


Figure 9. *PAPR performance for different schemes.*

Fig. 10 presents a comprehensive comparison of the BER for three different methods aimed at reducing the PAPR across a range of Optical Signal to Noise ratios (OSNRs), specifically from 5 to 40 dB. As indicated by the results, when the OSNR remains constant, the BER associated with the OFDM signal exhibits the highest rate of error. In contrast, the SLM method demonstrates a marked improvement, yielding a lower BER than the original optical OFDM signal. At a BER threshold of 10^{-3}, the AGA-SLM method shows improved SNR performance compared to other PAPR reduction methods and the original OFDM signal. This indicates that the AGA-SLM method not only enhances BER performance but also stands out as a more efficient option when it comes to PAPR reduction methods in optical communication systems. Overall, the AGA-SLM method demonstrates a significant advantage in achieving lower error rates, emphasizing its effectiveness in optimizing optical signal performance.

Table 2. *PAPR values of original OFDM signal, PTS, SLM, and AGA-SLM.*

PAPR Reduction Scheme	***PAPR (dB)***
Original	10.5
PTS, V=4	8.8
PTS, V=8	6.7
PTS, V=16	5.9
SLM, Number of phase factors (U) = 512	5.5
AGA-SLM, P*G = 32*16 = 512	5.3

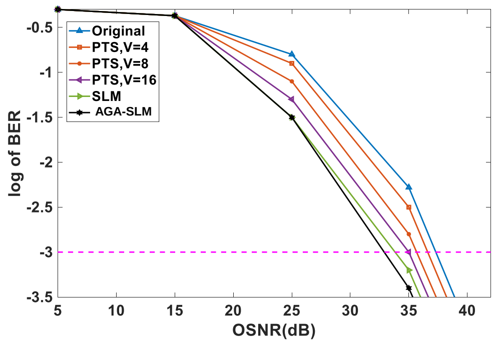


Figure 10. *Comparisons of BER performance among the simulated techniques.*

In comparing methods for PAPR reduction, it is essential to consider power-saving performance. This performance is defined by:

$$\text{Power saving (\%)} = 1 - \frac{\text{Reduced PAPR value}}{\text{Original PAPR value}} \times 100 \quad (9)$$

Based on Equation (9), we can calculate the power-saving performance of different PAPR reduction methods on the optical OFDM signal. PTS method shows a power saving within a range of 16 – 44%. While the classical GA method shows little power savings with a minimum of ~47.6 %, the proposed AGA-SLM approach shows the best power savings with a maximum of ~49.5 %. The results demonstrate that the proposed AGA-SLM approach provides significant increases in energy efficiency for optical OFDM systems, surpassing other PAPR reduction methods.

The total PSD of the optical signal is determined by adding the PSDs of all different subcarriers. Due to their orthogonality, the power contributions from these subcarriers combine positively, resulting in a flat total PSD across the frequency domain they occupy. This uniform PSD provides an even power distribution among the subcarriers, which effectively maximizes the use of the available spectrum. **Fig. 11** provides a clear depiction of the PSD for the Optical OFDM signal, along with the PAPR reduction methods applied for modulation indicated by QPSK. It is important to note that the increase in sidebands leads to significant spectrum leakage in the OFDM waveform. Studies have demonstrated that PAPR reduction algorithms can effectively reduce this spectrum leakage in optical OFDM systems. The graph reveals specific leakage values: approximately -73.18 dBm/Hz for AGA-SLM, -59.5 dBm/Hz for SLM, -58.7 dBm/Hz for PTS, and -57.61 dBm/Hz for the original signal, respectively. These results underscore the efficiency of these algorithms in enhancing system performance by minimizing spectral interference.

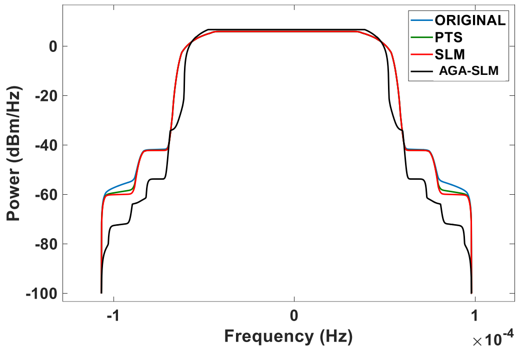


***Figure 11**. PSD graphs of the optical OFDM spectrum after using PAPR reduction methods.*

The computational complexity of each utilized optimization algorithm was evaluated to show the PAPR minimization performance at a certain CCDF = 10^{-3}. Firstly, the computational complexity of the PTS method (φ_{PTS}) is calculated as follows:

$$\varphi_{PTS} = 3 \times V \times N \times log_2 N + Search\ numbers \times (V-1) \times N \quad (10)$$

Secondly, the computational complexity of the SLM method (φ_{SLM}), denoted as ***U***, is directly proportional to the amount of IFFT processes achieved during the optimal phase sequence search, and it is represented as follows:

$$\varphi_{SLM} = \mathrm{U} \times \mathrm{N} \times \log_2 \mathrm{N} \quad (11)$$

It's easy to get the computational complexity of modified SLM strategies by taking out the search complexity of SLM given by U from the SLM complexity expression in Equation (11) and replacing it with the search numbers of SLM strategies based on intelligence swarm optimization algorithms. The computational complexity of the proposed PAPR reduction method is evaluated accordingly as below:

$$\varphi_{AGA-SLM} = \mathrm{P} \times \mathrm{G} \times \mathrm{N} \times \log_2 \mathrm{N} \quad (12)$$

The computational complexity of the proposed PAPR reduction, as outlined in Equation (11), is primarily influenced by its search numbers.

VI. Conclusion

This paper analyzed and simulated a cost-effective optical IM/DD OFDM communication system with QPSK modulation using MATLAB and the Optisystem software. For PAPR reduction, AGA-SLM method was proposed and applied to the simulated optical OFDM system for optimizing the phase factors of the SLM method. AGA-SLM technique effectively reduced the PAPR of the original optical OFDM signal by half and achieved more improvements in the performance compared to other PAPR reduction methods. The parameters of the AGA-SLM algorithm, such as population and generation sizes, affect the PAPR performance of the proposed optical OFDM system. The AGA-SLM method effectively reduced the PAPR of the original OFDM signal from 10.5 dB to 5.3 dB at a CCDF of 10^{-3}, achieving a total reduction of 5.2 dB. However, it is important to note that the AGA-SLM method exhibits a higher BER performance at a BER of 10^{-3}. The AGA-SLM method improves the optical OFDM system by enhancing the BER, and PSD performance, saving power, and reducing computational complexity. In future studies, different intelligent optimization algorithms proposed in recent years can be used to further reduce PAPR reduction performance.

Author Contributions

M. Alhalabi: Conceptualization, Experiments, Theoretical analysis, Writing

N. Taşpınar: Supervision, Review, and editing.

M. Wadi: Supervision, Review.

Disclosure Statement

The authors state that they have no known conflicting financial interests or relationships that might have influenced the research presented in this paper.

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