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Discrete Elephant Herding Optimization Algorithm for Analysis of PAPR, BER and Spectral Efficiency in FBMC/OQAM System

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Abstract: In wireless environments, multi-carrier modulation (MCM) schemes provides resistance against fading. These schemes have been thoroughly researched for use in 4G/5G wireless communications because of their benefits. Wireless communication systems that use multiple carriers are the most prevalent in modern technology for high-speed transmissions of data. Many researchers are currently interested in implementing new protocols and physical layers for Filter Bank Multicarrier (FBMC) with Offset Quadrature Amplitude Modulation (OQAM). 5G transmission systems are likely to utilize the FBMC/OQAM scheme. The FBMC/OQAM system has many advantages over Orthogonal Frequency Division Multiplexing (OFDM), but there are few disadvantages, one of which is its high PAPR. Because of the signal's overlapping nature in the FBMC system, conventional reduction techniques can't be applied to the subcarriers. High peak power also reduces the efficiency of FBMC/OQAM. It is essential to reduce as much as possible the peak power of a signal in communication systems. In this article, to minimize the peak-to-average power ratio (PAPR), a Discrete Elephant Herding Optimization Algorithm (DEHOA) is used. Using the proposed method, we reduce the drawback of high PAPR with lower amalgamations of optimum phase factors for each overlapping information symbol. According to simulation results, the proposed method reduces PAPR, BER and improves spectral efficiency (SE) performance.

Keywords: Bit Error Rate, DEHOA, FBMC, OQAM, OFDM, PAPR, PTS

1. Introduction

The physical layer transmission of 4G wireless is based on OFDM, a MCM technique that can efficiently handle frequency selective channels. As a result of stringent requirements in 5G, such as high SE, minimal out-of-band (OoB) radiation, high connectivity and availability, it is difficult to meet these requirements for OFDM. When OFDM is used in the uplink of a multi-user network, the base station input must be fully synchronized with the users' signals, which is difficult to achieve in a mobile environment. OFDM also introduces reductions in the spectral efficiency of each subcarrier due to cyclic prefix (CP) and rectangular pulses [1]. Research has found that FBMC/OQAM is well suited for implementing 5G networks, particularly multiple access networks and cognitive radios [2-3]. Due to its well-localized filter design and discarding of CP, FBMC/OQAM has higher SE, low spectral leakage, and it is better for emerging massive multiple-input and multiple-output (mMIMO) networks. But FBMC/OQAM systems also having issues related to their PAPRs [4]. High power amplifiers (HPAs) with high PAPR produces significant distortion when the signal enters into the nonlinear region, which may restrict the use of this technology in battery-powered mobile applications. A study is needed to investigate methods that reduce PAPR while being compatible with the system architecture. Among the MCM techniques used in 4G wireless systems, OFDM has gained popularity because of the advantages it can offer, such as high data rates, increased SE and high quality of service (QoS) [5-9]. It is not possible to use OFDM for 5G due to its numerous disadvantages. A 5G was introduced to address the disadvantages of 4G's OFDM system. Many researchers and academicians are interested in 5G. All multicarrier techniques suffer from PAPR. The researchers have developed and deployed many methods and techniques to reduce high PAPR. The authors present three effective techniques in [10], including Transform-Selective Mapping (T-SLM) and T-PTS, to minimize the high PAPR of OFDM. The proposed technique improves the performance of PAPR over SLM and PTS, as well as reducing the computational complexity and multipath fading improves BER. Using an optimization technique, the authors presented a method for minimizing the PAPR in an OFDM scheme in [11]. The BER for nonlinear OFDM systems is calculated using distortion prediction methods. The BER performance in OFDM systems can be improved by selecting nonlinear transmission phase sequences to increase cross-correlation between input and output. Due to its effectiveness, the method proposed in [12] is suitable for OFDM systems since it is not required FFT after the nonlinear HPA model nor does it require a complete understanding of HPA characters. In [13], GFDM is proposed to reduce OoB emissions and PAPR of OFDM. It is possible to design a hybrid analog and digital multiple user equalizer with a simple analog precoder for a mMIMO system. A hybrid equalizer calculates its analog constants by reducing the Mean Square Error (MSE). According to [14-17], the PAPR reduction techniques are described for FBMC. An SLM technique based on multi-blocks was proposed in [14]. The authors of [15] suggested a low latency trellis-based SLM (TSLM) method. The authors of [16] proposed a system based on partial complexity of TSLM. FBMC/OQAM systems share many of the same features as these trellis-based PAPR reduction schemes for SLM, as well as benefiting from improved performance over traditional SLM. The authors of [17] proposed using A-law and μ-law companding to minimize PAPR for FBMC systems. PAPR was reduced by sliding window tone reservation (SWTR) in [18]. In [19], a technique used for reducing PAPR using tone reservation (TR). An segment-PTS method was proposed in [20] that splits FBMC symbols into several blocks. Multi Block Tone Reservation (MBTR) was proposed to minimize PAPR of FBMC in [21]. To obtain the ideal shearing noise, the contiguous blocks of data are taken into account. A hybrid SLM and TR (SLMTR) method described in [22] to reduce the PAPR. The Tone Injection (TI) and companding methods are proposed in [23]. The hybrid-PTS and TR techniques are used in [24-25] to minimize PAPR of FBMC. To reduce PAPR, a hybrid approach that takes into consideration both clipping and nonlinear companding is given in [26]. The PTS approach results in a great deal of complexity when looking for the optimal phase combination, and several solutions to this issue have been put forth, including the flipping iteration methodology [27] and the phase coefficient searching method [28]. In [29], an active constellation extension (ACE) method for reducing PAPR in FBMC was developed. Described an iterative clipping-based methodology in [30], the authors of this study have suggested a gain measure that is used to the minimal number of iterations to attain the minimum PAPR should be determined. In [31], the traditional PTS (T-PTS) technique is optimized using dynamic programming (DP) methodology. In [32], a method for decreasing PAPR in an OFDM system using ant bee colony method was suggested. There is a great deal of complexity involved in the PTS for the FBMC/OQAM system. In FBMC/OQAM system, the main motivations are the interrelationship between adjacent statistics blocks and the combination of several section carriers for statistical indicators. A PTS method reduces PAPR most efficiently and with the least distortion. So, the FBMC/OQAM system is therefore considered using the PTS approach. Using the PTS scheme, segment factors are selected which are expected to reduce the PAPR of all sub-blocks combined. This article provides a better PAPR, BER minimization and high SE for FBMC/OQAM system.

High PAPR is one of the most important issues in FBMC waveform. Power amplifiers with extremely high power scope are needed to transmit signals with high PAPR. These amplifiers have a low efficiency and expensive. The linear power amplifier may not be able to handle a peak power that is too high. This results in non-linear distortion, which deteriorates performance by altering the signal spectrum's superposition. If the high PAPR is not reduced, the practical applications of the FBMC system may be severely limited. One reasonable way to mitigate high PAPR is to use amplifiers with wider trade-off ranges. Unfortunately, these amplifiers are not useful because they are typically very expensive and have low efficiency. Conversely, some algorithms were presented and demonstrated to reduce nonlinear distortion thereby improving BER performance and spectral efficiency. DEHOA is proposed. Some of the most promising PAPR reduction techniques available today are examined and contrasted. With the help of Matrix Laboratory (MATLAB) simulation software, the effectiveness of the proposed reduction strategies is assessed in terms of BER, PAPR and SE.

The main objective of research is to minimize high PAPR by utilizing the suitable PAPR reduction technique. To improve the subcarrier phase factor search's computational efficiency in the PTS approach various meta-heuristic optimization algorithm is used. It can maintain the FBMC based system performance with a required BER and better PAPR. DEHOA effectively reduce the PAPR and the framework's complexity. Furthermore, it is obvious that the proposed method is necessary to achieve better spectral and power characteristics compared to the 4G waveforms. The proposed method effectively increases spectral efficiency, PAPR performance and improves BER performance for both 5G and beyond 5G systems. The network structure is simulated in an AWGN channel configuration to examine spectral efficiency, PAPR and BER performances.

2. FBMC/OQAM Architecture

The FBMC method first presented in the 1960s. The FBMC is an advancement on OFDM. Among the several MCM techniques, FBMC is the most effective one for wireless communications in the future. The FBMC/OQAM transceiver is shown in Figure 1.

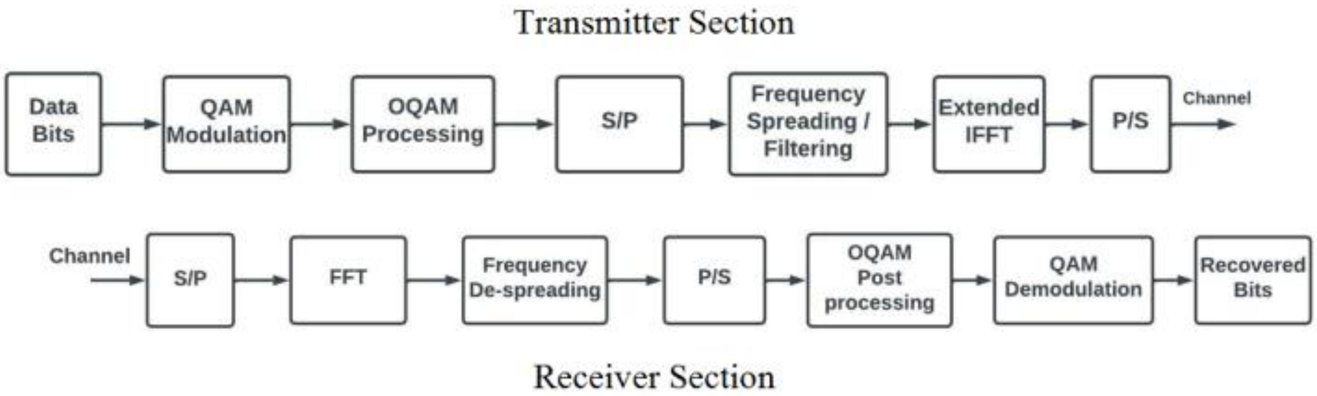

Figure 1. FBMC/OQAM Block Diagram

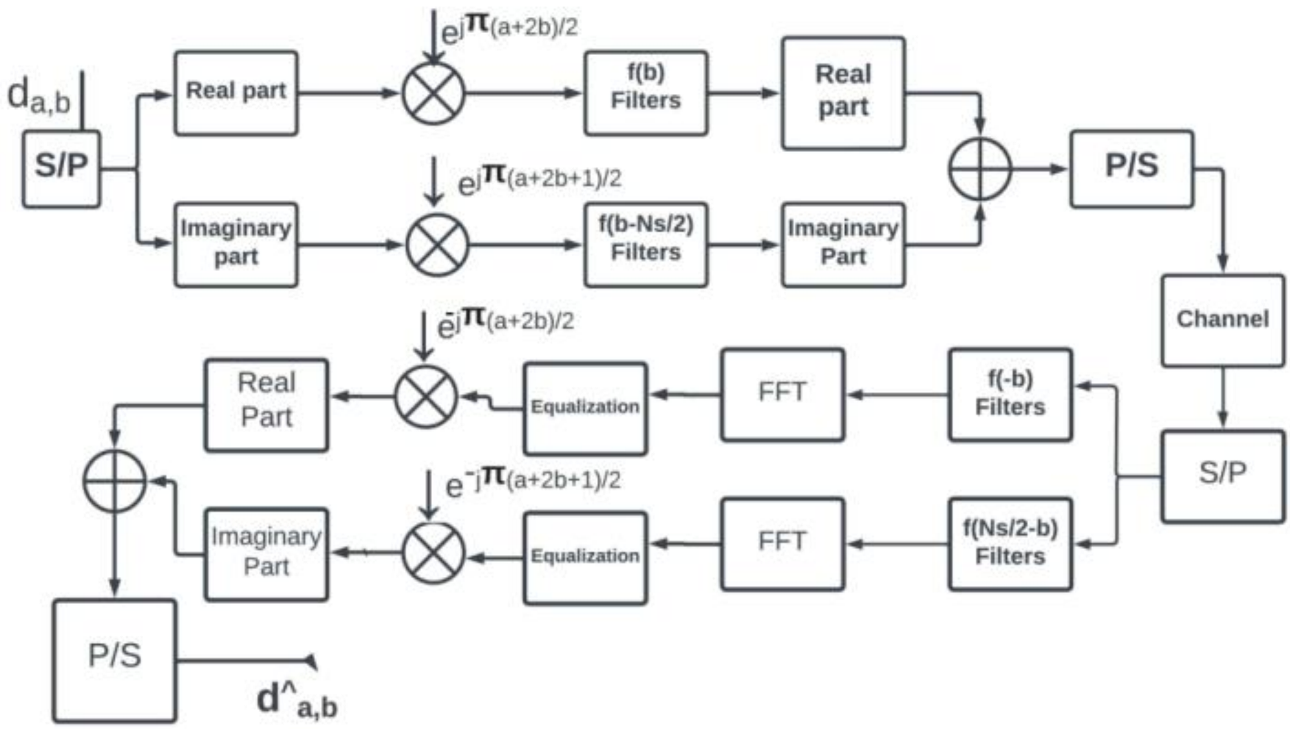

Figure 2. FBMC/OQAM System

OFDM and FBMC/OQAM can be implemented quickly using FFT algorithm. The FBMC scheme is a newer version of OFDM that offers greater bandwidth efficiency and is less sensitive to narrowband noise effects. A wideband channel is divided into several narrowband channels, called sub-channels, so that multiplexing and modulation can be integrated. FBMC maximizes spectrum efficiency by using OQAM for individual sub-carriers, thus allowing for higher data rates.

Figure 1 shows the transmitted data are modulated using QAM. Then it is passes through serial-to-parallel (S/P) converter. Instead of conventional QAM, FBMC/OQAM transmits real OQAM symbols. The OQAM is employed at FBMC in order to reduce channel interference. As opposed to OFDM, which requires orthogonality between all carriers, FBMC only requires orthogonality with neighbouring subcarriers [33]. FBMC splits a channel into multiple sub-channels, whereas OFDM utilizes a frequency bandwidth with multiple subcarriers. The maximum bit rate can be achieved with OQAM and filtering without any CP. Filtering and processing of OQAM is the difference between OFDM and FBMC. In FBMC, there is overlap between neighbouring sub-channels, making OQAM processing necessary to achieve orthogonality between subcarriers. A delay of half the symbol duration is used when OQAM processing is used to transmit real and imaginary parts simultaneously. It is the difference between the imaginary and real parts of a symbol, measured in time that is called the offset in OQAM. The symbol rate is also increased by 2 with OQAM.

After channel coding and symbol mapping, symbols are modulated using OQAM. Subcarriers are kept orthogonal through OQAM preprocessing. During OQAM preprocessing, complex symbols are processed both in real and in imaginary parts, and half a symbol period is interlaced within a time interval so that transmission symbols are formed. Subcarriers are formed by dividing a delay into real and imaginary parts. At the time of sampling, all neighboring subcarriers have orthogonal distribution. After performing IFFT on the transmission symbols, the PF banks with various offsets are then filtered. The modulation of fast MC technology is then realized by superimposing and transmitting the synthesized signals in the time domain. Additionally, a set of symmetrical PFs are used, which work similarly to the transmitter's PF banks. First, PF banks with various offsets filter the original signal. This signal is then reconstructed using FFT and OQAM. In OQAM, the real portion of the signal that was modulated to the subcarrier is taken, and it is then rebuilt into the complex signal by mutually converting the real and complex numbers. The system block diagram for FBMC/OQAM is represented in Figure 2.

Consider $d_{a,b}(t)$ is the complex transmitted symbols at a[th] subcarrier in the b[th] symbol and the shape of each subcarrier using well-localized transmitted prototype filter (PF) is $f_{a,b}(t)$ then the signal can be represented as

$$x(t)=\sum_{a=0}^{N_c-1}\sum_{b=0}^{N_s-1} d_{a,b}(t)\, f_{a,b}(t) \tag{1}$$

where $f_{a,b}(t)=f\left(t-n\tau_{ri}\right)e^{j2\Pi a\varepsilon t}e^{j\theta_{a,b}}$ (2)

Here number of subcarriers are N_c, number of symbols are N_s, prototype filter function is *f(t),* the time period between the imaginary and real is τ_{ri}, interval between adjacent subcarriers is $\varepsilon=\frac{1}{2\tau_{ri}}=\frac{1}{T_s}$, period of symbol is T_s and phase factor is $\theta_{a,b}$.

$$\theta_{a,b}=\frac{(a+b)\Pi}{2}-ab\Pi \tag{3}$$

The expression for product of the transmitting and receiving filters is

$$\langle f_{a,b}(t), f_{p,q}(t)\rangle_{\Re}=\Re\left\{\int_{-\infty}^{\infty} f_{p,q}^{*}(t)\, f_{a,b}(t)dt\right\} \tag{4}$$

$$=\Re\left\{\int_{-\infty}^{\infty} f^{*}(t-\tau_{ri}q)\, f(t-\tau_{ri}b)e^{j\varepsilon t2\Pi(a-p)}e^{\frac{j\Pi(a-p+b-q)}{2}}dt\right\} \tag{5}$$

It is possible to restore the outgoing signal accurately when the basis function $f_{a,b}(t)$ meets the orthogonal condition in Equation (6).

$$\langle f_{a,b}(t), f_{p,q}(t)\rangle_{\Re}=\delta_{a,p}.\delta_{b,q} \tag{6}$$

where δ indicates the impulse function and it is given by

$$\delta_{a,b}=\begin{cases}1; a=b\\ 0; a\neq b\end{cases} \tag{7}$$

The discrete time domain expression for the signal is

$$x(k)=\sum_{a=0}^{N_c-1}\sum_{b=0}^{N_s-1} d_{a,b}(k)\, f\left(k-\frac{bN_c}{2}\right)e^{j\theta_{a,b}}e^{\frac{j2\Pi a\left(k-\frac{N_l-1}{2}\right)}{N_c}} \tag{8}$$

where

$$f_{a,b}(k)=f\left(k-\frac{bN_c}{2}\right)e^{j\theta_{a,b}}e^{\frac{j2\Pi a\left(k-\frac{N_l-1}{2}\right)}{N_c}} \tag{9}$$

here, the prototype filter length is N_l. The discrete time domain expression for FBMC/OQAM signal can also represented as

$$x(k)=\sum_{b=0}^{N_s-1} s_b(k) \tag{10}$$

$$x_b(k)=\sum_{a=0}^{N_c-1} d_{a,b}(k)\, f\left(k-\frac{bN_c}{2}\right)e^{j\theta_{a,b}}e^{\frac{j2\Pi a\left(k-\frac{N_l-1}{2}\right)}{N_c}} \tag{11}$$

here $x_b(k)$ is *b*[th] data block signal.

High PAPR is the main drawback of the FBMC system. Utilizing FBMC, complex symbols are modulated at several subcarriers and produces a high PAPR. A PAPR can be calculated by dividing peak power (P_{peak}) by average power (P_{avg}).

The PAPR can be expressed as

$$PAPR=\frac{P_{peak}}{P_{avg}} \tag{12}$$

$$PAPR_n=\frac{Max\left|x(t)\right|^2}{E\left[\left|x(t)\right|^2\right]} \tag{13}$$

$$PAPR_{dB}=10.\log_{10}\left(PAPR\right) \tag{14}$$

To measure of PAPR performance, the FBMC/OQAM system uses the complementary cumulative distribution function (CCDF).

$$CCDF=P_p\left(PAPR\geq\alpha\right)=1-\left(1-e^{-\alpha}\right)^{N_c} \tag{15}$$

Here the probability of an event is P_p and threshold value is α.

3. Papr Minimization Method

3.1 PTS Method

Muller and Hubber introduced the PTS approach in 1997. To reduce peak power problems, the PTS method is frequently used to FBMC signals. The main concept of PTS is that data blocks are divided into non-overlapping sub-blocks with independently rotating factors. Data generated with this rotation factor have the lowest amplitude in the time domain. It works by splitting the FBMC symbol data into sub-data and then transmitting those sub-data into sub-blocks and then multiplying them by the weighted value which is differentiated by the phase rotation factor to arrive at the most suitable value with a low PAPR [34]. The drawback of PTS is that the difficulty of searching increases exponentially with the number of sub-blocks. The PTS structure is represented in figure 3.

The N_s symbol input block is divided into M_s disjoint sub-blocks. The IFFT is carried out independently for each subblock and weighted by a complex phase factor P_m.

$$p_m = e^{j\theta_m} \tag{16}$$

The phase variables are selected in order to decrease the PAPR of the signal from all sub-blocks. Orthogonal sub-blocks of size x_m are created from the input data stream x. An FFT operation is executed and then weighted by a phase factor for every sub-block. In order to reduce the combined time domain signal x's PAPR as much as possible, a set of phase factors is chosen.

$$x = \sum_{m=1}^{M_s} p_m x_m \tag{17}$$

$$x = \sum_{m=1}^{M_s} p_m \ \text{IFFT}\left[x_m\right] \tag{18}$$

$$x = \sum_{m=1}^{M_s} p_m^{\sim} x_m \tag{19}$$

The phase factor parameters are selected to reduce the PAPR and it is given by

$$\left[p_1^{\sim}, p_2^{\sim}, p_3^{\sim}, \ldots\ldots, p_{M_s-1}^{\sim}, p_{M_s}^{\sim}\right] = \arg\min\left[Max\left|\sum_{m=1}^{M_s} p_m x_m\right|\right] \tag{20}$$

By using the equation (11), we can compute the time-domain signal that has the minimal PAPR:

$$x = \sum_{m=1}^{M_s} p_m^{\sim} x_m \tag{21}$$

The computational complexity of the PTS method primarily depends on the following factors:

- **Number of Subblocks**: The more subblocks, the more combinations of phase factors need to be evaluated.
- **Phase Factors :** The size of the set of possible phase factors influences the number of combinations.
- **IFFT Operations**: Each subblock requires an IFFT operation, resulting in number of subblocks IFFTs for the entire process.

The flowchart for the implementation of the PTS method is shown in figure 4.

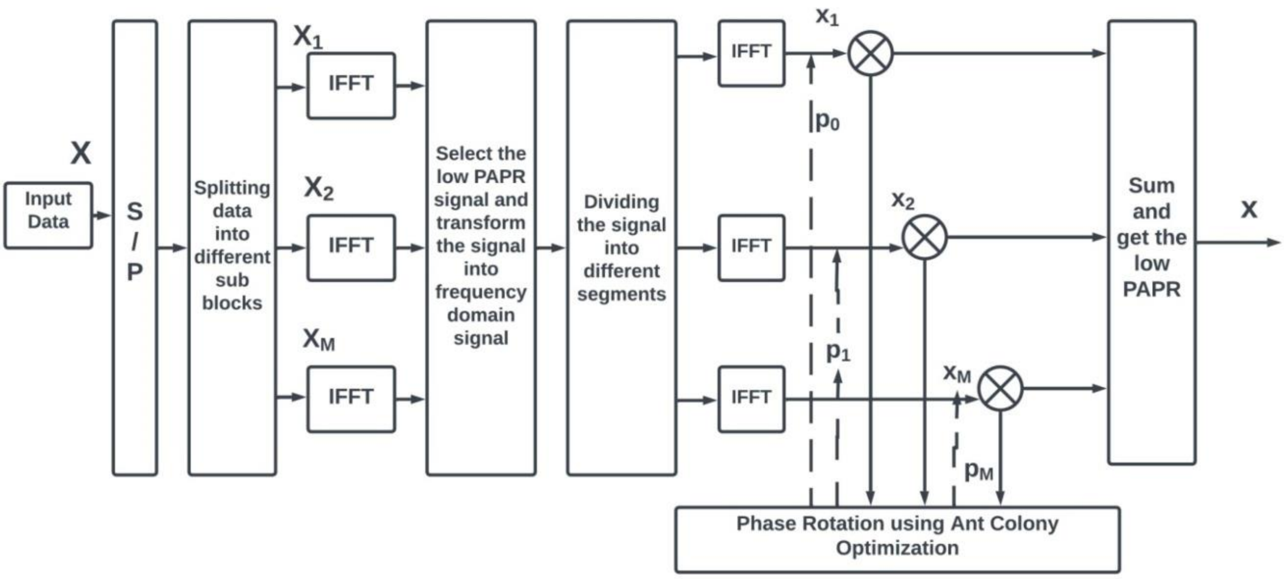

Figure 3. PTS Scheme

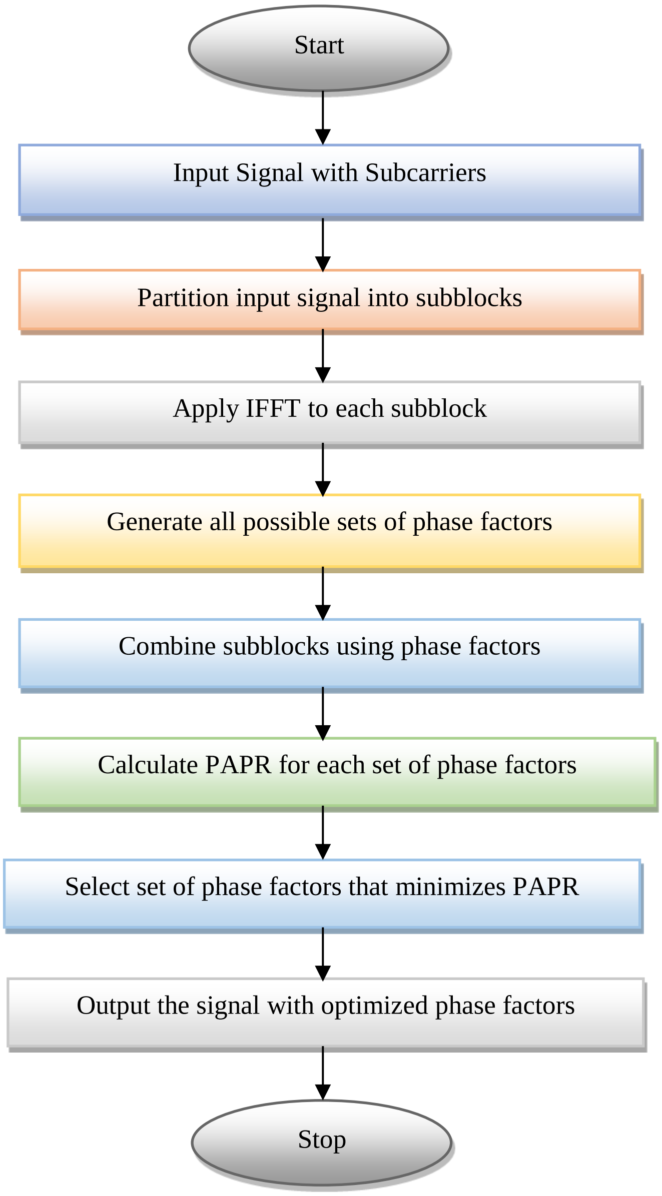

Figure 4. Flowchart for PTS method

The PTS method is effective in reducing the PAPR of signals, but its computational complexity can be high. Efficient search algorithms and heuristic methods can be used to reduce the computational burden while achieving a significant PAPR reduction.

4. Optimization Methods

4.1 Elephant Herding Optimization Algorithm (EHOA)

The EHOA was developed in 2015 by Wang et al. [35]. The algorithm derived its inspiration from the natural social behaviours exhibited by elephant herds. While the actual behaviours of elephants are considerably more complex, the following idealized principles were taken into account when designing the EHO algorithm: Each lineage within the elephant population comprises an equivalent number of subgroups. One elephant guides the remaining members of each clan in their quest for sustenance and water. Furthermore, it has been observed that individuals within each generation, upon reaching a specific age, depart from their clan and establish independent residences in remote regions, distinct from their familial community [36].

The EHO algorithm is a nature-inspired optimization technique that mimics the herding behavior of elephants. In the wild, elephants live in groups called clans, which consist of family units led by a matriarch. The EHO algorithm models the social dynamics and movement patterns of elephant herds to solve optimization problems. The EHO algorithm operates on a population of candidate solutions, representing individual elephants. The population is divided into multiple clans, and the optimization process involves two primary operators: the clan updating operator and the separating operator. These operators simulate the social behavior and movement patterns of elephants.

The key concepts are

- ***Clan:*** A group of elephants (candidate solutions) that move together under the leadership of a matriarch.
- ***Matriarch:*** The best-performing elephant in a clan, which guides the movement of the other elephants in the clan.
- ***Clan Updating Operator:*** Models the influence of the matriarch on the other elephants in the clan, encouraging them to move towards the matriarch.
- ***Separating Operator:*** Models the behavior of elephants that occasionally leave the clan to explore new areas, promoting diversity in the population.

Clan division and updating constitute the two primary phases of the typical EHO algorithm, respectively:

4.1.1 Clan updating phase

The elephant population is randomly created and then sorted based on fitness levels. Afterward, the population is divided into clans. The elephants with the highest fitness values in their clans have been selected to guide the rest of the tribe. To relocate the ith member of the jth clan (represented by c_j), use the equation below,

$$S_{new,c_j,i} = S_{c_j,i} + \sigma\left(S_{best,c_j} - S_{c_j,i}\right) r \quad (22)$$

where $S_{c_j,i}$ represents the previous elephant position in clan c_j, while $S_{new,c_j,i}$ denotes the new elephant position. S_{best,c_j} is the most powerful elephant in the clan c_j with the highest fitness value. The number $r \in [0,1]$ is generated at random with a uniform distribution. The parameter σ that determines the impact of the leader elephant of clan c_j on the ith elephant of the identical clan is assessed is denoted as $\sigma \in [0,1]$.

$$S_{new,c_j} = \rho . S_{center,c_j} \quad (23)$$

The parameter $\rho \in [0,1]$ determines how S_{center,c_j} generates a new individual S_{new,c_j} instead of S_{best,c_j} and S_{center,c_j} which symbolizes the clan centre, may be determined for the uth dimension given below,

$$S_{center,c_j,u} = \frac{\sum_{i=1}^{n_{c_j}} S_{c_j,i,u}}{n_{c_j}}; 1 \le u \le U \quad (24)$$

where U represents the overall dimension of the issue to be optimized. The variable n_{c_j} represents the quantity of elephants that are members of clan c_j, while $S_{c_j,i,u}$ signifies the uth dimension of the ith elephant within clan c_j.

4.1.2 Separating phase

A proportion of individuals who reach adulthood depart from their familial units in order to start on solitary lives in various locations. The division phase of the EHO algorithm incorporated a model of this social behaviour exhibited by the associated elephants. During this stage, the elephants with the lowest fitness values within their clans are relocated to locations distant from their clans. Equation (25) is used to ascertain the new locations of the associated individuals.

$$S_{worst,c_j} = S_{\min} + \left(1 - S_{\min} + S_{\max}\right) r_n \quad (25)$$

Here, S_{max} and S_{min} denote the maximum and minimum limits of the elephant position, respectively. A random number denoted by r_n is produced within the interval [0, 1].

The detailed Steps in Pseudocode is given below;

4.1.2.1 Initialization

- Initialize a population of elephants with random positions.
- Divide the population into clans.
- Set parameters such as the scaling factor, maximum number of iterations, and probability of separation.

4.1.2.2 Fitness Evaluation

- Evaluate the fitness of each elephant based on the objective function.
- Identify the matriarch (best-performing elephant) in each clan.

4.1.2.3 Position Update:

- For each clan, update the position of each elephant.
- With a certain probability, apply the separating operator to encourage exploration.
- Otherwise, apply the clan updating operator to move elephants towards the matriarch.

4.1.2.4 Matriarch Update

- Update the position of the matriarch if a better-performing elephant is found within the clan.

4.1.2.5 Iteration

- Repeat the process for a defined number of iterations or until convergence criteria are met.

4.1.2.6 Output

- Return the best solution found by the algorithm.

4.2 Discrete Elephant Herding Optimization Algorithm (DEHOA)

The discrete optimization problem of optimizing phase factors $b^v = \left[b^0, b^1, b^2, ..., b^{V-2}, b^{V-1}\right]$ in the PTS method cannot be simplified directly with the EHO algorithm, which was initially designed for continuous optimization problems. To address this, we devised the DEHOA, which optimizes the combination of phase factors multiplied by the sub-blocks in order to reduce the PAPR of transmission signals in the traditional PTS method.

$$S_p^u = \left[S_p^0, S_p^1, S_p^2, ..., S_p^{U-2}, S_p^{U-1}\right]; p = 1, 2, 3, ..., N_e \quad (26)$$

where each vector dimension has a value of 0 or 1 , $S_p^u \in \{0,1\}$ and N_e is the total number of elephants before they are separated into clans. The comparison between EHOA and DEHOA is given in Table 1.

4.2.1 Clan updating phase

Initially, the elephant population is seeded with N_e distinct position vectors generated at random. After selecting the population members based on their fitness levels, the entire elephant population is divided into many clans. Elephant placements varies among clans, as illustrated below:

$$S_{c,e}^u = \left[S_{c,y}^0, S_{c,y}^1, S_{c,y}^2, ..., S_{c,y}^{U-2}, S_{c,y}^{U-1}\right]; \\ p = 1, 2, 3, ..., N_e; \ y = 1, 2, 3, ..., Y \quad (27)$$

Let C represent the total number of clans and Y represent the number of solutions inside each clan. Multiplying the value of C by Y will get the population size represented by N_e. An example may be used to show how the elephant population is divided into clans. The process of partitioning the total population into a certain number of clans is conducted using the values N_e is 9 and C is 3.

$$P_M = \begin{bmatrix} S_1^0 & S_1^1 & ... & S_1^{U-1} \\ S_2^0 & S_2^1 & ... & S_2^{U-1} \\ S_3^0 & S_3^1 & ... & S_3^{U-1} \\ S_4^0 & S_4^1 & ... & S_4^{U-1} \\ S_5^0 & S_5^1 & ... & S_5^{U-1} \\ S_6^0 & S_6^1 & ... & S_6^{U-1} \\ S_7^0 & S_7^1 & ... & S_7^{U-1} \\ S_8^0 & S_8^1 & ... & S_8^{U-1} \\ S_9^0 & S_9^1 & ... & S_9^{U-1} \end{bmatrix}$$

$$M_1 = \begin{bmatrix} S_1^0 & S_1^1 & ... & S_1^{U-1} \\ S_4^0 & S_4^1 & ... & S_4^{U-1} \\ S_7^0 & S_7^1 & ... & S_7^{U-1} \end{bmatrix}$$

$$M_2 = \begin{bmatrix} S_2^0 & S_2^1 & ... & S_2^{U-1} \\ S_5^0 & S_5^1 & ... & S_5^{U-1} \\ S_8^0 & S_8^1 & ... & S_8^{U-1} \end{bmatrix}$$

$$M_3 = \begin{bmatrix} S_3^0 & S_3^1 & ... & S_3^{U-1} \\ S_6^0 & S_6^1 & ... & S_6^{U-1} \\ S_9^0 & S_9^1 & ... & S_9^{U-1} \end{bmatrix}$$

Here, P_M represents the population matrix; M_1, M_2, and M_3 denote the clan matrices that include the sets of solutions obtained during the separation procedure. The first three elements of the P_M matrix are allocated to the top rows of the clan matrices, beginning from M_1 to M_3. Subsequently, the second set of three solutions, ranging from x_4^u to x_6^u, are allocated to the second rows of M_1, M_2, and M_3 in the same matrix. Ultimately, the separation procedure concludes by inserting the last three members of the P_M matrix into the last rows of the corresponding clan matrices, in a certain sequence. After that, the cyclic bit flipping algorithm [37] is used to update the location of each elephant. For this purpose, first, the following flipping operator is used to each individual in the population, which are distributed among several clans:

$$S_{c,y}^{new} = flip\left(S_{c,y}\right)_n \quad (28)$$

The method $flip\left(S_{c,y}\right)_n$ modifies the n[th] element in the vector $S_{c,y}$, which has U dimensions, switching its value between 0 and 1, where $S_{c,y}$ is a [0,1]. If the new solution has a higher fitness value than the previous solution, $S_{c,y}$ is substituted with $S_{c,y}^{new}$. Alternatively, the previous solution $S_{c,y}$ is retained. Next performing the flipping and greedy selection processes on each member of the population, the parameter n, which is initially set to 1, is incremented by 1 for the following iteration.

$$n = n + 1 \quad (29)$$

To check that the bit flipping occurs frequently as the iterations advance, the value of n is updated after the increment process.

$$n = \mathrm{mod}(n - 1, U) + 1 \quad (30)$$

The function mod (n-1, U) calculates the modulo of (n-1) with regard to U. Consequently, throughout each iteration, the value of m is incremented by 1. Once it reaches U + 1, it is reset to 1, serving as the initial value for the parameter m, as shown by Equation (30). By using cyclic bit flipping for solution updates, we ensure that neighbouring solutions within the population are not left unvisited for extended periods of time.

4.2.2 Separating phase

After the completion of the clan updating process, when each elephant in C distinct clans undergoes the cyclic bit flipping method, the separation phase begins. During this phase, the least optimal solution from each clan is substituted with a solution vector that is randomly generated in the following manner:

$$S^{u}_{c,worst} = round\left(\min\left(S^{u}_{c,y}\right)+\left(\max\left(S^{u}_{c,y}\right)-\min\left(S^{u}_{c,y}\right)\right)r_n\right) \quad (31)$$

where $\min\left(S^{u}_{c,y}\right)$ and $\max\left(S^{u}_{c,y}\right)$ are the maximum and minimum limits of vector solution, the term 'rand' refers to the random number created inside the range of [0,1]. The function "round()" is used to round each component of the vector, which is produced randomly in the continuous space, to the closest integer. The maximum and minimum limits of the vector dimensions in the DEHO method are set to 1 and 0, respectively, since each dimension can only accept binary values. After the separation phase, the clans are merged together again to begin the next iteration of the optimization process starting from the clan update phase. To illustrate the recombination process, let's use an example where N_e is 9 and C is 3. The combining of three clans to create the population matrix is carried out as follows:

$$M_1 = \begin{bmatrix} S^0_{1,1} & S^1_{1,1} & \cdots & S^{U-1}_{1,1} \\ S^0_{1,2} & S^1_{1,2} & \cdots & S^{U-1}_{1,2} \\ S^0_{1,3} & S^1_{1,3} & \cdots & S^{U-1}_{1,3} \end{bmatrix}$$

$$M_2 = \begin{bmatrix} S^0_{2,1} & S^1_{2,1} & \cdots & S^{U-1}_{2,1} \\ S^0_{2,2} & S^1_{2,2} & \cdots & S^{U-1}_{2,2} \\ S^0_{2,3} & S^1_{2,3} & \cdots & S^{U-1}_{2,3} \end{bmatrix}$$

$$M_3 = \begin{bmatrix} S^0_{3,1} & S^1_{3,1} & \cdots & S^{U-1}_{3,1} \\ S^0_{3,2} & S^1_{3,2} & \cdots & S^{U-1}_{3,2} \\ S^0_{3,3} & S^1_{3,3} & \cdots & S^{U-1}_{3,3} \end{bmatrix}$$

$$P_M = \begin{bmatrix} S^0_{1,1} & S^1_{1,1} & \cdots & S^{U-1}_{1,1} \\ S^0_{2,1} & S^1_{2,1} & \cdots & S^{U-1}_{2,1} \\ S^0_{3,1} & S^1_{3,1} & \cdots & S^{U-1}_{3,1} \\ S^0_{1,2} & S^1_{1,2} & \cdots & S^{U-1}_{1,2} \\ S^0_{2,2} & S^1_{2,2} & \cdots & S^{U-1}_{2,2} \\ S^0_{3,2} & S^1_{3,2} & \cdots & S^{U-1}_{3,2} \\ S^0_{1,3} & S^1_{1,3} & \cdots & S^{U-1}_{1,3} \\ S^0_{2,3} & S^1_{2,3} & \cdots & S^{U-1}_{2,3} \\ S^0_{3,3} & S^1_{3,3} & \cdots & S^{U-1}_{3,3} \end{bmatrix}$$

Table 1. Comparisons between EHOA and DEHOA

Parameter	EHOA	DEHOA
Purpose	Designed for continuous optimization problems where the variables can take any value within a given range	Adapted for discrete optimization problems where the variables are discrete, such as integers, binary values, or categorical variables.
Representation of Solutions	Solutions are represented as continuous vectors. Each element in the vector can take any real value within a specified range	Solutions are represented as discrete variables. This can be in the form of binary strings, integer vectors, or permutations, depending on the problem
Clan Updating Operator	Uses continuous arithmetic operations to update the positions of elephants based on the matriarch's position.	Uses discrete operations such as crossover, mutation, or swap to update the positions of elephants based on the matriarch's position.
Separating Operator:	Generates new random positions within the continuous search space.	Generates new random discrete solutions within the discrete search space.
Fitness Evaluation	Evaluates the fitness of each continuous solution based on the objective function.	Evaluates the fitness of each discrete solution based on the objective function.
Movement Patterns	Elephants move in a continuous search space, making large jumps during exploration and fine-tuned adjustments during exploitation.	Elephants move in a discrete search space, using discrete transitions such as swaps or bit flips for exploration and exploitation.
Convergence Mechanism	Relies on continuous optimization techniques and parameters to balance exploration and exploitation.	Relies on discrete optimization techniques and parameters to balance exploration and exploitation.
Applications	Suitable for problems like continuous function optimization, parameter tuning, and other problems where variables are continuous.	Suitable for problems like scheduling, routing, allocation, and other problems where variables are discrete.

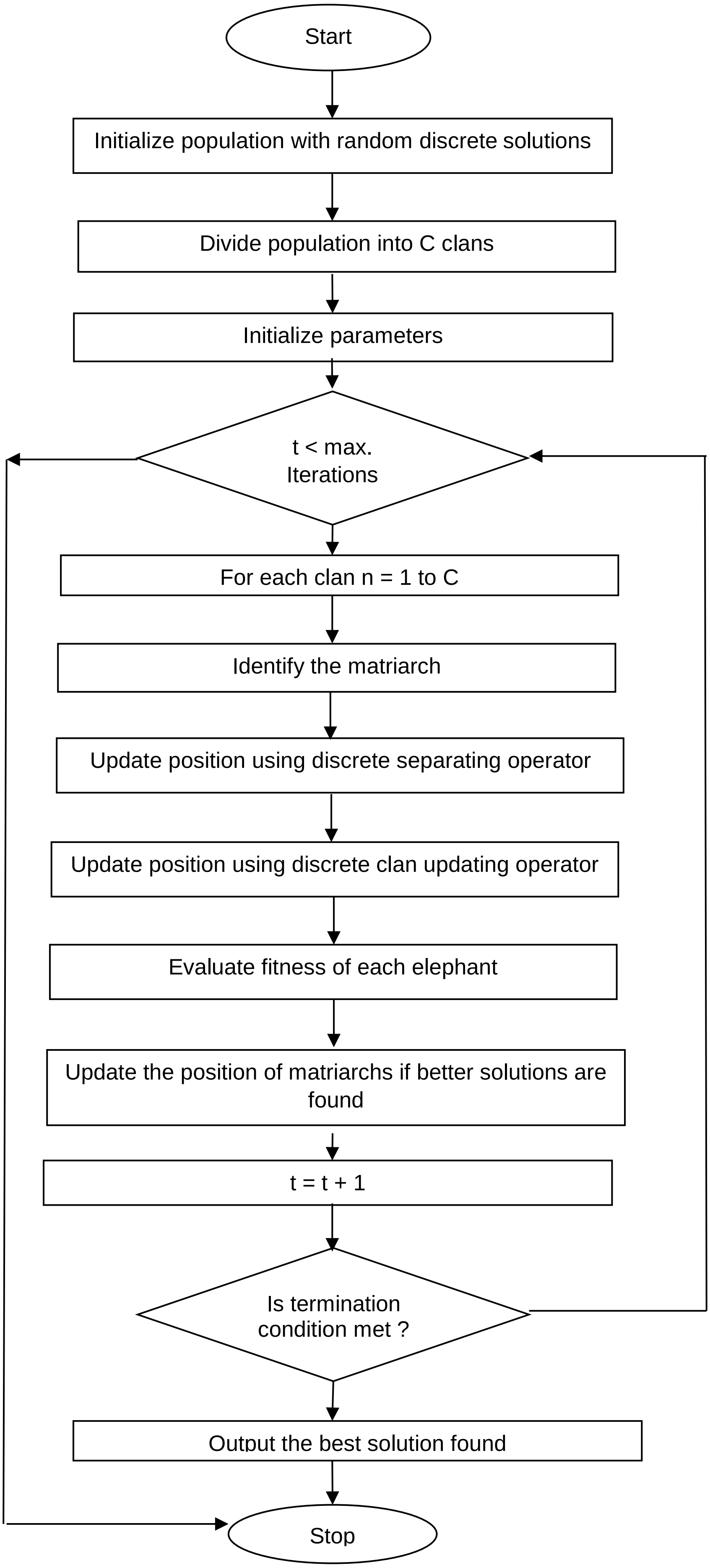

Figure 5. Flowchart for DEHO Algorithm

The solution vectors $S_{1,1}^{u}$, $S_{2,1}^{u}$ and $S_{3,1}^{u}$, representing the initial solutions of the M_1, M_2, and M_3 matrices, respectively, are assigned to the first three rows of the population matrix in sequential sequence. Subsequently, beginning with the $S_{1,2}^{u}$ symbolizing the second member of the first clan and continuing with the $S_{3,2}^{u}$ which represents the second person in the third clan, the second solutions of the M_1, M_2, and M_3 matrices are allocated to the next three rows of the P_M matrix. Finally, the recombination process is concluded by placing the last individuals from the corresponding clan matrices into the last three rows of the population matrix, in a certain sequence.

The DEHO modifies the traditional EHO algorithm to handle discrete optimization problems, where the solution space consists of discrete variables instead of continuous ones. These problems include tasks such as scheduling, routing, and allocation, where the variables are integers or categorical values. The flowchart for DEHOA is shown in figure 5.

The key modifications for discrete optimization are

- ***Discrete Representation**:* The candidate solutions (elephants) are represented as discrete variables, such as binary strings, permutations, or integer vectors.
- ***Discrete Clan Updating Operator**:* Adapt the clan updating operator to work with discrete variables.
- ***Discrete Separating Operator**:* Modify the separating operator to generate new discrete solution

4.2.3 Advantages of DEHOA over EHOA

- ***Handling Discrete Problems**:* DEHOA is specifically designed to handle discrete optimization problems, which EHOA cannot address effectively due to its reliance on continuous operations.
- ***Discrete Operators**:* DEHOA uses discrete operators like crossover, mutation, and swaps, making it suitable for combinatorial problems and ensuring that the solutions remain valid within the discrete search space.
- ***Diverse Applications**:* DEHOA can be applied to a wider range of practical problems in areas such as scheduling, routing, and resource allocation, which are inherently discrete in nature.
- ***Improved Exploration and Exploitation***: DEHOA balances exploration and exploitation effectively in discrete spaces, reducing the likelihood of getting stuck in local optima and enhancing the search for global optima.
- ***Customizability**:* DEHOA can be easily customized with different discrete operations to suit specific problem requirements, providing flexibility in handling various types of discrete optimization problems.

5. Simulation Results

In this work, we have developed a DEHOA approach for FBMC/OQAM system and utilized MATLAB to analyze the performance of PAPR, BER and SE. This paper investigates the PAPR, SE and BER performance of FBMC with optimization method. The simulation parameters are represented in Table 2.

Table 2. Simulation Parameters

Parameter	Value
Subcarriers	256
Prototype Filter	PHYDYAS
Overlapping Factor	4
Sub-Blocks	4, 8
FFT Length	512
Modulation	QAM
Cyclic Prefix Size	32
Filter Length	32
Sampling Frequency	15.36 MHz
Channel	AWGN
Type of HPA	SSPA
Number of Searches	128
PTS Sub-blocks	32

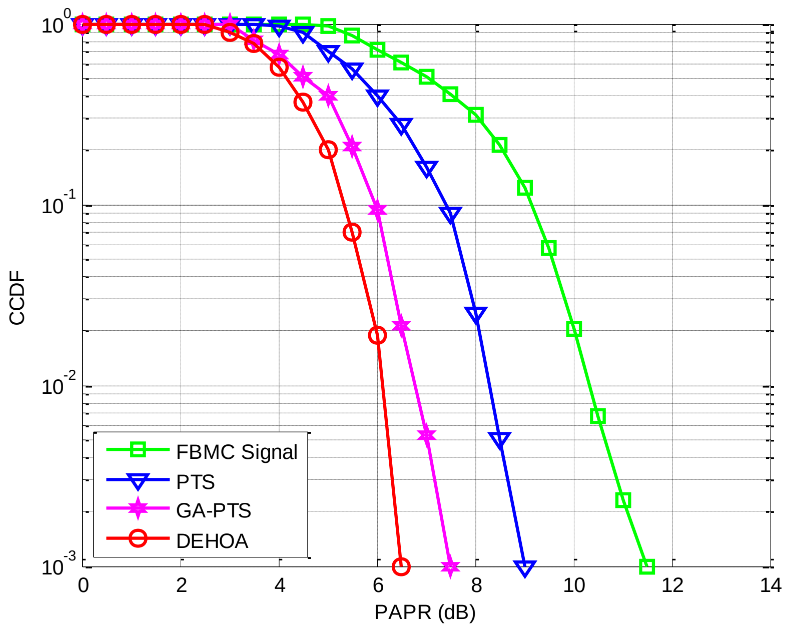

Figure 6. PAPR Comparison

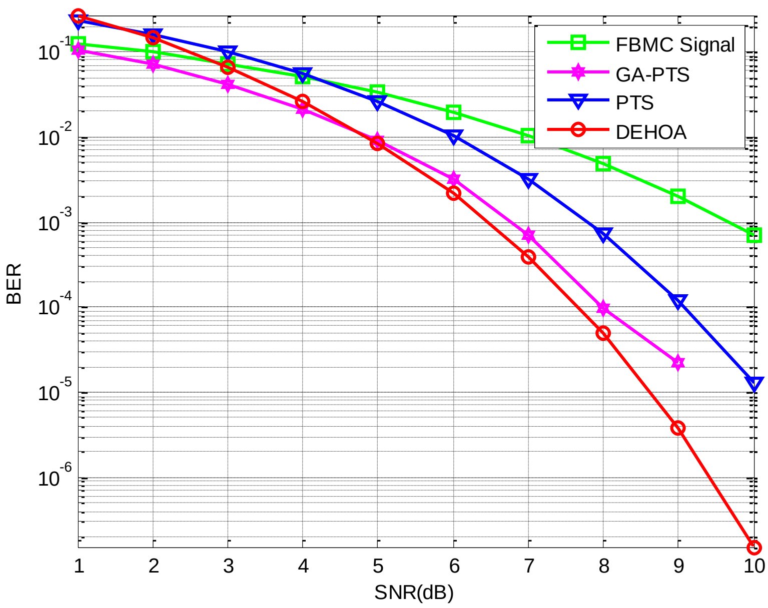

Figure 7. BER Performance

The simulations conducted a comparative analysis of the recommended DEHO approach, evaluating its performance against both the PTS and GA techniques. The PAPR reduction accomplishments of the approaches under consideration were assessed using the CCDF, which calculates the chance of generating a transmission signal with a PAPR value higher than a certain threshold level.

The CCDF for the original FBMC signal and reduction methods can be seen in the figure 6. PAPR decreases significantly when reduction and optimization methods are used. At CCDF=10^{-3}, the PAPR of the original FBMC is 11.83dB, PTS is 9.26dB, GA-PTS is 7.65dB and proposed method is 6.42dB; and for 8 sub-blocks, PTS is 8dB, proposed method 6.3dB. It can be seen from the figure 4 that the proposed method gives better results than the other methods.

The BER performance of the original FBMC signal and the proposed method is shown in the figure 7. There is a acceptable reduction of the BER caused by the proposed method. As a result, the overall performance of the system is greatly improved. The DEHOA technique has the highest level of BER performance, as seen by the Figure 5. The signal's vulnerability to degradation by the SSPA diminishes as the PAPR of the signal being amplified lowers. The comparative analysis is given in Table 3.

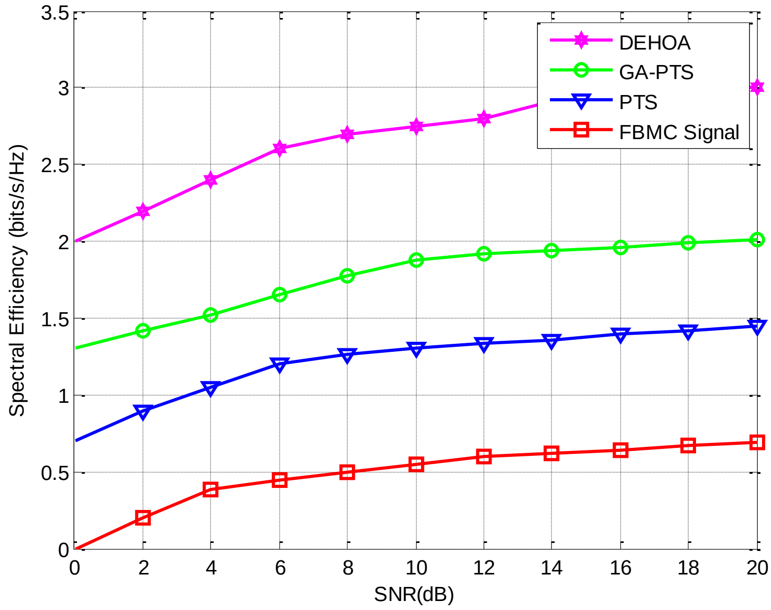

Figure 8. SNR vs SE

Table 3. Comparative analysis

Method	PAPR (dB) at CCDF = 10^{-3}	BER at SNR = 9dB	SE (bits/s/Hz) at SNR = 9dB
FBMC Signal	11.83	$2x10^{-3}$	0.71
PTS	9.26	$1.1x10^{-4}$	1.48
GA-PTS	7.65	$2x10^{-5}$	1.98
DEHOA	6.42	$3.4x10^{-6}$	3.1

Hence, attaining a superior BER performance is significantly related to reducing the degeneration of the transmission signal caused by the SSPA. At a SNR of 9 dB, the BER values are $3.4x10^{-6}$, $2x10^{-5}$, $1.1x10^{-4}$ and $2x10^{-3}$ for DEHOA, GA-PTS, PTS and original signal, respectively. The results shows the high efficiency of DEHOA in decreasing the BER, while requiring a minimal number of searches.

The SE for the proposed DEHOA and other approaches is shown in the Figure 8. The efficiency of the FBMC system may be assessed using the SE metric. The DEHOA approach has a better SE compared to other techniques. The SNR of 20 dB corresponds to a SE value of 3.1 bits/s/Hz for the DEHOA technique. The SE of GA-PTS is 1.98, whereas the SE of PTS is 1.48. The suggested approach offers superior spectrum efficiency in comparison to other methods.

5. Conclusion

This work presents a new DEHO algorithm that aims to reduce PAPR and BER while increasing the SE in the FBMC system. Our suggested DEHO approach was compared to the PTS and GA-PTS techniques in the simulations. The goal of 5G communication technologies is to deliver rapid, secure, and reliable connectivity anytime and everywhere. It's crucial to look for OFDM alternatives to do this. The multicarrier techniques are necessary for FBMC frameworks. It is seen to be one of the most promising candidates for modern portable correspondence architecture. However, the PAPR issue significantly lowers FBMC's performance. High-speed communication will be accompanied by the FBMC framework. A major issue of the FBMC framework is high PAPR. Reduce high amplitude power and enhance BER execution are the goals of the proposed study. This paper proposes a DEHOA for reducing PAPR in FBMC system. In addition to reducing PAPR, proposed method also impact overall system performance. From the simulation results, we can say that proposed method reduces PAPR significantly. As PAPR decreases, the BER performance increases. The simulated calculations show that the suggested method for PAPR reduction is capable of providing an enhanced PAPR performance for the FBMC with a low level of computational complexity.

References

[1] T. Ihalainen, A. Ikhlef, J. Louveaux, M. Renfors, Channel equalization for multi-antenna FBMC/OQAM receivers. IEEE Transactions on Vehicular Technology, 60(5), (2011) 2070–2085. https://doi.org/10.1109/TVT.2011.2145424

[2] B. Farhang-Boroujeny, OFDM versus filter bank multicarrier. IEEE Signal Processing Magazine, 28(3), (2011) 92–112. https://doi.org/10.1109/MSP.2011.940267

[3] B. Farhang-Boroujeny, C. Yuen, Cosine modulated and offset QAM filter bank multicarrier techniques: a continuous-time prospect. EURASIP Journal on Advances in Signal Processing, 2010, (2010) 1-16. https://doi.org/10.1155/2010/165654

[4] M. Schellmann, Z. Zhao, H. Lin, P. Siohan, N. Rajatheva, V. Luecken, A. Ishaque, (2014). FBMC-based air interface for 5G mobile: Challenges and proposed solutions. In 2014 9th international conference on cognitive radio oriented wireless networks and communications (CROWNCOM), IEEE. http://dx.doi.org/10.4108/icst.crowncom.2014.255708

[5] T. Hwang, C. Yang, G. Wu, S. Li, G.Y. Li, OFDM and its wireless applications: A survey. IEEE transactions on Vehicular Technology, 58(4), (2008) 1673-1694. https://doi.org/10.1109/TVT.2008.2004555

[6] P. Aggarwal, V.A. Bohara, A nonlinear downlink multiuser MIMO-OFDM systems. IEEE Wireless Communications Letters, 6(3), (2017) 414-417. https://doi.org/10.1109/LWC.2017.2699195

[7] Q. He, A. Schmeink, (2015) Comparison and evaluation between FBMC and OFDM systems. WSA 2015; 19th International ITG Workshop on Smart Antennas, VDE, Germany.

[8] P. Banelli, S. Buzzi, G. Colavolpe, A. Modenini, F. Rusek, A. Ugolini, Modulation formats and waveforms for 5G networks: Who will be the heir of OFDM?: An overview of alternative modulation schemes for improved spectral efficiency. IEEE Signal Processing Magazine, 31(6), (2014) 80-93. https://doi.org/10.1109/MSP.2014.2337391

[9] F.L. Luo, C.J. Zhang, (2016) Signal processing for 5G: algorithms and implementations. Wiley IEEE Press, Hoboken.

[10] M.S. Ahmed, S. Boussakta, A. Al-Dweik, B. Sharif, C.C. Tsimenidis, Efficient design of selective mapping and partial transmit sequence using T-OFDM. IEEE Transactions on Vehicular Technology, 69(3), (2019) 2636-2648. https://doi.org/10.1109/TVT.2019.2928361

[11] E. Al-Dalakta, A. Al-Dweik, A. Hazmi, C. Tsimenidis, B. Sharif, Efficient BER reduction technique for nonlinear OFDM transmission using distortion prediction. IEEE Transactions on Vehicular Technology, 61(5), (2012) 2330-2336. https://doi.org/10.1109/TVT.2012.2190950

[12] E. Al-Dalakta, A. Al-Dweik, A. Hazmi, C. Tsimenidis, B. Sharif, PAPR reduction scheme using maximum cross correlation. IEEE communications letters, 16(12), (2012) 2032-2035. https://doi.org/10.1109/LCOMM.2012.101712.122151

[13] J. Kassam, M. Miri, R. Magueta, D. Castanheira, P. Pedrosa, A. Silva, R. Dinis, A. Gameiro, Two-step multiuser equalization for hybrid mmwave massive mimo gfdm systems. Electronics, 9(8), (2020) 1220. https://doi.org/10.3390/electronics9081220

[14] M. Laabidi, R. Zayani, R. Bouallegue, (2015) A novel multi-block selective mapping scheme for PAPR reduction in FBMC/OQAM systems. In 2015 World Congress on Information Technology and Computer Applications (WCITCA), IEEE, Tunisia. https://doi.org/10.1109/WCITCA.2015.7367014

[15] S.S. Krishna, H. Hmaied, D. Roviras, Reducing the PAPR in FBMC/OQAM systems with low-latency trellis-based SLM technique. EURASIP Journal on Advances in Signal Processing, 1(132), (2016). https://doi.org/10.1186/s13634-016-0429-9

[16] P. Jirajaracheep, S. Sanpan, P. Boonsrimuang, P. Boonsrimuang, (2018) PAPR reduction in FBMC-OQAM signals with half complexity of trellis-based SLM. 20th International Conference on Advanced Communication Technology (ICACT), IEEE, Korea. https://doi.org/10.23919/ICACT.2018.8323624

[17] A. Hasan, M. Zeeshan, M.A. Mumtaz, M.W. Khan, (2018). PAPR reduction of FBMC-OQAM using A-law and Mu-law companding. In 2018 ELEKTRO, IEEE, Czech Republic. https://doi.org/10.1109/ELEKTRO.2018.8398246

[18] S. Lu, D. Qu, Y. He, Sliding window tone reservation technique for the peak-to-average power ratio reduction of FBMC-OQAM signals. IEEE Wireless Communications Letters, 1(4), (2012) 268-271. https://doi.org/10.1109/WCL.2012.062512.120360

[19] V.S. Kumar, S. Anuradha, (2015). Notice of removal: Sliding window tone reservation using smart gradient projection method for PAPR reduction of FBMC signals. International Conference on Electrical, Electronics, Signals, Communication and Optimization (EESCO), IEEE, India. https://doi.org/10.1109/EESCO.2015.7253695

[20] C. Ye, Z. Li, T. Jiang, C. Ni, Q. Qi, PAPR reduction of OQAM-OFDM signals using

segmental PTS scheme with low complexity. IEEE Transactions on Broadcasting, 60(1), (2013) 141-147. https://doi.org/10.1109/TBC.2013.2282732

[21] T. Jiang, C. Ni, C. Ye, Y. Wu, K. Luo, A novel multi-block tone reservation scheme for PAPR reduction in OQAM-OFDM systems. IEEE Transactions on Broadcasting, 61(4), (2015) 717-722. https://doi.org/10.1109/TBC.2015.2465146

[22] S. Vangala, S. Anuradha, (2015) Hybrid PAPR reduction scheme with selective mapping and tone reservation for FBMC/OQAM. In 2015 3rd international conference on signal processing, communication and networking (ICSCN) IEEE, India. https://doi.org/10.1109/ICSCN.2015.7219877

[23] R. Gopal, S.K. Patra, (2015). Combining tone injection and companding techniques for PAPR reduction of FBMC-OQAM system. In 2015 Global Conference on Communication Technologies (GCCT), IEEE, India. https://doi.org/10.1109/GCCT.2015.7342756

[24] A. Kumar, PAPR reduction of FBMC using hybrid and k-hybrid techniques. Radioelectronics and Communications Systems, 62(10), (2019) 501-509. https://doi.org/10.3103/S0735272719100029

[25] H. Wang, X. Wang, L. Xu, W. Du, Hybrid PAPR reduction scheme for FBMC/OQAM systems based on multi data block PTS and TR methods. IEEE Access, 4, (2016) 4761-4768. https://doi.org/10.1109/ACCESS.2016.2605008

[26] M.K. Srivastava, M.K. Shukla, N. Srivastava, A.K. Shankhwar, A hybrid scheme for low PAPR in filter bank multi carrier modulation. Wireless Personal Communications, 113(2), (2020)1009-1028.

[27] L.J. Cimini, N.R. Sollenberger, Peak-to-average power ratio reduction of an OFDM signal using partial transmit sequences. IEEE Communications letters, 4(3), (2000) 86-88. https://doi.org/10.1109/4234.831033

[28] P. Pantiko, T. Mata, P. Boonsrimuang, H. Kobayashi, (2011) A low complexity improved-PTS phase coefficient searching algorithm for OFDM system. In The 8th Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand-Conference 2011, IEEE, Thailand. https://doi.org/10.1109/ECTICON.2011.5947850

[29] N. Van der Neut, B.T. Maharaj, F. De Lange, G.J. González, F. Gregorio, J. Cousseau, PAPR reduction in FBMC using an ACE-based linear programming optimization. EURASIP Journal on Advances in Signal Processing, 2014, (2014) 1-21. https://doi.org/10.1186/1687-6180-2014-172

[30] Z. Kollár, L. Varga, B. Horváth, P. Bakki, J. Bitó, Evaluation of clipping based iterative PAPR reduction techniques for FBMC systems. The Scientific World Journal, 2014(1), (2014) 841680. https://doi.org/10.1155/2014/841680

[31] D. Qu, S. Lu, T. Jiang, Multi-block joint optimization for the peak-to-average power ratio reduction of FBMC-OQAM signals. IEEE transactions on signal processing, 61(7), (2013) 1605-1613. https://doi.org/10.1109/TSP.2013.2239991

[32] X. Cheng, D. Liu, S. Feng, H. Fang, D. Liu, (2017) An artificial bee colony-based SLM scheme for PAPR reduction in OFDM systems. In 2017 2nd IEEE International Conference on Computational Intelligence and Applications (ICCIA), IEEE, China. https://doi.org/10.1109/CIAPP.2017.8167258

[33] M. Bellanger, D. Le Ruyet, D. Roviras, M. Terré, J. Nossek, L. Baltar, Q. Bai, D. Waldhauser, M.Renfors, T.Ihalainen, A.Viholainen, T.H.Stitz, Ihalainen, T. FBMC physical layer: a primer. PHYDYAS, 25(4), (2010) 7-10.

[34] K.P. Anand, PAPR reduction technique: partial transmit sequence (PTS). International Research Journal of Engineering and Technology (IRJET), 4(3), (2017) 22-25.

[35] G.G. Wang, S. Deb, L.D.S. Coelho, (2015) Elephant herding optimization. In 2015 3rd international symposium on computational and business intelligence (ISCBI), IEEE, Indonesia. https://doi.org/10.1109/ISCBI.2015.8

[36] M.A. Elhosseini, R.A. El Sehiemy, Y.I. Rashwan, X.Z. Gao, On the performance improvement of elephant herding optimization algorithm. Knowledge-Based Systems, 166, (2019) 58-70. https://doi.org/10.1016/j.knosys.2018.12.012

[37] T. Nguyen, L. Lampe, On partial transmit sequences for PAR reduction in OFDM systems. IEEE transactions on wireless communications, 7(2), (2008) 746-755. https://doi.org/10.1109/TWC.2008.060664

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Vuppula Manohar: Conceptualization, methodology, software, validation, supervision, result analysis; R. Mohandas: Methodology, Data collection, Writing; Kiran Kumar Padakanti: Conceptualization, Formal analysis, validation; Karthik Kumar Vaigandla: Conceptualization, visualization, supervision, Writing-review and editing.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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