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PAPR reduction using artificial bee colony algorithm in OFDM systems

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Abstract

Partial transmit sequence (PTS) is an attractive scheme for peak-to-average power ratio (PAPR) reduction in orthogonal frequency division multiplexing (OFDM) systems, but its high computational complexity to find optimum phase factors is the main drawback. In this paper, we propose PTS based on an artificial bee colony (ABC) algorithm (ABC-PTS) for reducing the computational complexity of the PTS in the OFDM system. The ABC-PTS was compared to conventional PTS using a random search strategy (RS-PTS) and optimum PTS. In addition, the bit error rate (BER) performance of the ABC-PTS was shown when a high power amplifier (HPA) was used for additive white Gaussian noise (AWGN) and Rayleigh flat fading channel models. Solid state power amplifiers (SSPA) and traveling wave tube amplifiers (TWTA) are commonly used HPA models, and simulations were realized for both of these HPA models. Simulation results showed that the ABC-PTS is highly successful in reducing the computational complexity of the conventional PTS and BER performances in the OFDM system.

Key Words: *Orthogonal frequency division multiplexing (OFDM), peak-to-average power ratio (PAPR), partial transmit sequences (PTS), artificial bee colony (ABC), high power amplifier (HPA)*

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a widely used wireless communication system that requires a high bit rate and high capacity transmission [1]. Besides the advantages of the OFDM system, one of the main drawbacks is the high peak-to-average power ratio (PAPR) of the signal, which causes bit error rate (BER) performance degradation. In addition, the PAPR should be reduced for elimination of nonlinear distortion effects and for power efficiency of the high power amplifier (HPA) [2, 3].

To suppress this problem, many PAPR reduction methods have been developed in the literature, such as clipping [4], coding [5, 6], selected mapping (SLM) [7, 8], tone injection (TI) [9], tone reservation (TR) [9], active constellation extension (ACE) [10], and partial transmit sequence (PTS) [11–13]. Clipping is the simplest method for application, but it distorts the signal and decreases the BER of the system. TI, TR, and ACE do not distort the signal, but these methods cause energy increases of the transmitted signal. SLM neither distorts the signal nor causes energy increases in the signal, but its application is more complex than the others methods. PTS is a distortionless and efficient PAPR reduction method; for this reason, it is one of the most studied methods in PAPR reduction.

In this paper, we propose a PTS based on an artificial bee colony (ABC) algorithm (ABC-PTS) for reducing the PAPR with fewer searches in order to overcome the disadvantage of the conventional PTS. The ABC algorithm [14] is an intelligent swarm optimization algorithm recently developed by Karaboga, and it simulates the intelligent foraging behavior of a honey bee swarm. It shows superior performance over other metaheuristics such as particle swarm optimization (PSO), differential evolution (DE), and genetic algorithms (GA) [14–17].

In addition, the BER performance of the ABC-PTS was compared when a solid state power amplifier (SSPA) with different input back-off (IBO) and smoothness factor (p) values, and a traveling wave tube amplifier (TWTA) with different input back-off (IBO) values were used for additive white Gaussian noise (AWGN) and Rayleigh flat fading channel models.

This paper is organized as follows: In Section 2, the system model is described. In Section 3, the ABC-PTS algorithm is introduced and its application to the PAPR problem is presented. In Section 4, the simulation results and computational complexity of the ABC-PTS are given. Section 5 contains conclusions.

2. System model

Figure 1 shows the system model used for the simulations. First, bit streams from the users are interleaved to eliminate burst error caused by the communication channel. Interleaved signals are mapped with QAM, and then PTS is applied for PAPR reduction. The PTS requires side information, which has to be transmitted to get the original OFDM signal in the system receiver. The cycle prefix is then inserted in the signal, which is amplified by the HPA to eliminate intersymbol interference (ISI) derived from the communication channel. The cycle prefix is removed from the transmitted signal in the receiver. After the fast Fourier transform (FFT), phase rotation is applied to get the phase of the original OFDM signal from the side information. Then QAM demodulation is performed. Finally, each QAM demodulated symbol is carried to the original place in the bit stream by the deinterleaver.

2.1. PAPR of the OFDM signal

A continuous-time complex envelope of the transmitted OFDM signal is defined as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_k e^{j2\pi f_k t}, 0 \leq t < NT, \tag{1}$$

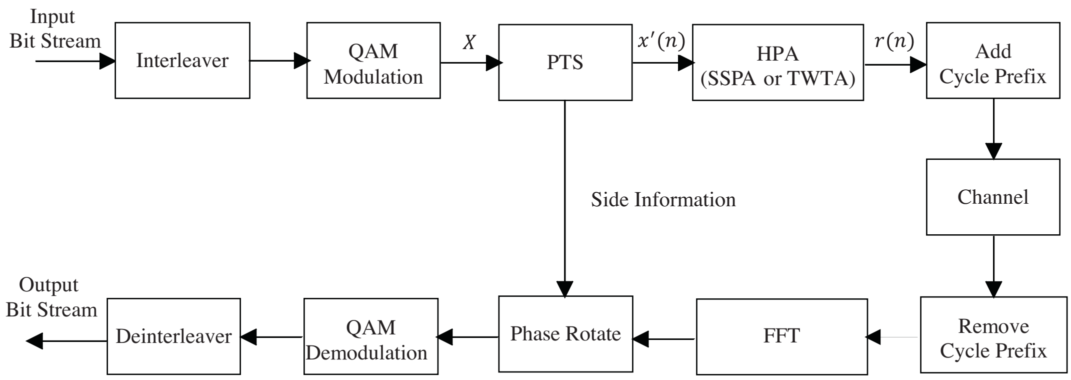

Figure 1. Block diagram of the system model.

where the input data vector is $\mathbf{X} = [X_0, X_1, \ldots, X_{N-1}]$, and N is the number of subcarriers. Each symbol in $\mathbf{X}$ is mapped with quadrature amplitude modulation (QAM) and each symbol is assigned to one subcarrier at a frequency of $f_k = k\Delta f, 0 \leq k \leq N-1$, where subcarrier spacing $\Delta f = 1/NT$ and T is the symbol period of one OFDM signal. However, PTS is required for discrete-time signals for PAPR reduction. For this reason, the discrete-time OFDM signal is given by

$$x(n) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi kn/LN}, 0 \leq n < LN, \tag{2}$$

where L is the oversampling factor. OFDM signals are oversampled as $L = 4$ In this way, the value of the PAPR in the discrete-time is nearly the same as the PAPR in the continuous-time. The oversampled OFDM signal is transformed as $\mathbf{x} = [x_0, x_1, \ldots, x_{LN-1}]$ and the PAPR of the discrete-time signal is expressed as

$$PAPR(x) = \frac{\max\limits_{0 \leq n \leq LN-1} \left\{ |x(n)|^2 \right\}}{E\left\{ |x(n)|^2 \right\}}, \tag{3}$$

where $E\{\cdot\}$ denotes the expected value of the OFDM signal. Complementary cumulative density function (CCDF) is a commonly used performance criterion to show the PAPR reduction, and it is described as $CCDF = \Pr\{PAPR(x) > PAPR_0\}$ where $PAPR_0$ is a certain level of PAPR.

2.2. PTS for PAPR reduction

The block diagram of the PTS method is shown in Figure 2. In the PTS, the input data vector $\mathbf{X}$ is partitioned into V disjointed subblocks. Three partitioning methods have been proposed in the literature [12], and we chose the random partitioning method, which provides the best PAPR reduction performance. The partitioned subblock $\mathbf{X}$ is denoted as

$$\mathbf{X} = \sum_{v=0}^{V-1} \mathbf{X}^{(v)}. \tag{4}$$

The subblock vectors are oversampled by $(L-1)N$ zero padding to measure the continuous-time value of the PAPR. Oversampled subblocks are subjected to inverse fast Fourier transform (IFFT) operating with size LN, and subblocks are transformed into $\mathbf{x}^{(v)} = \left[x_0^{(v)}, x_1^{(v)}, \ldots, x_{LN-1}^{(v)}\right]$, $0 \le v \le V-1$. Each subblock is rotated by phase factors $b_v = e^{j\phi}$, where $\phi \in [0, 2\pi)$, and finally the subblocks are summed. After the PTS operation, the OFDM signal becomes

$$x'(n) = \sum_{v=0}^{V-1} b_v x^{(v)}. \tag{5}$$

The aim in the PTS is to find the optimal phase factors. In the phase optimization, because the phase factor of the first subblock is taken as$b_0 = 1$, there are W^{V-1} alternative $\mathbf{b}$ combinations, where $\mathbf{b} = [b_1, b_2, \ldots, b_{V-1}]$ and W is the number of the phase factors. In sequence $\mathbf{b}$, b_v values are as follows:

$$b_v = \begin{cases} \{\pm 1\}, & if \quad W = 2 \\ \{\pm 1, \pm j\}, & if \quad W = 4 \end{cases} \tag{6}$$

Therefore, the side information (SI) consists of $\mathbf{b}$ and the length of the SI is $R = (V-1)\log_2(W)$ bits.

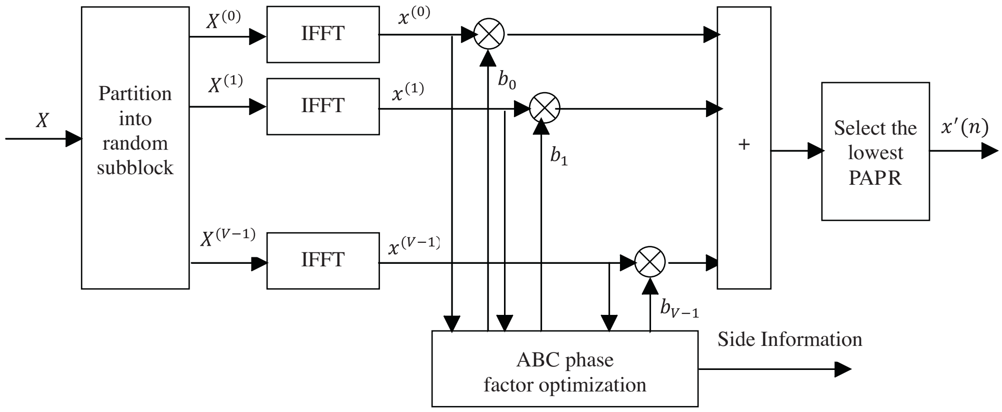

Figure 2. Block diagram of the ABC-PTS model.

2.3. SSPA and TWTA models

SSPA and TWTA are nonlinear amplifiers used for amplification of the OFDM signal. The signals are distorted and the BER performance of the system is degraded by use of the SSPA and TWTA. Amplitude/amplitude (AM/AM) and amplitude/phase (AM/PM) characteristics of SSPA are

$$A_{SSPA}(|x'(n)|) = \frac{|x'(n)|}{\left[1 + \left(\frac{|x'(n)|}{A_0}\right)^{2p}\right]^{\frac{1}{2p}}}, \tag{7}$$

$$\phi_{SSPA}(x'(n)) = 0, \tag{8}$$

where $|x'(n)|$ is the input signal amplitude, A_0 is the output saturation amplitude, p is the smoothness control coefficient, A_{SSPA} is the output signal amplitude, and ϕ_{SSPA} is the output phase response of the SSPA. The output signal of the SSPA is defined as

$$r(n) = A_{SSPA}(|x'(n)|)\, e^{j\left\{\theta(x'(n)) + \phi_{SSPA}(x'(n))\right\}}, \tag{9}$$

where $\theta(x'(n))$ is the phase of $x'(n)$. The amplitude/amplitude (AM/AM) and amplitude/phase (AM/PM) characteristics of the TWTA are

$$A_{TWTA}\left(\left|x'(n)\right|\right) = \frac{A_{in}^2\left|x'(n)\right|}{\left|x'(n)\right|^2 + A_{in}^2}, \tag{10}$$

$$\phi_{TWTA}\left(x'(n)\right) = \frac{\pi}{3}\frac{\left|x'(n)\right|^2}{\left|x'(n)\right|^2 + A_{in}^2}, \tag{11}$$

where A_{in} is the input saturation voltage, A_{TWTA} is the output signal amplitude, and ϕ_{TWTA} is the output phase response of the TWTA. The output signal of the TWTA is defined as

$$r(n) = A_{TWTA}\left(\left|x'(n)\right|\right) e^{j\left\{\theta\left(x'(n)\right)+\phi_{TWTA}\left(x'(n)\right)\right\}}. \tag{12}$$

The operating point of the SSPA or the TWTA is generally determined by the IBO parameter and is expressed as

$$IBO = 10\log_{10}\left(\frac{P_{\max}}{P_{ave,in}}\right), \tag{13}$$

where $P_{ave,in}$ is the mean power of the input signal $x'(n)$ and $P_{\max}$ is the peak power of the SSPA or TWTA.

3. ABC algorithm for PTS

The artificial bee colony (ABC) algorithm, which simulates the foraging behavior of honey bee colonies, was recently proposed by Karaboga [14]. In the ABC algorithm, employed bees, onlooker bees, and scout bees are tasked with finding optimum food sources, and first the food source positions are generated randomly. In the PAPR reduction problem, a food source position is equivalent to phase vector $\mathbf{b}_i = \left[b_{i1}, b_{i2}, \ldots, b_{i(V-1)}\right]$, $i = 1, \ldots, SN$, where SN denotes the population size, which is composed of the employed bees or the onlooker bees. The employed bees look for a new food source within the neighborhood of the previous source. If the nectar amount of the new source is higher than the previous one, the new source is memorized as a possible optimum solution. In the ABC-PTS, the new phase vector (the new food source) is expressed by

$$\mathbf{b}_i' = \mathbf{b}_i + \phi_i\left(\mathbf{b}_i - \mathbf{b}_k\right), \tag{14}$$

where $\mathbf{b}_k$ is a solution within the neighborhood of $\mathbf{b}_i$, and ϕ_i is a random number in the range of $[-1, 1]$. The nectar amount of the food source determines the quality or fitness of the solution. The fitness of a solution is expressed as

$$fit\left(\mathbf{b}_i\right) = \left\{\begin{array}{ll} \frac{1}{1+f(\mathbf{b}_i)} & if \quad f\left(\mathbf{b}_i\right) \geq 0 \\ 1 + abs\left(f\left(\mathbf{b}_i\right)\right) & if \quad f\left(\mathbf{b}_i\right) < 0 \end{array}\right\}, \tag{15}$$

where $f(\mathbf{b}_i)$ represents the PAPR value of the signal and is desired to be at a minimum. Employed bees share the fitness of the food sources with onlooker bees in the hive. The onlooker bees then move to a food source depending on its fitness value. The probability of an onlooker bee selecting a food source is calculated as

$$p_i = \frac{fit\left(\mathbf{b}_i\right)}{\sum\limits_{i=1}^{SN} fit\left(\mathbf{b}_i\right)}. \tag{16}$$

After an onlooker bee reaches a food source, it looks for a new source within the neighborhood of the previous one and memorizes the food sources according to their fitness. After the employed bees and onlooker bees complete their searches, if the fitness values of the food sources do not improve with a number of iterations that is called the "limit" value, employed bees become the scout bees. The scout bees look for new food sources randomly by

$$\mathbf{b}_i = \min(\mathbf{b}_i) + rand\,(0,1) * (\max(\mathbf{b}_i) - \min(\mathbf{b}_i)), \tag{17}$$

where $\min(\mathbf{b}_i)$ and $\max(\mathbf{b}_i)$ are the lower and upper bounds of the phase vector.

The above steps are repeated within in a cycle, called the maximum number of cycles (MCN). In a cycle, possible SN solutions are produced. In the ABC-PTS algorithm, $MCN * SN$ possible solutions are produced to find the optimum phase vector.

The main steps of the ABC-PTS algorithm are as follows:

1. Initialize the phase vector $\mathbf{b}_i$
2. randomly.
3. Evaluate the fitness of the each phase vector using equation (15).
4. Repeat.
5. New phase vector $\mathbf{b}'_i$ is produced within the neighborhood of $\mathbf{b}_i$ by the employed bees using equation (14) and evaluating the fitness of each $\mathbf{b}'_i$ using equation (15).
6. Onlooker bees select food sources using equation (16).
7. Onlooker bees look for new phase vectors using equation (14) and evaluate the fitness of the each $\mathbf{b}'_i$ using equation (15).
8. If the limit value is not reached, go to step 6. Otherwise, continue.
9. Send the scout bees randomly to find new phase vectors using equation (17).
10. Memorize the solution of the best phase vector.
11. Until cycle = maximum cycle number (MCN).

4. Simulation results

In this section, we show the ABC-PTS performance in terms of the PAPR reduction and BER criteria. In our simulations, the OFDM system had $N = 256$ subcarriers and employed QAM modulation with Gray coding. SSPA was used with $IBO = 0, 3, 6$ dB and $p = 0.5, 2$. TWTA was used with $IBO = 0, 3, 6, 9$ dB. The oversampling factor of the transmitted signal was $L = 4$. The communication channels were AWGN and Rayleigh flat fading models. In the PTS, the OFDM signals were randomly partitioned into $V = 16$ subblocks, and when the number of the phase factor was selected as $W = 2$, the phase factors became $b_v \in \pm 1$. The ABC-PTS and the RS-PTS were compared by the number of search criteria, and for each search, a $\mathbf{b} = [b_1, b_2, \ldots, b_{V-1}]$ sequence was created. In the RS-PTS, elements of the b were selected randomly.

In Figure 3, the PAPR reduction performances are shown for the original OFDM signal, the ABC-PTS, and the optimum-PTS. In the ABC-PTS, the number of searches were chosen for $I = [64, 256, 1024]$, where $I = MCN * SN$. $MCN * SN$ values were chosen as $16*4$, $64*4$, and $256*4$ for 64, 256, and 1024 searches, respectively. The "limit" value was chosen as 10. The PAPR of the original OFDM signal was 11.22 dB when $\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$. The PAPR of the ABC-PTS with 64, 256, and 1024 searches were 7.50 dB, 7.17 dB, and 6.91 dB, respectively. The PAPR of the optimum-PTS was 6.64 dB.

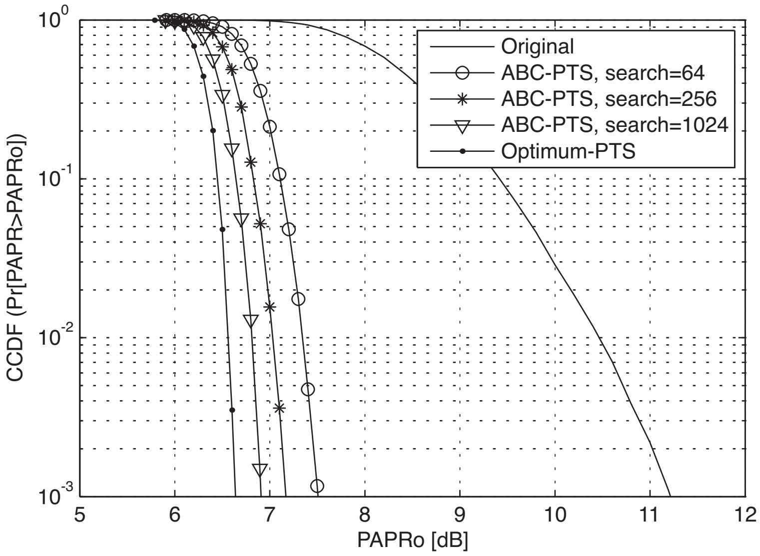

Figure 3. PAPR comparison of ABC-PTS, optimum-PTS, and original OFDM signals.

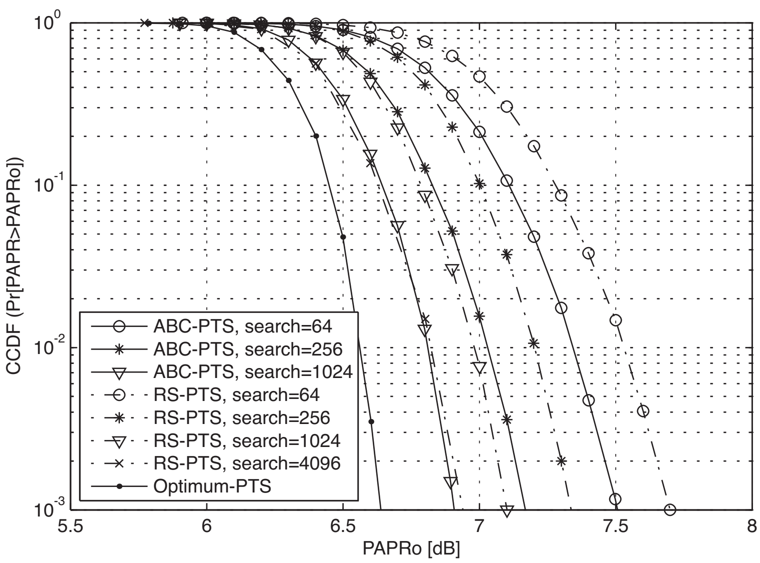

Figure 4. PAPR comparison of the ABC-PTS, the RS-PTS, and the optimum-PTS.

In Figure 4, PAPR reduction performances are shown for the ABC-PTS and the random search PTS (RS-PTS) for $I = [64, 256, 1024]$ number of searches. In addition, RS-PTS was simulated for $I = 4096$. The

PAPR of the RS-PTS with 64, 256, 1024 and 4096 searches was 7.70 dB, 7.34 dB, 7.10 dB, and 6.94 dB, respectively, at $\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$. When compared to the PAPR, differences between the ABC-PTS and the RS-PTS with the same search numbers for 64, 256 and 1024 were 0.20 dB, 0.17 dB, and 0.19 dB, respectively. The ABC-PTS converged faster than RS-PTS by the increment of search numbers. The ABC-PTS with 1024 searches and the RS-PTS with 4096 searches displayed similar performances at $\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$; in this case, the search cost for the ABC-PTS decreased 4 times.

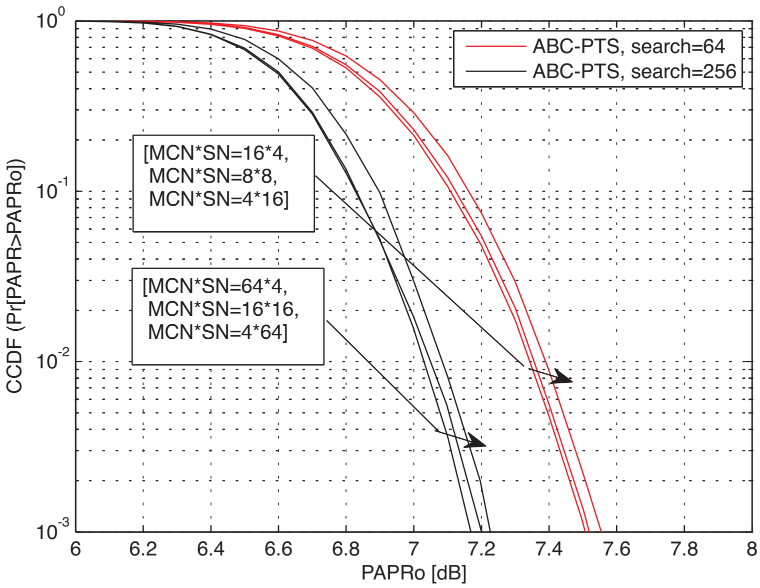

Figure 5. PAPR comparison of the ABC-PTS with 64 and 256 searches for different combinations of $MCN * SN$.

In Figure 5, we compare the effects of the different MCN and SN values on the PAPR reduction performances for 64 and 256 searches. $MCN * SN = [16 * 4, 8 * 8, 4 * 16]$ were selected for 64 searches and $MCN * SN = [64 * 4, 16 * 16, 4 * 64]$ were selected for 256 searches. As shown in Figure 5, the effects of the different $MCN * SN$ combinations are very limited for PAPR reduction performances. The PAPR of the ABC-PTS with 64 searches for $MCN * SN = [16 * 4, 8 * 8, 4 * 16]$ was 7.50 dB, 7.52 dB, and 7.55 dB, respectively. The difference of the PAPR was only 0.05 dB for 64 searches at $\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$. Similarly, the PAPR of the ABC-PTS with 256 searches for $MCN * SN = [64 * 4, 16 * 16, 4 * 64]$ was 7.17 dB, 7.20 dB, and 7.22 dB, respectively. The difference of the PAPR was only 0.05 dB for 256 searches. This is one advantage of the ABC-PTS; it is not necessary to consume time to find the optimum combination of $MCN * SN$.

The Table shows the required number of searches to find the phase factor sequences of the different PTS methods at $\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$. As we can see, ABC-PTS with 1024 searches and RS-PTS with 4096 searches demonstrated nearly the same performances. This shows that the computational complexity of the ABC-PTS was only one-fourth when compared to the RS-PTS. The optimum PTS necessitates an exhaustive search and requires $W^{V-1} = 2^{16-1} = 32768$ searches for testing all of the phase factor sequence combinations. The ABC-PTS with 1024 searches was only 0.33 dB higher than the optimum PTS, but the ABC-PTS had only $1024/32768 = 1/32$ computational complexity when compared to the optimum PTS.

Table. Computational complexity of the different PTS methods.

Method	Number of Searches	$\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$
Original	0	11.22 dB
Optimum-PTS	$W^{V-1} = 2^{16-1} = 32768$	6.64 dB
ABC-PTS	$MCN * SN = 16 * 4 = 64$	7.50 dB
ABC-PTS	$MCN * SN = 64 * 4 = 256$	7.17 dB
ABC-PTS	$MCN * SN = 256 * 4 = 1024$	6.91 dB
RS-PTS	64	7.70 dB
RS-PTS	256	7.34 dB
RS-PTS	1024	7.10 dB
RS-PTS	4096	6.94 dB

Figure 6 shows the BER performance of the OFDM system using ABC-PTS with 1024 searches on an AWGN channel. SSPA and a linear amplifier were used for amplification of the OFDM signal. SSPA was used with $IBO = 0, 3, 6$ dB and $p = 0.5, 2$ values. As seen from Figure 6, IBO and p parameters are very important for the system's BER performance. IBO affects the operating point of the SSPA and p affects the linearity of the SSPA. The higher the IBO is, the more the SSPA works in the linear region of amplification. In the case of high values of IBO and p, the SSPA and linear amplifier show nearly the same BER performances. But low values of the IBO and p cause distortion of the OFDM signal, and the BER performance of the system decreases. The BER performance of the linear amplifier was about $SNR = 6.7$ dB at $BER = 10^{-5}$, and this value was only 0.2 dB lower than SSPA with $IBO = 6$ dB, $p = 2$. In the case of $p = 0.5$, the SNR values were 13.5 dB, 9.1 dB, and 7.2 dB for $IBO = 0, 3, 6$ dB, respectively, at $BER = 10^{-5}$. Similarly, in the case of $p = 2$, the SNR values were 8.2 dB, 7.6 dB, and 6.9 dB for $IBO = 0, 3, 6$ dB, respectively, at $BER = 10^{-5}$. When compared to $IBO = 0$ dB, $p = 0.5$, and $IBO = 0$, $p = 2$, the difference of the SNR performances was 5.3 dB at $BER = 10^{-5}$. This value shows that the p is very important for the BER performance of the OFDM system.

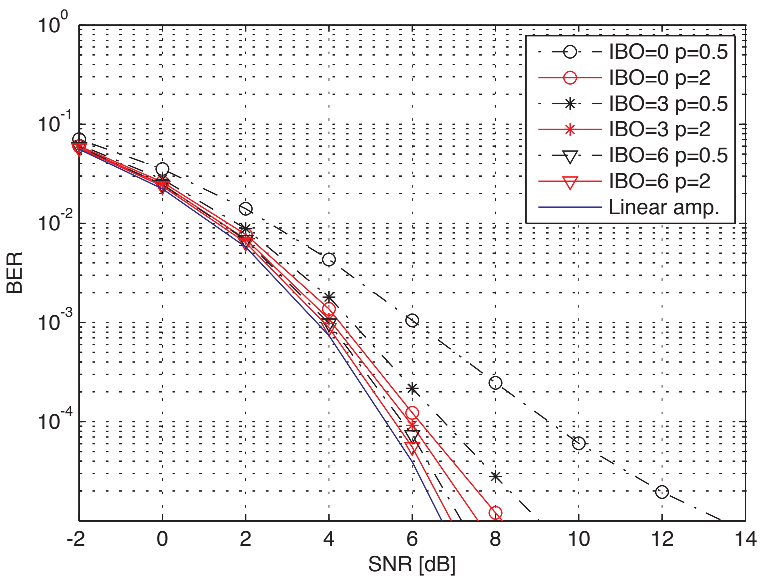

Figure 6. BER performances of the OFDM system for ABC-PTS when a linear amplifier and SSPA with $p = 0.5, 2$ and $IBO = 0, 3, 6$ dB are used on an AWGN channel.

Figure 7 shows the BER performance of the OFDM system using ABC-PTS with 1024 searches on a Rayleigh flat fading channel. The BER performance of the linear amplifier was about $SNR = 12$ dB at $BER = 10^{-5}$, and this value was 0.9 dB lower than the SSPA with $IBO = 6$ dB, $p = 2$. In case of $p = 2$, SNR values were 16.3 dB, 14.2 dB, and 12.9 dB for $IBO = 0, 3, 6$ dB, respectively, at $BER = 10^{-5}$. The BER performances of the SSPA with $IBO = 3$ dB, $p = 0.5$, and $IBO = 3$, $p = 2$ were $SNR = 16$ dB and $SNR = 12$ dB, respectively, at $BER = 10^{-4}$.

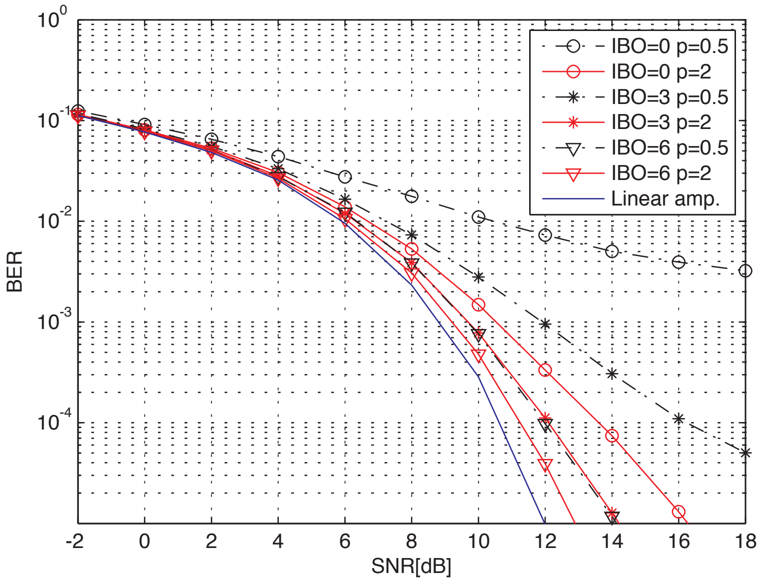

Figure 7. BER performances of the OFDM system for ABC-PTS when a linear amplifier and SSPA with $p = 0.5, 2$ and $IBO = 0, 3, 6$ dB are used on a Rayleigh flat fading channel.

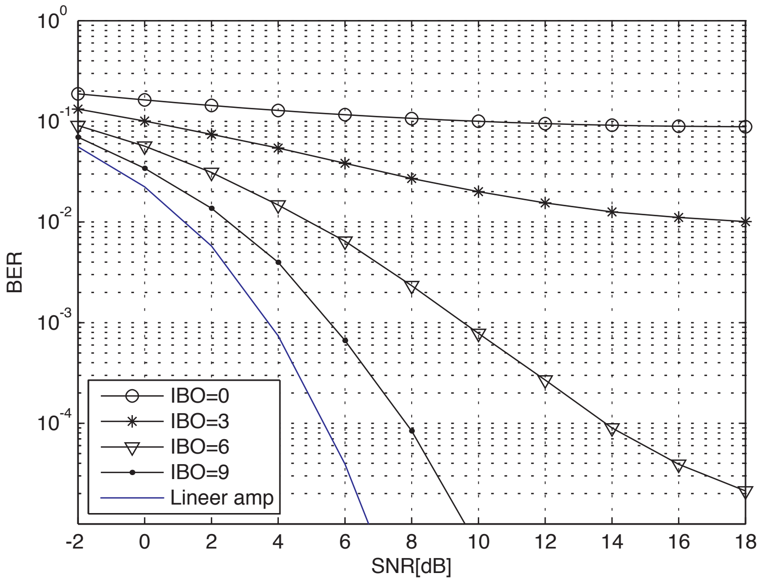

Figure 8. BER performances of the OFDM system for ABC-PTS when a linear amplifier and TWTA with $IBO = 0, 3, 6, 9$ dB are used on an AWGN channel.

Figure 8 shows the BER performance of the OFDM system using ABC-PTS with 1024 searches when the TWTA was used on an AWGN channel. The IBO is very important for the BER performance of the system, because IBO affects both the working point of the TWTA and the phase of the OFDM signal. Simulations were generalized for $IBO = 0, 3, 6, 9$ dB. It can be seen from Figure 8 that when IBO values increase, the BER values of the system decrease.

5. Conclusion

In this paper, we propose the ABC-PTS algorithm to reduce the computational complexity of the PTS for the OFDM system. Simulation results showed that the ABC-PTS with 1024 searches and the RS-PTS with 4096 searches had nearly the same PAPR performances. Therefore, the computational complexity of the ABC-PTS is less than 4 times that of the RS-PTS. The other advantage of the ABC-PTS is that it is less dependent on the combinations of $MCN * SN$ in the same searches. The difference of the PAPR was only 0.05 dB with different $MCN * SN$ combinations for 64 or 256 searches at $\Pr\{PAPR(x) > PAPR_0\} = 10^{-3}$.

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