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Efficient Technique for Sidelobe Suppression and PAPR Reduction in OFDM-Based Cognitive Radios

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Abstract Orthogonal Frequency Division Multiplexing (OFDM) is a transceiver technology able to achieve spectrally efficient and high data rate wireless transmissions. It is also able to transmit in a non-contiguous (NC) fashion by utilizing several separate spectral whitespaces. Cognitive radio (CR) is an efficient solution for solving the spectrum scarcity problem, while OFDM based CR system, i.e. NC OFDM system is used as modulation scheme. NC-OFDM has two significant problems, high peak to average power ratio (PAPR) and high sidelobe power, which cause out of band radiation and interference with primary users (PU). Many solutions were proposed for solving either of these problems while in this paper, an efficient technique for reducing both PAPR and sidelobe power is proposed. This technique is based on using the Advanced Cancelation Carriers combined with signal set expansion and gives an efficient reduction for both PAPR and sidelobe power. A modified version is also proposed which reduces the transmitted power and decreases the complexity but gives a little reduction for PAPR. Simulation results cover the PAPR and sidelobe reduction for both the proposed technique and its modified version for comparison purposes.

Keywords NC-OFDM · PAPR · ACC · SSE and BER

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1 Introduction

In order to meet the growing demand for high-speed wireless access while making better utilization of the spectrum, many researches are proposed to achieve more efficient use of spectrum resources. It is known that the spectrums allocated to the licensed (primary) users are unused most of time, as represented in the Spectrum Policy Task Force (SPTF) appointed by Federal Communication Commission (FCC) [1]. Cognitive radio (CR) is studied in [2, 3] that is used for spectrum utilization, while it exploits the spectrum band which is not used. The main issue in cognitive radio is dynamic spectrum sensing that is used to activate and deactivate the spectrum. Precision in CR sensing leads to efficient use of the spectrum. Orthogonal Frequency Division Multiplexing (OFDM) technique is a superior modulation scheme for cognitive radios due to its influence to confront frequency-selective channel and capability to support high data rate. NC-OFDM is the incorporation between OFDM and cognitive radio [4].

The challenges of NC-OFDM have collected into three categories, high peak to average power ratio (PAPR), high sidelobe power, and frequency offset. The first and second problems are the subject of this paper. The entered signal to the power amplifier (PA) must be in the dynamic range in order to operate well, but when this signal has high PAPR, this oblige the PA to work in nonlinear region leading nonlinear distortion, out of band distortion and Intercarrier Interference (ICI). The problem of high sidelobe causes Out-of-band (OOB) radiation and interaction between the licensed system and CR system. These problems disturb the PU, reduce PA efficiency, and increase the bit error rate.

There are many techniques for reducing sidelobe power which can be classified into two categories time domain methods such as windowing technique [5], and frequency domain methods such as insertion of guard band [5], subcarrier weighting (SW) [6], cancellation carrier (CC) [7], adaptive symbol transition [8], constellation expansion (CE) [9], multiple choice sequences (MCS) [10], and extended data carrier [11]. With windowing technique, the symbol duration is prolonged and throughput reduced, where the spectral resources are wasted in guard band technique. SW technique causes degradation in bit error rate, while CC technique suppresses sidelobe efficiently but increases PAPR and is sensitive to cyclic prefix. CE technique increases the computational complexity, while MCS requires a small amount of redundancy. There are also many techniques for reducing PAPR problem [12] such as interleaving [13], clipping, compander [14], selective mapping (SLM) [15], partial transmit sequence (PTS) [16, 17], tone reservation [18], coding technique, adaptive mode with low complexity [19, 20], signal set expansion [21], and active constellation expansion [22]. Clipping method causes distortion to the signal and degradation to bit error rate, while both SLM and PTS need additional complexity. All the above studies consider either sidelobe suppression alone or PAPR reduction alone. There are some techniques which reduce sidelobe with PAPR together such as SLM with MCS [23], active point modification [24], advanced constellation expansion [25], and phase adjustment [26].

In this paper, a technique for reducing sidelobe power and PAPR together in NC-OFDM is proposed. This technique is a combination between the proposed Advanced Cancellation Carrier (ACC) and Signal Set Expansion (SSE). CC technique depends on adding additive carriers, which reduce the sidelobe power and do not cause intersymbol interference, but increases PAPR and computational complexity. This is the reason for proposing ACC technique which gives more efficient in sidelobe suppression with low complexity, but it increases the PAPR therefore SSE is added in order to combat the increase of PAPR. The idea of signal set expansion method used to reduce PAPR, is the same idea of constellation expansion used for reducing sidelobe power. SSE exploits the fact that different sequences have different PAPR and hence employs a SSE based iterative approach to achieve an efficient reduction in PAPR. While the important advantage in SSE technique is that there is no side information to be transmitted. The proposed (ACC with SSE) can reduce the OOB radiation caused by high sidelobe and high PAPR. The performance of the proposed technique has been presented in terms of the Complementary Cumulative Distribution Function (CCDF). A modified version for the proposed is presented to reduce the power needed for transmission and gives little reduction of PAPR and sidelobe power than the proposed technique.

The rest of the paper is organized as follows: In Sect. 2, the system model of NC-OFDM with the proposed technique is explained. The details of the proposed technique (ACC with SSE) are presented in Sect. 3. The performance and simulation results are introduced and discussed in Sect. 4. Finally, the conclusions are included in Sect. 5, followed by references.

2 System Model

System model of NC-OFDM is shown in Fig. 1 that includes the proposed (ACC with SSE) techniques. The serial input bits **X** are mapped to complex data symbol by M-ary phase shift keying (MPSK) or Quadrature amplitude modulation (QAM), then these complex data are split into N slower data using serial to parallel converter. The dynamic spectrum sensing is the basic idea in cognitive radio networks, which detect the occupancy of primary user. Spectrum sensing deactivates the subcarriers that are occupied with PU and activates the other free subcarrier to be used by any secondary user easily. Signal set

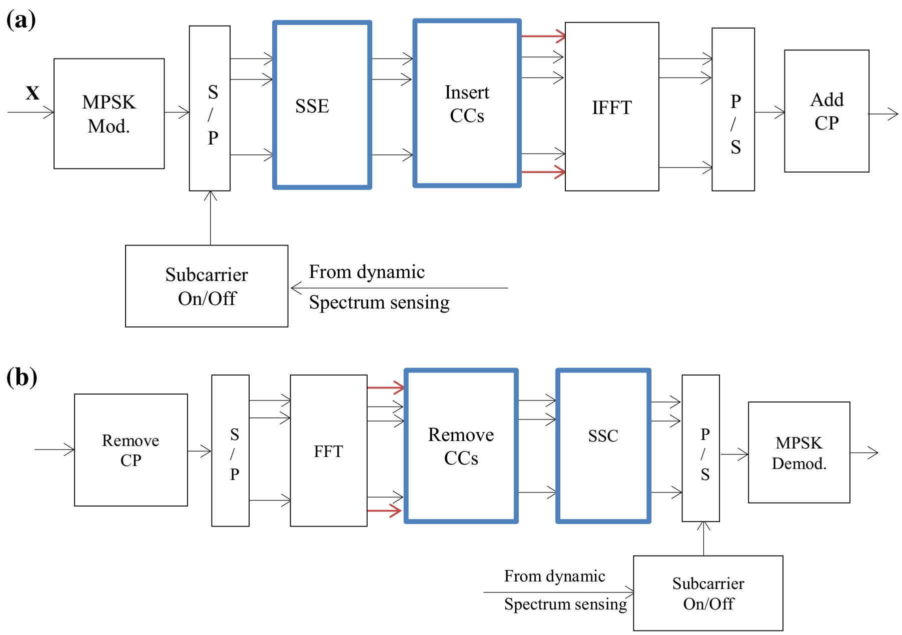


Fig. 1 Block diagram of an NC-OFDM with ACC and SSE proposed technique. **a** NC-OFDM transmitter with the proposed technique. **b** NC-OFDM receiver with the proposed technique

expansion outlined in the next section, is used to determine a sequence with low PAPR. To reduce sidelobe also M cancellation carriers are inserted in the left and right hand side of the lowest PAPR sequence. These CCs are not used for data transmission, but carry weighting factors $w_m, m = 1, \ldots M$, which can determined such that the sidelobes in CCs cancel the sidelobes of the lowest PAPR sequence.

Therefore, sidelobe power and PAPR can be reduced together. Then inverse fast Fourier transform (IFFT) is applied in the resulting sequence in order to modulate it onto $N + M$ subcarriers and follow by parallel to serial converter (P/S). Cyclic prefix is inserted at the beginning in each OFDM symbol with guard interval exceeding delay spread of the multipath channel to mitigate the effect of intersymbol interference (ISI). This symbol converted to analog signal $x(t)$ which up converted to the desired frequency, amplified with PA, and transmitted over the channel.

At the receiver, the reverse operations are performed. The received signal is down converted then CP is removed and then S/P is applied to convert from serial to parallel. FFT is applied to transform time domain signal to frequency domain while the carriers that do not carry information are removed and then signal set compression (SSC) is performed. The resulting signal is converted to serial and then demodulated.

3 Proposed Technique

3.1 SSE for PAPR Reduction

Assume that $\mathbf{X} = [X_0, X_1, \ldots, X_{N-1}]^T$ is an input sequence in frequency domain, N is the number of subcarriers, X_n is the complex data of the nth subcarrier where the nth subcarrier is a quadrature amplitude modulation (QAM) or phase-shift keying (PSK) signal, and $[.]^T$ denotes transpose. The OFDM symbol $\mathrm{x} = [x_0, x_1, \ldots x_{N-1}]$ is the inverse fast Fourier transform of $\mathbf{X}$. The complex envelope of the baseband NC-OFDM signal, defined over the time interval $t \in [0, T_0]$, is expressed as:

$$x(\mathrm{t}) = \frac{1}{N}\sum_{n=0}^{N-1} X_n e^{j2\pi nt/T_0} \qquad (1)$$

where, T_0 is the duration of OFDM symbol. The PAPR is the ratio between maximum instantaneous power to the average power, and is defined as

$$\mathrm{PAPR}[x(\mathrm{t})] = \frac{\max\limits_{0 \le t < T_0} |x(t)|^2}{E\left[|x(t)|^2\right]} \qquad (2)$$

The key idea is of signal set expansion is to exploit the expanded signal from the original signal to reduce the PAPR. The symbols of a modulation technique that modulates K bits/symbol, which consist of 2^K constellation points, are mapped to another modulation that modulates $(K + a)$ bits/symbol, which consist of 2^{K+a} points. Therefore each point in original symbol is associated with $R = 2^{K+a}/2^K$ points in expanded symbol. Then each one of these expanded points is selected on random basis producing 2^N different combinations for original OFDM symbols. The idea is to compute the PAPR for different combinations and choose the sequence with minimum PAPR for transmission. The transmitter and the receiver are assumed to know the points of the expanded signal set that are associated with

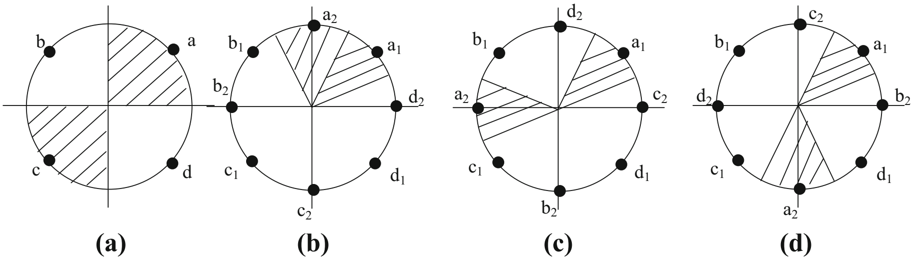


Fig. 2 Mapping symbols from QPSK to 8-PSK [21]. **a** QPSK. **b** 8-PSK, $\Phi = \pi/4$. **c** 8-PSK, $\Phi = 3\pi/4$. **d** 8-PSK, $\Phi = 5\pi/4$

the points in the original signal therefore no side information are needed at the receiver to demodulate the transmitted data. For example, let us consider mapping QPSK to 8-PSK as shown in Fig. 2, each subcarrier can take either a, b, c, d (data symbol), point a is associated with a_1, a_2 and also the rest of points each point is expanded to two points. The phase difference between two points in expanded signal that are associated to one point in the original signal is Φ, which can be $\pi/4$, $3\pi/4$, $5\pi/4$, and $7\pi/4$.

The mapping from original signal to expanded signal may be done by many ways that differ in computational complexity. Mapping all symbols of original signal to their associated points at once is the most complex method and achieves large reduction. This method is practically not realizable because of its complexity, therefore another simple mapping method is used. This method is changing the first symbol among all R associated points one by one and computing the PAPR for each case and the signal point achieves the lowest PAPR is chosen. Then these procedures are repeated in the same way for all X_n. Assume $X_n = A_i, i = (1, 2, 3, 4)$ and each symbol of A_i is mapped to one of R associated points $A_{i,r}, r = 1, 2, \ldots R$. All X_n will be modified to $X_n^{'}$ as this equation forming $\mathbf{X}' = (X_0^{'}, X_1^{'}, \ldots, X_n^{'})$

$$X_n^{'} = \arg \min_{X_n \in A_{i,r}} \text{PAPR for } [X_n] \tag{3}$$

There is another method that is used for this mapping which is called data block mapping method. It depends on dividing the symbol $\mathbf{X}$ into B sub-blocks while each sub-block contains *N/B* carriers. This changes the symbols of $\mathbf{X}$ block by block instead of one by one as mentioned previous. This method reduces the complexity but does not reduce the PAPR efficiently as simple mapping method.

At the receiver, the signal points lay in the area that is more close to a_1 or a_2 is converted to a point in expanded signal set which has minimum Euclidean distance from each received symbol. Therefore side information is not needed for recovering the original signal. In this section $X_n^{'}$ with minimum PAPR is achieved from X_n input data by applying SSE technique. But the high sidelobe power constrains is still exist and it should be illuminated to achieve the reduction for joint PAPR and sidelobe power.

3.2 ACC Technique

In this section, a low complexity technique for reducing the sidelobe power is proposed. The number of subcarriers are N and M cancellation carriers are added to achieve this reduction. After reducing the PAPR, $\mathbf{X}'$ with minimum PAPR is used to compute the spectrum and the sidelobe power. While the spectrum of each individual subcarrier is defined as:

$$S_l(y) = X_l'.\frac{\sin(\pi(y - z_l))}{\pi(y - z_l)}, \quad l = -N/2, \ldots, N/2 - 1 \tag{4}$$

where $y = (f - f_0)T_0$, and $z_l = (f_l - f_0)T_0$. Here y is normalized frequency shifted to center frequency f_0 and normalized to sampling frequency $1/T_0$, z_l is normalized center frequency of l-th subcarrier. The spectrum of OFDM symbol is the sum of the individual subcarriers spectrum which is given by,

$$S(y) = \sum_{l=-N/2}^{N/2-1} S_l(y) \tag{5}$$

The average sidelobe power equation over K samples is denoted by [23],

$$Q = \frac{1}{K}\sum_{k=1}^{K}\left|\sum_{l=-N/2}^{N/2-1} X_l'.\frac{\sin(\pi(y_k - z_l))}{\pi(y_k - z_l)}\right|^2 \tag{6}$$

where, y_k is the normalized frequency sample at kth sample.

The cancellation carrier technique operates with inserting carriers that do not carry any information in the left and right hand side of OFDM spectrum with optimized weights. The main idea is calculating this optimized weight to cancel out the sidelobes of the original OFDM signal. There are three existing types of CC, which varies in computing the amplitude of cancellation carriers. A method for calculating the amplitudes of CCs by solving linear least squares problems in [7], which called optimization-based algorithm. The second algebraic algorithm [27] that calculates amplitudes of CCs which is called a heuristic algorithm. The third algorithm depends on genetic algorithm [28].

ACC technique depends on inserting M carriers in the left and right hand side of OFDM spectrum. The spectrum of mth cancellation carrier is expressed as,

$$c_m(y) = \frac{\sin(\pi(y - g_m))}{\pi(y - g_m)}, \quad m = 1, \ldots, M \tag{7}$$

where g_m is normalized center frequency of mth CC. These carriers are multiplied with $w_m, m = 1, \ldots, M$ weighting factor which must calculate such that minimum average sidelobe power is achieved to reduce the sidelobes in the OFDM spectrum. The total spectrum of OFDM symbol with inserting M CC is given by,

$$S_T(y) = S(y) + \sum_{m=1}^{M} w_m.c_m(y) \tag{8}$$

Average sidelobe power over k samples for total spectrum of OFDM symbol is

$$Q_T = \frac{1}{K}\sum_{k=1}^{K}|S_T(y_k)|^2. \tag{9}$$

Computing of weighting factors depends on iterative technique to find the optimal weight. Optimization weight w_m is a complex values that lies between 0, 1. In the first

$w_m = 0$ is put as initial values and total OFDM spectrum and average sidelobe power are computed which equals to the original spectrum without adding CCs. Then w_m is changed randomly under range from 0 to 1 and the total OFDM spectrum and average sidelobe power are computed again. This procedure is repeated iteratively as shown in Fig. 3 until the minimum average sidelobe power is obtained. At that power optimum weighting factors are obtained for each cancellation carrier.

This technique is simpler than CC in [7] while the proposed technique depends on the whole spectrum in computing the weighting factor but, the later depends on only a certain frequency range spanning a few number of sidelobes for obtaining the weighting factor and reduces the spectrum to a certain number of samples. This means that the proposed technique is more efficient reduction on sidelobe power than any other techniques.

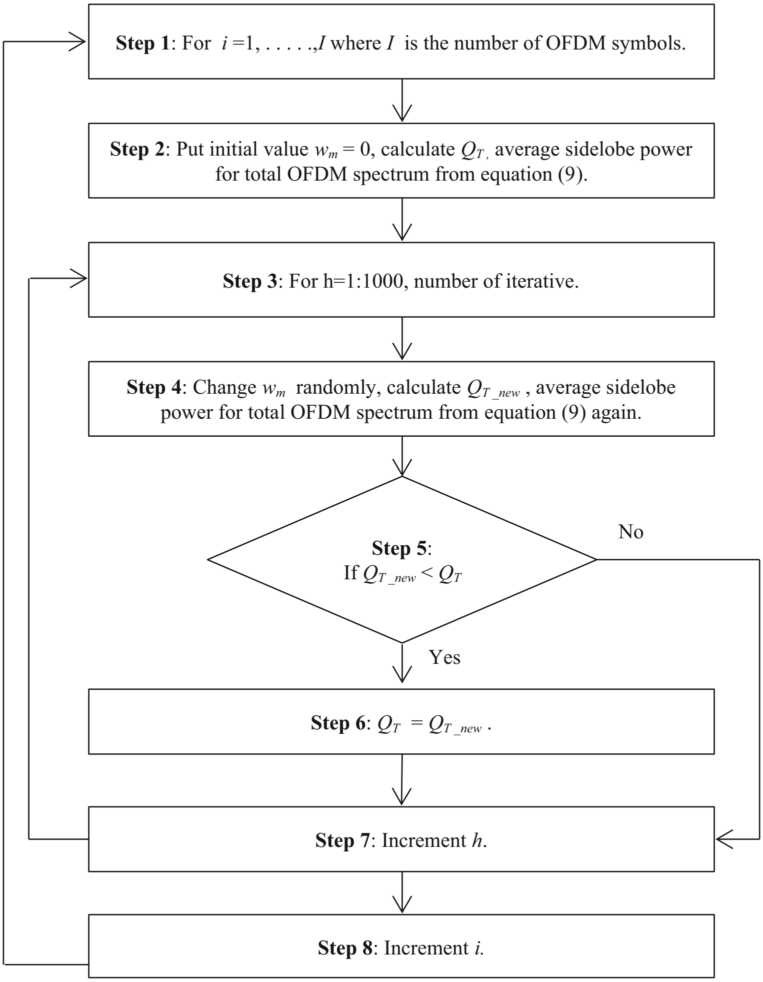


Fig. 3 Flow chart of the technique used for choosing the minimum sidelobe power

4 Simulation Results

4.1 The Proposed Technique

NC-OFDM signals with random distributions of 64 subcarriers including CCs are used in our simulation. This simulation focuses on comparing with the previous techniques and testing the effectiveness of the proposed technique on sidelobe suppression, PAPR reduction, and bit error rate (BER) performance. The details of the Implementation parameters of the proposed technique are included in Table 1.

The comparison between the performance of the original CC and ACC with SSE is shown in Fig. 4. The normalized power spectral density of original NC-OFDM with 64 subcarriers is compared with original CC technique with adding 4 CCs and proposed ACC with SSE technique with also adding 4 CCs and the phase difference is 3pi/4. In this case, we assume that the input data only consists of ones and each subcarrier is modulated with BPSK symbol whose power is normalized to $|X_n|^2 = 1$. As this modulation is real value therefore, the weighting factors of CCs are also real value. The same assumptions in the original CCs in [7] are taken in this case for accurate comparing the two techniques. These assumptions are applied in this case only while the rest of simulations have other parameters and other circumstances. This figure shows that the proposed technique is more efficient than the original CC technique in sidelobe suppression. The power of the sidelobes that lays outside the transmission bandwidth averaged over 64 sidelobe can be suppressed by 29 dB for original CC and 43.7 dB for proposed technique.

The sidelobe suppression for the proposed technique over the original NC-OFDM technique is shown in Fig. 5. Here 1000 random input symbol modulated with QPSK is expanded to 8-PSK then 4 CCs are added in the left and right hand side of the OFDM symbol (2CCs in each side) and the phase difference is 3pi/4. Normalized power spectral density is computed for the two techniques and the average power of sidelobes in the two sides are also computed. In Fig. 5a, the number of subcarriers used is 16 subcarriers. This figure shows that the sidelobe power is reduced efficiently, while the average power of sidelobes over 16 sidelobe is reduced by 35.5 dB from the original NC-OFDM in the average case. In Fig. 5b the average sidelobe power over 64 subcarriers is reduced by 34.8 dB from the original NC-OFDM.

Table 1 Implementation parameters of the proposed technique

Parameter	Value
Number of subcarriers	60
Number of cancellation carriers	4
Pilot subcarriers	4
Modulation scheme	QPSK
Expanded modulation scheme	8-PSK
Phase difference	3pi/4
Number of iteration	1000
fc (GHz)	5.003
Sampling time	2 μs
Tg/T0	1/8

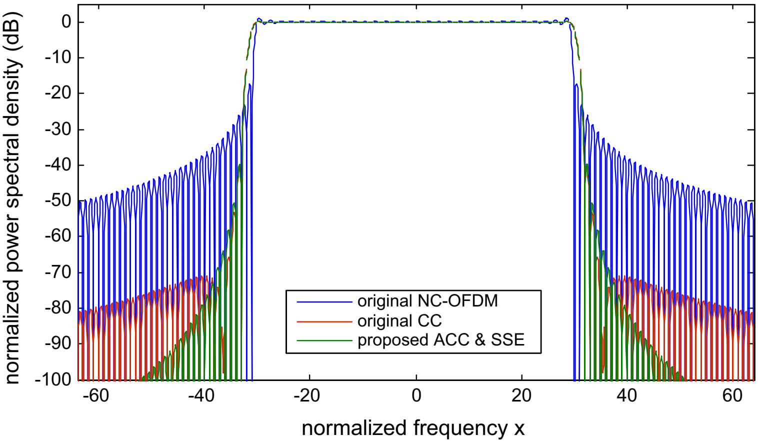


Fig. 4 Comparison between the original CC and the proposed (ACC with SSE)

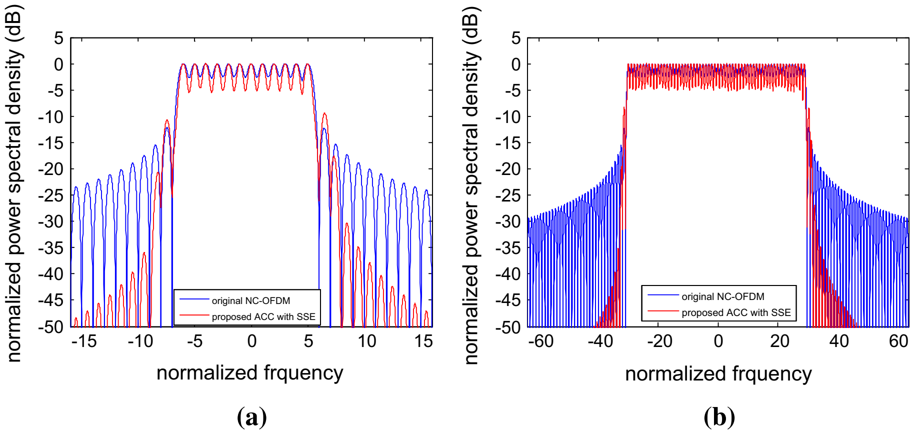


Fig. 5 Sidelobe suppression in proposed (ACC with SSE) technique compared with original NC-OFDM at **a** $N = 16$, **b** $N = 64$

The simulations of PAPR that are given in terms of CCDF will be shown. The CCDF is defined as the probability of exceeding the PAPR of an NC-OFDM signal over a given threshold PAPR_0 as,

$$\mathrm{CCDF}(\mathrm{PAPR}(\mathrm{x})) = \Pr(\mathrm{PAPR}(\mathrm{x}) > \mathrm{PAPR}_0). \quad (10)$$

Figure 6, shows the variation of CCDF with PAPR for different number of subcarriers $N = (16, 64, 128, 512)$. This Figure shows the performance of original NC-OFDM technique and proposed ACC with SSE technique. For 16 subcarriers the PAPR reduction from original NC-OFDM at CCDF $= 10^{-3}$ is about 3.9 dB Moreover, It decreased by 4.4, 4.6, and 5 dB at $N = 64$, 128 and 512, respectively.

The simulation of CCDF with PAPR for the original NC-OFDM and the ACC with SSE under different values of phase shift difference Φ is shown in Fig. 7. While changing the

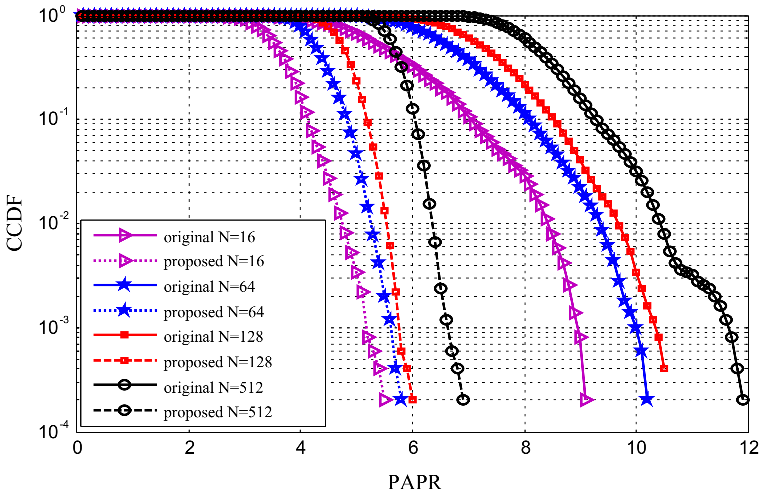


Fig. 6 CCDFs of PAPR for original NC-OFDM and proposed ACC with SSE for different values of *N*

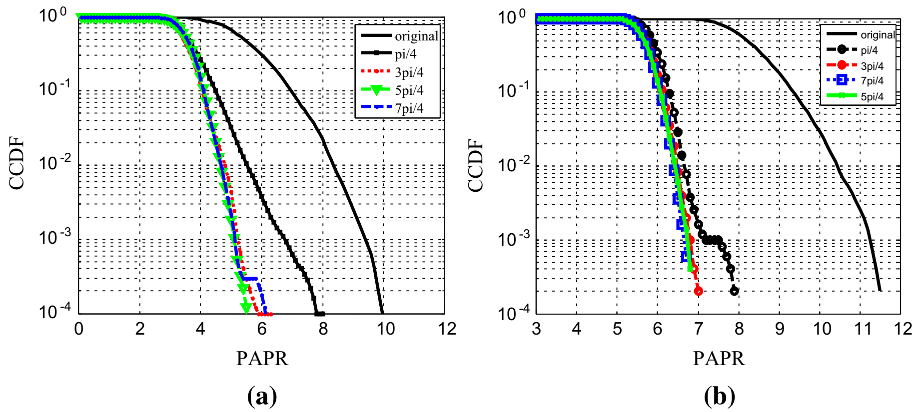


Fig. 7 CCDFs of PAPR for original NC-OFDM and the proposed (ACC with SSE) for different values of Φ. **a** $N = 16$, **b** $N = 64$

value of Φ that is used, changes the PAPR. In Fig. 7a the number of subcarriers used is 16. Also this figure shows that at Φ = pi/4 the PAPR reduced by about 2.5 dB from original NC-OFDM at CCDF = 10^{-3}. From this figure, we can also conclude that the PAPR at Φ = 3pi/4, 5pi/4, and 7pi/4 are approximately at the same range and reduced by about 4.2 dB at CCDF = 10^{-3}. Figure 7b shows that 64 subcarriers are used and also at Φ = pi/4 the PAPR reduced by about 3.6 dB from the original NC-OFDM. At Φ = 3pi/4, 5pi/4, and 7pi/4, PAPR gives approximately at the same range and reduces by about 4.8 dB. These figures also shows that using Φ = 3pi/4 is better than using Φ = pi/4 while at Φ = 3pi/4 gives more reduction than any other value.

The performance of the signal to noise ratio (SNR) with bit error rate (BER) under Additive White Gaussian Noise (AWGN) channel for original NC-OFDM and the proposed (ACC with SSE) techniques is shown in Fig. 8a, where 512 is the number of subcarriers used in this case and $\Phi = 3\text{pi}/4$. As a result of reduction of joint PAPR and sidelobe power, the BER performance is reduced. From this figure, we can conclude that the SNR increased by about 7.5 dB from the original NC-OFDM at BER $= 10^{-2}$. Figure 8b shows the performance of the BER of the original and the proposed techniques under (Rayleigh fading) channel while independent identically distributed Rayleigh fading is assumed for each carrier. The SNR increased by about 7 dB from the original NC-OFDM at BER $= 10^{-2}$.

Another representation of mean power spectral density is CCDF which is shown in Fig. 9. The CCDF is defined as the probability of exceeding the mean power spectral density of an NC-OFDM signal over a given threshold. The relation between the CCDF and threshold is shown. While this figure shows the sidelobe reduction for the proposed ACC with SSE reduction over original NC-OFDM at 64 subcarriers and $\Phi = 3\text{pi}/4$.

4.2 The Modified Technique

The proposed (ACC with SSE) technique has two main problems. The first is increasing the computational complexity because of computing the PAPR for the all different combinations. The second is the transmitted signal power needs to be increased due to the amount of power that is spent in cancellation carriers and is not available for data transmission. This increasing in power causes degradation in bit error rate (BER) performance. To overcome these problems, a modified technique is proposed.

For reducing the complexity, the modified technique divides OFDM symbols into three groups as shown in Fig. 10. Instead of applying the SSE on the all subcarriers as mentioned previously, the modified technique applies the SSE on L subcarriers only and the rest $N - L$ subcarriers carry the original signal. Therefore, the computational complexity reduces due to reducing the number of combination used to compute the PAPR. SSE may be applied with two methods, the first method is expanding the first and last $L/2$ subcarriers of each OFDM symbol as shown in Fig. 10. The second method is expanding every 2, 4, or 6

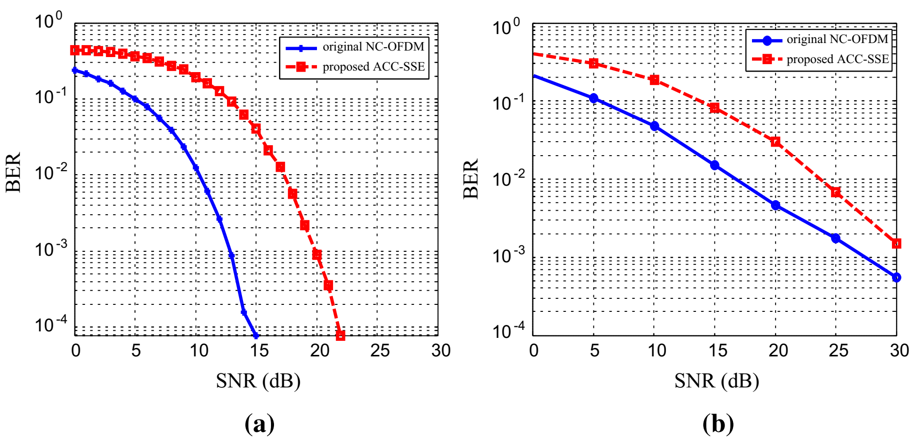


Fig. 8 Performance of SNR with BER for the original NC-OFDM and the proposed (ACC with SSE). **a** Under additive white Gaussian noise channel. **b** Under Rayleigh fading channel

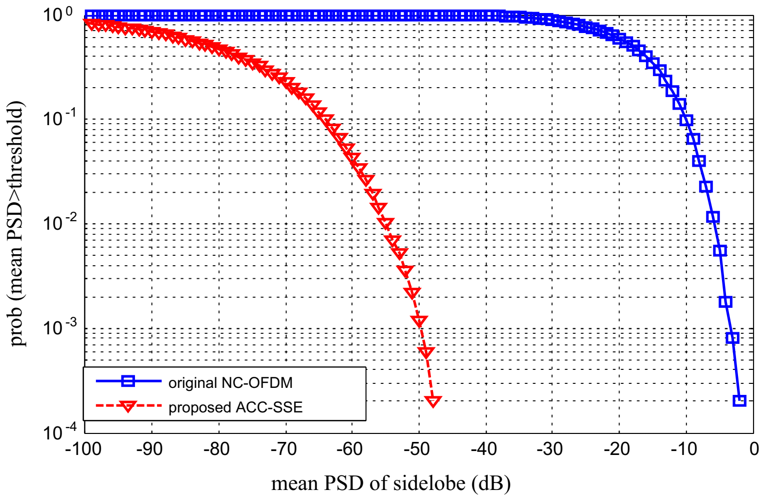
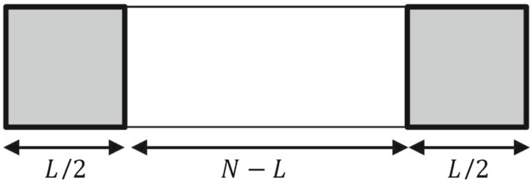


Fig. 9 CCDF of sidelobe power for original NC-OFDM and proposed ACC with SSE

Fig. 10 OFDM symbol structure in the modified technique



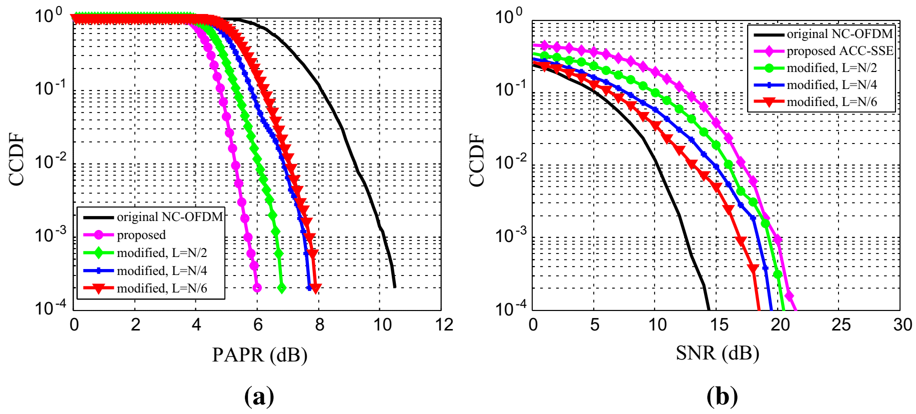


Fig. 11 Comparison between the original, the proposed (ACC with SSE), and its modified version. **a** CCDF with PAPR performance. **b** Performance of BER with SNR

subcarriers only. In this modified technique the first method is used for expansion while the two methods are convergent and give approximately the same range.

After that, the ACC technique is applied by adding M CCs that do not carry any information in the left and right hand side of OFDM spectrum with optimized weights.

This optimized weights is calculated to cancel out the sidelobes of the original OFDM signal as the previous sequence shown in Fig. 3.

On the other side, the power spent in CCs can be limited to a certain value to keep the power in the acceptable range and do not waste it. This modified technique alleviates the performance degradation of BER and reduces the amount of complexity, but the amount of PAPR and sidelobe power reduction might be smaller than unmodified technique.

The comparison between the proposed technique and its modified version is shown in Fig. 11. The number of subcarriers used here are 64, and the phase difference is 3pi/4. The modification is based on applying the SSE on L subcarriers and limitation on the power spent in CCs to a certain range to reduce the power. Figure 11a shows the CCDF of original NC-OFDM, proposed ACC with SSE, and its modified version with different value of L, while L is the number of modified subcarriers. Here $L = N/2, N/4$, or $N/6$ is used as shown in the figure while, the increase of L leads to more reduction of PAPR until $L = N$ which is the case of the proposed technique and it gives the maximum reduction. Figure 11b shows the performance of BER with SNR in AWGN channel for proposed technique and its modified version with different values of L. Increasing of L, causes improvement in BER performance that is the aim of the modified version while at BER $= 10^{-2}$, the proposed technique increases SNR by about 7 dB but modified version increases SNR by about 5 dB at $L = N/4$.

There is a tradeoff between PAPR reduction and BER performance, while increasing L, leads to improve in BER performance but reduces the PAPR. Therefore, we must compromise between the PAPR and BER to achieve our requirements. The tradeoff between the PAPR and BER is due to the PA that operates in the linear region in order to reduce the PAPR but this increases the BER. While operating the PA in the saturation region causes improvement in BER performance but reduce the PAPR.

Table 2 Comparative study between the simulation results of the different simulation techniques (original NC-OFDM, proposed (ACC with SSE), and its modified)

	Original NC-OFDM technique	Proposed (ACC with SSE) technique	Modified version
(a) Case N = 16			
PAPR at CCDF = 10^{-3}	9 dB	5.1 dB	6.9 dB
SNR at BER = 10^{-2} and $L = N/4$	10.5 dB	17 dB	14 dB
CPU time	3.45 min	20.25 min	19.15 min
Transmitted power	Normal power	Increased power	Reduced power
Complexity	Not complex	Slightly complex	Reduced than the proposed
(b) Case N = 64			
PAPR at CCDF = 10^{-3}	10.1 dB	5.7 dB	7.5 dB
SNR at BER = 10^{-2} at $L = N/4$	10 dB	17 dB	15 dB
CPU time	5.20 min	30.40 min	27.20 min
Transmitted power	Normal power	Increased power	Reduced power
Complexity	Not complex	Slightly complex	Reduced than the proposed

Table 2 presents a comparative study between the simulation results of the different simulation techniques (original NC-OFDM, proposed (ACC with SSE), and its modified version). In this comparison the phase shift is 3pi/4. Table 2a, b show the comparisons for the cases of $N = 16$ and 64 respectively. The proposed and its modified version show the tradeoff between the PAPR and the BER performance. The modified version reduces the complexity and the transmitted power than the proposed technique.

5 Conclusions

In this paper, an efficient technique was proposed that reduced both the PAPR and the sidelobe power for NC-OFDM based on cognitive radio. This technique combines (ACC and SSE) which reduced the PAPR by 3.9 dB for 16 subcarriers and 4.4 dB for 64 subcarriers compared with original NC-OFDM. The modified version of the proposed technique reduced the PAPR by about 3.1 dB at 16 subcarriers and 3.3 dB for at 64 subcarriers. This means that the modified version gives little reduction for PAPR while gives more improvement in BER. The SNR increases by about 7.5 dB for the proposed technique and by about 5 dB for the modified version for 64 subcarriers at L = N/4. There are a conflict between PAPR reduction and BER. The modified version reduced the transmitted power than the proposed technique while gives low complexity.

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