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ORIGINAL ARTICLE

SIDELOBE SUPPRESSION FOR OFDM SYSTEMS USING MODIFIED SEQUENCING OF SYMBOLS FROM EXPANDED CONSTELLATION

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ABSTRACT: Orthogonal frequency division multiplexing (OFDM) is a main multicarrier modulation that used in recent years because it has high spectral efficiency but, OFDM suffers from high sidelobes. In this letter, we propose a new method for sidelobe suppression of OFDM modulation that based on the previously introduced Constellation Expansion (CE) method. CE is one of the methods for reduction of OFDM sidelobes that has a good performance. In CE, no side information needs to be transmitted and it doesn't involve complex optimization problem but, it has an increment in the bit error rate (BER) and peak to average power ratio (PAPR) parameters. CE method uses the iterative algorithm and in this algorithm, the different sequences of symbols of extended constellation are randomly selected and examined to achieve a sequence with desired sidelobe power. If the number of subcarriers is large, we have to test a very large number of sequences to obtain the proper one. Here, we present an algorithm for symbol by symbol construction of appropriate sequence in extended constellation that called Modified Sequence CE (MS-CE). Simulation results show that the MS-CE has a sidelobe reduction performance better than CE with much lower computations. Moreover, MS-CE does not have significant impacts on the system parameters such as BER and PAPR.

Keywords: OFDM, sidelobe suppression, constellation expansion, power spectrum.

INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation that has been a prime candidate for many recent communication systems. OFDM has high spectral efficiency and is robust against channel imperfections (Weiss and Jondral, 2004). Recently, high demands for scarce spectrum resources forced us to use overly systems such as cognitive radio (CR). In CR systems, the white space of licensed frequency band utilizes for secondary users (SUs). OFDM system does not require continuous frequency spectrum therefore, it is one of the best candidates for the CR system (Weiss and Jondral, 2004; Mitola, 1999). On the other hand, OFDM suffers from high sidelobes power level that radiates to Out-Of-Band (OOB) and interferes with licensed users (LUs). Therefore, the sidelobe of SUs signals need to be suppressed sufficiently in order to enable coexistence between SUs and LUs (Weiss et al., 2004).

The first two methods for sidelobe suppression include the windowing of transmitted signal in time domain and insertion of a frequency guard band. But, the first method causes that the transmitted signal expands in time domain and latter method wastes the scarce bandwidth (Weiss et al., 2004). The other methods include: Insertion of cancellation carriers (CCs) (Brandes et al., 2006) that, it has complex optimization problem to determine the CCs index and a number of subcarriers sacrifice in this method. Subcarrier weighting (SW) (Cosovic et al., 2005) that, it involves complex computation proportional with the number of subcarriers and degradation in BER performance. Constellation expansion (CE) (Pagadarai et al., 2008) that, in this method the symbol mapped into a higher constellation but, it has to tradeoff in the increase of the number of iterations and the sidelobes reduction because it uses iterative algorithm. The other sidelobes reduction methods exist such as multiple choice sequences (MCS) (Cosovic, Janardhanam, 2005), carrier by carrier partial response signaling (Naghsh, Omidi, 2010), adaptive symbol transition (AST) (Hisham et al., 2008) and constellation adjustment (CA) (Li et al., 2009). But every of them, inside of their advantages have shortages in degradation of system performance, complexity of computation and level of the sidelobes reduction.

In the CE method, the signal constellation will be expanded such that each symbol can be mapped to two points. For a sequence of symbols, there will be several available sequences in extended constellation with different sidelobes power level. If the length of the sequence is large, the number of available sequences will be very high and the complete search for selection the best sequence has a very large computation. Therefore, a limited number of sequences are selected and tested to choose a proper sequence. If the receiver knows the mapping rule, no side information needs to be transmitted.

In this letter, we propose a new algorithm to construct step-by-step a proper sequence of symbols from extended constellation. The algorithm is referred to the MS-CE.

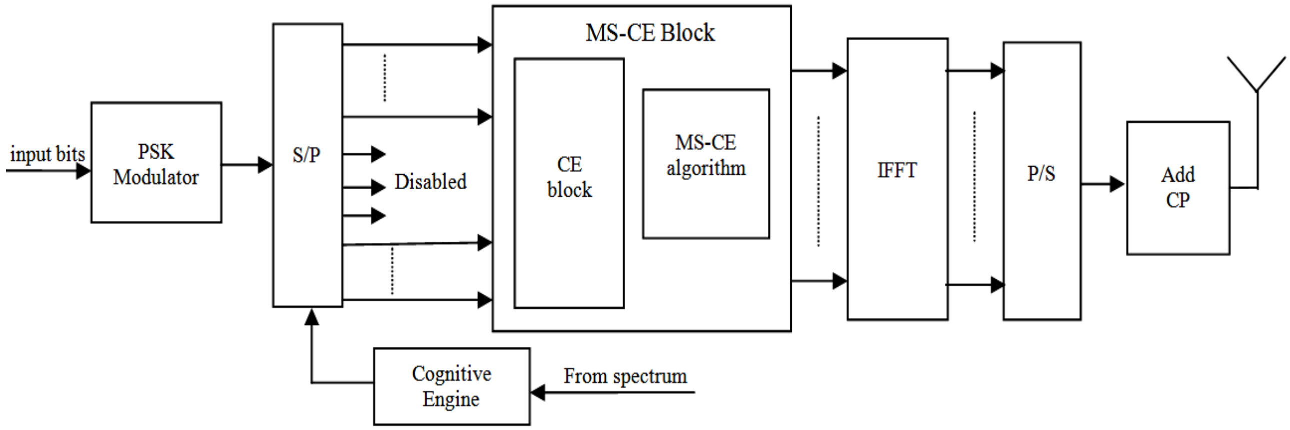

Fig. 1 Block diagram of transmitter for OFDM based CR with using MS-CE method

SYSTEM MODEL WITH USING MS-CE BLOCK

Fig. 1 illustrates the block diagram of CR transmitter that used OFDM and MS-CE method for reduction of the sidelobes. At the transmitter of the OFDM system, the input bits are first modulated to symbols and then, split into *N* parallel data stream in serial-to-parallel (S/P) converter, where *N* is the number of OFDM subcarriers. Cognitive engine block senses the spectrum for detection of the LUs and then, disables the frequency index related to LUs in S/P converter. The remaining active subcarriers are fed into the CE block that in this unit, the symbols map to extended constellation and then, the MS-CE algorithm selects the sequence of *N* symbols with a low OOB radiation. The inverse fast fourier transform (IFFT) applies to the selected sequence and cyclic prefix (CP) is added to signal followed by the parallel-to-serial (P/S) converter. The length of the CP should be greater than the channel delay in order to combat with inter-symbol-interference (ISI).

At the receiver, the inverse of operation that used in transmitter performs. At the first, the CP of signal discard and after S/P conversion, the fast fourier transform (FFT) applies. Then with using P/S converter, the symbol sequence is ready for demodulation. With assumption of that the extended constellation is known for receiver, no side information needs to be transmitted.

The OFDM signal spectrum consists of *N* Sinc functions that, every Sinc function carries one data symbol. Therefore, the sidelobe power level is given by [8]:

$$\mathrm{S}(x)=\sum_{n=1}^{N} d_n \frac{\sin(\pi(x-x_n))}{\pi(x-x_n)} \qquad (1)$$

Where $S(x)$ is the OFDM signal spectrum, d_n is data symbol, N is the number of subcarriers and x is the normalized frequency which is given by:

$$x=(f-f_0)T_0 \qquad (2)$$

where f_0 is the center frequency, T_0 is the OFDM symbol duration and x_n represents the normalized frequency of the nth subcarrier.

CONSTELLATION EXPANSION (CE) METHOD

The constellation expansion is a new method in reduction of OFDM sidelobes. In fact, this method uses an idea that, the different symbol sequences have different sidelobes power. CE method consists of two parts. In the first, the symbols map to the extended constellation with use of a proper map and then with use of iterative algorithm, the best sequence of symbols which has minimum sidelobes power selects for transmission.

In constellation expansion that proposed in reference (Pagadarai et al., 2008), the constellation is extended for new sequences production of the symbols. Assume that, we used a MPSK modulation scheme that every K bits are modulated into one symbol therefore, the constellation consists of 2^K points. In CE, every point of constellation is mapped to two points in an extended constellation and we have two choices for every symbol. Therefore, the extended constellation consists of 2^{K+1} points. With assumption that, the receiver is aware of the relationship between the main constellation and the extended constellation; no side information needs to be transmitted.

We consider an OFDM system with N subcarriers and we have two choices in extended constellation for every symbol therefore, the 2^N new sequences produce with different sidelobes power and the best sequence can be chosen. In reference (Pagadarai et al., 2008), an iterative algorithm is used and by computation of the sequences sidelobes power, the sequence that has minimum sidelobes power chooses for transition. By considering the high number of iterations, this approach leads to high computation for system. So, there is a tradeoff in the increase of the number of iterations and the sidelobes reduction. In (Pagadarai et al., 2008), the iteration number is chosen 64.

The CE method consists of two parts that the first part depends on the selected map for symbols. This map affects on the reduction of sidelobes and increment of BER directly. In CE method, we have two points in extended constellation for every symbol that, the selected map determines the position of these two points. If the positions of these two points are in same quadrant, the degree of freedom decreases for production of the symbols sequence and if these two points have further difference in real or imaginary part, the degree of freedom increases and therefore, we obtain further sidelobes reduction.

In fig. 2, the mapping of the BPSK constellation to the QPSK constellation is shown. The extended symbols have the maximum difference with together and therefore produce the best degree of freedom. The extended constellation points can be considered as union of the sets CE1 and CE2 where CE1= {a1, b1} and CE2= {a2, b2}.

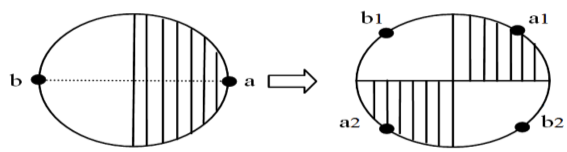

Fig. 2 The mapping from the BPSK constellation to the QPSK

The mapping of the QPSK constellation to the 8PSK constellation is shown in Fig. 3. The extended constellation points can be considered as union of the sets CE1 and CE2 where CE1= {a1, b1, c1, d1} and CE2= {a2, b2, c2, d2}. In this map the extended symbols have maximum difference with together same as the fig. 2 because they have different sign in real and imaginary parts. But in fig. 4, the extended symbols have same sign in real and imaginary parts and therefore this map has minimum degree of freedom. In simulations, we use map of the fig. 3 for QPSK modulation that has the best sidelobes reduction.

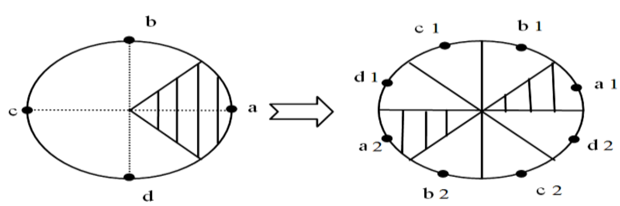

Fig. 3 The mapping from the QPSK constellation to the 8PSK with different sign in real and imaginary parts for extended symbols

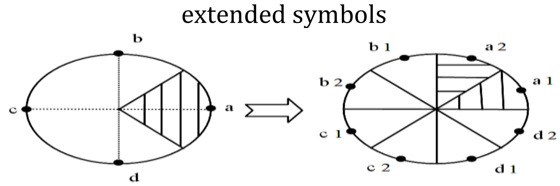

Fig. 4 The mapping from the QPSK constellation to the 8PSK with same sign in real and imaginary parts for extended symbols

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MS-CE METHOD

The main demerit of the CE method is that all of the available sequences should be examined to select the sequence that has minimum sidelobes power. To overcome this demerit, the calculation of the sidelobes power is performed for a limited number of all sequences (e.g. 64 sequences in (Pagadarai et al., 2008)).

In this letter, a special sequencing of symbols in the CE algorithm which is referred to the MS-CE (that is the abbreviation of the Modifies Sequencing CE), is proposed. In this algorithm, the best sequence in extended constellation is chosen via a symbol-by-symbol selection method.

The four vital basis that MS-CE algorithm is based on them are: the sidelobe power is square of the sidelobe magnitude; the sidelobe magnitude for every subcarrier has a Sinc function form; at points out of the allowed frequency band, the sidelobes of two adjacent subcarriers have different signs; and finally, the subcarriers which are near to the edge of the allowed frequency band, have the most effect in sidelobe power. As a matter of fact, the MS-CE attempts to reduce the sidelobe of each subcarrier by the next subcarrier.

A brief schematic of the MS-CE algorithm is shown in Fig. 5. First of all, according to this figure, the symbols are mapped from MPSK to 2M-PSK constellation properly. The algorithm commences to select the symbol at the N^{th} subcarrier which is located at the edge of the used bandwidth.

The MS-CE consists of two main stages (illustrated with k variable in Fig. 5). At the first stage, the symbol of N^{th} subcarrier is selected from CE1 but for $(N-1)^{th}$ subcarrier, every two choices of the related symbol from the CE1 and CE2 are examined. At both time, algorithm calculates the total sidelobes power just for the N^{th} and $(N-1)^{th}$ subcarriers and selects the symbol that has minimum sidelobes power. In following, for other subcarriers this scheme performs but for n^{th} subcarrier, the total sidelobes power calculates just for $\{N, N-1, ..., n\}^{th}$ subcarriers.

At the second stage (k=2), the same process is carried out; however this time, the N^{th} subcarrier symbol is selected from CE2. Finally, we have two sequences S_1 and S_2, at the end of these two stages, and then the one with the smaller sidelobes power is selected. This procedure is repeated for every OFDM symbols.

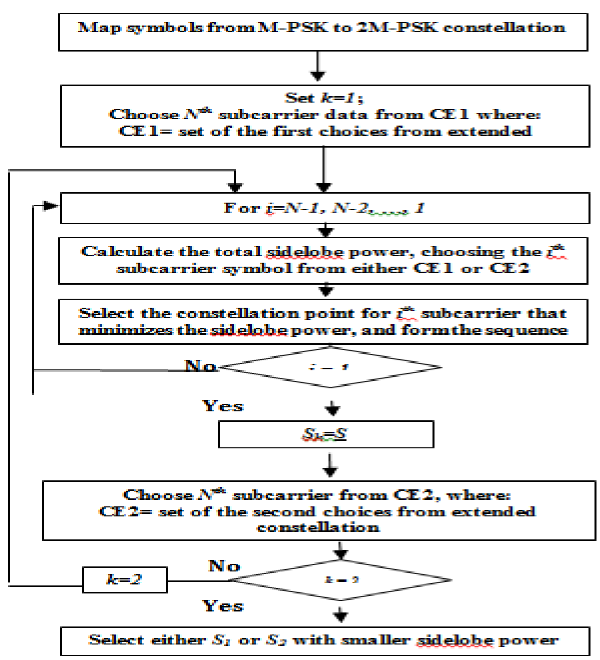

Fig. 5 The MS-CE algorithm

The MS-CE method uses every subcarrier sidelobes for reduction of the prior subcarriers sidelobes. In each step, the sidelobes power is calculated twice for every subcarrier (except for the symbol of N^{th} subcarrier) and finally, sidelobes power is calculated for two sequences. Therefore, the number of sidelobes calculations is given by the following relationship:

$$2\times[(N-1)\times 2]+2=4N-2 \quad (3)$$

In conventional CE method, all of the 2^N sequences should be evaluated in ideal manner to select the best sequence with minimum sidelobes power. In Table I, the number of sidelobes power calculations for two methods are compared for different number of subcarriers. It is notable that the ideal CE is almost impractical, because of the huge number of calculations.

Table 1: Comparison between the ideal CE and the MS-CE method

Number of subcarriers	Number of ideal CE calculation	Number of MS-CE calculation
64	1.84×10^{19}	254
128	3.4×10^{38}	510
256	1.15×10^{77}	1022

SIMULATION RESULTS

In this section, an OFDM system with *N=8* subcarriers is considered for accomplishing a comparison between the ideal CE (i.e., examined all 2^N possible sequences) and the MS-CE method. Moreover, an OFDM system with *N=128* subcarriers is considered for comparison of the CE with 64 randomly selected sequences and the MS-CE method.

In other word, two separate comparisons for better clarification are accomplished i.e., the MS-CE method is compared, at first, with the ideal CE (in OFDM system with N=8 subcarriers); and then, with the CE including 64 sequences (in OFDM system with 128 subcarriers). All of the results shown are averaged over 2500 OFDM symbols. The BPSK and QPSK modulations are used in simulations and their extended constellation are QPSK and 8PSK respectively.

In Fig. 6 and 7, the normalized Power Spectral Density (PSD) of the OFDM signals with *N=8* subcarriers are illustrated for the following three cases, original signal (i.e., without sidelobe suppression), the ideal CE method (with 2^N sequences), and the MS-CE method. For the ideal CE method, all of the 2^8 available sequences are examined for every OFDM symbol. The simulation results show that the difference between MS-CE method and ideal CE is in average equal to approximately 1.5 and 3dB in peaks of sidelobes for BPSK and QPSK respectively.

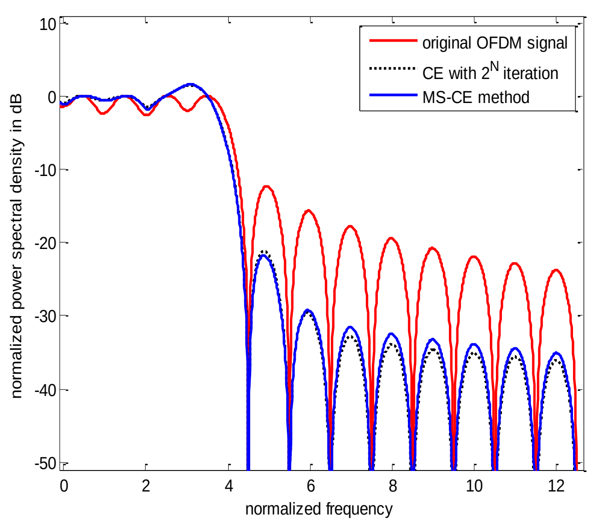

Fig. 6 Power spectrum of original OFDM signal, the CE with 2^N sequences and the MS-CE method with BPSK modulation

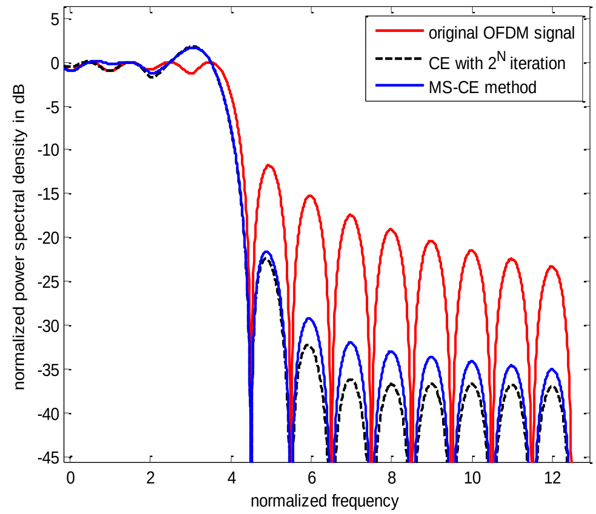

Fig. 7 Power spectrum of original OFDM signal, the CE with 2^N sequences and the MS-CE method with QPSK modulation

In Fig. 8 and 9, the PSD of the OFDM signals with *N=128* subcarriers are illustrated for the original OFDM signals, CE method with 64 sequences (Pagadarai et al., 2008) and the MS-CE method. The simulation results show that the MS-CE method reduces the sidelobes level in average about 28dB in peaks of sidelobes for both of the BPSK and QPSK modulations and it has a better performance than the CE method, which can be seen by a difference of approximately 16dB in peaks of sidelobes. This significant reduction represents that the MS-CE method has an effective performance in sidelobe reduction.

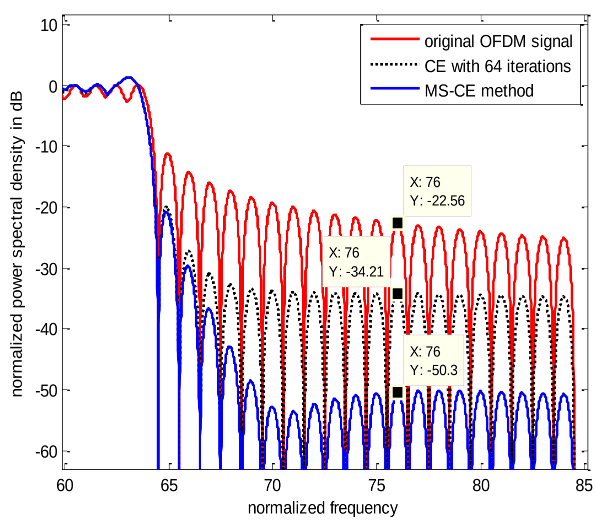

Fig. 8 Power spectrum of original OFDM signal, the CE with 64 iterations and the MS-CE method with BPSK modulation

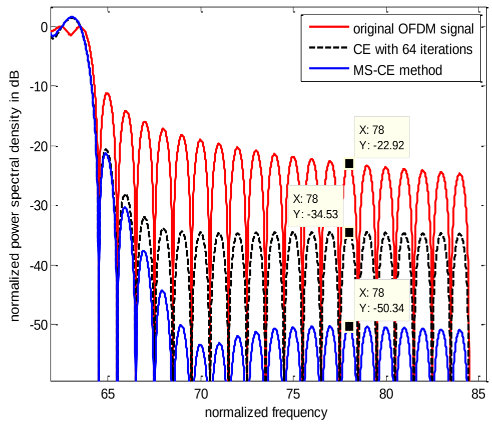

Fig. 9 Power spectrum of original OFDM signal, the CE with 64 iterations and the MS-CE method with QPSK modulation

In Fig. 10, the interference suppression is shown in the one spectrum sharing scenario. In this scenario, we have two license users that include 'a' and 'b'. The 'a' and 'b' license users have 11 and 17 subcarriers respectively. In addition, there are three secondary users include 'A', 'B' and 'C' that they utilize the white space in this scenario. The 'A', 'B' and 'C' secondary users have 30, 64 and 40 subcarriers respectively. In this scenario, the QPSK modulation is used.

In Fig. 10, the PSD of the OFDM signals are illustrated for the original OFDM signals and the MS-CE method. The simulation results show that the secondary users (A, B, C) have the big sidelobes in license users (a, b) and it causes the interference between them. With use of the MS-CE method, the sidelobes power is reduced significantly and coexistence between the secondary and license users is enable.

In the CE method, for the symbols sequence that is selected from the higher order constellation, degradation in the BER and Peak to Average Power Ratio (PAPR) is expected. However, this degradation is not significant (Pagadarai et al., 2008). The MS-CE does not cause any additional degradation compared to the CE method. This is because the MS-CE method differs from the CE only in the sequence selection algorithm.

In Fig. 11 and 12, the BER plots of an OFDM system with 32 subcarriers, modulated with QPSK modulation; are considered for different SNRs and are illustrated for the original OFDM signals, CE method with 64 sequences (Pagadarai et al., 2008) and the MS-CE method.

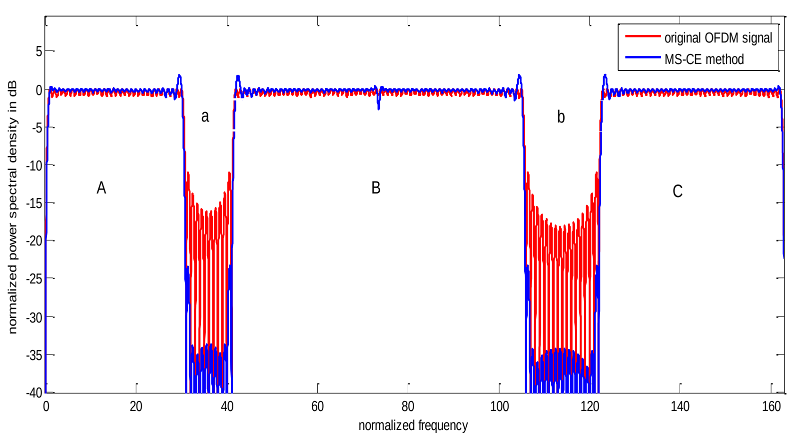

Fig. 10 Power spectrum of original OFDM signal and the MS-CE method in a spectrum sharing scenario with two LUs and three SUs with QPSK modulatio

In figure 11, the channel is assumed to be AWGN but in figure 12, the used channel is a five-tap Rayleigh channel that its taps gain include [1/2 1/4 1/6 1/20 1/30]. The simulation results show that the MS-CE and the CE methods have the same degradation in BER parameter.

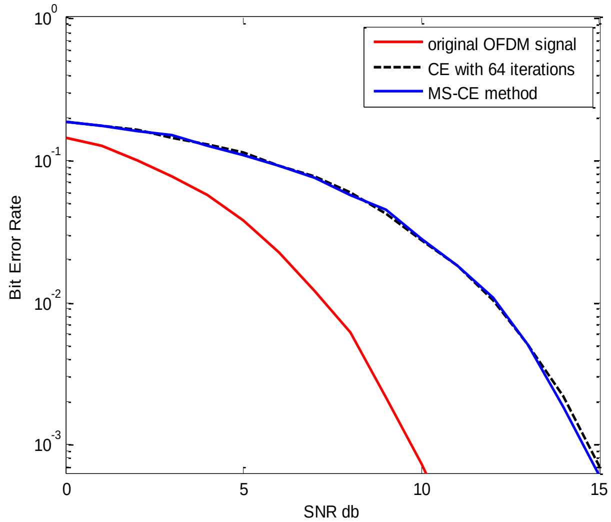

Fig. 11 BER plot with AWGN channel for original OFDM signal, CE with 64 iterations and MS-CE method with QPSK modulation

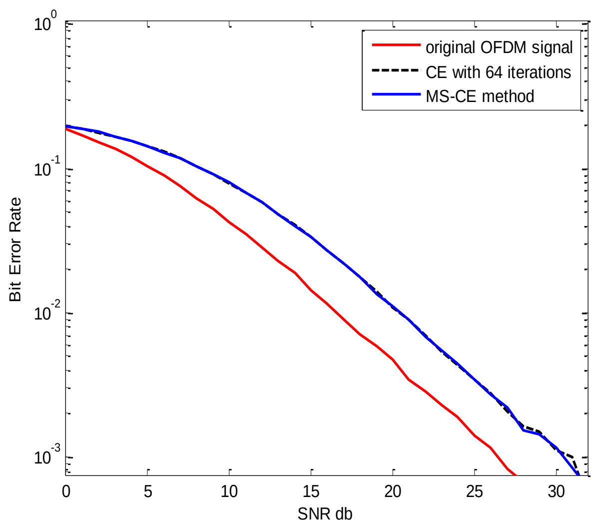

Fig. 12 BER plot with Rayleigh channel for original OFDM signal, CE with 64 iterations and MS-CE method with QPSK modulation

In Fig. 13, the PAPR plot is shown for OFDM signal with 32 subcarriers and modulated with the QPSK modulations. Simulation results show that the MS-CE method has the degradation in PAPR parameter same as the CE method.

The figures 11, 12 and 13 illustrate that the MS-CE method don't increase BER and PAPR parameter compared to the CE method because MS-CE method differs with CE method just in the used algorithm but the selected map is same as the CE method and the important factor in BER and PAPR parameters is the selection of the proper map.

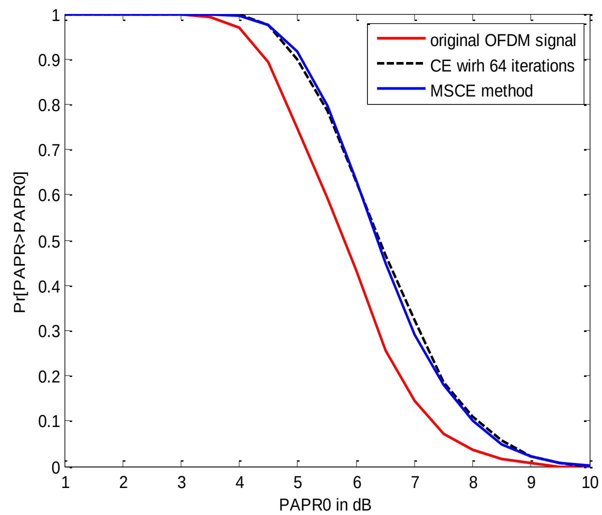

Fig. 13 PAPR plot of the original OFDM signal, the CE with 64 iterations and the MS-CE method with QPSK modulation

CONCLUSION

A method to reduce the OFDM OOB radiations, based on constellation expansion that referred to as MS-CE; is here proposed. In this method, instead of examining a large number of sequences, the best choice for every symbol in extended constellation is sequentially selected. The MS-CE significantly reduces the number of sidelobe power level computations. Simulation results show that this method has the sidelobe reduction performance better than the CE method. In the case of OFDM signal, with 128 subcarriers, the MS-CE algorithm reduces the OOB radiations about 28dB only with considering 510 sidelobe power computations. In addition, similar to the CE method, the MS-CE does not require transmission of any side information. The MS-CE method has two important advantages. It improves CE performance in reduction of OOB radiation and extremely reduces CE method calculations. The MS-CE achieves these advantages without any additional degradation compared to the CE. In addition to PSK modulation, the authors, for the time being, concentrate on the extension of this algorithm to other modulation techniques.

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