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Side Lobe Suppression in NC-OFDM Systems Using Variable Cancellation Basis Function

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ABSTRACT In non-continuous orthogonal frequency division multiplexing (NC-OFDM)-based cognitive radio system, the sidelobe suppression methods use the fixed length rectangular windowing functions for canceling carriers (CCs) like the extended active interference cancellation (EAIC) and active interference cancellation (AIC) methods. The AIC and its EAIC methods reduce the interference a lot, but the CCs in different frequency have a non-uniform assignment for sidelobe suppression. To overcome this problem a novel variable basis function proposed in which the CCs are grouped by frequency positions and modeled with different waveforms of different length to suppress NC-OFDM side lobes effectively while reducing inter carrier interference (ICI) at the same time. Simulation results show that using variable basis functions of the proposed method, −60-dB sidelobe suppression depth is reached even with higher order 64-QAM symbol mapping and the ICI caused by the subcarriers is almost negligible.

INDEX TERMS Active interference cancellation, canceling carriers, cognitive radio, non-continuous orthogonal frequency division multiplexing.

I. INTRODUCTION

Cognitive Radio has drawn significant attention from academic and industrial communities to meet the ever growing needs for spectrum resources [1]. NC-OFDM is often employed as physical layer technology for CR networks due to its ability to exploit spectrum holes in underutilized licensed bands by adapting the parameters of wireless communication systems intelligently according to the communication environment. However, the spectrum of NC-OFDM signal sidelobe may cause severe interference to the licensed user [2]. Therefore most researchers have provided various solutions to reduce the interference.

Although the NC-OFDM based CR system has many advantages, there are still some challenging issues remained unsolved in the design of the system. One of its main drawbacks is the large spectrum sidelobe. In [3], time domain windowing method is used to suppress the side lobes. However, the windowing technique is a more robust solution with lower complexity. This comes at the cost of an increase in the symbol duration which reduces the spectral efficiency. Adaptive symbol transition [4] is similar to the windowing method, but in adaptive symbol transition the OFDM symbols are extended in time to reduce the effect of symbol transition, the transition signal is optimized adaptively for each symbol to improve the sidelobe suppression effect, but it is subjected to more computational complexity. Constellation expansion method [5] and spectral pre-coding method [6] degrades the cognitive user bit error rate (BER) and the spectrum efficiency. Active Interference Cancellation (AIC) [7] generates an interference cancellation signal to reduce the NC-OFDM side lobes and to enhance spectral efficiency, but the depth of the side lobe suppression needs to be still improved. Although, Optimization Cancellation Carrier Selection (OCCS) method [8] optimize the cancellation carrier (CC) locations, it requires a large (up to 19 carriers) frequency bands for CC insertion, thereby reducing the spectrum efficiency, limited sidelobe suppression depth (only −43dB) and increase the computational complexity. Extended Active Interference Cancellation with Cyclic Prefix (EAIC-CP) [2] and Extended Active Interference Cancellation with

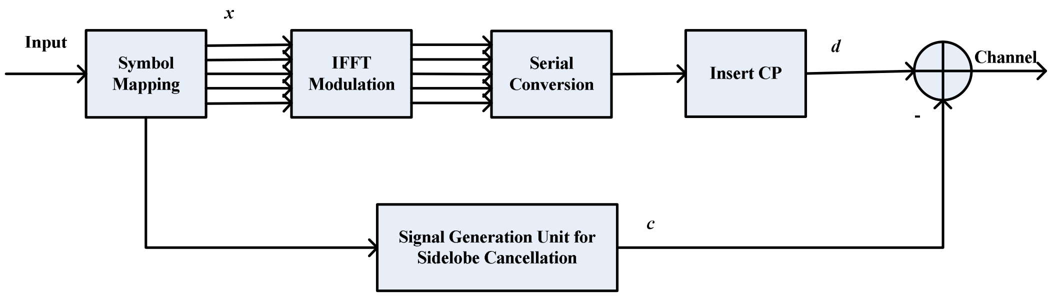

FIGURE 1. **NC-OFDM system with active interference suppression model.**

Self-Interferences Constraint (EAIC-IC) [9] method increases the length and density of the CC, thus increasing the side lobe suppression effect, but the introduction of interference cancellation signals to NC-OFDM signals results in large ICI.

This study found that, in the active interference suppression methods, the CCs inserted at different frequency positions to suppress the NC-OFDM sidelobes is not exactly the same. Existing active interference suppression methods are not taken into account this feature, using the equal length rectangular shape basis function. In this paper, CC are grouped by frequency positions and shaped with different waveforms of different length to suppress NC-OFDM side lobes effectively while reducing ICI at the same time. The simulation results show that the variable interference cancellation basis function design proposed in the NC-OFDM signal reduces the sidelobe with almost negligible SNR loss. These proposed implementations are also suitable for medical telemetry applications [10].

II. SYSTEM MODEL

Fig.1 illustrates the equivalent discrete complex baseband NC-OFDM based CR system, the cognitive users send x symbol vector making use of the N subcarriers. To reduce interference to the primary user, the inner guard band subcarriers located near PU band in OFDM are turned off, i.e., $x(l) = 0, l \in \{l_{min} : 1 : l_{max}\}$ subcarriers index position is off. The modulated data after IFFT parallel to serial converted. And then the cyclic prefix of length L_{cp}(CP) is inserted. Thus, the baseband OFDM signal can be written as

$$d = F_d x \tag{1}$$

where F_d $(N + L_{CP}) \times N$ a matrix, N is the number of subcarriers and each element in F_d matrix is defined as $F_d(n, m) = \frac{1}{\sqrt{N}} \exp\left(\frac{j2\pi nm}{N}\right), -L_{cp} \leq n < N, 0 \leq m < N$, where n and m represent the normalized sampling time interval and normalized carrier frequency interval, respectively. The spectrum of signal d can be obtained by applying DFT and is expressed as:

$$s_d = F_{od}^{-1} d \tag{2}$$

where F_{od}^{-1} the oversampling DFT analysis matrix [3], whose elements are defined as $F_d^{-1}(m, n) = \frac{1}{\sqrt{N}} \exp\left(\frac{-j2\pi nm}{vN}\right), 0 \leq m < N, -L_{cp} \leq n < N$, where v is the oversampling factor.

Combining (1) and (2) gives

$$s_d = F_{od}^{-1} F_d x = P_d x \tag{3}$$

Although the NC-OFDM system has closed PU frequency band subcarrier, but the side lobe still leaks into the PU band, introducing interference to PU band. If the interference without suppression can be up to −13dB. The interference spectrum is given as $\bar{S}_d = S_d(l) = P_d(l, :)x$, where $l = [v(l_{\min} + b) : 1 : v(l_{\min} - b)]^T$ b is the number of guard band subcarrier at each end.

Thus, the active interference suppression methods (AIC, EAIC-IC, EAIC-CP, etc.) reduce the sidelobe of NC-OFDM signal' by active interference cancellation signal 'c'. Sidelobe canceling signal c be viewed as a group of weighted interference cancellation basis functions:

$$c = B_c w \tag{4}$$

where B_c a subcarrier interference cancellation carriers (CC) function matrix whose column constituting the group, w is a weighting factor. Active Interference Cancellation c is used to offset the spectrum $\bar{s}_d$, but the introduction of c may bring new interference. Therefore, taking into consideration interference cancellation carriers B_c and w as design optimization, it is necessary to suppress NC-OFDM signals sidelobe as much as possible and also to reduce new interference.

AIC [7] basis functions B_c^{AIC} are an orthogonal group of the same length, whose elements be written as

$$B_c^{AIC}(n, l) = \frac{1}{\sqrt{N}} \exp\left(\frac{j2\pi mn}{N}\right), \quad l = [l_{\min} : 1 : l_{\max}], \quad -L_{cp} \leq n \leq N$$

Although AIC method doesn't introduce ICI to the NC-OFDM signal, the side lobe suppression depth is limited, only if a wide guard band is employed, but this reduces the spectral efficiency. OCCS doesn't change the definition of CC, but for the insertion of CC it searches for a large set of optimal frequency positions. The EAIC-IC [9] method uses a longer and more intensive CC, its basis functions be written as $B_c^{EAIC-IC}(n, l) = \frac{1}{\sqrt{N}} \exp\left(\frac{j2\pi mn}{N}\right), l = [l_{\min} : 1/2 : l_{\max}], 0 \leq n \leq 2N$. However, EAIC-IC method increases NC-OFDM sidelobe suppression effect, but because the NC-OFDM and CC signals are non-orthogonal, the ISI is large, therefore resulting in a poor error performance of cognitive users. EAIC-CP [2] is similar to EAIC-IC, but the CC is reduced to $N + L_{cp}$, to avoid inter-symbol interference and it also reducing the side lobe suppression. In the following section, new interference cancellation basis function is derived based on the analysis of frequency position and the sidelobe characteristics. The interference cancellation basis function is grouped by frequency locations and shaped with different waveforms of different lengths to satisfy better sidelobe suppression performance while reducing new interferences at the same time.

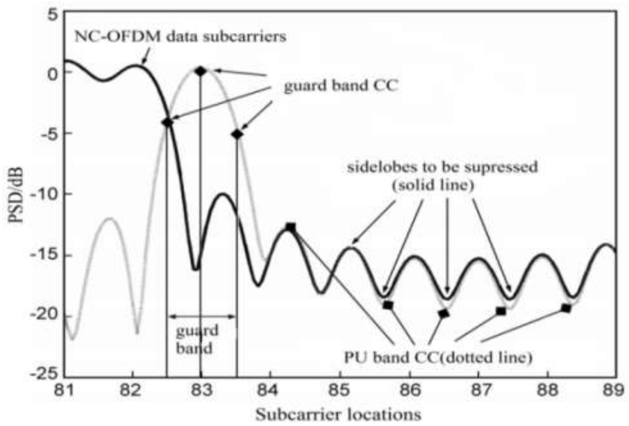

FIGURE 2. NC-OFDM subcarrier interference cancellation signal spectrum.

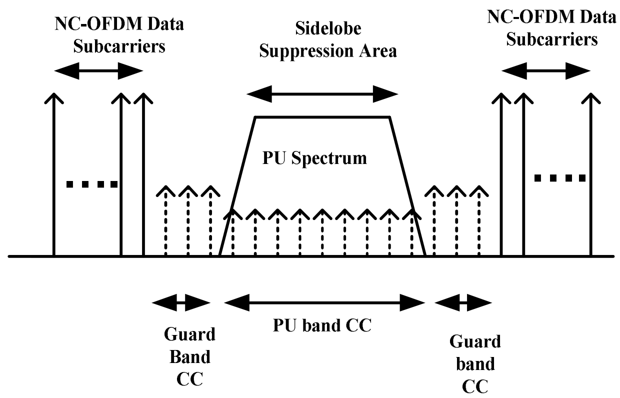

FIGURE 3. Subcarriers interference cancellation using frequency grouping.

III. A NOVEL INTERFERENCE CANCELLATION BASIS FUNCTION FOR SIDELOBE SUPPRESSION

A. THE DESIGN OF VARIABLE INTERFERENCE CANCELLATION BASIS FUNCTIONS

Fig. 2 illustrates the sidelobe spectrum of NC-OFDM signal and CC spectral characteristics; these results are obtained by simulating EAIC-IC (EAIC-CP) method. Fig.3 illustrates that the CC insertion is divided into groups based on the frequency position and energy, i.e., guard band (GU) and PU band separately. To suppress NC-OFDM sidelobe, the CC main lobe is inserted in the guard band, however NC-OFDM sidelobes cannot be suppressed directly with its main lobe, but the NC-OFDM sidelobes are suppressed indirectly with CC sidelobe, therefore it is observed that the energy of guard band CC to be larger and its energy efficiency is lower. CC inserted PU band spectrum main lobe and NC-OFDM spectrum sidelobes overlapping are closer, and its main lobe can directly reduce NC-OFDM sidelobes. Therefore it is more energy efficient, but less energy.

On the other hand, CC of guard band is closer than the CC of PU frequency band of the NC-OFDM data subcarrier, the energy is also larger, and it is more likely to cause ICI interference. Especially when the CC length exceeds NC-OFDM data, such as EAIC-IC, guard band CC will cause larger intersymbol interference (ISI). Therefore, by effectively solving the problem of interference cancellation signal, the ISI and ICI introduced by guard band CC is effectively reduced while trying not to reduce the sidelobe suppression. The optimal interference cancellation basis function for NC-OFDM is determined based on the statistical characteristics of sidelobe spectrum, the bandwidth of the guard band, CP length, but there are difficulties in direct solving. Therefore suboptimal interference cancellation basis function B_v is defined, and its elements are:

$$B_v(n,l) = \frac{1}{\sqrt{N}} r_l(n) \exp\left(\frac{j2\pi \ln}{N}\right), \quad l = [l_{\min} : 1/2 : l_{\max}], \quad -\frac{N}{4} \leq n \leq \frac{5N}{4} \tag{5}$$

The main difference with the existing literature lies in the introduction of B_v with the frequency location of the window function $r_l(n)$. When time $l = \left[l_{\min} + b + \frac{b}{2} : \frac{1}{2} : b_{\max} - b - \frac{1}{2}\right] r_l(n) = r_{pu}(n)$, is typical PU band CC window function. $r_{pu}(n)$ is defined as

$$r_{pu}(n) = \begin{cases} \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi(n + L_{CP})}{\frac{N}{4} - L_{CP}}\right), & \frac{N}{4} \leq n < -L_{CP} \\ 1, & -L_{CP} \leq n < N + L_{CP} \\ \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi(n - N - L_{CP})}{\frac{N}{4} - L_{CP}}\right), & L_{CP} \leq n < \frac{N}{4} \end{cases} \tag{6}$$

When time $[l_{\min} : 1/2 : l_{\min} + b] \cup [l_{\max} - b : 1/2 : l_{\max}]$, $r_l(n) = r_{gu}(n)$ represents a guard band CC window function. $r_{gu}(n)$ is defined as

$$r_{gu}(n) = \begin{cases} 1, & -L_{CP} \leq n < N \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

From (6) and (7) it is observed that both the CC waveform are of different length. First, the CC waveform $r_{pu}(n)$ is longer than one OFDM symbol duration and has a smooth roll off curve as shown in Fig.4. The reason for this design are: as the PU band CC is longer, it has a good sidelobe cancellation capability; and the introduction of ICI is not too large because of the small PU band CC energy, and is away from NC-OFDM data subcarriers; and as the fluctuations of

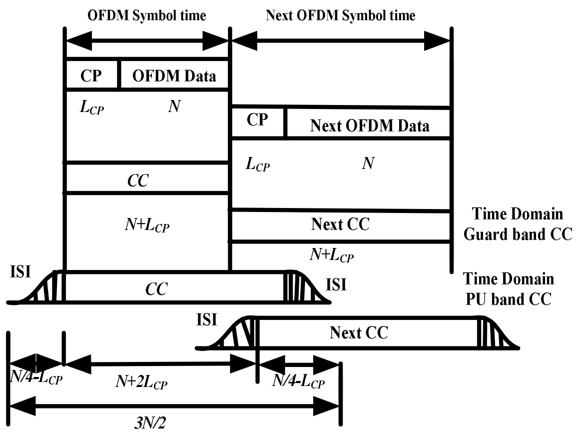

FIGURE 4. **Time domain interference cancellation subcarriers.**

$r_{pu}(n)$ waveform is a slow process from beginning to ending and it can further reduce the interference to adjacent symbols; $r_{pu}(n)$ with the roll-off factor L_{CP} change, because of active interference suppression performance are affected by the length of the CP, with the L_{CP} dynamic roll-off factor can improve the problem. Here, $r_{gu}(n)$ is a rectangular window of length N+L_{cp}. The CC inserted in the guard band is closer to the NC-OFDM data subcarrier and has more energy, so to avoid interferences with adjacent symbols the CC length is taken as $N + L_{CP}$. Further, the guard band CC depends on its side lobes rather than the main lobe as an energy efficient interference cancellation, and it has more appropriate rectangular window side-lobes.

Because the window function only affects the CC but does not change the data subcarrier waveform, therefore they do not destroy the OFDM data subcarriers orthogonality and does not introduce any new interference. When new basis function is designed for interference cancellation signal, because this basis function is optimized for the cancellation of NC-OFDM sidelobe, so it's better for side lobe suppression, and the ICI introduced to the data subcarriers is also smaller. In the following section, CC signal interference condition of the data subcarriers in constraint solving interference cancellation signals is shown.

In the following section, the constraints solving the interference cancellation signals is shown.

B. CONSTRAINTS OF INTERFERENCE CANCELLATION SIGNAL CAUSED BY ICI AND ISI

From the definition of B_v, the normalized frequency portion of the CC is not an integer, i.e., NC-OFDM data subcarriers are not orthogonal, cognitive user data subcarriers cause interference (ICI). Even if the CC length exceeds beyond one OFDM symbol causes inter-symbol interference (ISI). Active Interference Canceller side lobe suppression effect to be limited by the cognitive user to tolerate ICI and ISI, which is analyzed below.

At the receiving end, Interference cancellation signal removes the prefix and suffix, to get $\hat{c} = c\left(\frac{N}{2} + L_{CP} : \frac{3N}{2} + L_{CP} - 1\right)$. And then the DFT / FFT demodulation to obtain:

$$e = F_{N\times N}\hat{c} = F_{N\times N}F^{ici}_{N\times L}w = P^{ici}w \tag{8}$$

where $P^{ici} = F^{-1}_{N\times N}F^{ici}_{N\times L}$, $F^{-1}_{N\times N}$ is the standard Fourier analysis matrix and its elements is defined as $F^{-1}_{N\times N} = \frac{1}{\sqrt{N}}\exp\left(\frac{-j2\pi nm}{N}\right)$, $0 \le n, m < N$, $F^{ici}_{N\times N}$ is to take the group function matrix B_v current symbol time corresponding to the line to get that: $F^{ici}_{N\times N} = B_v\left(\frac{N}{2} + L_{CP} : \frac{3N}{2} + L_{CP} - 1, :\right)$ GU and PU because the band does not include data subcarriers, so that ICI can be expressed as $e^{ici} = e\left(0 : l_{\min} - 1, l_{\max} + 1 : N - 1\right) = P^{ici}_{su}w$, where P^{ici}_{su} obtained by removing the rows $l_{\min} : 1 : l_{\max}$ from matrix P^{ici}. Interference cancellation signal in the beginning of a symbol time after FFT demodulation is $d^{formal} = F^{-1}_{N\times N}F^{formal}_{N\times L}w$, where $F^{formal}_{N\times L} = \left[0_{3N/4\times L} : B_c\left(1 : \frac{N}{4}, :\right)\right]$. as NC-OFDM does not contain useful data subcarrier in a closed position, the previous symbols interference of CC is $d^{formal}_{su} = d^{formal}\left(0 : l_{\min-1}, l_{\max-1} : N, :\right)$. Similarly, the CC interferences later are denoted as d^{later}_{su}. Thus, the sidelobe cancellation performance is limited by the introduction of ICI and ISI, thus the optimized equation can be written as:

$$\begin{aligned} &\min\ \left\|\bar{s}_d - \bar{s}_c\right\|^2 \\ &s.t.\ \left\|e^{ICI}\right\|^2 + \left\|d^{formal}_{su}\right\|^2 + \left\|d^{later}_{su}\right\|^2 < \lambda \end{aligned} \tag{9}$$

where $\bar{s}_c = s_c(I)$, $I = \left[v\left(l_{\min} + b\right) : 1 : v\left(l_{\max} - b\right)\right]^T$ the int-erfereence cancellation signal spectrum position in PU, $s_c = F^{-1}_{oc}c = F^{-1}_{oc}B_v w$, F^{-1}_{oc} is the Fourier analysis matrix with v times oversampling. Obviously (9) is a convex quadratically constrained quadratic program problem, it can be solved directly, or it can be converted to an unconstrained least square problem similar to EAIC-CP and EAIC-IC methods. In this paper, a suboptimal least squares method is presented to solve and the results are compared with EAIC-CP, EAIC-IC methods.

IV. SIMULATION RESULTS

In this section, simulation results are evaluated to new interference cancellation carrier basis function and compared with EAIC-CP, EAIC-IC methods. Although OCCS method does not introduce the self-interference to the data subcarriers, but requires much more frequency band, thereby increasing the cost, therefore a direct comparison is not easy. This section also simulates the effect of L_{CP} on the performance of interference cancellation, were L_{CP} is taken as 8, 16, 32, 64, respectively. Assuming the NC-OFDM system with N=256 subcarriers, using 64QAM symbol mapping and Gaussian white noise channel; PU subcarrier positions in the NC-OFDM is [84:90], closed SU subcarrier position is [83:91], b=1, that is, a total of 2 subcarriers are used as guard band bandwidth. To compare the effect of side lobe suppression, all data subcarriers spectral power is normalization, and an oversampling factor of DFT spectrum analysis is taken as $v = 16$.

TABLE 1. Side lobe performance comparison with ICI=−30dB.

Methods	Side Lobe Suppression depth (dB)			
	L_{cp}=8	L_{cp}=16	L_{cp}=32	L_{cp}=64
EAIC-CP	-52	-58	-61	-66
EAIC-IC	-89	-84	-84	-78
Proposed method	-95	-98	-103	-88

TABLE 2. Side lobe performance comparison with ICI=−40dB.

Methods	Side Lobe Suppression depth (dB)			
	L_{cp}=8	L_{cp}=16	L_{cp}=32	L_{cp}=64
EAIC-CP	-47	-49	-51	-53
EAIC-IC	-51	-56	-64	-65
Proposed method	-74	-80	-83	-78

Table 1, Table 2 compares the side lobe suppression performances using different interference cancellation basis function with the introduction of ICI at −30dB and −40dB conditions, respectively. Simulation results show that: (1) no matter what the CP length (L_{CP} = 8, 16, 32, 64), when the size of ICI is same, variable basis function suppression performance is better than EAIC-CP and EAIC-IC's side lobes; (2) Three methods sidelobe suppression performance is limited by the size of the incoming ICI, when the ICI introduced is smaller, the performance of 3 methods will become worse. But to achieve the side lobe suppression depth (such as −60dB), a new method is introduced by a much smaller ICI; (3) the three kinds of methods are subject to L_{cp} impact but to varying degrees. EAIC-CP method performance degrades as the L_{CP} length is varied. This is because as the CP is shortened, the CC of EAIC-CP must be shortened. Especially when L_{CP} = 0, interference cancellation signal of length N, the data subcarriers of the same length, although the frequency of CC interval is set to 1/2, but the actual effect is equivalent to the traditional method of AIC, then more intensive basis functions only will cause unnecessary effect and it will not improve the sidelobe suppression effect. EAIC-IC with ICI=−30dB, the shorter CP side-lobe cancellation ability is stronger; but when ICI=−40dB, the long CP effect is better; therefore EAIC-IC is unstable to L_{cp}. The proposed method performance is better with the influence of CP length, which is because of balanced variable basis function roll-off factor.

Fig.5-8 compares the NC-OFDM systems to achieve the same sidelobe suppression depth (−60db, then LTE standard −59dB deep 1dB), with the use of different interference suppression basis function for the system at the same symbol error rate (SER). The Higher order 64QAM symbol mapping and additive white Gaussian noise channel can highlight the new basis function method with very small ICI features.

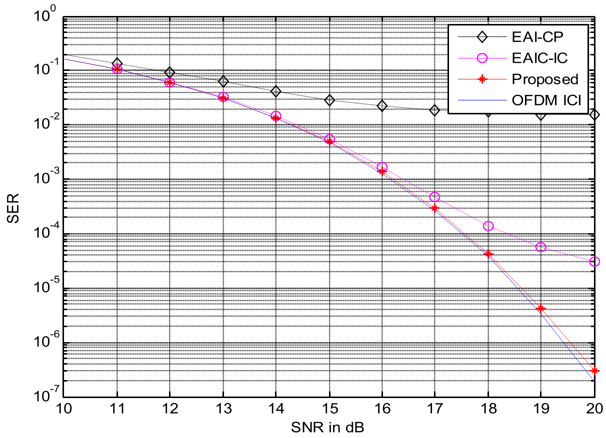

FIGURE 5. BER performance of the proposed method with existing methods with −60dB depth for L_{CP} = 8.

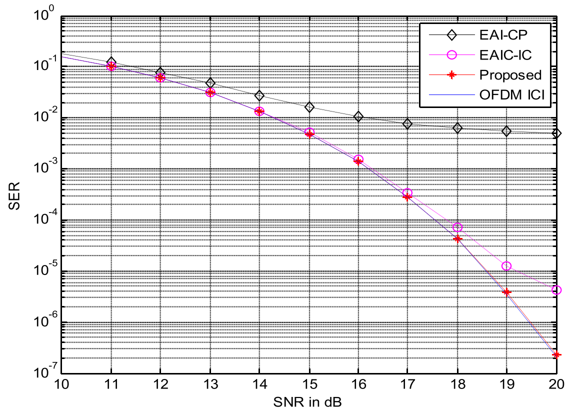

FIGURE 6. BER performance of the proposed method with existing methods with −60dB depth for L_{CP} = 16.

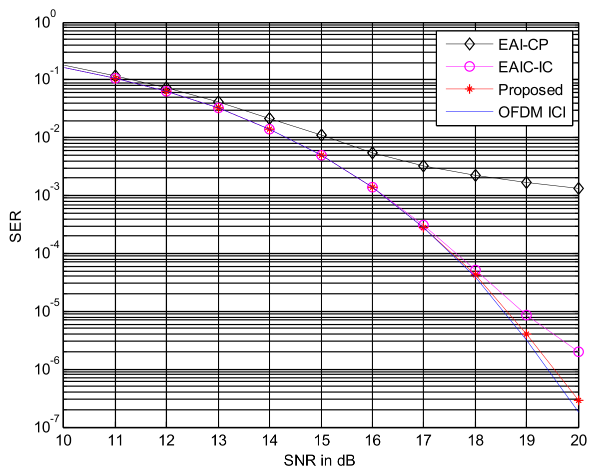

FIGURE 7. BER performance of the proposed method with existing methods with −60dB depth for L_{CP} = 32.

For lower order symbol modulation or worse wireless fading channel environment, the ICI introduced due to CC insertion cannot become a major factor in the degradation of the SER, and can be ignored. Fig.5-8 shows that at the same sidelobe

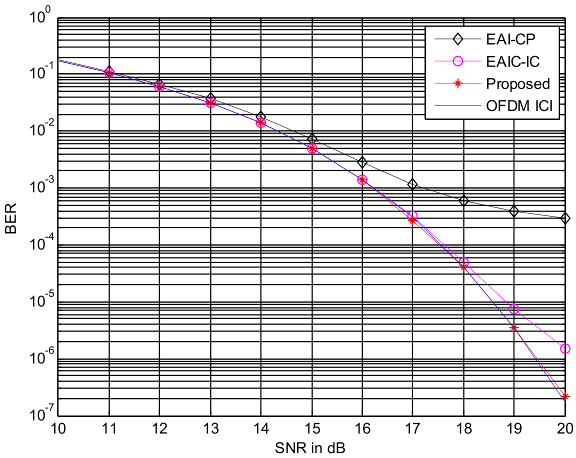

FIGURE 8. BER performance of the proposed method with existing methods with −60dB depth for $L_{CP} = 64$.

suppression depth (−60dB), it is obvious that the SER performance of the proposed method is better than the EAIC-IC and EAIC-CP methods. Although the proposed method's SER performance is affected by the length of the CP, but the introduction of ICI in all 4 cases are very small, and even there is no ICI compared to white noise channel (SER $= 10^{-5}$) and is almost negligible.

V. CONCLUSION

Aiming at the NC-OFDM larger side lobes problem a new interference cancellation basis functions is proposed. In this method to suppress the NC-OFDM sidelobes more effectively, the basis function is grouped according to the frequency location and variable length windowing function. Simulation results validate that the proposed method performance is superior to existing EAIC-IC and EAIC-CP methods. Using the new interference cancellation basis function, when the sidelobe suppression depth achieves −60dB, the ICI introduced in the NC-OFDM system is almost negligible.

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