ADVANCED INTERFERENCE REDUCTION IN NC-OFDM BASED COGNITIVE RADIO WITH CANCELLATION CARRIERS

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ABSTRACT

Reduction of the out-of-band (OOB) emission is essential for Cognitive Radio (CR) systems to enable coexistence with licensed (primary) systems operating in the adjacent frequency bands. This paper proposes an algorithm for the Non Contiguous Orthogonal Frequency Division Multiplexing (NC-OFDM)-based CR, to reduce the interference caused by both OOB radiation and by non-ideal frequency selectivity of a primary user (PU) receiver. It is based on a concept to use a set of subcarriers called Cancellation Carriers (CCs). By being aware of the PU's carrier frequency, the observed interference power can by decreased by about 10 dB in comparison with the standard OOB-power minimizing algorithms.

***Index Terms*—** cognitive radio, enhanced OFDM, Out-of-Band radiation, cancellation carriers, NC-OFDM

1. INTRODUCTION

The main goal of the Cognitive Radio (CR) technology is to exploit unused spectral resources, while protecting licensed spectrum users (called Primary Users- PUs). One of the commonly considered CR scenario is the opportunistic use of spectrum portions in the UHF band (e.g. TV white spaces) by the so-called Secondary Users (SU). In this scenario, the licensed systems include digital TV, as well as the narrowband transmission of wireless microphones (WMs). It might be a challenge to protect these narrowband PU transmissions and to utilize the remaining band efficiently by the SUs. The CR transmitter should be able to aggregate available spectrum while shaping its signal spectrum in such a way to cause only negligible interference to PUs transmission. In such a case, OFDM-based CR system [1, 2] can use subcarriers not overlapping the PU's band. Such an extension of OFDM is called Non-Contiguous OFDM (NC-OFDM).

Although simple turning off subcarriers lying in PUs bands (known as guard-subcarriers method [3]) decreases interference power, it might be not enough to protect the PU transmission. Simple band-stop filtering may be applied after NC-OFDM modulator, however, it will cause degradation of NC-OFDM reception quality as an effective duration of fading channel impulse response will be prolonged [4]. Moreover, in the dynamic environment, the PU transmission can be initiated and completed dynamically, and the redesign of filters every time PUs status changes is too complicated task. In [5], it was shown that filtering would require much more computational power than spectrum shaping method utilizing characteristic NC-OFDM waveform.

As each OFDM subcarrier is a continuous complex harmonic wave windowed with rectangular pulse, the spectrum shape of a single subcarrier is *Sinc*-like. This shape is utilized in spectrum shaping methods varying from computationally-simple but spectrally inefficient e.g. time-domain windowing [3] to computationally complex and spectrally efficient ones e.g. precoding methods [6–9]. A promising method called Cancellation Carriers (CCs) has been proposed in [10]. It allots some data carriers (DCs) for complex symbols, which decrease OOB radiation caused by subcarrier sidelobes. It outperforms filtering in the OOB radiation power especially when narrowband and deep spectrum notches are required [11]. Recently, we have proposed computationally simple method of calculating symbols modulating CCs that allows for utilization of their values for improving DCs reception quality [12]. Moreover, the Optimized CC Selection (OCCS) method has been described in [12]. It allows to allot optimal CCs positions, that might be different than typically assumed location at the spectrum edges of the SUs band.

The above-mentioned methods minimize the SU's OOB radiation power over the band of PUs, while it is the interference power observed at the PU receiver that should be minimized. The effective interference power is the power of the SU signal after passing the PU reception chain, i.e. the receiver radio circuits and baseband processing. Due to limited selectivity of a PU practical receiver, the overall interference observed by the PU is higher than just the SU's OOB power. Note that the PU receiver selectivity can be modeled as a filter, as discussed in [13] for the case of WM.

In this paper, we present a method for calculation of the CCs symbols in order to minimize overall interference power, and compare it against ordinary minimization of the OOB power. It is done for both traditional CC and OCCS [12] method. It is a step ahead of previously proposed method for the definition of a dynamic spectrum emission mask [14] as it considers ”cost” of spectrum shaping. It takes the number and

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the power of CCs into account and neglects intermodulation effect in the SU transmitter chain.

In Section 2 and 3 CC and OCCS methods are presented for OOB-power and for the interference-power minimization. System performance metrics are defined in Section 4. Numerical results and conclusions are presented in Section 5 and 6.

2. SYSTEM MODEL WITH OOB POWER MINIMIZATION

The considered system consists of NC-OFDM modulator extended with CCs calculation module. The NC-OFDM is based on N-point Inverse Fast Fourier Transform (IFFT) in which α subcarriers of indices $\mathbf{I}_{\mathrm{DC}} = \{I_{\mathrm{DC}j}\}$, i.e. Data Carriers (DCs), are modulated with QAM data symbols defined as vector $\mathbf{d}_{\mathrm{DC}}$. Vector $\mathbf{d}_{\mathrm{CC}}$ of β elements modulates disjoint set of CCs, indiced by$\mathbf{I}_{\mathrm{CC}} = \{I_{\mathrm{CC}l}\}$. The n-th sample of the time-domain signal of a single OFDM symbol equals:

$$x_n = \sum_{j=1}^{\alpha} d_{\mathrm{DC}j} e^{\jmath 2\pi \frac{n I_{\mathrm{DC}j}}{N}} + \sum_{l=1}^{\beta} d_{\mathrm{CC}l} e^{\jmath 2\pi \frac{n I_{\mathrm{CC}l}}{N}}. \quad (1)$$

The Fourier transform of the above equation over all time samples, including cyclic prefix (CP) of N_{CP} samples, $n = \{-N_{\mathrm{CP}}, ..., N-1\}$ of a single OFDM symbol gives the following spectrum value at frequency ν [12]:

$$S(\nu) = \sum_{j=1}^{\alpha} d_{\mathrm{DC}I_{\mathrm{DC}j}} S(\nu, I_{\mathrm{DC}j}) + \sum_{l=1}^{\beta} d_{\mathrm{CC}I_{\mathrm{DC}l}} S(\nu, I_{\mathrm{CC}l}) \quad (2)$$

where the spectrum value at frequency ν originating from a single subcarrier k equals:

$$S(\nu, k) = \frac{1}{N + N_{\mathrm{CP}}} \sum_{n=-N_{\mathrm{CP}}}^{N-1} e^{\jmath 2\pi \frac{n(k-\nu)}{N}}. \quad (3)$$

In order to calculate CCs symbols values, the samples of the OOB spectrum for the vector of normalized frequency sampling points $\mathbf{V} = \{V_i\}$ (where $i = 1, ..., \gamma$) have to be calculated [12]. Using (3), vectors of the OOB spectrum values originating from the DCs (vector $\mathbf{s}_{\mathrm{DC}}$) and CCs (vector $\mathbf{s}_{\mathrm{CC}}$) can be calculated in the following way: $\mathbf{s}_{\mathrm{DC}} = \mathbf{P}_{\mathrm{DC}}\mathbf{d}_{\mathrm{DC}}$ and $\mathbf{s}_{\mathrm{CC}} = \mathbf{P}_{\mathrm{CC}}\mathbf{d}_{\mathrm{CC}}$ for data carriers and cancellation carriers, respectively. The elements of $\gamma \times \alpha$ matrix $\mathbf{P}_{\mathrm{DC}} = \{P_{\mathrm{DC}i,j}\}$ and the elements of $\gamma \times \beta$ matrix $\mathbf{P}_{\mathrm{CC}} = \{P_{\mathrm{CC}i,l}\}$ are calculated as $S(V_i, I_{\mathrm{DC}j})$ and $S(V_i, I_{\mathrm{CC}l})$, respectively. The CCs symbols are found to minimize the OOB power, i.e.

$$\text{find} \ \min_{\mathbf{d}_{\mathrm{CC}}} \|\mathbf{P}_{\mathrm{DC}}\mathbf{d}_{\mathrm{DC}} + \mathbf{P}_{\mathrm{CC}}\mathbf{d}_{\mathrm{CC}}\|^2, \quad (4)$$

$$\text{s.t.} \ \mathbb{E}\left[\|\mathbf{d}_{\mathrm{CC}}\|^2\right] \leq \beta, \quad (5)$$

where constraint (5) is introduced to prohibit CCs from using too much power, part of the OFDM symbol power. Thus, β CCs are allowed to use maximum average power equal to the DCs power they replaced. We assume normalized DC power. As in [12], expected power of CCs is limited instead of instantaneous power as in [10]. This allows for low-complex CCs calculation. Using Lagrange multipliers we obtain [12]:

$$\mathbf{d}_{\mathrm{CC}} = -\left(\mathbf{P}_{\mathrm{CC}}{}^{\mathcal{H}}\mathbf{P}_{\mathrm{CC}} + \theta\mathbf{I}\right)\mathbf{P}_{\mathrm{CC}}{}^{\mathcal{H}}\mathbf{P}_{\mathrm{DC}}\mathbf{d}_{\mathrm{DC}} = \mathbf{W}\mathbf{d}_{\mathrm{DC}} \quad (6)$$

where Lagrange multiplier θ is found by solving (7):

$$\mathbb{E}\left[\|\mathbf{d}_{\mathrm{CC}}\|^2\right] = \sum_{p=1}^{\delta} \frac{A_{p,p}|S_{p,p}|^2}{\left(\theta + |S_{p,p}|^2\right)^2} \leq \beta. \quad (7)$$

This requires singular value decomposition of $\mathbf{P}_{\mathrm{CC}} = \mathbf{KSB}^{\mathcal{H}}$ and calculation of $\mathbf{A} = \mathbf{K}^{\mathcal{H}}\mathbf{P}_{\mathrm{DC}}\mathbf{P}_{\mathrm{DC}}{}^{\mathcal{H}}\mathbf{K}$. The summation in (7) is done over δ elements, i.e. the number of non-zero singular values of $\mathbf{P}_{\mathrm{CC}}$. Although it depends on the choice of $\mathbf{V}$, δ equals usually the minimum of β and γ.

The computational complexity of this solution is relatively low in comparison to standard convex optimization presented in [10]. Calculation of matrix $\mathbf{W}$ is to be done once off-line, i.e. before OFDM symbols transmission begin, for a given set of system parameters, e.g. for the selected pattern of data and cancellation carriers. Then, the CCs values are obtained by matrix-vector multiplication.

2.1. Standard and optimized CCs selection

Typically subcarriers located closest to the PU band are chosen to serve as CCs [10]. However, as shown in [12], introduction of every CC causes correlation between IFFT inputs that should be taken into account when selecting the next subcarrier to serve as CC. The summarized spectrum samples caused by both DCs and CCs for a given NC-OFDM symbol can be calculated introducing (6) into formula (4). Thus:

$$\mathbf{s}_{\mathrm{DC}} + \mathbf{s}_{\mathrm{CC}} = \left(\mathbf{P}_{\mathrm{DC}} + \mathbf{P}_{\mathrm{CC}}\mathbf{W}\right)\mathbf{d}_{\mathrm{DC}} = \mathbf{G}\mathbf{d}_{\mathrm{DC}}. \quad (8)$$

As each element of vector $\mathbf{d}_{\mathrm{DC}}$ is an independent random variable of variance 1, the element $|G_{i,j}|^2$ is the power of the OOB spectrum at frequency V_i caused by j-th data carrier. It can be observed that the j^*-th data subcarrier defined as

$$j^* = \operatorname*{argmax}_{j} \sum_{i=1}^{\gamma} |G_{i,j}|^2 \quad (9)$$

is the one having the highest impact on the OOB power and will reduce it the most if chosen to be CC. This process is iterative, i.e. after choosing one CC, matrices $\mathbf{W}$ and $\mathbf{G}$ must be calculated before finding the next optimum CC position. Block diagram of it is presented in [12].

3. INTERFERENCE POWER MINIMIZING CCS

Our ultimate goal of spectrum shaping in the considered system is to minimize interference power observed at the PU re-

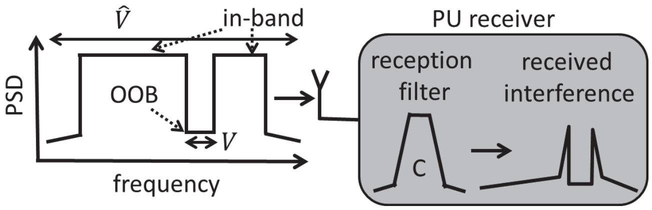

Fig. 1. The SU signal PSDs before and after the PU RX filter.

ceiver, not solely the SU OOB power minimization. The difference between these values (OOB power and interference power) is presented in Fig. 1.

In the previous section, the SU OOB power was minimized in the SU signal reaching the PU receiver (RX) antenna (on the left of Fig. 1). However, after passing the PU RX-chain, the interference signal in the PU receiver, composes of both the SU generated OOB power and the interference caused by imperfect PU RX filter selectivity, visible as the PSD peaks on the right in Fig. 1. Let us define a new vector of frequency sampling points $\widehat{\mathbf{V}} = \{\widehat{V}_{\widehat{i}}\}$ of length $\widehat{\gamma}$ spanning the whole SU band. Analogously to $\mathbf{P}_{\mathrm{CC}}$ and $\mathbf{P}_{\mathrm{DC}}$, matrices $\widehat{\mathbf{P}_{\mathrm{CC}}}$ and $\widehat{\mathbf{P}_{\mathrm{DC}}}$ have to be defined for this vector using (3).

The impact of the SU's radiated power on the interference power received by the PU at a given frequency, depends on the PU RX filter characteristic. For the WM receivers it can be estimated as in [13]. Based on this specification diagonal matrix $\mathbf{C}$ can be defined with elements $C_{\widehat{i},\widehat{i}}$ being the square root of the PU RX filter characteristic at frequency $\widehat{V}_{\widehat{i}}$. When the PU RX filter characteristic is normalized, the optimization problem is formulated as:

$$\text{find} \ \min_{\mathbf{d}_{\mathrm{CC}}} \left\| \mathbf{C} \left(\widehat{\mathbf{P}_{\mathrm{DC}}} \mathbf{d}_{\mathrm{DC}} + \widehat{\mathbf{P}_{\mathrm{CC}}} \mathbf{d}_{\mathrm{CC}} \right) \right\|^2 \tag{10}$$

$$\text{s.t.} \ \mathbb{E}\left[\|\mathbf{d}_{\mathrm{CC}}\|^2 \right] \leq \beta, \tag{11}$$

which can be solved by substituting $\mathbf{C}\widehat{\mathbf{P}_{\mathrm{DC}}}$ for $\mathbf{P}_{\mathrm{DC}}$ and $\mathbf{C}\widehat{\mathbf{P}_{\mathrm{CC}}}$ for $\mathbf{P}_{\mathrm{CC}}$ in (6) and (7). Compared to the OOB minimization, the computational complexity of (10) increases at the off-line phase, when matrix $\widehat{\mathbf{W}}$, instead of $\mathbf{W}$, is calculated. This is caused by higher size of $\widehat{\mathbf{P}_{\mathrm{CC}}}$ and $\widehat{\mathbf{P}_{\mathrm{DC}}}$ matrices as $\widehat{\gamma} > \gamma$. Additionally, multiplication by diagonal matrix $\mathbf{C}$ has to be made. The complexity of the on-line phase, i.e. calculation of CCs values based on DCs, is the same as in the regular CCs method, because $\widehat{\mathbf{W}}$ has the same size as $\mathbf{W}$.

3.1. Standard and optimized CCs selection

Importantly, both the standard CCs method and OCCS, can be adopted to the proposed interference-power minimizing method. In case of OCCS, the matrix transforming data symbols to spectrum samples at frequencies $\widehat{\mathbf{V}}$ can be defined as:

$$\widehat{\mathbf{G}} = \mathbf{C} \left(\widehat{\mathbf{P}_{\mathrm{DC}}} + \widehat{\mathbf{P}_{\mathrm{CC}}} \widehat{\mathbf{W}} \right). \tag{12}$$

The criteria for finding new subcarrier $\widehat{j}^*$ to be used as the CC is similar as previously defined in Section 2.1, i.e.

$$\widehat{j}^* = \underset{\widehat{j}}{\operatorname{argmax}} \sum_{\widehat{i}=1}^{\widehat{\gamma}} |\widehat{G}_{\widehat{i},\widehat{j}}|^2. \tag{13}$$

4. PERFORMANCE EVALUATION METRICS

Below, we define three metrics to evaluate the performance of the proposed algorithm. Assuming that the $\mathbf{d}_{\mathrm{CC}}$ vector consists of independent random variables of variance 1, the Adjacent Channel Interference Ratio (ACIR) at the PU receiver, is the ratio of the SU signal power at the PU RX antenna to the SU signal power after passing PU RX filter:

$$ACIR = 10 \log_{10} \left(\frac{\|\widehat{\mathbf{P}_{\mathrm{DC}}} + \widehat{\mathbf{P}_{\mathrm{CC}}} \widehat{\mathbf{W}}\|^2}{\|\mathbf{C} \left(\widehat{\mathbf{P}_{\mathrm{DC}}} + \widehat{\mathbf{P}_{\mathrm{CC}}} \widehat{\mathbf{W}} \right) \|^2} \right). \tag{14}$$

The mean SU OOB power relative to the mean in-band SU power is defined as:

$$OOB = -10 \log_{10} \left(\frac{\|\mathbf{P}_{\mathrm{DC}} + \mathbf{P}_{\mathrm{CC}} \widehat{\mathbf{W}}\|^2}{\gamma} \right), \tag{15}$$

while the mean CC power relative to the mean DC power at the SU's transmitter output equals:

$$CC_{\mathrm{power}} = 10 \log_{10} \left(\frac{\|\widehat{\mathbf{W}}\|^2}{\beta} \right) \tag{16}$$

where $\| \ \|^2$ is second matrix norm. If we consider sole OOB power minimization, matrix $\widehat{\mathbf{W}}$ should be replaced in formulas (14)-(16) by matrix $\mathbf{W}$ and by matrix of zeros for the standard CCs and for the guard-subcarriers method respectively.

5. SIMULATION RESULTS

Our considered SU system utilizes IFFT of $N = 256$ points and CP of $N/32$ samples. The subcarrier spacing equals 15 kHz as in the LTE system. For easiness of digital-analog conversion some subcarriers at the edges of band are turned off, as well as the $0th$ subcarrier. Before CCs insertion, all subcarriers $\{-100, ..., -1, 1, ..., 100\}$ are modulated by data symbols, i.e. $\alpha = 200, \beta = 0$. The SU transmitter is aware of the primary system being the WM of 200 kHz bandwidth. We assume that the PU center frequency normalized to the SU NC-OFDM subcarrier spacing is 24. Two vectors of the spectrum sampling points have been defined: $\mathbf{V}$ of $\gamma = 54$ covering the PU band, and $\widehat{\mathbf{V}}$ of $\widehat{\gamma} = 1024$ covering the whole SU band. Four spectrum-sampling points per subcarrier spacing are assumed for both sampling regions.

The interference power reduction is obtained iteratively, increasing the number of CCs by one in each iteration for

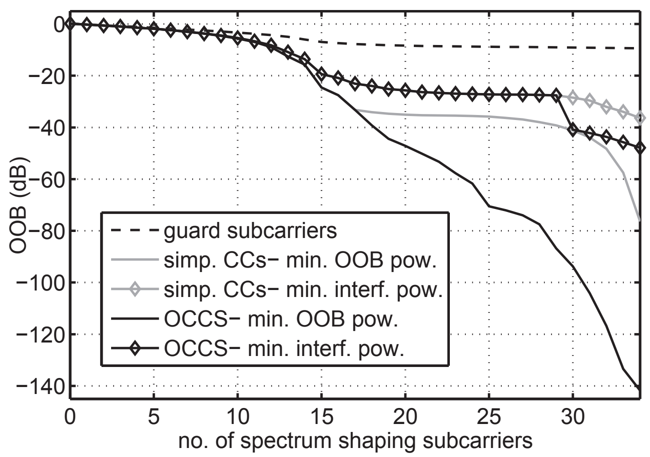

Fig. 2. Mean OOB power observed in the PU band vs. the number of spectrum shaping subcarriers.

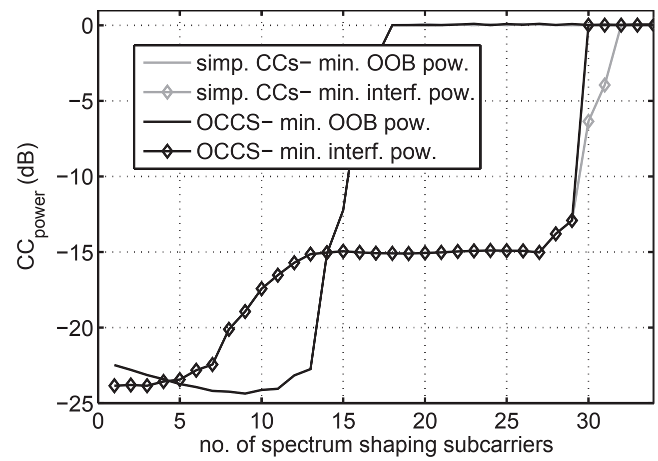

Fig. 4. Mean CC power normalised to the mean DCs power for the CC-based scenarios vs. the number of CCs.

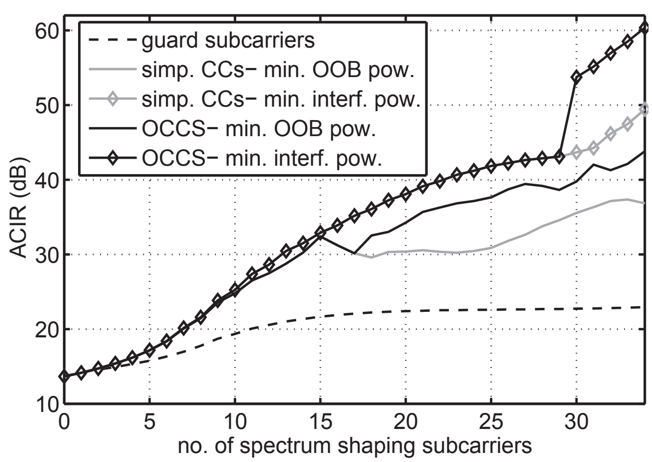

Fig. 3. Mean ACIR caused by the SU transmitter to the PU receiver vs. the number of spectrum shaping subcarriers.

5 compared systems: (i) using **guard subcarrier** [3], chosen as the one closest to the WM carrier frequency, (ii) using a CC **minimizing SU OOB power** according to (4)-(5), and chosen as the subcarrier closest to the WM carrier frequency (standard CCs selection), (iii) using a CC **minimizing SU OOB power** according to (4)-(5), and chosen using (9) (OCCS), (iv) using a CC, **minimizing PU received interference power** according to (10)-(11), and chosen as a subcarrier closest to the WM carrier frequency, and (v) using a CC, **minimizing PU received interference power** according to (10)-(11), and chosen using (13) (OCCS).

In Fig. 2, the mean OOB power over the WM band of 200 kHz calculated using (15) is depicted. The mean ACIR calculated using (14) for the considered systems is depicted in Fig. 3. Although for a low number of spectrum shaping subcarriers, the performance of all scenarios is similar, when this number increases the guard subcarriers method is outperformed by all other approaches. The OOB power is reduced most efficiently with OCCS applied for OOB power minimization. The standard CCs selection results in higher OOB power. The gap increases the more CCs are used. In case of the ACIR metric, both interference-power minimizing methods outperform the OOB-power minimizing ones. The OCCS shows its merits outperforming standard CCs selection by 10 dB of ACIR for the number of CCs higher than 29.

In Fig. 4 the mean CC power defined by (16) can be observed. Interestingly, for the OOB-power minimization schemes (curves for both CCs selection methods coincide), the mean CCs power is very low as long as all CCs lay in the PU band. In case of interference-power minimization, the mean CCs power is low (below 0 dB) even for higher number of CCs. It means that for higher β, e.g. for $\beta = 20$, the proposed system decreases interference power experienced by the PU receiver by about 3.8 dB while using only 3% of CCs power used in OOB-power minimizing system with OCCS. The optimization constraint (11) is met when some CCs have their mainlobes at frequencies of strong WM reception filter selectivity and try therefore to increase their power in order to increase sidelobes suppression capabilities.

In order to verify numerical results, simulation of the considered systems have been performed based on 10^4 NC-OFDM transmitted symbols with $\beta = 34$ spectrum-shaping subcarriers. In each NC-OFDM symbol all DCs are modulated with random QPSK symbols. The PSDs were calculated using Welch method in 256 points utilizing Blackman window of 20480 samples. The plots before and after the WM reception filter are presented in Fig. 5 and Fig. 6, respectively. The OOB-power minimizing methods obtain lower PSD level in the PU band at the PU RX input than all other systems. However, the minimum interference power after PU reception filter, i.e. integral over whole SU band in Fig. 6, is obtained by the interference-power minimizing scheme using

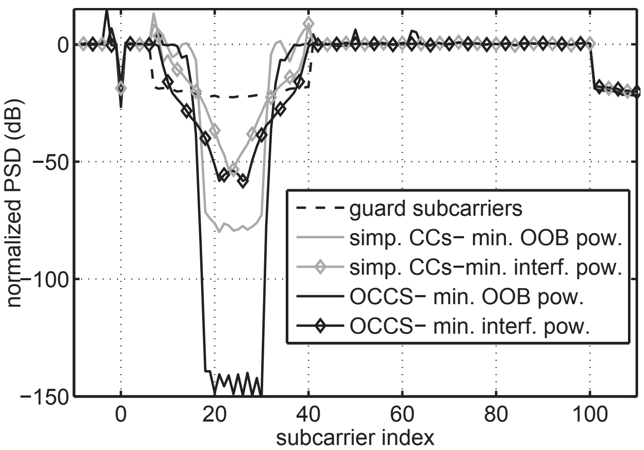

Fig. 5. Normalized PSDs for the considered scenarios at the PU RX antenna (before filtering); $\beta = 34$.

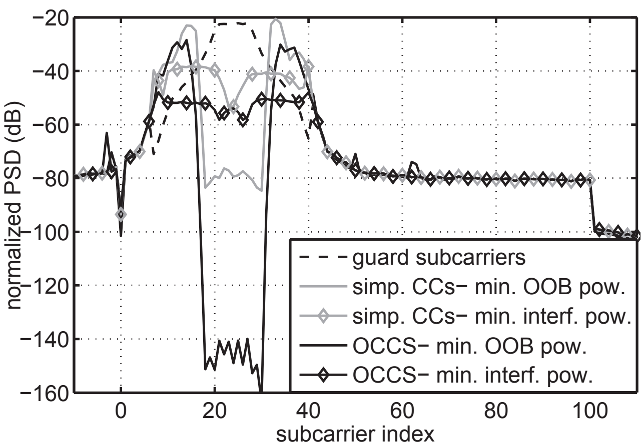

Fig. 6. Normalized PSDs for the considered scenarios after the PU RX filter; $\beta = 34$.

OCCS. This method decreases the PSD components close to the PU band what prevents interference ”leakage” caused by the imperfect PU reception filter. Simulation results confirm analytical solutions shown in Fig. 2–4.

6. CONCLUSION

The proposed method for reduction of the interference power which takes PU receiver selectivity into account significantly improves the protection of the PU transmission against the CR-based interference. It shows that PU-aware spectrum shaping is advantageous in NC-OFDM based SU systems over the existing OOB-power reduction methods.

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