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Study the effect of PAPR on wideband cognitive OFDM radio networks

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Abstract Cognitive radio (CR) technology is viewed as a novel approach for maximizing the utilization of the radio electromagnetic spectrum. Spectrum sensing methods are often used for finding free channels to be used by CR. Recently, Orthogonal Frequency Division Multiplexing system (OFDM) has been suggested as a candidate technology for multicarrier-based CR systems. However, one problem that appears in OFDM systems is the high Peak to Average Power Ratio (PAPR). In this paper, the effect of PAPR reduction of the primary signal on the performance of the multi-band joint detection for wideband spectrum sensing and the profit of the primary user will be investigated. Moreover, the optimal solutions for the multi-band joint detection for the non-cooperative and cooperative schemes will be analyzed by considering the primary user's PAPR reduction. Also, the wideband cooperative spectrum sensing to improve the signal detection with high reduction in the PAPR will be suggested. Simulation results show that the PAPR reduction decreases the total price of the primary user and the aggregate opportunistic throughput of the secondary user. The cooperative scheme is effective in improving the performance in terms of the aggregate opportunistic throughput with PAPR reduction.

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1 Introduction

The number of wireless applications have been growing over the last decade. Most of the frequency spectrum has already been licensed by government agencies, such as Federal Communications Commission (FCC). Therefore, there is an apparent spectrum scarcity for new wireless applications and services. CR [1–3] has been considered as a key mechanism in addressing the problem of spectrum scarcity [4–6] in wireless communication systems. Spectrum sensing [7, 8] is the most important task among others for establishing the CRs because they need to sense the spectrum and decide to use the spectrum band if a spectrum hole exists, which is described in detail in [9–12]. In addition, they need to sense the spectrum periodically to sense the primary user reappearance.

Actually, because of the attractive features of OFDM systems, it has been successfully used in numerous wireless standards and technologies. It plays an important role in realizing the cognitive radio concept as well by providing a proven, scalable, and adaptive technology for the air interface [13]. The challenges of OFDM based CR can be grouped into three categories which are described in details in [14]. One of these categories is related to PAPR reduction and the effect of this reduction on the spectrum sensing. The problem of reducing PAPR occurring in cognitive radio has been studied before [15–19]. Qingwen in [15] proposed new adaptive algorithm with low complexity. This new adaptive algorithm is based on combining between adaptive PAPR reduction technology and power adjustment. Selective Mapping Method (SLM) is another technique to reduce

PAPR in CR [16]. PTS is also proposed in [17] to achieve this reduction.A technique combining subcarriers precoding with tone reservation was proposed to reduce peak-to-average power ratio in [18]. An adaptive PAPR reduction technique to effectively reducing PAPR problem was proposed in [19], the algorithm adaptively decides upon computing between linear combination approach and subcarrier phase adjustment or a combination of both and implemented by FPGA.

In this paper, we take another point of view for studying the effect of PAPR. We assume the reduction has already been made by using any method. The important problem tackled in this paper is that the effect of PAPR reduction of the primary signal on the performance of the multiband joint detection for wideband spectrum sensing and the profit of the primary user. We study the new problem of PAPR reduction effect with multi-band joint detection. We formulate the problem as an optimization one and obtain an optimal solution for wideband spectrum sensing by taking into consideration the effect of PAPR reduction. Moreover, hard decision combing based cooperative spectrum sensing will be applied to improve the aggregate opportunistic throughput of cognitive radios and the profit of the primary user with minimum interference to the primary communication systems. An energy based detection [12] by the secondary users is assumed throughout the paper due to its simplicity. In addition, it does not need any prior information about the primary users' signals. Therefore, it has been thoroughly studied both in local spectrum sensing [9–12] and cooperative spectrum sensing [20–23].

The rest of this paper is organized as follows. In Sect. 2, the system model is briefly introduced. In Sect. 3, Energy detection scheme for wideband OFDM will be explained. Optimization of joint detection with PAPR reduction will be formulated in Sect. 4. In Sect. 5, the cooperative joint detection considering the effect of PAPR reduction will be investigated. In Sect. 6, the optimization problem with respect to the profit of primary user will be formulated. Finally, Conclusions are made in Sect. 7.

2 System model

We consider an OFDM system with K subchannels. When a secondary user is sensing each subchannel k, there are two hypotheses $H_{0,k}$ and $H_{1,k}$ for the k-th subchannel which are absent or present:

$$Y_k = \begin{cases} H_k X_k + W_k, & H_{1,k} \\ W_k, & H_{0,k} \end{cases} \tag{1}$$

where X_k represents the primary transmitted signal at subchannel k. W_k gives the received noise in frequency domain and H_k denotes the discrete frequency response of the wideband channel.

There are two probabilities of interest which are used for spectrum sensing: probability of detection (P_D), which defines under hypothesis H_1, the probability of the algorithm correctly detecting the presence of primary signal; and probability of false alarm (P_F), which defines under hypothesis H_0, the probability of the algorithm falsely declaring the presence of primary signal. From the Primary User's (PU's) perspective, if the probability of detection is high, the received protection will be better. From the secondary user's perspective, however, if the probability of false alarm is low, there are more chances from which the secondary users can use the frequency bands when they are available. Obviously, for a good detection algorithm, the probability of detection should be as high as possible while the probability of false alarm should be as low as possible.

3 Energy detection scheme for wideband OFDM

In energy detection approach, the radio frequency energy in each subchannel k is measured to determine if the channel is occupied or empty. A decision statistic of the energy detector for each subchannel k, is given by [23],

$$T_k = \sum_{m=1}^{M} \left|Y_k(m)\right|^2 \tag{2}$$

where M denotes the number of collected samples.

If the noise term $w(t)$ is assumed to be Circularly Symmetric Complex Gaussian (CSCG) by using central limit theorem, the probability density function (PDF) of the test statistics T_k under $H_{0,k}$ can be approximated by a Gaussian distribution with mean $E(T_k) = M\sigma_w^2$ and variance $Var(T_k) = 2M\sigma_w^4$. Then, the probability of false alarm P_f^k denotes by [24]:

$$P_f^k(\lambda_k) = \Pr(T_k > \lambda_k / H_{0,k}) = Q\left(\frac{\lambda_k - M\sigma_w^2}{\sigma_w^2\sqrt{2M}}\right) \tag{3}$$

where $Q(.)$ is the Q-function that is defined as $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2}dt$. λ_k is the detection threshold for each subchannel and σ_w^2 is the variance of the noise.

Under hypothesis $H_{1,k}$ for selected threshold λ_k, the probability of detection for transmitted signal with variance σ_x^2 is described by:

$$\begin{aligned} P_d^k(\lambda_k) &= \Pr(T_k > \lambda_k / H_{1,k}) \\ &= Q\left(\frac{\lambda_k - M(\sigma_w^2 + |H_k|^2 P_x)}{\sqrt{2M(\sigma_w^2 + 2|H_k|^2\sigma_x^2)\sigma_w^2}}\right) \end{aligned} \tag{4}$$

where P_x: The power of transmitted signal.

4 Optimization of joint detection with PAPR reduction

The objective of this optimization problem is to find the optimal detection threshold for each subchannel to maximize the aggregate opportunistic throughput under a constraint of a maximum aggregate interference over the primary users, which is described as $\sum_{k=1}^{K} I_k(\lambda_k)$, over the primary users. Therefore, the optimization problem can be formulated as:

$$\text{Max} \sum_{k=1}^{K} R_k(\lambda_k)$$

$$\text{s.t.} \quad \sum_{k=1}^{K} I_k(\lambda_k) \leq \varepsilon \tag{5}$$

$$\lambda_{\min,k} \leq \lambda_k \leq \lambda_{\max,k}$$

where R_k and I_k represent the opportunistic throughput on each subchannel k and the Interference to the primary user on each subchannel k, respectively.

$$R_k(\lambda_k) = \tau_k\left(1 - P_f^k(\lambda_k)\right)$$

In which $\tau_k$gives the achievable throughput on each subchannel k.

$$\left(1 - P_f^k(\lambda_k)\right)$$

denotes the probability that subchannel k is empty.

$$I_k(\lambda_k) = g_k\left(1 - P_d^k(\lambda_k)\right)$$

where g_k denotes the value of interference from the cognitive users with PU.

The last constraint determines the upper and lower bounds on the thresholds of each subchannel. Those bounds can be obtained by setting a limit on the total of $1 - P_f^k$ and P_d^k for each subchannel k such that

$$P_d^k \geq \beta_k \quad \text{and} \quad 1 - P_f^k \geq \alpha_k \tag{6}$$

Where the values of α_k and β_k are ranged from 0.5 and 1 [25] to make the optimization problem convex where these values are practical values for cognitive radio networks.

For the constraint $P_d^k \geq \beta_k$, by using (4) and (5), we get:

$$\lambda_k \leq \lambda_{\max,k}$$

where

$$\lambda_{\max,k} \triangleq M\left(\sigma_w^2 + |H_k|^2 P_{x,PAPR}\right) + \sigma_w \sqrt{2M\left(\sigma_w^2 + 2|H_k|^2 P_{x,PAPR}\right)}\, Q^{-1}(\beta_k) \tag{7}$$

$$P_{x,PAPR} = \xi . P_x$$

where ξ is the Scaling Factor (SF) < 1. It is defined in [26, 27] which is selected depending on the value of the PAPR reduction that depends on the linear region of the power amplifier.

$$\xi = \frac{\bar{\rho}}{\rho} \tag{8}$$

$\bar{\rho}$: The PAPR value when PAPR reduction method is applied.

ρ: The PAPR value when no PAPR reduction method is applied.

For the constraint $1 - P_f^k \geq \alpha_k$ by using (3) and (5), we get:

$$\lambda_k \geq \lambda_{\min,k}$$

where (9)

$$\lambda_{\min,k} \triangleq \sigma_w^2\left[M + \sqrt{2M}\, Q^{-1}(1 - \alpha_k)\right]$$

4.1 Simulation results

One primary user with $K = 8$ subchannels will be assumed. Only one cognitive user will be assumed. The main parameters, that are used, are listed in Table 1. The channel condition between the primary user and the cognitive user, the opportunistic throughput over each subchannel, and the interference of each subchannel will be generated randomly using Matlab program. Now, the effect of PAPR reduction on the performance of the multiband joint detection for wideband spectrum sensing will be investigated, where the effect of PAPR reduction on the throughput that depends on the probability of false alarm and the interference that depends on the probability of miss detection will be studied.

Figure 1 shows the maximum aggregate opportunistic throughput versus aggregate interference for three cases that are without PAPR reduction method and with PAPR reduction method at SF = 0.95 and 0.9. The maximum aggregate opportunistic throughput in Fig. 1 is obtained using the optimal values of the threshold λ_k. The optimal values of lambda's are obtained by using trust-region-reflective algorithm, which is selected due to its simpler and faster than another algorithm such as Active set algorithm using quasi-Newton approximation. Actually, all these algorithms give

Table 1 Simulation parameters

The number of subchannel, K	8
The number of collected samples, M	100
The Scaling Factor (SF)	1, 0.95, 0.9
The power of transmitted signal, P_x	1
The variance of the noise, σ_w^2	1
β_k	0.9
α_k	0.8

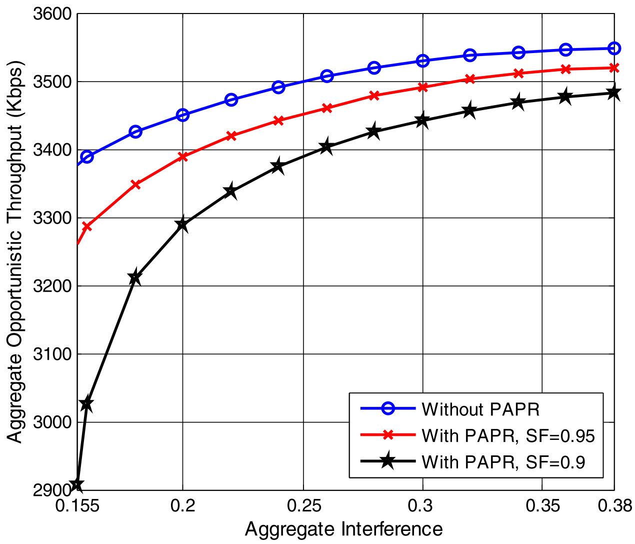

Fig. 1 Maximum aggregate opportunistic throughput vs. the constraint on the aggregate interference for different SF of PAPR

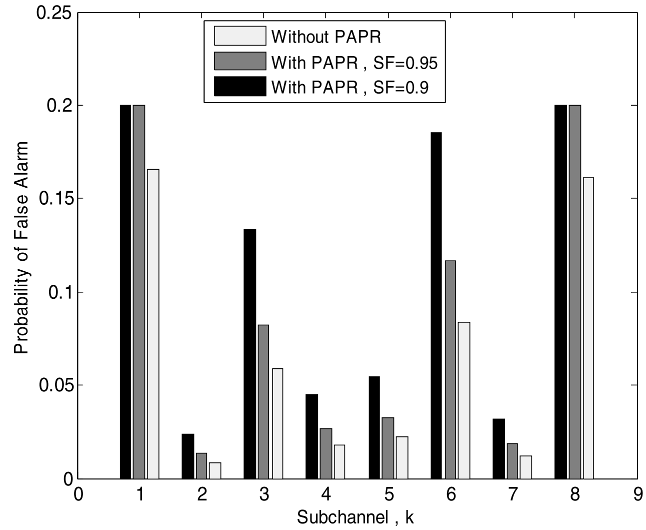

Fig. 2 The probability of false alarm for each subchannel k for different values of SF and $\varepsilon = 0.22$

approximately the same results. For example at aggregate interference $= 0.2$, the optimal values of the threshold without PAPR by trust-region-reflective algorithms using constrained nonlinear optimization in Matlab are:

$$\lambda_1^{opt} = 112.5535, \quad \lambda_2^{opt} = 132.9482,$$
$$\lambda_3^{opt} = 121.1619, \quad \lambda_4^{opt} = 128.8863,$$
$$\lambda_5^{opt} = 127.5614 \quad \lambda_6^{opt} = 118.5905,$$
$$\lambda_7^{opt} = 131.0587, \quad \lambda_8^{opt} = 112.8901$$

The optimal values of the threshold with PAPR at SF $= 0.95$ are:

$$\lambda_1^{opt} = 111.9023, \quad \lambda_2^{opt} = 130.1315,$$
$$\lambda_3^{opt} = 117.8743, \quad \lambda_4^{opt} = 125.9993,$$
$$\lambda_5^{opt} = 124.6457, \quad \lambda_6^{opt} = 115.0818,$$
$$\lambda_7^{opt} = 128.2411, \quad \lambda_8^{opt} = 111.9023$$

Moreover, from this figure, it is clear that if SF value decreases, the aggregate throughput of the secondary user is degraded because the probability of false alarm (miss detection for the vacant band) increases with decreasing SF. Figure 2 shows the probability of false alarm P_f for the different cases of PAPR reduction (SF $= 0.9$ and 0.95) and without PAPR reduction case when limiting the interference on primary user to $\varepsilon = 0.22$.

Based on the previous simulation results, the reduction of the degradation on the aggregate throughput of the cognitive user can be achieved by the following:

1. The cooperation is used to reduce the effect of PAPR reduction.
2. The primary user has an incentive to select the low value of the PAPR reduction where it can get more profit (as a price from the cognitive users due to leasing the spectrum band).

We will discuss the two suggestions in the following sections.

5 Cooperative joint detection considering the effect of reduction of PAPR

Figure 3 shows a cognitive radio network composed of N cognitive radios (secondary users) and a common receiver. The common receiver is introduced as a base station (BS) which manages the cognitive radio network and all associated N cognitive radios. Each cognitive radio performs local spectrum sensing independently. Cooperative spectrum sensing has been shown to greatly increase the probability of detecting of PU [20–22].

In cooperative spectrum sensing, local spectrum sensing information from multiple CRs are combined for PU detection. In centralized CR network, a common receiver plays a key role in collecting the local spectrum sensing information and detecting spectrum holes.

Cooperative spectrum sensing based on decision fusion can be summarized as follows:

- Each secondary user i, for $i = 1, \ldots, N$, performs spectrum sensing individually, i.e., energy detection with a result of Y_i. Furthermore, each secondary user has identical threshold values which are assumed. The secondary users will report its local decision A_i according to T_i. $A_i \in \{0, 1\}$ will be used to denote the information that the fusion center receives from the ith secondary users.

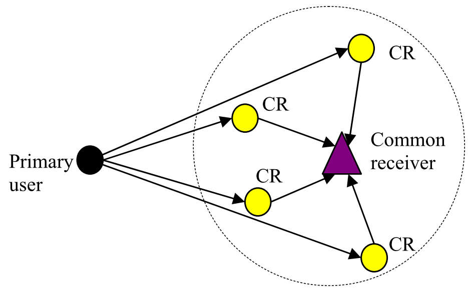

Fig. 3 System model of cooperative spectrum sensing

Where, {0} indicates that the CR infers the absence of the PU and {1} indicates that the CR infers the presence of the PU.

- The fusion center makes a final decision according to decision fusion, that is defined by:

$$FD = \begin{cases} 1 & \sum_{i=1}^{N} A_i \geq D \\ 0 & \text{Otherwise} \end{cases} \tag{10}$$

The case of $D = 1$ corresponds to OR rule and the case of $D = N$ corresponds to AND rule.

The optimization problem for cooperative sensing is the same as (5). In the following we obtain the optimal threshold for each subchannel k to jointly maximize the aggregate opportunistic throughput while PAPR reduction is taken into consideration.

5.1 Using AND rule

The probability of false alarm and probability of detection of the final decision for AND rule are given by [28]:

$$P_f^k(\lambda_k) = \prod_{i=1}^{N} P_{f,i}^k \tag{11}$$

$$P_d^k(\lambda_k) = \prod_{i=1}^{N} P_{d,i}^k \tag{12}$$

where $P_{f,i}^k$ and $P_{d,i}^k$ are the false alarm probability and detection probability of the ith secondary user for k subchannel, respectively. These are given by:

$$P_{f,i}^k(\lambda_{k.i}) = \Pr(T_{k,i} > \lambda_{k,i}/H_{0,k}) = Q\left(\frac{\lambda_{k,i} - M\sigma_w^2}{\sigma_w^2\sqrt{2M}}\right) \tag{13}$$

$$P_{d,i}^k(\lambda_{k,i}) = \Pr(T_{k,i} > \lambda_{k,i}/H_{1,k}) = Q\left(\frac{\lambda_{k,i} - M(\sigma_w^2 + |H_{k,i}|^2 P_x)}{\sqrt{2M(\sigma_w^2 + 2|H_{k,i}|^2\sigma_x^2)\sigma_w^2}}\right) \tag{14}$$

where $\lambda_{k,i}$ gives the detection threshold for each subchannel at i secondary user.

The false alarm probability of the ith secondary user for k subchannel is given by:

$$P_{f,i}^k = \sqrt[N]{P_f^k(\lambda_k)} \tag{15}$$

For the optimization problem in (5), and the limit on the total $1 - P_f^k$ and P_d^k for each subchannel k in (6), the lower bound on the thresholds for each user i for each subchannel k is obtained from (13) and (15) as:

$$\begin{aligned} &\lambda_{k,i} \geq \lambda_{\min,k,i} \\ &\lambda_{\min,k,i} \triangleq \sigma_w^2\left[M + \sqrt{2M}\, Q^{-1}\left(\sqrt[N]{1-\alpha_k}\right)\right] \end{aligned} \tag{16}$$

Similarity for P_d^k, the detection probability of the ith secondary user for k subchannel is given by:

$$P_{d,i}^k = \sqrt[N]{P_d^k(\lambda_k)} \tag{17}$$

By using (5), (6), (14), and (17), we get the upper bound on the thresholds of each subchannel k as:

$$\begin{aligned} &\lambda_{k,i} \leq \lambda_{\max,k,i} \\ &\lambda_{\max,k,i} \triangleq M\left(\sigma_w^2 + |H_{k,i}|^2 P_{x,PAPR}\right) \\ &\qquad + \sigma_w\sqrt{2M\left(\sigma_w^2 + 2|H_{k,i}|^2 P_{x,PAPR}\right)}\, Q^{-1}\left(\sqrt[N]{\beta_k}\right) \end{aligned} \tag{18}$$

5.2 Using OR rule

The probability of false alarm and probability of detection of the final decision for OR rule are given by:

$$P_f^k(\lambda_k) = 1 - \prod_{i=1}^{N}\left(1 - P_{f,i}^k\right) \tag{19}$$

$$P_d^k(\lambda_k) = 1 - \prod_{i=1}^{N}\left(1 - P_{d,i}^k\right) \tag{20}$$

Similarity for AND rule, from (19) and (20), the false alarm probability and detection probability of the ith secondary user for subchannel k are given by:

$$P_{f,i}^k = 1 - \sqrt[N]{1 - P_f^k(\lambda_k)} \tag{21}$$

$$P_{d,i}^k = 1 - \sqrt[N]{1 - P_d^k(\lambda_k)} \tag{22}$$

Therefore, the lower and upper bound on the thresholds of each subchannel k are obtained as:

$\lambda_{k,i} \geq \lambda_{\min,k,i}$

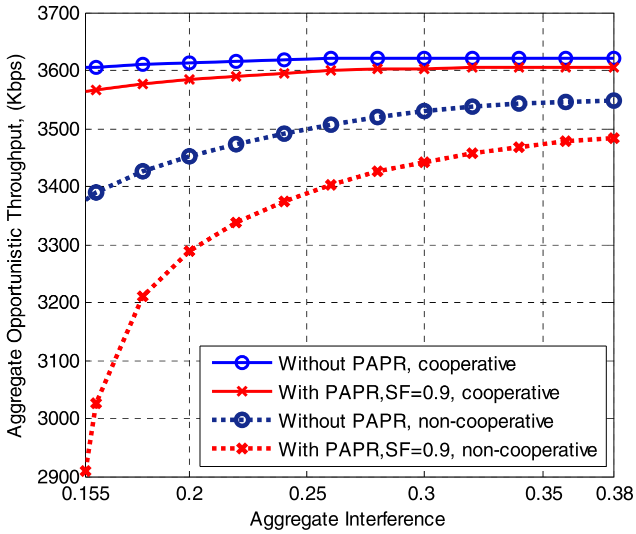

Fig. 4 The aggregate opportunistic throughputs vs. the constraint on the aggregate interference for cooperative and non cooperative scheme with PAPR reduction (SF = 0.9) and without PAPR reduction, OR rule

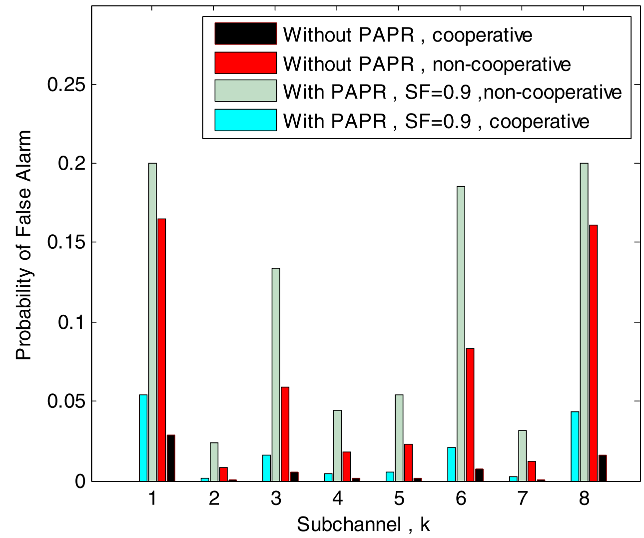

Fig. 5 The probability of false alarm for each subchannel k for cooperative and non cooperative scheme with PAPR reduction (SF = 0.9) and without PAPR reduction for $\varepsilon = 0.22$, OR rule

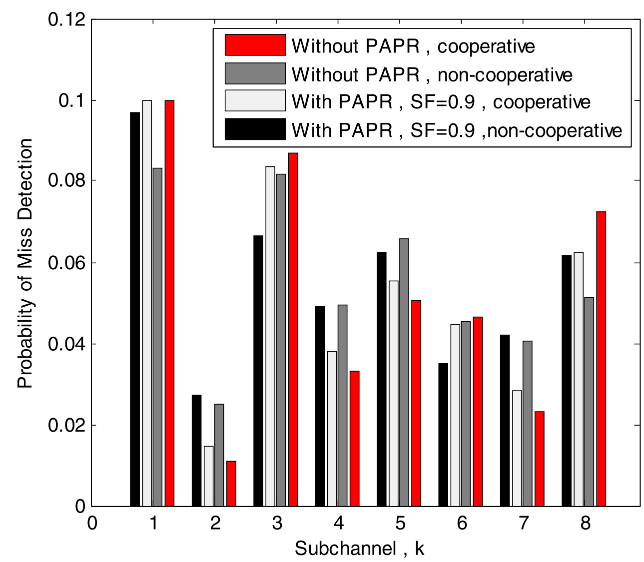

Fig. 6 The probability of miss detection for each subchannel k for cooperative and non cooperative scheme with PAPR reduction (SF = 0.9) and without PAPR reduction for $\varepsilon = 0.22$, OR rule

where (23)

$$\lambda_{\min,k,i} \triangleq \sigma_w^2\left[M + \sqrt{2M}\,Q^{-1}\left(1 - \sqrt[N]{\alpha_k}\right)\right],$$

$$\lambda_{k,i} \leq \lambda_{\max,k,i}$$

where

$$\lambda_{\max,k,i} \triangleq M\left(\sigma_w^2 + |H_{k,i}|^2 P_{x,PAPR}\right) + \sigma_w\sqrt{2M\left(\sigma_w^2 + 2|H_{k,i}|^2 P_{x,PAPR}\right)} \times Q^{-1}\left(1 - \sqrt[N]{1-\beta_k}\right) \qquad (24)$$

5.3 Simulation results

The same assumptions and parameters used in the previous section will be used in the following sections in despite that the number of cooperative users are equal to 2. Now, the cooperative spectrum sensing scheme and non cooperative scheme will be investigated. Also, in following simulation results, the improvement in the performance of the multi-band joint detection for wideband spectrum sensing using cooperative scheme to sense the primary signal will be explained when PAPR reduction is applied. The effect of cooperative scheme on the throughput that depends on the probability of false alarm and the Interference that depends on the probability of miss detection will be studied.

Figure 4 shows the improvement in the aggregate opportunistic throughput with cooperative scheme for OR rule. From this figure, the performance comparison of cooperative and non cooperative scheme is shown without PAPR reduction and with PAPR reduction at SF = 0.9. From these results, it is clear that the aggregate opportunistic throughput for cooperative scheme is better than without cooperative scheme in all cases of the PAPR reduction, even if we use cooperative scheme with SF = 0.9. It is still better than non cooperative scheme in case of without PAPR reduction.

Figures 5 and 6, show the probability of false alarm P_f and the probability of miss detection P_m with the PAPR reduction method (SF = 0.9) and without PAPR reduction method for cooperative scheme and non cooperative scheme when the interference on primary user is limited to a value equals to 0.22. We conclude that P_f is smaller in case of cooperative scheme than the non cooperative scheme. More-

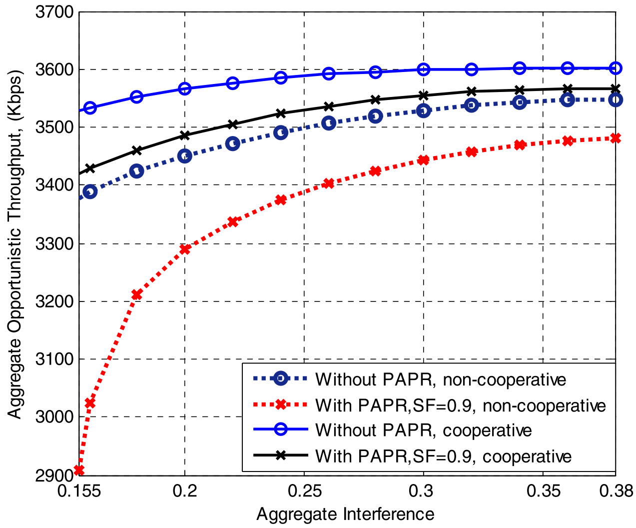

Fig. 7 The aggregate opportunistic throughputs vs. the constraint on the aggregate interference for cooperative and non cooperative scheme with PAPR reduction (SF = 0.9) and without PAPR reduction, AND rule

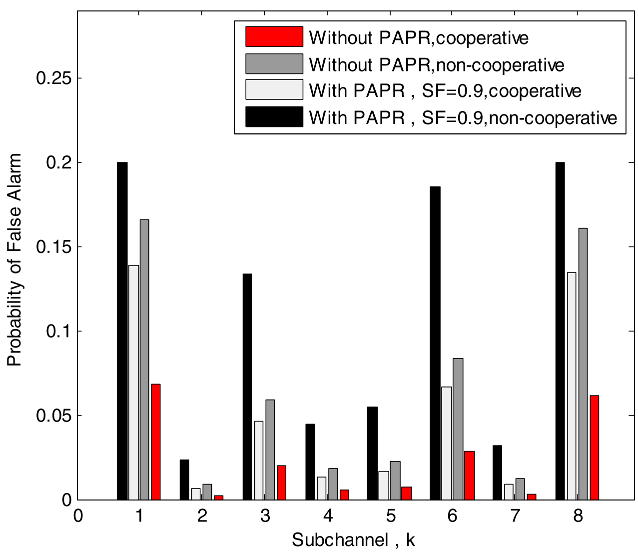

Fig. 8 The probability of false alarm for each subchannel k for cooperative and non cooperative scheme with PAPR reduction (SF = 0.9) and without PAPR reduction for $\varepsilon = 0.22$, AND rule

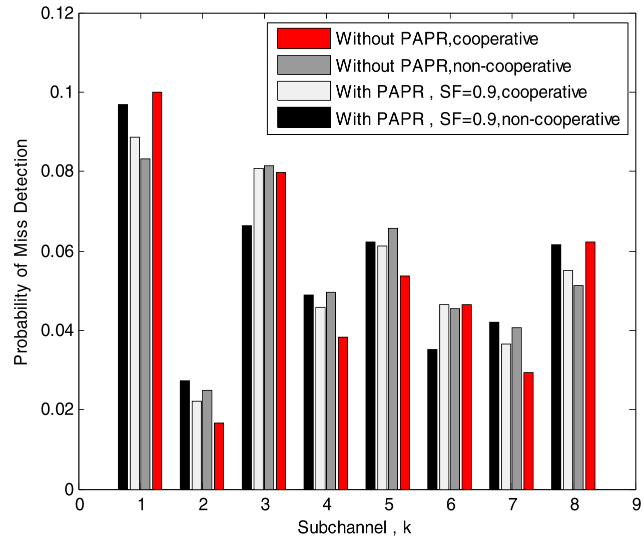

Fig. 9 The probability of miss detection for each subchannel k for cooperative and non cooperative scheme with PAPR reduction (SF = 0.9) and without PAPR reduction for $\varepsilon = 0.22$, AND rule

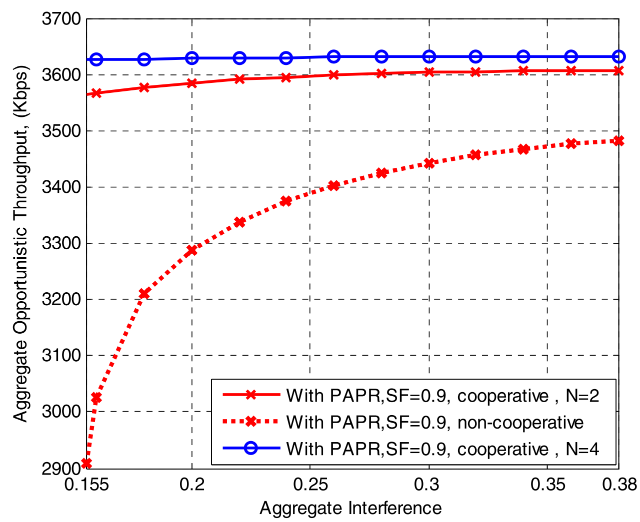

Fig. 10 The aggregate opportunistic throughputs vs. the constraint on the aggregate interference for different number of cooperative users and non cooperative scheme with PAPR reduction (SF = 0.9)

over, the value of P_m is not exceeding $1 - \beta_k = 0.1$ for all cases in Fig. 6, to save the primary user from interference while maximizing the throughput. OR rule is used with cooperative scheme in Figs. 4, 5, and 6. AND rule is used with cooperative scheme in Figs. 7, 8, and 9.

Figure 7 shows the improvement in the aggregate opportunistic throughput with cooperative scheme for AND rule. From this figure, we conclude that the aggregate opportunistic throughput for cooperative scheme using AND rule is better than non cooperative scheme in all cases of the PAPR reduction. Figures 8 and 9 show P_f and P_m for the PAPR reduction method (SF = 0.9) and without PAPR reduction method with cooperative scheme and non cooperative scheme using AND rule when the interference on primary user is limited to value equal 0.22. From these figures, we conclude that the improvement using OR rule with cooperative scheme is better than the case when using AND rule. Because the OR rule is very conservative for the CRs to access the licensed band. As such, the chance of causing interference to the PU is minimized.

Figures 10 and 11 show the performance of the system for using different number of cooperative users compared with non cooperative users.

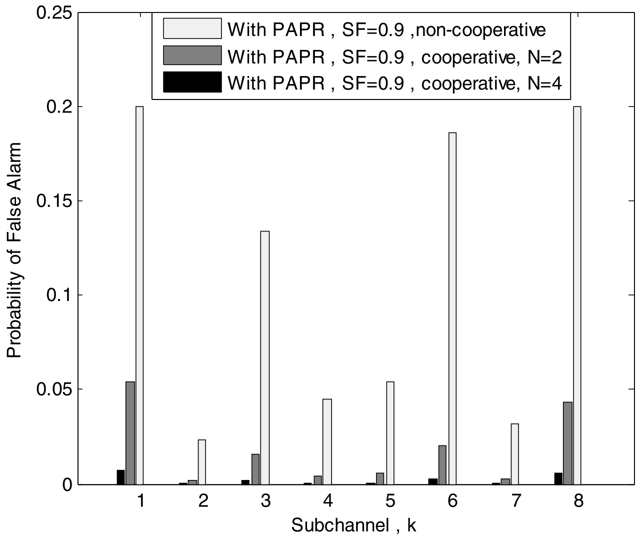

Fig. 11 The probability of false alarm for each subchannel k for different number of cooperative users and non cooperative scheme with PAPR reduction (SF $= 0.9$)

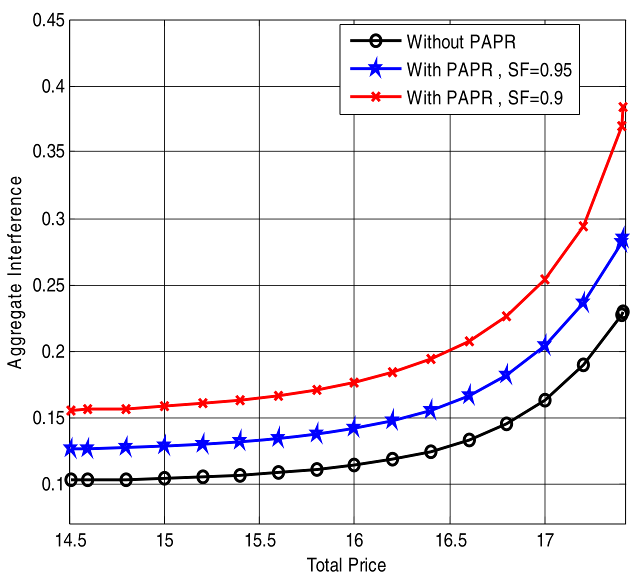

Fig. 12 Minimum aggregate interference vs. the constraint on the price for different SF of PAPR

Figure 11 The probability of false alarm for each subchannel k for different number of cooperative users and non cooperative scheme with PAPR reduction (SF $= 0.9$).

6 Optimization problem considering the profit of primary user

The incentive of the primary user to choose small value in PAPR reduction is to get certain price with minimum interference.

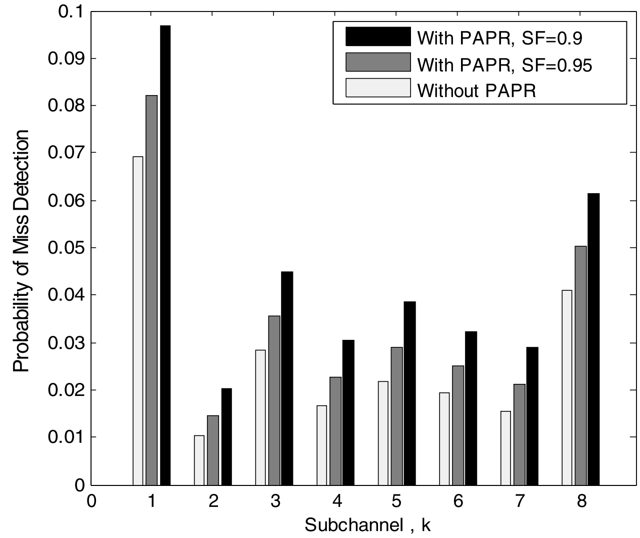

Fig. 13 The probability of miss detection for each subchannel k for different values of SF and $r = 16.2$

The optimization problem for minimizing the aggregate interference constraint to limit the charge price can be formulated as:

$$\begin{aligned} &\text{Min} \quad \sum I_k(\lambda_k) \\ &\text{s.t.} \quad \sum_{k=1}^{K} PR_k(\lambda_k) \geq r \\ &\lambda_{\min,k} \leq \lambda_k \leq \lambda_{\max,k} \end{aligned} \tag{25}$$

where $PR_k(\lambda_k) = \upsilon_k(1 - P_f^k(\lambda_k))$ and υ_k gives the charge price of each subchannel k.

6.1 Simulation Results

Figure 12 shows the minimum aggregate interference for different values of the total price for the cases that are without PAPR reduction method and with PAPR reduction method for SF $= 0.95$ and SF $= 0.9$. We randomly generate the channel condition between the primary user and the cognitive user, the price over each subchannel, and the interference of each subchannel. From this figure, we conclude that when the SF decreases, the aggregate interference to the primary user increases because the probability of miss detection increases with decreasing SF as shown in Fig. 13 when limiting the total price to $r = 16.2$ that is paid to primary user.

7 Conclusions

In this paper, the effect of PAPR reduction on the wideband spectrum sensing was studied which is not clarified until now. Moreover, the optimization problem for the multi-band joint detection for the non-cooperative and cooperative schemes was analyzed by considering the primary user's PAPR reduction. The optimal solutions for multi-band joint detection were suggested under peak power reduction of the primary user. The wideband cooperation spectrum sensing to improve the signal detection with high reduction in the PAPR was proposed. From simulation results, the PAPR reduction decreased the total price of the primary user and the aggregate opportunistic throughput of the secondary user. Moreover, the cooperative scheme is effective in improving the performance in terms of the aggregate opportunistic throughput with PAPR reduction.

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