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Practical Implementation of the Combinational Cooperative Detection Method

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Abstract In conventional cooperative detection, a fusion center decides on the presence or the absence of a primary user (PU) by gathering all the information from secondary users (SUs) and conveys this decision to all users. This approach does not take into account the locations of the SUs, where a user far from the PU may also have to keep silent. An alternative method referred to as the combinational cooperative detection method in this study, was recently proposed to solve this problem. This method is based on combining received signals from more than two users, obtaining decision tables, and deciding individually for each user. While the proposed method showed promising results for the SUs, there were unclear issues regarding the practical implementation of this method. Motivated by this, we address these issues from a realistic implementation point of view in this paper. Accordingly, (i) the effects of location and distribution of the SUs on the detection performance are studied in terms of system parameters; (ii) the conventional cooperative detection performance is clearly defined as a benchmark; and (iii) a novel method is developed to improve the combinational cooperative detection performance, where the achievable false detection and miss-detection probabilities are quantified. The results of this study are important to define the conditions where the implementation of the combinational cooperative detection method may be preferred over the conventional cooperative detection method.

Keywords Cognitive radio · Conventional cooperative detection · Combinational cooperative detection

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1 Introduction

Cognitive radio was first proposed by Joseph Mitola [1]. The cognitive radio technology provides usage of licensed spectrum by unlicensed users when it is available. Licensed and unlicensed users are called primary user (PU) and secondary user (SU), respectively, according to the usage of the spectrum. Although PUs have the priority of usage of the spectrum, most of the spectrum is unused [2]. In a cognitive radio network, SUs have to decide on the absence of a PU in order to start data transmission, and also have to leave the channel unoccupied when the PU starts data transmission. In a cognitive radio network, there are multiple SUs present for communications. If SUs individually detect the presence of a PU, the result of each decision may be not reliable and different. This renders difficulty in deciding correctly on the presence of a PU. Cooperative detection method can overcome this problem [3,4].

In cooperative detection, every SU detects the PU's signal and forwards its observed signal to the fusion center. Then, the fusion center decides on the presence of a PU based on the gathered information [3,4]. This detection method is based on the collaboration of SUs to reduce the effects of shadowing and fading. There are many cooperative techniques proposed in the literature. In [5], light-weight cooperation as a means is suggested to reduce the sensitivity requirements on an individual SU. In [6], a uniform quantization scheme for cooperative sensing is proposed, which is shown to perform better than hard decision algorithms. In [7], benefits of cooperation in cognitive radios are illustrated and it is shown that the detection time is reduced and SUs' agility is increased by cooperating. If the agility gains of cooperative detection method and non-cooperative detection method are compared, cooperative detection method reduces the detection time for SUs by as much as 35 % [8,9]. The length of sensing time at SUs is proportional to sensing accuracy, and the sensing time decreases the transmission time. It is called sensing efficiency problem and discussed in [10]. In [11], a two-phase algorithm for the spectrum sensing and power rate control of a cognitive radio is proposed, and the reliability of issuing data transmission permission is quantified as a performance measure. In [12], single and multiple scheduled spectrum sensing scheme is proposed to reduce the complexity of spectrum sensing and energy consumption. Proposed schemes are shown to be more efficient in terms of the number of sensing operations required for a given sum-false alarm probability and the sum-missed detection probability. In [13], a multichannel cooperative sensing scheme, where SUs have heterogeneous sensing ability as opposed to homogeneous sensing ability, is proposed and the performance improvement is quantified. In [14], it is shown that increasing the number of SUs does not always increase the throughput of spectrum sensing. The optimal number of users for the highest throughput also depends on the sensing length. In [15], the optimal number of SUs for cooperative spectrum sensing is derived in terms of minimizing detection error probability and optimal spectrum sensing time. In [16], a cooperative spectrum sensing scheme is proposed to alleviate the feedback error between SU and cognitive base station caused by imperfect channel conditions.

The common result for [4–16] is that the PU detection is improved and a single decision (either the PU is active or passive) is conveyed to the SUs. Although cooperative detection method provides improved performance, it does not take into account the locations of SUs. Fusion center provides one solution and all the SUs have to follow this decision. Accordingly, an SU may have to keep silent even though it may be far from the PU, or even worse, an SU near the PU may start communications and interfere with the PU due to most of the SUs being far from the PU and sending the fusion center the PU not-active information.

To overcome this problem, there is a recent method that takes into account the evaluation of various combined signal energies from different SUs and makes a decision separately for each SU [17]. While the authors do not give a specific name to their method, we refer to it as the "combinational cooperative detection" (CCD) method since various combinations of signals are used in cooperative detection. Although the method proposed is promising, there are few implementation issues regarding this method. First of all, the location and distribution of the SUs have a direct effect on the detection performance, however, are not investigated in [17]. Secondly, the conventional cooperative detection performance, which serves as a benchmark performance, is not determined accurately. Moreover, the detection performance of the CCD method may be subject to further improvements using different signal combinations. Hence, the implementation of the CCD method from a practical perspective needs further investigation. In [18], the effects of location and distribution of the SUs were studied; however, the effects of the selection of system parameters were not discussed in detail.

In this paper, motivated by the conditions summarized above, we consider the practical implementation of the CCD method. Initially, the performance of the conventional cooperative detection is quantified and determined correctly as it serves as a benchmark for the CCD method. Then, the effects of location and distribution of SUs in the CCD method are evaluated for possible cases. In [17], the location and distribution information was not discussed, hence, the contribution was limited. The evaluation results in [17] showed only the effects of the η and Q parameters, however, the assumed locations and distributions, and their effects on the performance were not clear. Accordingly, this is addressed in detail in this study. Finally, an improved method for CCD is proposed assuming that there is at least one SU near the PU (i.e., may cause interference) and one away from the PU (i.e., free to talk). It is shown that the probabilities of error can be sufficiently reduced with this approach, where these probabilities are quantified. In summary, the results of this study are important to realize the practical implementation of the CCD method.

The rest of the paper is organized as follows. In Sect. 2, conventional and CCD methods are explained. In Sect. 3, implementation of the CCD method is presented in detail in terms of system parameters, and the effects of these parameters on the detection performance are discussed. In Sect. 4, an improved method is proposed and the improvements in the detection performance are quantified. Concluding remarks are given in Sect. 5.

2 System Model

In this section, initially the most commonly used detection method, i.e., energy detection method [19], will be presented followed by the conventional cooperative detection method and the CCD method [17].

2.1 Energy Detection Method

The signal energy detected by the SU is compared to a threshold value for deciding whether the PU is present or absent. Let us assume that the signal observed by the SU has the following form

$$y_l = s_l + n_l \tag{1}$$

where s_l and n_l, respectively, denote the received primary signal sample and zero mean complex-valued additive white Gaussian noise (AWGN) term with variance σ_n^2 (i.e., $n_l \sim N(0, \sigma_n^2)$). When the energy detection method is used the test statistic is formulated by $Y = \sum_{l=1}^{L} |y_l|^2$, where L is the number of samples. There are two hypotheses, where H_0 denotes PU is absent and H_1 denotes PU is present:

$$Y = \begin{cases} \sum_{l=1}^{L} |n_l|^2, & H_0 \\ \sum_{l=1}^{L} |s_l + n_l|^2, & H_1. \end{cases} \tag{2}$$

Here, the variable Y is central Chi-square distributed with $2L$ degrees of freedom in the case of H_0. Similarly, under H_1, Y has a non-central chi-square distribution with $2L$ degrees of freedom and non-centrality parameter 2γ, where γ is the signal-to-noise-ratio (SNR) and is given by

$$\gamma = \frac{P_{TX}/d_{PU}^2}{\sigma_n^2} \tag{3}$$

where d_{PU} is the distance between PU and SU, and P_{TX} is the power of the signal transmitted by PU. Here, the received signal power is denoted by $|s_l|^2 = \frac{P_{TX}}{d_{PU}^2}$. If L is large enough, Y is normally distributed according to the Central Limit Theorem. In this paper, L is assumed to be large, hence, Gaussian distribution will be considered. Accordingly, the signal received by SU are given by [17]

$$Y = \begin{cases} N\Big(L\sigma_n^2, L\sigma_n^4\Big), & H_0 \\ N\Big(L(\sigma_n^2 + \gamma), L\sigma_n^2(\sigma_n^2 + 2\gamma)\Big), & H_1. \end{cases} \tag{4}$$

The energy detector decides on the absence or presence of the PU by comparing the received signal energy (Y) to the detection threshold (λ). Probability of false alarm, P_f, and probability of miss-detection, P_{md}, are conditional probabilities of error given by

$$P_f = \Pr[Y \geq \lambda | H_0] = Q\left(\frac{\lambda - \mu_{Y|H_0}}{\sigma_{Y|H_0}}\right) \tag{5}$$

$$P_{md} = \Pr[Y < \lambda | H_1] = Q\left(\frac{\mu_{Y|H_1} - \lambda}{\sigma_{Y|H_1}}\right) \tag{6}$$

where $Q(x) = \int_x^{+\infty} \frac{1}{\sqrt{2\pi}} \exp\Big(-\frac{t^2}{2}\Big) dt$.

2.2 Conventional Cooperative Detection Method

In conventional cooperative detection, the observed signal at the k-th SU is given by

$$Y_k = \begin{cases} \sum_{l=1}^{L} |n_{k,l}|^2, & H_0 \\ \sum_{l=1}^{L} |s_{k,l} + n_{k,l}|^2, & H_1 \end{cases} \tag{7}$$

for $k = 1, 2, \ldots, K$, where $s_{k,l}$ and $n_{k,l}$ denote the received primary signal sample and the AWGN term observed at the k-th SU, respectively. The k-th SU passes this signal to the fusion center. The instantaneous SNR (γ_k) of the signal that the fusion center receives from the k-th user is given by

$$\gamma_k = \frac{P_{TX}}{\sigma_n^2 d_{PU,k}^2 d_{M,k}^2} \tag{8}$$

where $d_{M,k}$ is the distance between the k-th SU and the fusion center. The combined signal is $Z = \frac{1}{K}\sum_{k=1}^{K} W_k Y_k$, where K is the number of SUs and W_k is the weight of each user. Since the locations of SUs are not known, Equal Gain Combining (EGC) (i.e., $W_k = 1$) is assumed. The signal combined by the fusion center is given by

$$Z = \begin{cases} N\left(L\sigma_n^2, \frac{L}{K}L\sigma_n^4\right), & H_0 \\ N\left(\frac{L}{K}\sum_{k=1}^{K}(\sigma_n^2+\gamma_k), \frac{L\sigma_n^2}{K^2}\sum_{k=1}^{K}(\sigma_n^2+2\gamma_k)\right), & H_1\,. \end{cases} \tag{9}$$

The fusion center decides on the presence or the absence of the PU by comparing Z with a threshold λ, and sends the result to all individual SUs. If the combined signal $Z \geq \lambda$, the fusion center decides PU is present, if $Z < \lambda$, then it decides PU is absent. All SUs have to follow this decision regardless of their locations.

2.3 Combinational Cooperative Detection (CCD) Method

The cooperative detection method is described in the previous subsection. Fusion center decides on the presence or the absence of the PU by gathering all the information from SUs and conveys this decision to all SUs, and all have to follow the decision. This approach does not take into account the locations of SUs, where a user far from the PU may also have to keep silent or vice versa. In this subsection the CCD method proposed in [17] to overcome this problem will be presented. In contrast to cooperative detection, in the CCD method fusion center does not provide one decision for all SUs; it delivers different decisions to the SUs.

The detection procedure of CCD method can be explained in 8 steps:

Step 1: Every SU observes the signal Y_k in (7) and sends it to the fusion center. The fusion center receives K signals in total.
Step 2: Fusion center chooses Q different SUs, and combines all possible observed signals. There are $U = \binom{K}{Q}$ possible combinations. Let $\mathbf{W}_u$ represent the combined data set where $u = 1, \ldots, U$.
Step 3: The combination output Z_u from (9) (for EGC, $W_k = 1$) is given by

$$Z_u = \frac{1}{Q}\sum_{k\in\mathbf{W}_u} Y_k, \quad u = 1, \ldots, U. \tag{10}$$

Step 4: A combination table is created by using the combination outputs $\{Z_u\}$. Combination table for $K = 4$, $Q = 3$ is given in Table 1. The values of Z_u can be obtained from (9) for different combinations as in (10).
Step 5: All combination output values $\{Z_u\}$ in the combination table are compared with a threshold value for deciding on the presence of the PU. Accordingly, an availability table is created, where 1 and 0, respectively, denote PU is present and absent. This is illustrated in Table 2. For example, the value “0” shows that $\frac{Y_1+Y_2+Y_4}{3} < \lambda$.
Step 6: Each column of the table represents an SU. For example, the first column gives the decisions for the first SU. Total number of decisions (present or absent) for each SU is $\binom{K-1}{Q-1}$.
Step 7: m_k is the total number of present decisions of the $k-th$ column. M and m_k are compared to decide which SU can talk and which should keep silent. M is defined as

$$M = \eta \times \binom{K-1}{Q-1}, \quad 0 \leq \eta \leq 1 \tag{11}$$

where η is a threshold corresponding to the percentage of presence required to make a decision. Decision of the fusion center for each SU is

Table 1 Combination table for $K = 4$, $Q = 3$

	1	2	3	4
1 and 2	–	–	$\frac{Y_1+Y_2+Y_3}{3}$	$\frac{Y_1+Y_2+Y_4}{3}$
1 and 3	–	$\frac{Y_1+Y_2+Y_3}{3}$	–	$\frac{Y_1+Y_3+Y_4}{3}$
1 and 4	–	$\frac{Y_1+Y_2+Y_4}{3}$	$\frac{Y_1+Y_3+Y_4}{3}$	–
2 and 3	$\frac{Y_1+Y_2+Y_3}{3}$	–	–	$\frac{Y_2+Y_3+Y_4}{3}$
2 and 4	$\frac{Y_1+Y_2+Y_4}{3}$	–	$\frac{Y_2+Y_3+Y_4}{3}$	–
3 and 4	$\frac{Y_1+Y_3+Y_4}{3}$	$\frac{Y_2+Y_3+Y_4}{3}$	–	–

Table 2 Availability table

	1	2	3	4
1 and 2	–	–	1	0
1 and 3	–	1	–	1
1 and 4	–	0	1	–
2 and 3	1	–	–	1
2 and 4	0	–	1	–
3 and 4	1	1	–	–
m_k	2	2	3	2

$$\begin{aligned} m_k &\geq M \rightarrow \text{PU present}, \\ m_k &< M \rightarrow \text{PU absent}. \end{aligned} \tag{12}$$

If the fusion center decides PU is present for an SU, this SU has to remain quiet. In the CCD method, decision on an SU depends on combination with $Q-1$ other SUs. The conventional cooperative detection method is indeed a sub-method of CCD, where $K = Q$, and one decision is made for all.

Step 8: Probabilities of false detection and miss-detection are defined to evaluate the system performance. These probabilities are different from the probabilities defined in (5) and (6). If a PU is assumed to be always present, the new probability definitions are as follows:

> P_{md} (miss-detection): Fusion center decides "PU is absent" for the SUs in the overlapped communication area (overlapped communication area: The area where SUs are located in creates interference to the PU. Hence, SUs have to be silent.).
>
> P_{fd} (false detection):[1] Fusion center decides "PU is present" for the SUs in the non-overlapped communication area (non-overlapped communication area: The area where SUs are located in does not create interference to the PU. Hence, SUs can communicate.).

The best performances are obtained when P_{md} and P_{f_d} have the smallest values. The detection performance can be evaluated in terms of the system parameters η, K, Q, etc.

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[1] The conventional *probability of false alarm* expression, P_f, and the newly defined *probability of false detection* expression, P_{fd}, should not be confused. The new expression, P_{fd}, is related to the detection of the PU by the unharmful users when the PU is active.

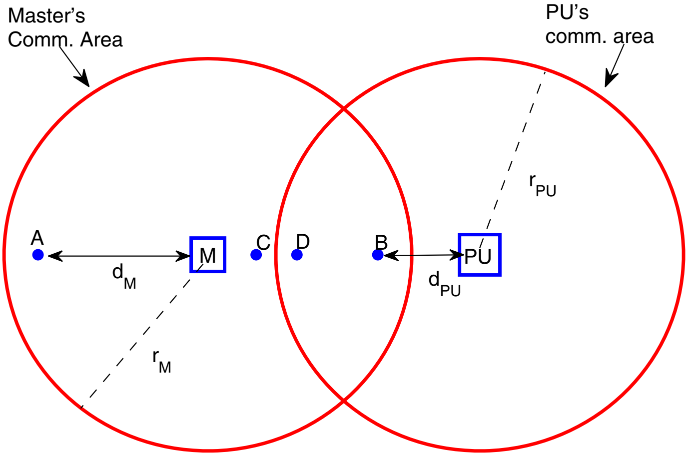

Fig. 1 The locations of SUs and the PU

3 Implementation of the CCD Method

In the previous study [17], where the CCD method is proposed, there is not enough information about the location and number of SUs. Accordingly, it is not possible to examine the system performance efficiently. For this reason, location and distribution of SUs are detailed in this section.

In Fig. 1, PU and M, respectively, denote the PU and the fusion center (i.e., Master). A, B, C, D are the locations of the SUs [18]. The SUs at location A and C are in the non-overlapped area, and can communicate without causing interference to the PU. The SUs at location B and D are in the overlapped area, and have to remain quiet. Let x be the number of SUs in the non-overlapped area, and y be the number of SUs in the overlapped area. Accordingly, there are $x + y = K$ users. The locations A, B, C, D are selected near the border communication areas. These locations serve as a benchmark for the best (A, B) and worst (C, D) performance evaluations. SUs are assumed to be at the designated points (A, B or C, D) and very close to each other. Probabilities of error for the SUs at designated points and locations are evaluated and compared with the conventional cooperative detection method for various system parameters. It is assumed that $r_M = r_{PU} = 6m$, $d_M = \{5, 5, 1.5, 2.5\}m$ and $d_{PU} = \{13, 3, 6.5, 5.5\}m$ for points A, B, C, D, respectively. Furthermore, $P_{TX} = 100$ and $L = 100$ are used throughout the study. In Table 3, a summary of commonly used variables and notations to assess the detection performance of the CCD method is given for convenience.

Before presenting the effects of SU locations on the CCD method performance, we present the implementation and performance of the conventional cooperative detection method next.

3.1 Conventional Cooperative Detection Method Performance

It is very important to determine the performance of the conventional cooperative detection method correctly as it is used as a benchmark performance. For that, we consider the newly defined probability of error expressions presented in the previous section. The accurate performance evaluation of the conventional cooperative detection can be explained as follows.

Table 3 Commonly used variables and notations

Variables/ notations	Explanations
K	Number of users ($K = x + y$)
Q	Number of combination ($Q < K$)
x	Number of SUs in the non-overlapped area
y	Number of SUs in the overlapped area
η	Threshold corresponding to the percentage of presence ($0 \leq \eta \leq 1$)
P_{md}	Probability of miss-detection: fusion center decides "PU is absent" for the SUs in the overlapped communication area
P_{fd}	Probability of false detection: fusion center decides "PU is present" for the SUs in the non-overlapped communication area

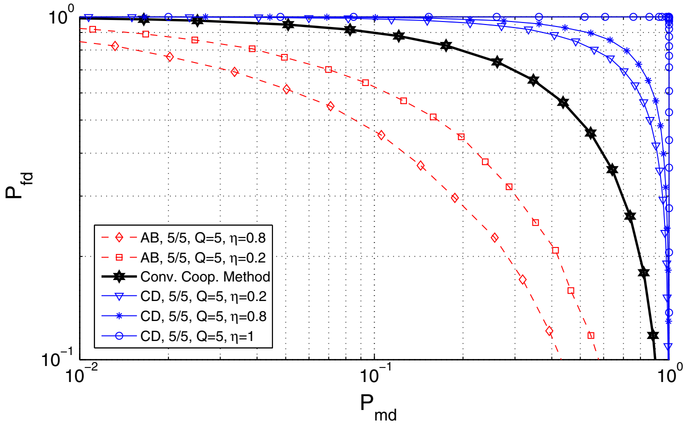

Fig. 2 The performance of the conventional cooperative detection as a benchmark and the effect of η on the CCD method performance

Fusion center decides on the presence or absence of the PU and conveys this single decision to all users. According to the definition of P_{fd} and P_{md}, this decision is true for all x SUs in the non-overlapped area, and wrong for all y SUs in the overlapped area (or vice versa). Accordingly:

- If the decision is true for x SUs, the probabilities of error P_{fd} and P_{md} will be 0 and 1, respectively.
- If the decision is true for y SUs, the probabilities of error P_{fd} and P_{md} will be 1 and 0, respectively. Therefore,

$$P_{md} + P_{fd} = 1. \tag{13}$$

In Fig. 2, the tradeoff between P_{fd} and P_{md} is shown using computer simulations. It can be observed that $P_{md} + P_{fd} = 1$ is satisfied for every scenario tested. Hence, this performance serves as a benchmark independent of SU locations and numbers. It should be noted that the conventional cooperative detection performance results provided in [17] do not satisfy (13). Next, the effects of system parameters on the detection performance are investigated.

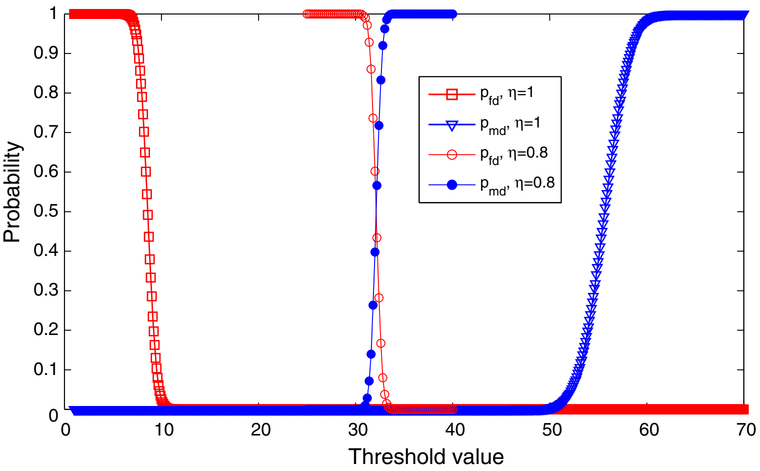

Fig. 3 Probabilities of error with respect to threshold values

3.2 Effect of the Percentage Ratio on the CCD Method Performance

The effect of the percentage ratio (η) on locations A, B and C, D is examined when the combination number is $Q = 5$ and equal distributions in each region ($x|y = 5|5$) are assumed. The performance results are shown in Fig. 2. It can be observed that the probabilities of error for SUs located close to each other (C, D) are always greater than the probabilities of error of conventional cooperative detection method. On the other hand, error probabilities of SUs located away from each other are always smaller.

When the value of η is increased, the probabilities of error for SUs located at (A, B) are decreased. Contrary to the conventional cooperative detection method, probabilities of error are $P_{fd} = P_{md} = 0$ for $\eta = 1$ within a threshold interval. This is illustrated in Fig. 3 for $\eta = 1$ and $\eta = 0.8$. For $\eta = 1$, $P_{fd} = P_{md} = 0$ for threshold values $10 < \lambda < 50$. Hence, a threshold value selected in this interval can achieve no error performance. When $\eta = 0.8$, there is an overlapping region for P_{fd} and P_{md} when $30 < \lambda < 34$, where the tradeoff can be observed. For the further cases, $\eta = 1$ is selected for similar simulation conditions.

3.3 Effect of the Combination Number on the CCD Method Performance

The effect of the combination number (Q) on locations A, B and C, D is examined when the percentage ratio is $\eta = 1$ and equal distributions in each region ($x|y = 5|5$) are assumed. The performance results are shown in Fig. 4. When the value of Q is decreased, the probabilities of error for SUs located at (A, B) are decreased. Contrary to this, the probabilities of error for SUs located at (C, D) are increased. This can be explained as follows. The signals received by the fusion center from SUs located at (C, D) have similar magnitudes. If the number of combined SUs is increased, the decision of the fusion center will be better but not smaller than the probabilities of error for conventional cooperative detection method. On the other hand, the magnitudes of received signals from the SUs located at (A, B) are significantly different. For $Q > x$, low and high magnitude signals will be combined. Therefore, the number of combined SUs must be decreased (i.e., smaller Q value) for better results.

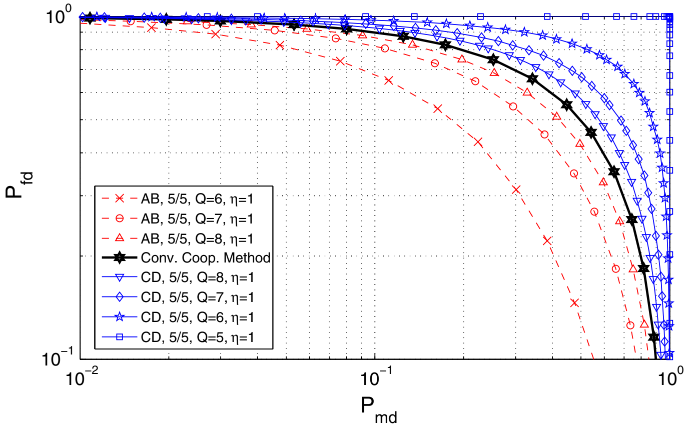

Fig. 4 Effect of Q on the CCD method performance

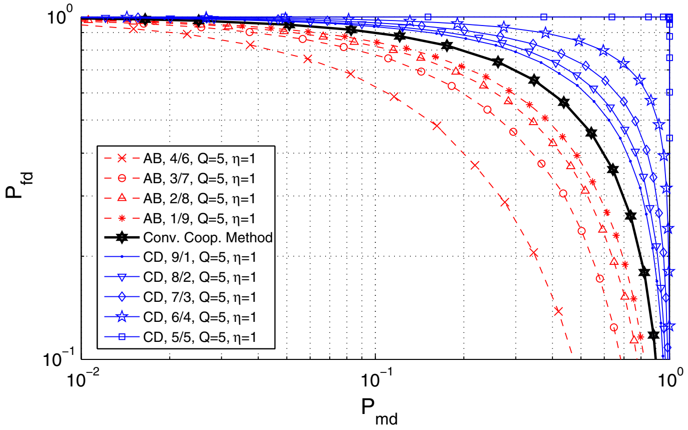

Fig. 5 Effect of SU distribution on the CCD method performance

3.4 Effect of the Distribution on the CCD Method Performance

Next, the effect of the distribution (i.e., $x|y$) on locations A, B and C, D is examined when the percentage ratio is $\eta = 1$ and the combination number is $Q = 5$. The performance results are shown in Fig. 5.

It can be observed that the probabilities of error for SUs located at (C, D) are always greater than the probabilities of error for conventional cooperative detection method regardless of the distribution of SUs. On the other hand the probabilities of error for the SUs located at (A, B) are always better. If the number of SUs in the non-overlapped communication area (x) increases, then the probabilities of error become smaller. Probabilities of error for SUs located at (C, D) approach the conventional cooperative detection method performance when x is increased. For the SUs located at (A, B), probabilities of error are $P_{fd} = P_{md} = 0$ within a threshold interval when $x \geq Q$. This observation is consistent with the remarks made in the previous subsection.

Table 4 Complexity and performance comparison depending on combination number

	Combinational coop. detection	Conventional coop. detection
Number of summation operations	$(Q-1)\binom{K}{Q}+K\left[\binom{K-1}{Q-1}-1\right]$	$K-1$
Number of comparison operations	$\binom{K}{Q}+K$	1
Performance	Locations A and B: performance of CCD method improving as Q decreasing. Locations C and D: performance of CCD method improving and approaching conventional performance as Q increasing	

3.5 Computational Complexity and Performance Improvement

The CCD method intends to determine a decision for every SU separately, as opposed to the conventional cooperative detection method determining a single decision for all SUs. This comes at the expense of increased complexity mainly due to the combination with $Q-1$ other SUs. The increased complexity can be explained in terms of summation and comparison operations as a function of combination number, Q, and the total number of SUs, K. This is illustrated in Table 4. Since both summation and comparison operations are dominated by the value of $\binom{K}{Q}$, for a fixed value of K the complexity is maximized when $Q=\frac{K}{2}$ (for an even number of K SUs). On the other hand, if "Q is small" or "Q is close to K", the complexity decreases. As explained in Sect. 3.3, the performance of the CCD method not only depends on Q but also depends on locations of SUs. Accordingly, as Q decreases the performance of CCD method improves at distant locations (A, B), whereas as Q increases the performance of CCD method improves at closer locations (C, D) as summarized in Table 4. Hence, selection of either a "small" or a "large" value of Q (depending on SU distributions) will improve the performance of CCD method while retaining the computational complexity at a relatively low level compared to $Q\approx\frac{K}{2}$.

4 Improved CCD Method

In this section, the CCD method will be modified to reduce the probabilities of error, P_{md} and P_{fd}. According to the CCD method, for a small threshold value the fusion center decides on the presence of the PU, and all SUs have to keep silent. This decision is false for the SUs in the non-overlapped communication area. In the same way, for a large threshold value the fusion center decides on the absence of the PU. It is a false decision for SUs in the overlapped communication area. The values of P_{fd} and P_{md} are accordingly

$$P_{fd}=[1\ 0] \text{ and } P_{md}=[0\ 1] \tag{14}$$

i.e., the maximum values of probabilities of error P_{fd} and P_{md} are equal to 1. The main aim of the proposed method is to decrease the maximum value of the probabilities of error, assuming that there is at least one SU in the overlapped and one in the non-overlapped communication area.

According to simulation results (Figs. 2, 4, 5), probabilities of error for SUs at distant locations (A, B) are smaller than the probabilities of error for SUs at close locations (C, D). While this method can be used for either location, we obtain mathematical expressions for probabilities of error for the (A, B) location. The models for improving the probabilities of false detection and miss-detection are described below.

4.1 Improving False Detection Probability

The maximum value of P_{fd} is attained if the threshold value is small. In the case there is at least one SU in the non-overlapped communication area, the maximum value of P_{fd} is reduced when the smallest combination value of each row in the combination table is set as "absent" (refer to Table 2). This operation ensures that the decision for one SU is correct. P_{fd} can be formulated as below

$$
\begin{aligned}
P_{fd} &= \left[P_{fd}(min), P_{fd}(max)\right], \text{ where } P_{fd}(min) = 0, \\
P_{fd}\,(max) &= \begin{cases} 0, & \text{if } x \le Q \\ \frac{x-Q}{x}, & \text{if } x > Q \end{cases}
\end{aligned}
\tag{15}
$$

where $Q \neq K$. Maximum value of P_{fd} depends on the number of SUs in the non-overlapped communication area and the combination number Q. Minimum value of P_{fd} is detected at a large threshold value and it is always 0.

4.2 Improving Miss-Detection Probability

The maximum value of P_{md} is attained if the threshold value is large. The maximum value of P_{md} is reduced when the largest combination value of each row in the combination table is set as "present" (refer to Table 2). This operation ensures that the decision for at least one SU in the overlapped communication area is always correct. P_{md} can be formulated as below

$$
\begin{aligned}
P_{md} &= \left[P_{md}(min), P_{md}(max)\right], \text{ where} \\
P_{md}(min) &= \begin{cases} 0, & \text{if } y < K - Q + 1 \\ \frac{y-(K-Q+1)+1}{y}, & \text{if } y \ge K - Q + 1 \end{cases} \\
P_{md}(max) &= \frac{y-1}{y}
\end{aligned}
\tag{16}
$$

where $Q \neq K$. Minimum value of P_{md} depends on the number of SUs in the overlapped communication area and the combination number Q. Maximum value depends only on the number of SUs in the overlapped communication area.

In the following, we present some examples of the improved CCD method. Note that these examples illustrate the relative performances of the improved CCD method for various parameters with respect to the same threshold values. Obtaining optimal threshold values are application-specific and is out of scope of this paper.

4.3 Relevant Examples for the Improved CCD Method

It is assumed that there is at least one SU in the overlapped and one in the non-overlapped communication area, and the combination number is not equal to the total number of SUs, i.e., $Q \neq K$.

Improving false detection probability: Figures 6 and 7 shows the simulation results for improving the maximum value of P_{fd} for different values of Q and distributions, respectively. The effect of combination number (Q) is examined in Fig. 6 in the case of percentage ratio

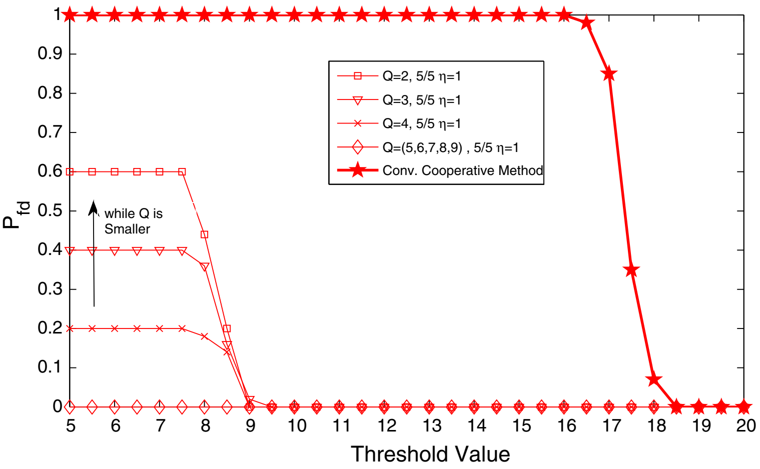

Fig. 6 Results for improving the maximum value of P_{fd} for different Q values

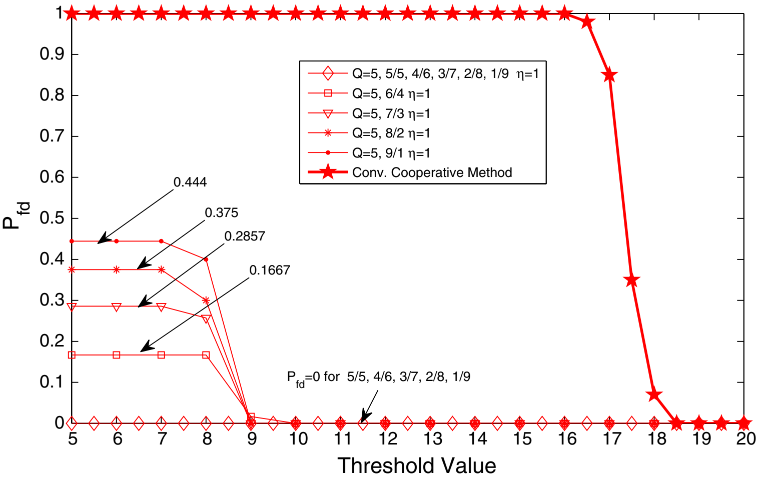

Fig. 7 Results for improving the maximum value of P_{fd} for different distributions

$\eta = 1$ and equal distributions in each region $(x|y = 5|5)$. The maximum value of P_{fd} is decreased from 1 to 0.8 in the worst case scenario. False detection probability value approaches zero for large threshold values, where the minimum value is always zero. The maximum value of P_{fd} depends on the combination number and number of SUs in the non-overlapped communication area.

The effect of distribution $(x|y)$ is examined in Fig. 7 in the case of percentage ratio $\eta = 1$ and combination number $Q = 5$. The maximum value of false detection is proportional to the number of SUs in the non-overlapped communication area for a combination number fixed. The maximum probability values obtained from simulations are consistent with the numerical values obtained from (15).

Improving miss-detection probability: The minimum value of P_{fd} is always zero regardless of the combination number and the distributions. However, the minimum value of P_{md}

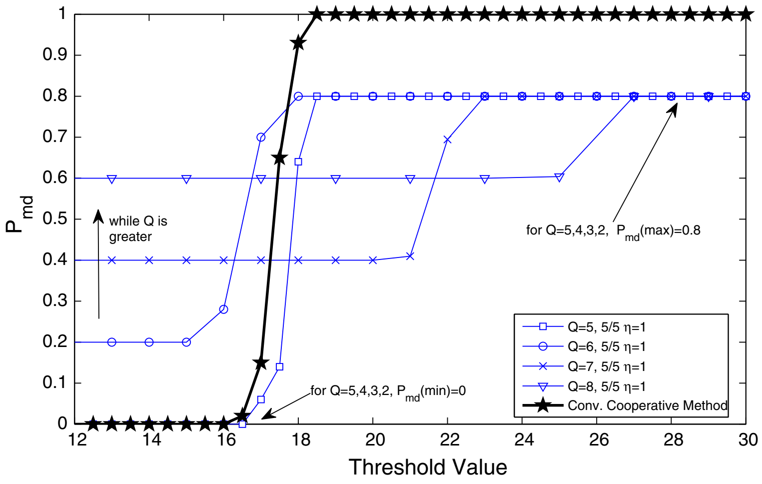

Fig. 8 Results for improving the maximum value of P_{md} for different Q values

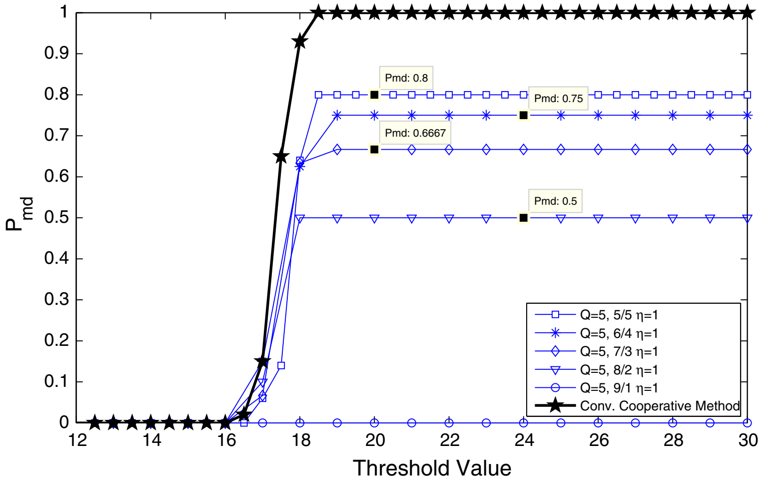

Fig. 9 Results for improving the maximum value of P_{md} for different distributions when $x \geq Q$

is not always zero for the improved method. It depends on the combination number and the distribution of SUs. The effect of Q on P_{md} is examined in Fig. 8 in the case of percentage ratio $\eta = 1$ when equal distributions in each region $(x|y = 5|5)$ are assumed. The average signal power for an SU in the overlapped communication area is decreased when the value of Q is large. According to improving false detection method, decision for smallest combination value in a row is set as absent. Therefore, it will be a false decision for the SUs in overlapped communication area and the minimum value of P_{md} will not be 0.

The effect of distributions $(x|y)$ is examined in the case of percentage ratio $\eta = 1$ and combination number $Q = 5$. The effects of distribution for $x \geq Q$ and $x < Q$ are shown in Figs. 9 and 10, respectively. The maximum value of P_{md} depends on the number of SUs in the overlapped communication area. Improved miss-detection method ensures at least one true decision for these SUs. On the other hand, while the $P_{md}(min) = 0$ can be maintained

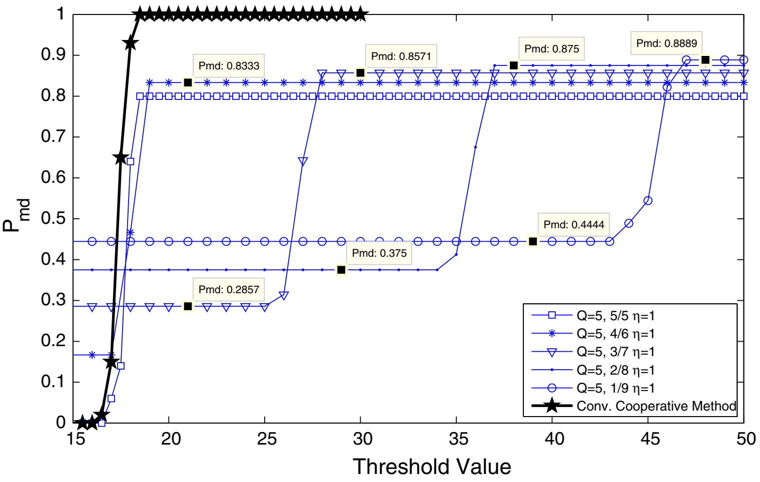

Fig. 10 Results for improving the maximum value of P_{md} for different distributions when $x < Q$

for $x \geq Q$, $P_{md}(min) > 0$ for $x < Q$. The maximum and minimum values of miss-detection probability obtained via simulation in Figs. 8, 9 and 10 are consistent with (16).

5 Conclusion

In this paper, practical implementation issues of the CCD method [17] were considered. Accordingly, (i) conventional cooperative detection performance was determined correctly as a benchmark; (ii) the detection performance of the CCD method was investigated in terms of system parameters considering the effects of the SU location and distribution; and (iii) a novel method was developed that improves the detection performance of the CCD method. It is shown that the performance of the CCD method strongly depends on the SU location and distribution as well as the combination parameter Q. Moreover, the performance of the CCD method can be further improved, and the maximum and minimum error probability values can be determined using the proposed approach. In summary, the results of this study can be used to implement the CCD method for practical considerations.

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