KADIR HAS UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

PRACTICAL IMPLEMENTATION OF COMBINATIONAL COOPERATIVE DETECTION METHOD

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PRACTICAL IMPLEMENTATION OF COMBINATIONAL COOPERATIVE DETECTION METHOD

Abstract

In conventional cooperative detection, a fusion center decides on the presence or the absence of the primary user by gathering all the information from the 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 primary user (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 secondary users, there were unclear issues regarding the practical implementation of this method. These issues include the effect of the location and the distribution of the SUs, as well as, determining the conventional cooperative detection performance as a benchmark.

Motivated by these conditions, the practical implementation of the combinational cooperative detection method is pursued in this thesis. Accordingly, (i) the effects of the location and the distribution of the SUs on the detection performance is 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 alarm and miss-detection probabilities are quantified. The results of this thesis are important to define the conditions where the implementation of the combinational cooperative detection may be preferred over the conventional cooperative detection.

KOMBİNASYONEL İŞBİRLİKLİ ALGILAMA YÖNTEMİN PRATİK GERÇEKLEŞTİRİMİ

Özet

Klasik işbirlikli algılama yönteminde, füzyon merkezi ikincil kullanıcılardan gelen sinyalleri işleyerek birincil kullanıcının aktif olup olmadığına karar verir ve bu bilgiyi tüm kullanıcılara iletir. Bu yaklaşımda ikincil kullanıcı konumları dikkate alınmadığı için birincil kullanıcıya girişim yaratmayacak uzaklıktaki bir kullanıcı iletişime geçmeyecektir. Bu sorunun üstesinden gelmek için daha önce kombinasyonel işbirlikli algılama yöntemi olarak adlandırılan bir yöntem önerilmiştir. Bu yöntemde ikiden fazla ikincil kullanıcının algıladığı sinyallerin kombinasyonlarına göre karar tabloları oluşturularak her bir kullanıcı için karar verilmektedir. Önerilen bu yöntemle, ikincil kullanıcılar için iyileşmiş sonuçlar elde edilse de pratik uygulamasına ilişkin konular açık değildir. Kullanıcı konum ve dağılımları ile karşılaştırma ölçütü olarak alınan işbirlikli algılama yöntem performansı bu konulardan önemli olanlarıdır.

Bu eksikliklerden yola çıkarak, kombinasyonel işbirlikli algılama yöntemin pratik gerçekleştirimi incelenmiştir. Buna göre, bu tezde (i) sistem parametrelerine göre ikincil kullanıcıların ve dağılımlarının etkisi incelenmiş, (ii) karşılaştırma ölçütü olan işbirlikli algılama performansı doğru tanımlanmış, ve (iii) yeni geliştirilen yöntemle kombinasyonel işbirlikli algılama yöntemi hata oranları iyileştirilmiş ve başarılan hata olasılıklarının niceliği belirlenmiştir. Bu çalışma, hangi durumlarda kombinasyonlu işbirlikli algılama yönteminin, geleneksel işbirlikli algılama yöntemine tercih edilmesi gerektiği konusunda önemli sonuçlar vermektedir.

Keywords: Bilişsel radyo, işbirlikli algılama, enerji algılama, spektrum sezme

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This work is dedicated to my beloved husband, F. Özgür Çatak.

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CHAPTER 1 INTRODUCTION

The 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.

There are various methods to assess the presence of a PU [3]. The most common spectrum sensing techniques used in cognitive radios are explained below:

<u>Matched Filtering Based Sensing:</u> When the SUs know the PU's signal [4], this method can be used. Its main advantage is the short time to achieve a certain error probability as compared to other sensing methods. On the other hand, the received signals are demodulated by SUs. Hence it is required to know features of PU's signal such as bandwidth, frequency, modulation type and order, pulse shaping, frame format, etc. Moreover, since cognitive radio needs receivers for all signal types, implementation complexity of sensing unit is impractically large [5].

<u>Cyclostationarity-Based Sensing:</u> It has been introduced for detecting weak signals using cognitive radios. It has a desirable performance under low signal-to-noise ratio (SNR) and can be used for signal recognition and classification [6]. The disadvantage with cyclostationary spectrum sensing is its high complexity which results in high cost [7].

<u>Energy Detector-Based Sensing:</u> Energy detection method is the most common way of spectrum sensing because of its low computational and implementation complexities [8]- [9]. In this method, it is not necessary to know any knowledge about the primary users' signals. The signal detected by an SU is compared with a threshold value for deciding on the presence

of a PU. The selection of a threshold value for detecting PUs is an important challenge for the energy detector based sensing [10]. In practice, the threshold is chosen to obtain a certain false alarm rate [11]. The other challenges are difficulty in distinguishing interference from primary users, and detection of a PU under low SNR values [9], [12]. Moreover, energy detectors do not work efficiently for detecting spread spectrum signals [13]. Despite the disadvantages, energy detection is the most practical method for cognitive radios.

In a cognitive radio network, there are multiple SUs present for communications. If SUs individually detect the presence of a PU, the results 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 of this problem [9]. There is a comprehensive literature on cooperative detection methods. Some important methods are summarized in the next section.

1.1 Literature on Cooperative Detection

Among the cooperative detection methods, there are various approaches proposed.

Every SU detects the signal and forwards its observed signal to the Master. Then, the Master decides on the presence of a PU based on the gathered information [9]. This detection method is based on the collaboration of the SUs to reduce the effects of shadowing and fading. Under varying channel conditions due to fading and shadowing, a low energy signal may be assumed as a spectrum hole, and the SU may cause interference to the PU. It can be mitigated by allowing different SUs to share their signals and by collaboratively making a decision [14]. In [15], light-weight cooperation as a means is suggested to reduce the sensitivity requirements on an individual SU.

In [16], benefits of cooperation in cognitive radio are illustrated and it is shown that the detection time is reduced and SUs' agility is increased by cooperating. If the agility gain 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% [17], [18]. The length of sensing time at SUs is proportional to sensing accuracy and sensing time decreases the transmission time. It is called sensing efficiency problem and discussed in [19], and [20].

The sensing performance is improved when SUs are cooperated. The performance of cooperative spectrum sensing for different number of SUs is investigated in [21], [22]. Probability of detection is increased when the numbers of SUs increase.

The common results for [14]-[22] 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 gives improved performance, it does not take into account the locations of SUs. Master 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 Master 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 making a decision separately for each SU. In [23], decision on the absence or presence of the PU by combinations of received signals is proposed. Although the method proposed in [23] is promising, there are few implementation issues regarding the method. These are the effects the location and distribution of the SUs on the detection performance. Moreover, the conventional cooperative detection performance, which serves as a benchmark performance is not determined accurately.

1.2 Contribution of the Thesis

Motivated by the above conditions, the practical implementation of the method in [23] is considered in detail.

While the authors of [23] 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. Besides exploring the CCD method for practical implementation considerations, also an improved method is proposed for CCD.

The contributions of this thesis can be summarized as follows:

1) It is shown that evaluation of the conventional method in [23] is not accurate. Accordingly, the performance of the conventional method is quantified and serves as a benchmark for CCD.
2) The effects of the location and distribution of SUs in CCD method are evaluated for possible cases as benchmarks. In [23], the location and distribution information was not discussed, hence, the contribution was limited.
3) 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 far away from the PU (i.e., free to talk). With this approach, probabilities of error can be significantly reduced.
4) The probabilities of error expressions for the improved CCD method are quantified.

1.3. Organization of the Thesis

This thesis is presented in four chapters and is organized as follows:

Chapter 2 presents single-user energy detection method, cooperative energy detection method and the combinational cooperative detection method. The CCD method implementation and the claimed performances in [23] are also presented.

Chapter 3 presents the practical implementation of CCD [23] considering the effects of the location and distribution of the SUs on the detection performance. In addition, the benchmark performance, i.e., the conventional cooperative detection performance is clearly explained. Finally, a new method that can improve the CCD performance is presented and the resulting probability error expressions are quantified. Also, relevant practical examples are presented to show the improved CCD performances.

Chapter 4 presents the conclusions, summarizes the observations and points out directions for future work.

CHAPTER 2 SPECTRUM SENSING TECHNIQUES

In this chapter, mathematical models for conventional spectrum sensing techniques and the CCD method are presented in detail.

2.1 CONVENTIONAL SPECTRUM SENSING TECHNIQUES

There are various proposed methods for identifying whether the PU is present (i.e., active) or absent (i.e., passive).
In this section, the most common spectrum sensing technique, i.e., energy detection method, and the cooperative energy detection method are explained.

2.1.1 Energy Detection Method

Energy detection method is a common technique for spectrum sensing because of low computational and implementation complexities. Moreover, it is not necessary to know any knowledge about the PU's signal. In the case of a single SU, the signal 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

$$y_l = s_l + n_l \tag{2.1}$$

where s_l and n_l, respectively, denote the received primary signal sample and zero mean complex-valued additive white Gaussian noise (AWGN) with variance σ^2 (i.e., $n_l \sim N(0, \sigma^2)$). When the energy detection method is used the test statistic is formulated by

$$Y = \sum_{l=1}^{L} |y_l|^2 \tag{2.2}$$

where L is the number of the samples. There are two hypotheses, where H_0 denotes PU is absent and H_1 denotes PU is present:

$$Y = \begin{cases} \sum_{l=1}^{L} |n_l|^2, & H_O \\ \sum_{l=1}^{L} |n_l + s_l|^2, & H_1 \end{cases} \tag{2.3}$$

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 SNR and is given by

$$\gamma = \frac{\mathrm{P_{TX}}/\mathrm{d_{PU}}^2}{\sigma_\mathrm{n}^2} \tag{2.4}$$

where $\mathrm{d_{PU}}$ is distance between PU and SU and P_{TX} is the power of the transmitted signal 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 thesis, L is assumed to be large, hence, Gaussian distribution will be considered. Accordingly, the mean and variance of Y conditioned on each hypothesis are given by

$$\mu_{Y|H_0} = E[Y|H_0] = L\sigma_n{}^2 \tag{2.5}$$

$$\sigma^2{}_{Y|H_0} = VAR[Y|H_0] = L\,\sigma_n{}^4 \tag{2.6}$$

$$\mu_{Y|H_1} = E[Y|H_1] = \mathrm{L}(\sigma_\mathrm{n}{}^2 + \gamma) \tag{2.7}$$

$$\sigma^2{}_{Y|H_1} = VAR[Y|H_1] = \mathrm{L}\sigma_\mathrm{n}{}^2(\sigma_\mathrm{n}{}^2 + 2\gamma). \tag{2.8}$$

The energy detector decides on the absence or presence of the PU by comparing the received signal energy (Y) to the detection threshold (λ). When the PU is absent and the received signal energy is greater than the detection threshold, there occurs false alarm (P_f). On the other hand, when the PU is present and received signal energy is smaller than the detection threshold, there occurs miss-detection (P_{md}). Both P_f and P_{md} are conditional probabilities of error and are given by

$$P_f \;= \Pr[Y \geq \lambda|H_0] \tag{2.9}$$
$$P_{md} = \Pr[Y < \lambda|H_1]. \tag{2.10}$$

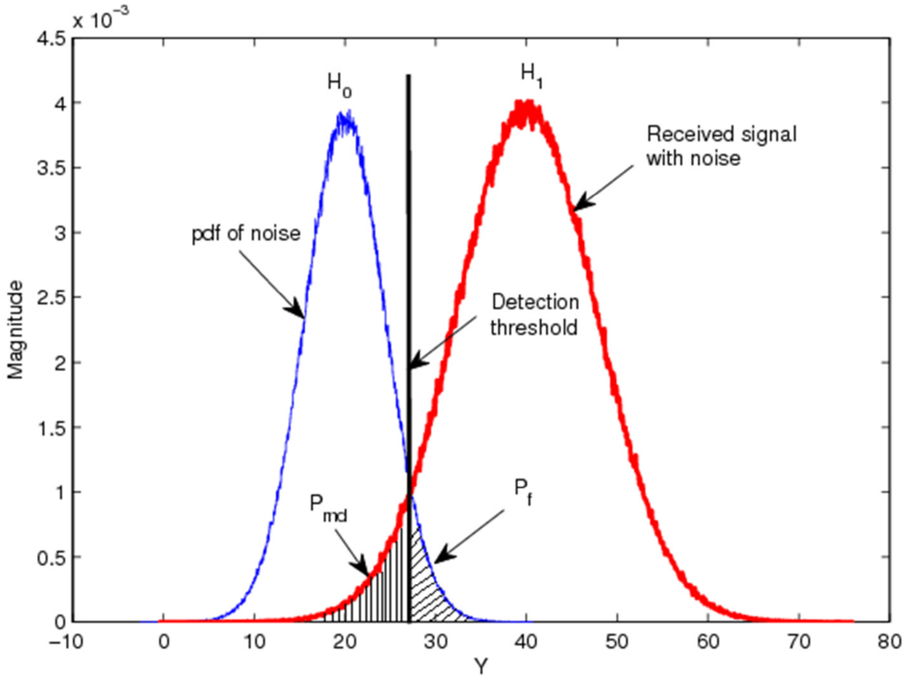

Fig. 1: False alarm and miss-detection probabilities

Considering (2.5)-(2.8), the signal received by SU can be compactly written as

$$Y \sim \begin{cases} N(L{\sigma_n}^2, L\,{\sigma_n}^4), & H_0 \\ N\big(L({\sigma_n}^2+\gamma), L{\sigma_n}^2({\sigma_n}^2+2\gamma)\big), & H_1 \end{cases} \tag{2.11}$$

and based on (2.9) and (2.10), P_{md} and P_f can be approximated as

$$P_f = Q\left(\frac{\lambda - \mu_{Y|H_0}}{\sigma_{Y|H_0}}\right) \tag{2.12}$$

$$P_{md} = Q\left(\frac{\mu_{Y|H_1} - \lambda}{\sigma_{Y|H_1}}\right) \tag{2.13}$$

where

$$Q(x) = \int_x^{+\infty} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{t^2}{2}\right) dt. \tag{2.14}$$

In Fig.1 probabilities of false alarm and miss-detection are illustrated.

The value of P_f is the area under the H_0 hypothesis greater than the threshold. Similarly, P_{md} is the area under the H_1 hypothesis less than the threshold as shown in Fig. 1.

In case the threshold value changes within the interval [0 80], the value of P_f and P_{md} are calculated with (2.12) and (2.13) as shown in Fig. 2

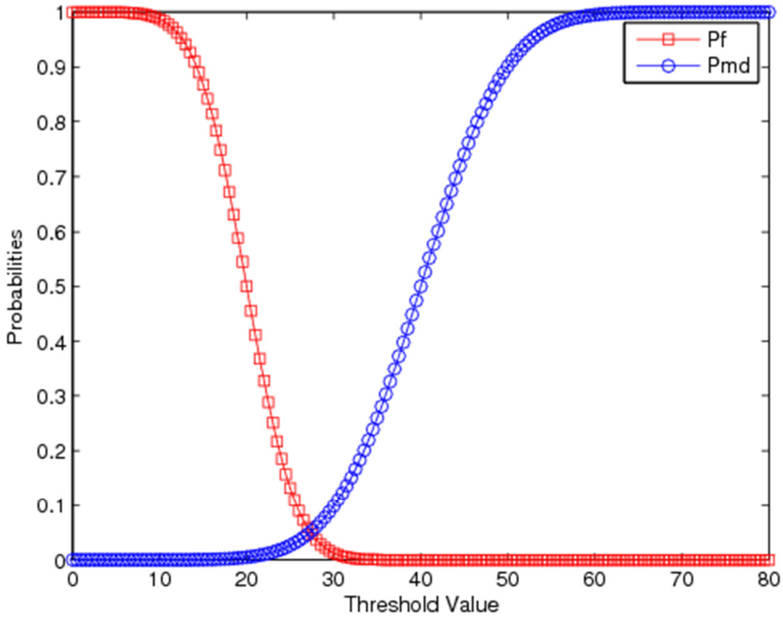

Fig. 2: Trade-off between P_f and P_{md} values

By changing threshold value, the trade-off between P_f and P_{md} values can be observed.

In Fig. 3, Y values obtained from (2.11) and tested in (2.9) and (2.10) are compared to the analysis values obtained from (2.12) and (2.13) for $L = 20$, $\gamma = 0dB$. The simulation and analysis results perfectly match on the complementary receiver operating characteristic (ROC) curve (i.e., P_f vs P_{md}). It should be also noted that the trade-off is achieved by varying the threshold value.

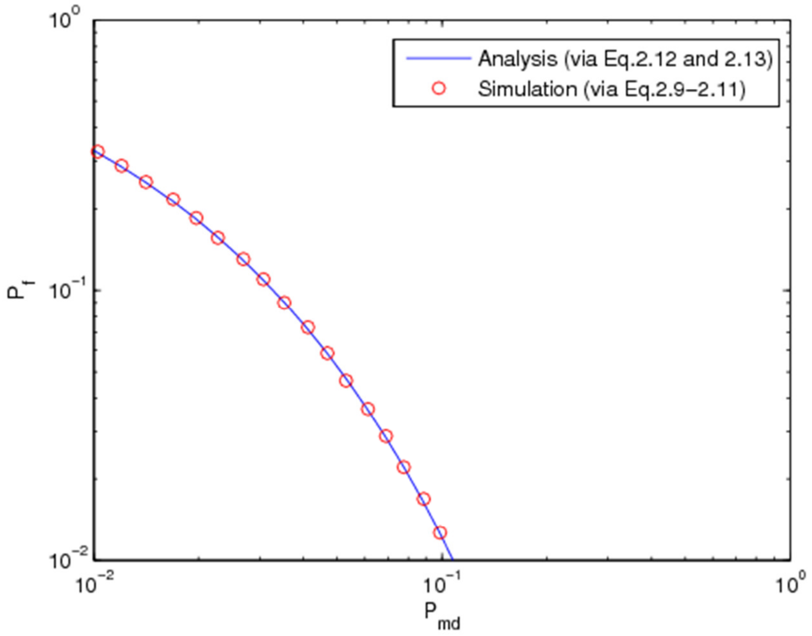

Fig. 3: Complementary ROC curve for simulated and analyzed values

2.1.2 Cooperative Energy Detection Method

For improved detection performance, the cooperative detection method will be presented next. In general the basic model used for this technique is as follows:

- Every SU detects the signal independently.
- All the SUs forward their observed signals to the Master.
- Master combines the received signals from each SU and makes a decision on the absence or the presence of the PU.
- All SUs follow the decision given by the Master.

Fig. 4 shows the cooperative system model for an ultra-wideband (UWB) system.

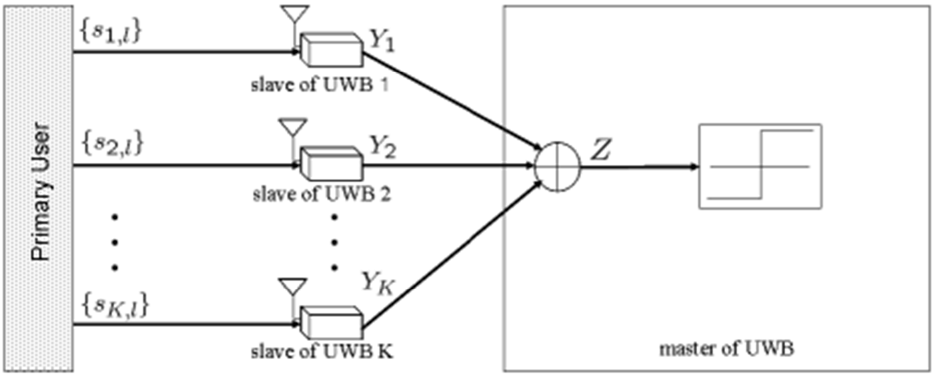

Fig. 4: Cooperative detection method [23]

The observed signal at the k-th SU is given by

$$Y_k = \begin{cases} \sum_{l=1}^{L} \left| n_{k,l} \right|^2, & H_O \\ \sum_{l=1}^{L} \left| n_{k,l} + s_{k,l} \right|^2, & H_1 \end{cases} \qquad (k = 1,2, \dots, K) \tag{2.15}$$

where $s_{k,l}$ and $n_{k,l}$ denote the signal transmitted from PU and the AWGN term observed at the k-th SU. The k-th SU passes this signal to the Master. The instantaneous SNR (γ_k) of the signal that the Master receives from the k-th user is given by

$$\gamma_k = \frac{1}{L} \sum_{l=1}^{L} \frac{P_{TX}}{\sigma_n{}^2 d_{PU,l}{}^2 d_{M,l}{}^2} \tag{2.16}$$

where $d_{M,l}$ is distance between the k-th SU and the Master.

The Master combines received signals from each SU. The combined signal Z is given by

$$\mathrm{Z} = \frac{1}{K}\sum_{k=1}^{K} W_k Y_k \tag{2.17}$$

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 (i.e., $W_k = 1$) is assumed. Using (2.15)-(2.17), the signal combined by the Master is given by

$$Z \sim \begin{cases} N\left(L{\sigma_n}^2, \frac{L}{K}\,{\sigma_n}^4\right), & H_0 \\ N\left(\frac{L}{K}\sum_{k=1}^{K}({\sigma_n}^2 + \gamma_k), \frac{L}{K^2}{\sigma_n}^2\sum_{k=1}^{K}({\sigma_n}^2 + 2\gamma_k)\right), & H_1. \end{cases} \tag{2.18}$$

Master decides on the presence or absence of PU by comparing Z with a threshold λ, and sends the result to individual SUs. If the combined signal $Z \geq \lambda$, the master decides PU is present, if $Z < \lambda$ decides PU is absent.

2.2 COMBINATIONAL COOPERATIVE DETECTION METHOD

The cooperative detection method is described in the previous section. Master decides on the presence or the absence of the primary user by gathering all the information from secondary users and conveys this decision to all SUs and all need to follow the decision. This approach does not take into account the locations of the secondary users, where a user far from the primary user may also have to keep silent or vice versa. In this section the combinational cooperative detection (CCD) method proposed in [23] to overcome this problem will be presented.

In contrast to cooperative detection, in the CCD method Master does not provide one decision for all SUs; it delivers different decisions to the SUs. The basic model used for this technique is summarized as follows:

- Every SU detects the PU signal independently.
- All the SUs forward their observed signals to the Master.
- Master combines the received signals from each SU in different combinations and makes a decision table. Using this table (depending on system parameter) the Master decides individually for each SU and sends these decisions.
- SUs follow their own decision given by the Master.

2.2.1 The Method and Performance Measures

The detection procedure can be explained in 8 steps:

Step 1: Every SU observes the signal Y_k in (2.15) and sends it to the Master. The Master receives K signals in total.

Step 2: Master 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 $u = 1, \dots, U$.

Step 3: The combination output Z_u from (2.17) (adopt EGC, $W_k = 1$) is given by

$$Z_u = \frac{1}{Q} \sum_{k \in \mathbf{W}_u} Y_k \quad u = 1, \dots, U \tag{2.19}$$

Step 4: The Combination Table is created by using combination output $\{Z_u\}$. Combination table for $K = 4$, $Q = 3$ is given in Table 1.

	1	2	3	4
1 & 2	-	-	$\frac{1}{3}(Y_1 + Y_2 + Y_3)$	$\frac{1}{3}(Y_1 + Y_2 + Y_4)$
1 & 3	-	$\frac{1}{3}(Y_1 + Y_2 + Y_3)$	-	$\frac{1}{3}(Y_1 + Y_3 + Y_4)$
1 & 4	-	$\frac{1}{3}(Y_1 + Y_2 + Y_4)$	$\frac{1}{3}(Y_1 + Y_3 + Y_4)$	-
2 & 3	$\frac{1}{3}(Y_1 + Y_2 + Y_3)$	-	-	$\frac{1}{3}(Y_2 + Y_3 + Y_4)$
2 & 4	$\frac{1}{3}(Y_1 + Y_2 + Y_4)$	-	$\frac{1}{3}(Y_2 + Y_3 + Y_4)$	-
3 & 4	$\frac{1}{3}(Y_1 + Y_3 + Y_4)$	$\frac{1}{3}(Y_2 + Y_3 + Y_4)$	-	-

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

The values of Z_u can be obtained from (2.18) for different combinations as in (2.19).

Step 5: All combination output values $\{Z_u\}$ in the combination table are compared with λ threshold value for deciding on the presence of the PU. Accordingly, an availability table is created.

	1	2	3	4
1&2	-	-	1	0
1&3	-	1	-	1
1&4	-	0	1	-
2&3	1	-	-	1
2&4	0	-	1	-
3&4	1	1	-	-
m_k	2	2	3	2

Table 2: Availability table

where 1 and 0, respectively, denote the PU is present and absent. In Table 2, an availability table is presented as an illustration. For example, the value “0” shows that $\frac{1}{3}(Y_1 + Y_2 + Y_4) < \lambda$.

Step 6: Each column of the table represents an SU. For example, the first column gives the decision about the $1st$ 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 $k-th$ column. M and m_k are compared to decide which SU can talk and which should keep silent. M is defined as

$$M = \eta \times \binom{K-1}{Q-1}, \quad 0 \leq \eta \leq 1 \tag{2.20}$$

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

$$\begin{array}{lcl} m_k \geq M & \rightarrow & PU\ present \\ m_k < M & \rightarrow & PU\ absent \end{array} \tag{2.21}$$

If the Master decides PU is present for an SU, this SU has to remain quiet.

In 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 (2.9) and (2.10). If a PU is assumed to be always present, the new probability definitions are as follows:

$\underline{\mathrm{P_{md}}\ (\mathrm{miss-detection}):}$ Master decides "PU is absent" for the SUs in the overlapped communication area (overlapped communication area: The area where SU is located in creates interference to the PU. Hence, SUs have to be silent).

$\underline{\mathrm{P_f}\ (\mathrm{false\ detection}):}$ Master decides "PU is present" for the SUs in the not-overlapped communication area (not-overlapped communication area: The area where SU is located in does not create interference to PU. Hence, SUs can communicate).

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

2.2.2 Claimed Performance Results [23]

In [23], the parameters that may affect the probabilities of error are not studied in detail. Although probabilities of error definitions are related (indirectly) to SUs' location, the locations of SUs are not present. On the other hand, the distribution of SUs in overlapped and not-overlapped communication areas is not specified. The evaluation results show only the effect of η and Q, but it is not clear which location and distributions are assumed. Also, conventional cooperative detection method is used as a benchmark performance; however, the performance results presented are not accurate.

CHAPTER 3 IMPLEMENTATION OF THE CCD METHOD

In the previous study [23], there is not enough information about the location and number of SUs as explained in the previous chapter. Accordingly, it is not possible to examine the system performance efficiently. For this reason, location and distribution of SUs are detailed in this chapter.

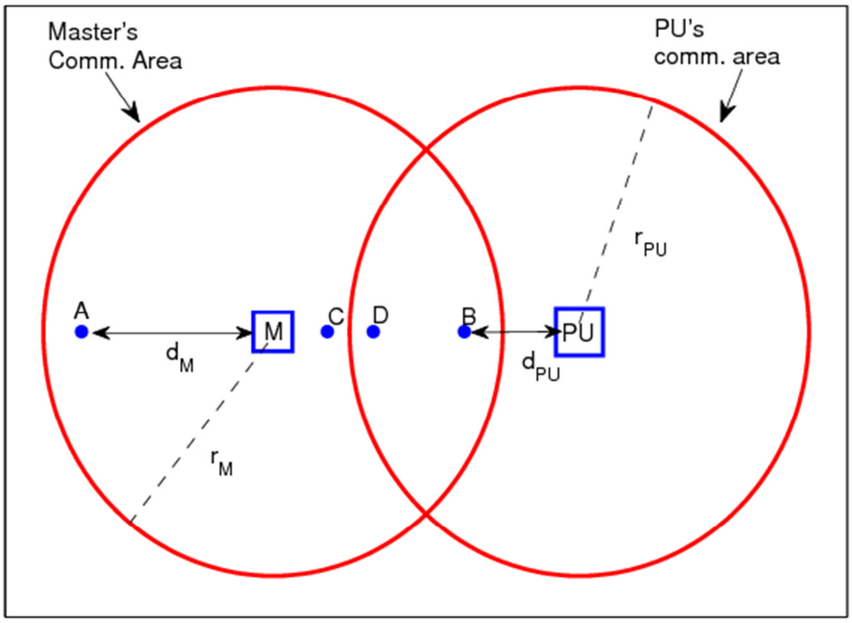

Fig. 5: The locations of SUs and the PU

In Fig. 5, PU and M, respectively, denote the primary user and the Master. A, B, C, D are the locations of the SUs. The SUs at location A and C are in the not-overlapped area, and can communicate without generating 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 not-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 in 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, $P_{TX} = 100$, $L = 100$ are used throughout the study.

The probabilities of error are calculated for a threshold interval to cover all combination values. For each threshold value, probabilities of error are calculated by averaging over 10,000 runs. Before presenting the effects of SU locations on the CCD 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 correct performance of the conventional cooperative detection method as it is used as a benchmark performance. The results represented in [23] were not consistent as explained earlier.

Here is the accurate performance evaluation of a conventional cooperative detection. Master decides on the presence or absence of primary user and conveys this decision to all users. According to definition of P_f and P_{md}, this decision is true for all x SUs in the not-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_f and P_{md} will be 0 and 1, respectively.
- If the decision is true for y SUs, the probabilities of error P_f and P_{md} will be 1 and 0, respectively.

By changing the threshold value and averaging over many trials, it can be shown that

$$P_{md} + P_f = 1.$$

In Fig. 6, the tradeoff between P_f and P_{md} is shown using computer simulations. It can be observed that $P_{md} + P_f = 1$ is satisfied for every scenario tested. Hence, this performance serves as a benchmark independent of SU locations and numbers.

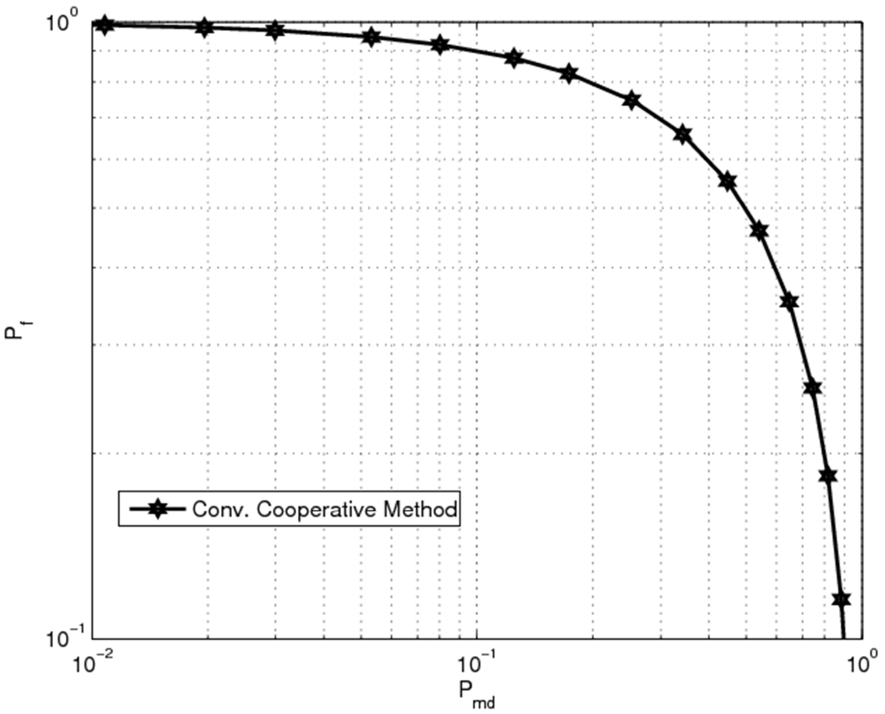

Fig. 6: Performance of the conventional cooperative detection method

While the above plot is independent from user distributions, $x|y$, the total amount of interference caused to PU depends on x and y. Hence, we further define the following probabilities assuming the PU is always active:

P_{useful}: Probability that SUs can safely transmit.

$$P_u = \left(1 - P_f\right)\frac{x}{x+y} \tag{2.22}$$

$P_{harmful}$: Probability that SUs create interference to the PU.

$$P_h = (P_{md})\frac{y}{x+y} \tag{2.23}$$

P_{quiet}: Probability that SUs are quiet.

$$P_{quiet} = P_f\frac{x}{x+y} + (1 - P_{md})\frac{y}{x+y} \tag{2.24}$$

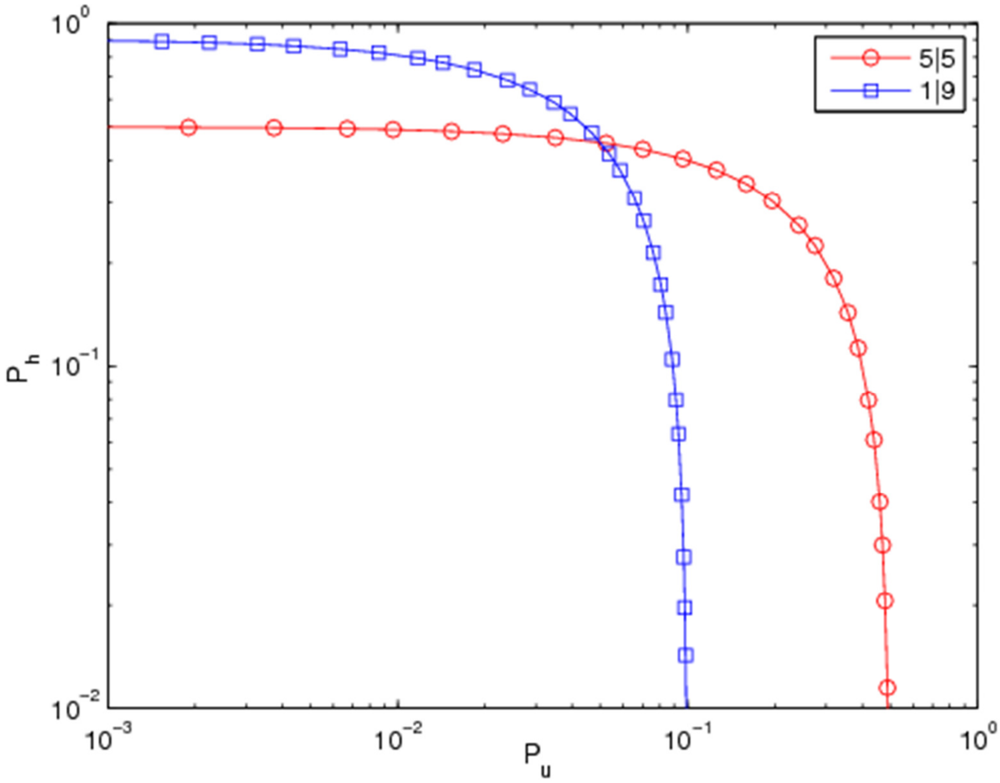

Fig. 7: Useful and Harmful Usage of Channel

In Fig.7 , useful and harmful usage of channel is presented for the distributions $(1|9)$ and $(5|5)$. While both distributions achieve the same detection performance $P_{md} + P_f = 1$ as in Fig. 6, the channel usage depends on the number of SUs in the overlapped and not-overlapped areas.

3.2 EFFECT of SU LOCATIONS on the CCD METHOD PERFORMANCE

In this section, the effects of locations and distributions of SUs and the related parameters (η and Q) are studied.

3.2.1 Effect of the Percentage Ratio (η) on Probabilities of Error

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. 8.

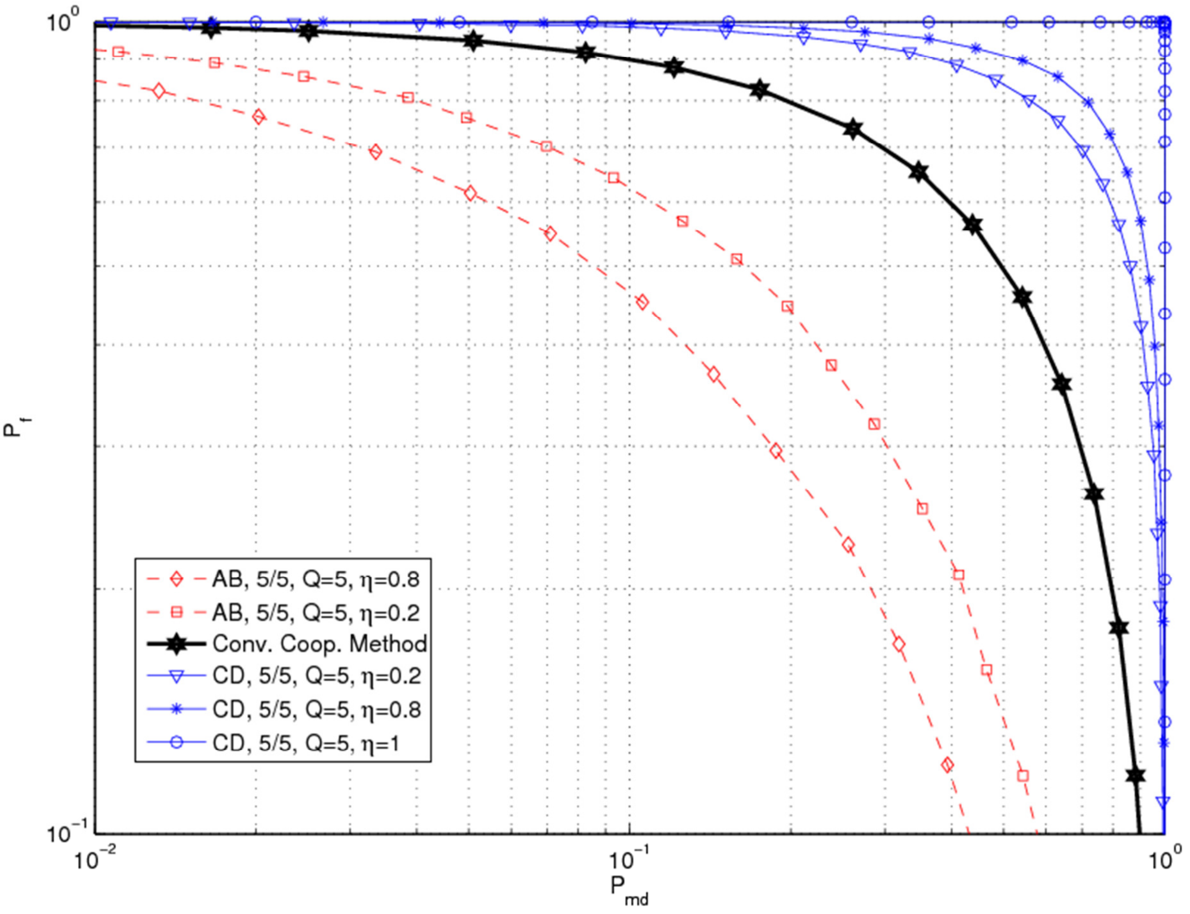

Fig. 8: Effect of η on the CCD method performance

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 is 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 $P_f = P_{md} = 0$ for $\eta = 1$ within a threshold interval. This is shown in Fig. 9 as will be explained next.

Probabilities of error (P_f, P_{md}) becoming zero can be explained better with the following example. Assume that $\eta = 1$ and there is equal distribution in each region $(x|y = 5|5)$ as in Fig. 8. The values of η, Q and $x|y$ affect the P_f and P_{md} values and this can be observed by changing the threshold value.

The values of P_f and P_{md} can be

- 0 within the same threshold interval,
- 1 within the same threshold interval, or
- different within the same threshold interval.

This is illustrated in Fig. 9 for $\eta = 1$ and $\eta = 0.8$. For $\eta = 1, P_f = P_{md} = 0$ 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_f and P_{md} when $30 < \lambda < 34$, where the tradeoff can be observed. For the further cases, $\eta = 1$ is selected for the similar conditions.

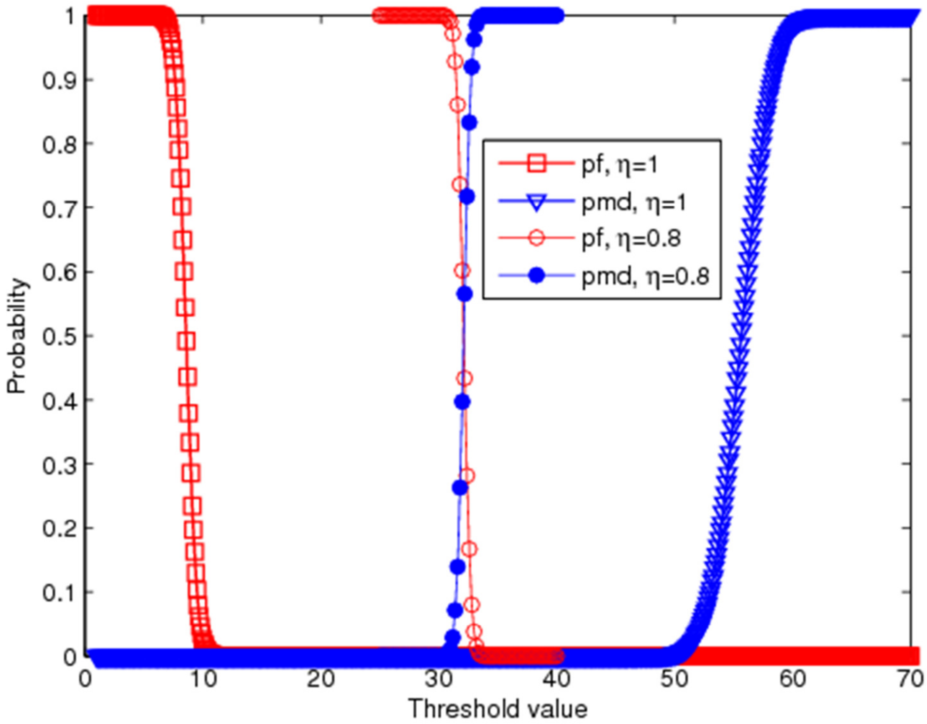

Fig. 9: Probabilities of error with respect to threshold values

3.2.2 Effect of Combination Number (Q) on Error Probabilities

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. 10.

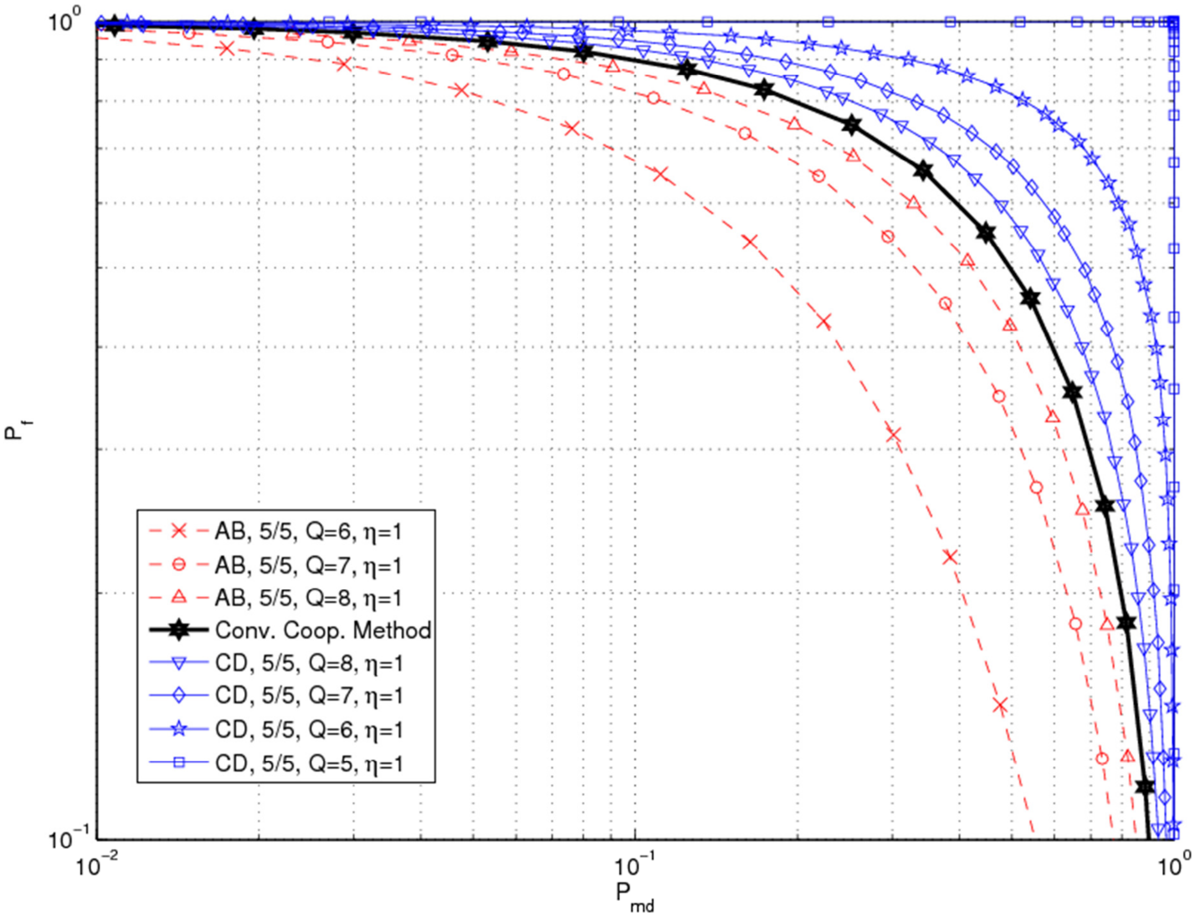

Fig. 10: Effect of Q on the CCD method performance

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. It can be explained as follows:

The signals received by the Master from SUs located at (C, D) have similar magnitudes. If number of combined SUs is increased, the decision of the Master 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 distinctly different. Therefore, the number of combined SUs must be decreased (i.e., smaller Q value) for better results.

3.2.3 Effect of the Distribution on Probabilities of Error

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.11.

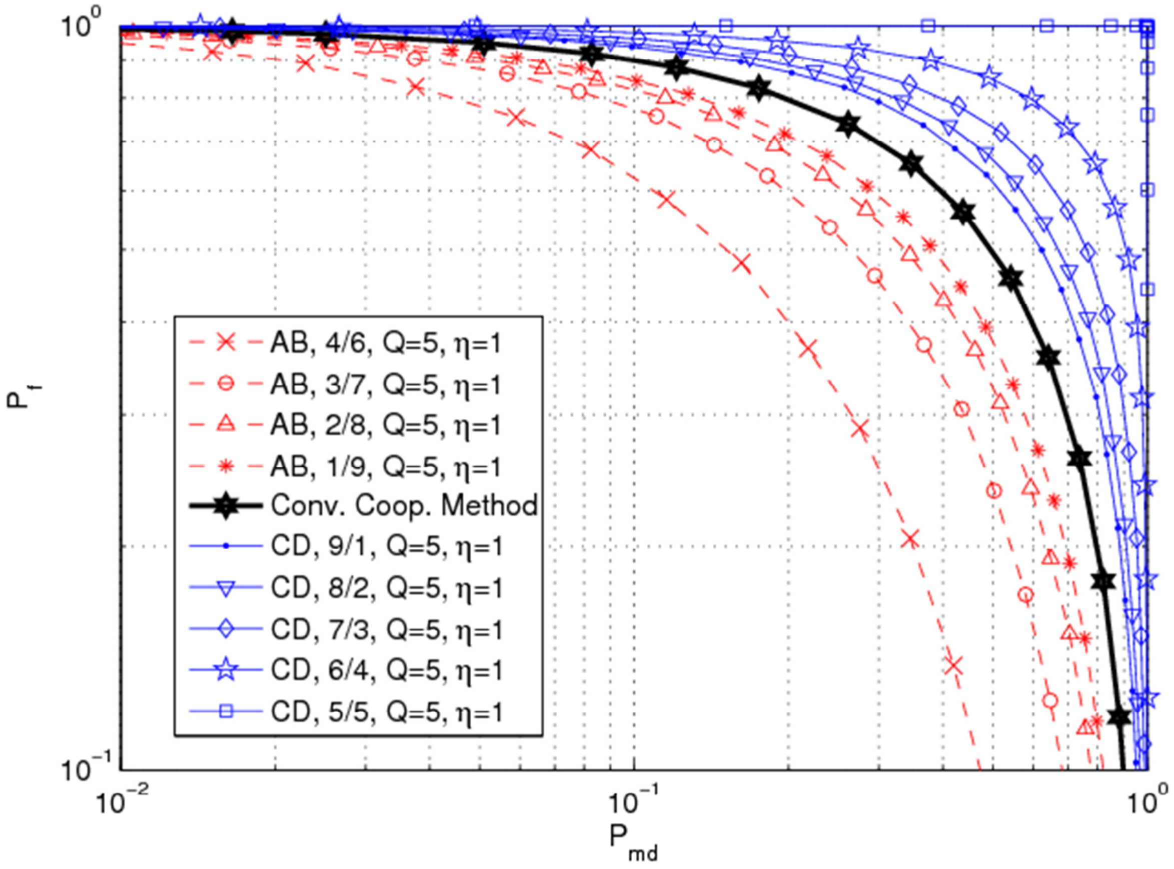

Fig. 11: Effect of SU distribution on the CCD method performance

It can be observed that the probabilities of error for SUs located at (C, D) is always greater than the probabilities of error of 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 less.

If the number of SUs in the not-overlapped communication area (x) increases, then the probabilities of error become smaller. Probabilities of error for SUs located at (C, D) approach conventional cooperative detection method performance when x is increased.
For the SUs located at (A, B), probabilities of error are $P_f = P_{md} = 0$ within a threshold interval when $x \geq Q$. This observation is consistent with the remarks made in section 3.2.2.

In this section, we evaluated the user location and distribution on the CCD performance. Next, we propose a method to improve the CCD method performance.

3.3 IMPROVED CCD METHOD

In this section, the combinational cooperative detection will be modified to reduce the probabilities of error P_{md} and P_f. According to the CCD method, value the Master decides on the presence of the PU, and all SUs have to keep silent. This decision is false for the SUs in the not-overlapped communication area. In the same way, for a large threshold value the Master decides on the absence of the PU. It is a false decision for SUs in the overlapped communication area. The values of P_f and P_{md} are accordingly

$$P_f = [1\ 0],\ \ and\ \ P_{md} = [0\ 1] \tag{3.1}$$

i.e., the maximum value of probabilities of error P_f and P_{md} is equal to 1. The purpose 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 not-overlapped communication area.

According to simulation results in Section 3.2, probabilities of error for SUs at distant locations (A, B) are smaller than error probabilities of SUs at closed location (C, D). While this method can be used for either location, we obtain mathematical expressions for probabilities of error for (A, B) location. The improving models for false detection and miss-detection probabilities are described as below.

3.3.1 Improving False Detection Probability (P_f):

The maximum value of P_f is attained if the threshold (λ) value is small. In the case there is at least one SU in the not-overlapped communication area, the maximum value of P_f is reduced when the smallest combination value of each row in the combination table is set as "absent" (refer to Tables 1, 2 pages 11, 12). This operation ensures that decision for one SU is correct. P_f can be formulated as below

$$P_f = [P_f(min), \quad P_f(max)], \text{ where}$$

$$P_f(min) = 0, \qquad P_f(max) = \begin{cases} if\ x \leq Q, & 0 \\ if\ x > Q, & \dfrac{x - Q}{x} \end{cases} \tag{3.2}$$

where $Q \neq K$. Maximum value of P_f depends on the number of SUs in the not-overlapped communication area and the combination number Q. Minimum value of P_f is detected at a large threshold value and it is always 0.

An Example:

Assume that A and B are the locations of SUs (Fig.5). Let us calculate the maximum false detection probability for different combinations of number and distributions.

a. Let the equal number of SUs for each communication area be $x = 5, y = 5$.
The total number of SUs is $K\ \ x + y = 10$.
For $Q = 5$, the range for P_f is as follows.
The condition $x = Q$ is valid, so $P_f = [P_f(min), \quad P_f(max)] = [0\ 0]$

b. Let the number SUs is 7 and 3 for the not-overlapped and the overlapped communication areas, respectively.
Total number of SUs is $K = 10$.
For $Q = 5$, the range for P_f is as follows.
The condition $x > Q$ is valid (7 > 5),

$$P_f = \left[0, \quad \left(\frac{x - Q}{x}\right)\right] = \left[0, \quad \left(\frac{7 - 5}{7}\right)\right]$$

$$P_f = \left[0, \quad \frac{2}{7}\right]$$

3.3.2 Improving Miss-Detection Probability (P_{md}):

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 Tables 1, 2 pages 11, 12). This operation ensures that decision for one SU in the overlapped communication area is correct. P_{md} can be formulated as below

$$P_{md} = [P_{md}(min), \quad P_{md}(max)], \text{ where}$$

$$P_{md}(min) = \begin{cases} if\ y < K - Q + 1, & 0 \\ if\ y \geq K - Q + 1, & \dfrac{y - (K - Q + 1) + 1}{y} \end{cases}$$
$$P_{md}(max) = \frac{y - 1}{y} \tag{3.3}$$

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.

3.3.3 Relevant Examples for Improved CCD Method

In this section, simulation results for improved probabilities of error, P_f and P_{md} are presented. We are assuming that there is at least one SU in the overlapped and one in the not-overlapped communication area and the combination number is not equal to the total number of SUs ($Q \neq K$).

Improving False Detection Probability (P_f):

Fig. 12 and Fig. 13 show the simulation results for improving the maximum value of P_f for different values of Q and distributions, respectively.

The effect of combination number (Q) is examined in the case of percentage ratio $\eta = 1$ and equal distributions in each region ($x|y = 5|5$). The maximum value of P_f is decreased from 1 to 0.8 in the worst case scenario.

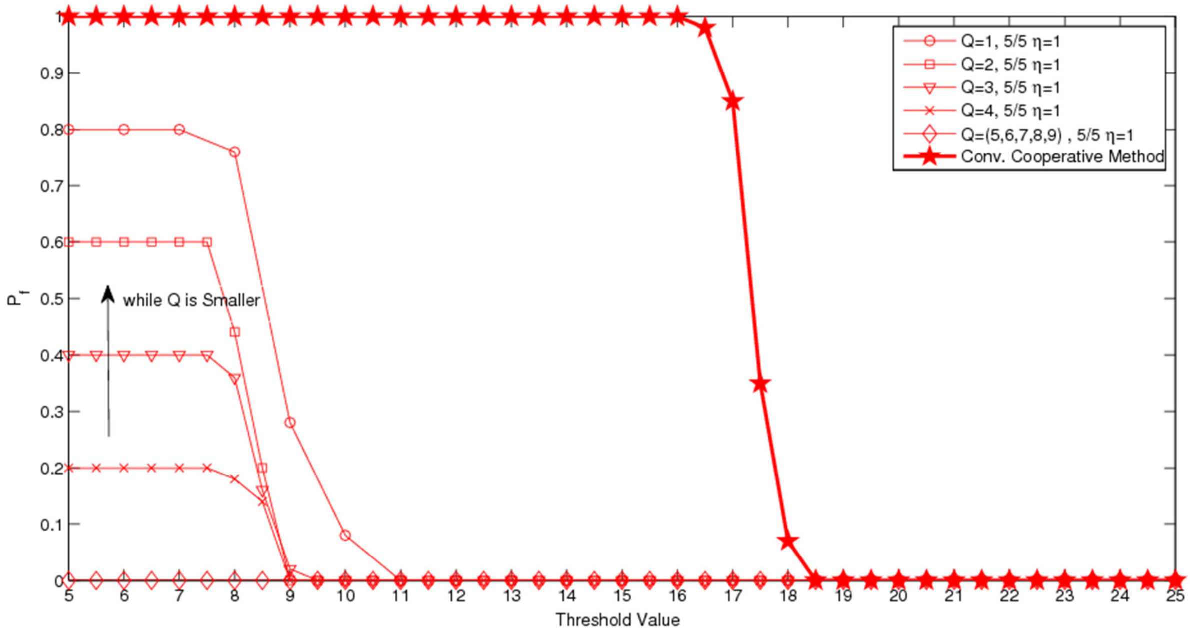

Fig. 12: Results for improving the maximum value of P_f for different Q

False detection probability (P_f) value approaches zero for large threshold values. The minimum value is always zero. The maximum value P_f depends on the combination number and number of SUs in the not-overlapped communication area.

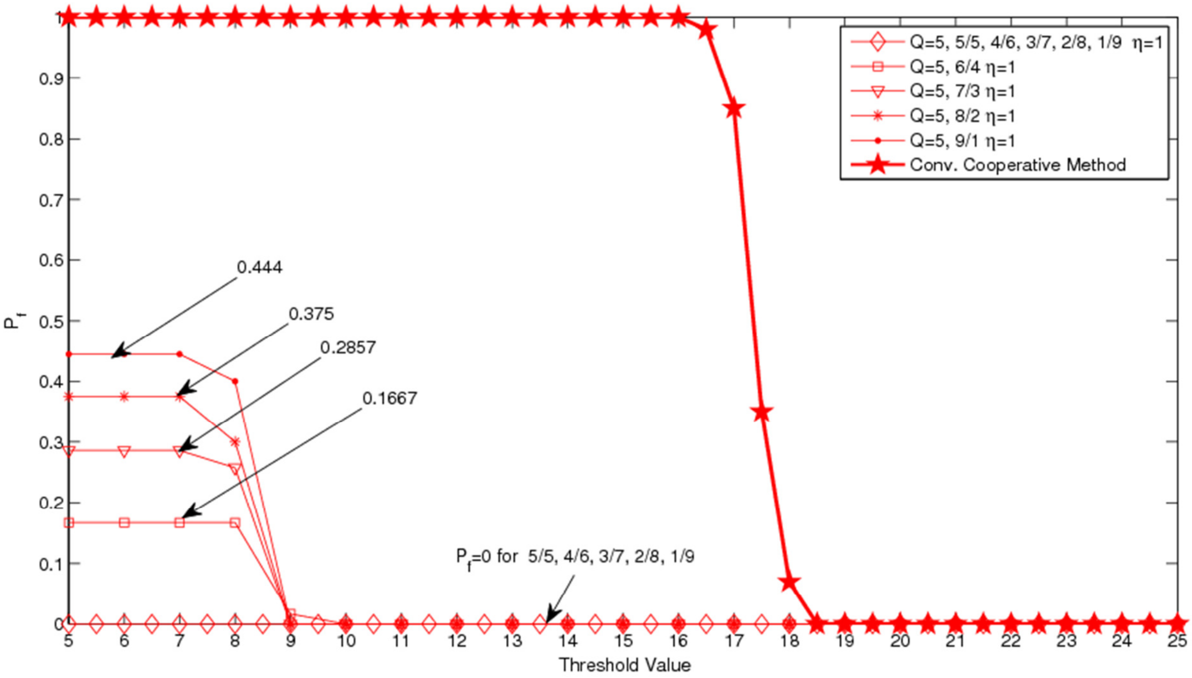

Fig. 13: Results for improving the maximum value of P_f for different distributions

The effect of distribution $(x|y)$ is examined in the case of percentage ratio $\eta = 1$ and equal combination number $(Q = 5)$. The maximum value of false detection is proportional to the number of SUs in the not-overlapped communication area for a combination number fixed. The maximum probability values are consistent with the numerical values obtained from (3.2).

Improving Miss-detection Probability $(\mathrm{P_{md}})$:

The minimum value of P_f is always zero regardless of the combination number and the distributions. However, the minimum value of P_{md} is not always zero for the improved method. It depends on the combination number and distribution of SUs.

The effect of Q on P_{md} is examined in Fig. 14 in the case of percentage ratio $\eta = 1$ when equal distributions in each region $(x|y = 5|5)$ are assumed.

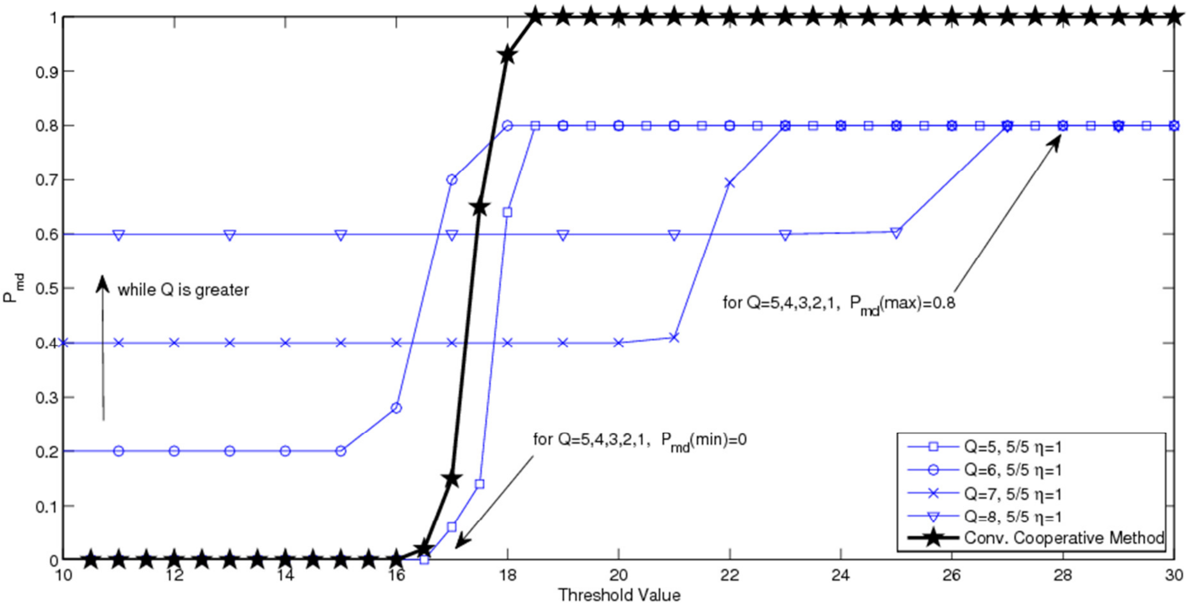

Fig. 14: Results for improving the maximum value of P_{md} for different Q

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 the 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 equal combination number $(Q = 5)$. The effects of distribution for $x \geq Q$ and $x < Q$ are shown in Fig. 14 and Fig. 15, respectively.

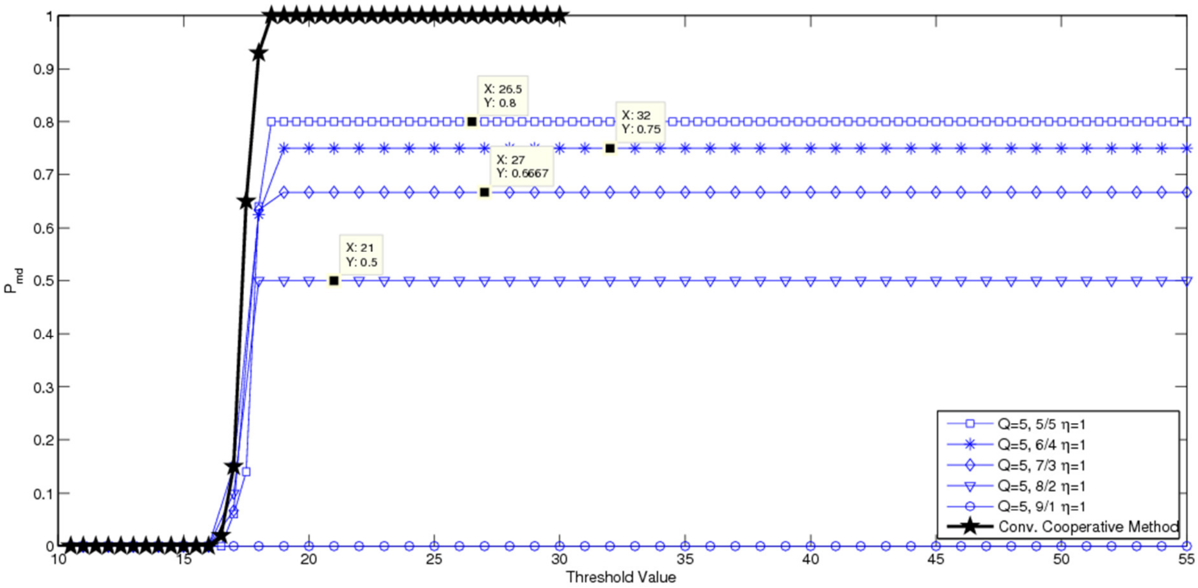

Fig. 15: Results for improving the maximum value of P_{md} for distribution $x \geq Q$

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 for $x \geq Q$, $P_{md}(\min) > 0$ for $x < Q$.

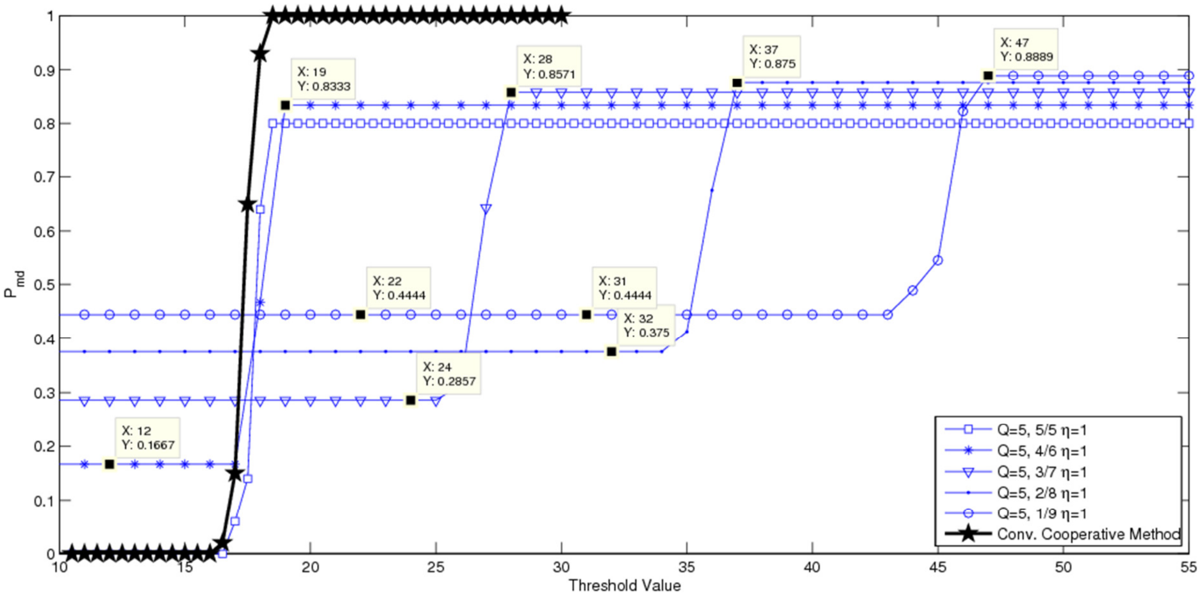

Fig. 16: Results for improving the maximum value of P_{md} for distribution $x < Q$

The maximum and minimum values of miss-detection probability in Figs. 14, 15 and 16 are confirmed with (3.3).

CHAPTER 4 CONCLUSIONS AND FUTURE RESEARCH

4.1 CONCLUSIONS

Combinational Cooperative Detection Method

In this thesis, the practical implementation issues of the method in [23] was further investigated. This proposed method is based on the combination of received signals from more than two users. It is an alternative method to the conventional cooperative detection method. The main difference is that, proposed method does not provide one solution for all SUs, the Master delivers different decisions to each SU. While the proposed method in [23] showed promising results for the secondary users, the effect of the user distribution was not investigated. In this study, we considered the effect of secondary user locations and numbers on the detection performance. Also, we showed that the evaluation of the conventional detection method in the proposed method was not accurate.

The following conclusions can be drawn from the current study.

- In contrast to the previous study [23], the sum of the probabilities of false detection and miss-detection for conventional cooperative detection is always 1.
- Probabilities of error for the SUs located close to each other are always greater than the probabilities of error for the conventional cooperative detection method.
- Probabilities of error for SUs located away from each other are always smaller than the probabilities of error for conventional cooperative detection method.
- The performance gains are quantified for various practical scenarios.

Improved Combinational Cooperative Detection Method

In addition, we improved the proposed method of Fuji et al. in [23] to decrease the maximum values of probabilities of errors. Assuming that there is at least one SU in the overlapped and one in the not-overlapped communication area, improved method is implemented as follows:

- The SU is set as absent, for the smallest combination value in each row. This operation ensured that the decision for an SU in the not-overlapped communication area is correct for at least one SU. Hence, the maximum value of false detection probability was decreased.
- Maximum value of miss-detection probability was decreased as the SU is set as present for the largest combination value in each row.
- The combination number must be different from total number of SUs to perform the improved method.

The following conclusions can be drawn from the current study.

- The minimum value of miss-detection probability is not always zero unlike false detection probability for the improved method.
- The average signal energy combined decreases if $Q \geq y$. Therefore, it causes a false decision for the SUs in the overlapped communication area for a small threshold value. Hence, the minimum value of miss-detection is not 0.
- Maximum value of false detection probability depends on the number of SUs in the not-overlapped communication area and the combination number.
- The maximum value of miss-detection probability is directly proportional to number of the SUs in overlapped communication area.

4.2 FUTURE RESEARCH

Combinational Cooperative Detection Method

- The effect of location and distributions of SUs were examined in this study as a benchmark. Further possible different locations and distributions may be examined and compared with benchmark results of this study.

- In combinational cooperative detection method, the probabilities of error become zero within a threshold interval. We know that this threshold interval depends on many parameters ($i.e.,\ \eta, Q, P_{TX}$). Accordingly, the probabilities of error may be mathematically evaluated and expressed in closed-form expressions.

Improved Combinational Cooperative Detection Method

- The improved method relied on the assumption that there exists at least one SU in the overlapped and one in the not-overlapped communication areas. Further extentions could be the study of detection performance when (i) there is no prior knowledge on the number of the SUs, and (ii) more than one user(s) are set as present and absent.

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Curriculum Vitae

I received my BS degree in Electrical and Electronics Engineering from Eskisehir Osmangazi University. My research interests include communication theory, signal processing, wireless communication.

Publications

[1] E. Çatak and S. Erküçük, “The Effect of Secondary User Locations on the Cooperative Detection Performance,” *IEEE Signal Proc. Appl. Conf.*’ 2012, Fethiye, Turkey. (in Turkish).