Soft Combination and Detection for Cooperative Spectrum Sensing in Cognitive Radio Networks

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***Abstract*—In this letter, we consider cooperative spectrum sensing based on energy detection in cognitive radio networks. Soft combination of the observed energies from different cognitive radio users is investigated. Based on the Neyman-Pearson criterion, we obtain an *optimal soft combination* scheme that maximizes the detection probability for a given false alarm probability. Encouraged by the performance gain of soft combination, we further propose a new *softened* hard combination scheme with two-bit overhead for each user and achieve a good tradeoff between detection performance and complexity.**

***Index Terms*—Cognitive radio, cooperative spectrum sensing, energy detection, hard combination, soft combination.**

I. INTRODUCTION

COGNITIVE radio (CR) enables much higher spectrum efficiency by dynamic spectrum access [1], [2]. Therefore, it is a potential technique for future wireless communications to mitigate the spectrum scarcity issue. As unlicensed (secondary) users of the spectrum band, CR operators are allowed to utilize the spectral resources only when it does not cause interference to the primary (licensed) users, which entails continuous spectrum sensing in CR networks. Therefore, it becomes a critical issue in cognitive radio to reliably and quickly detect the presence of the primary users.

The existing spectrum sensing techniques can be broadly divided into three categories [5]: energy detection, matched filter detection, and cyclostationary detection. Among them, energy detection has been widely applied since it does not require any *a priori* knowledge of the primary signals and has much lower complexity than the other two schemes. Therefore, we only consider energy detection for spectrum sensing throughout this letter.

Spectrum sensing is a tough task because of shadowing, fading, and time-varying natures of wireless channels. To combat these impacts, cooperative spectrum sensing schemes have been proposed to obtain the spatial diversity in multiuser CR networks [6]–[9]. In cooperative spectrum sensing, information from different CR users is combined to make a decision on the presence or absence of the primary user. In [8] and [9], only the conventional hard combination is considered, in which each CR user feedbacks one-bit message regarding whether its observed energy is above a certain threshold. In this letter, soft combination is investigated, in which the accurate sensing energies from different CR users are combined to make a better decision. Based on the Neyman-Pearson criterion [12], we obtain an optimal soft combination scheme that maximizes the detection probability for a given false alarm probability. It is demonstrated that soft combination schemes, even simple equal gain combination, have significant performance improvement over the conventional hard combination. Encouraged by the performance gain of soft combination, we further propose a new *softened* hard combination scheme with only two-bit overhead for each CR user, which, however, exhibits much better performance than the conventional one-bit hard combination scheme.

The rest of this letter is organized as follows. In Section II, we formulate the problem of primary signal detection in CR networks. Then we investigate different soft combination schemes in Section III and propose a new *softened* two-bit hard combination scheme in Section IV, respectively. Conclusions are given in Section V.

II. PROBLEM FORMULATION

In this letter, we investigate cooperative spectrum sensing in a centralized CR network consisting of an access point or base station[1] and a number of CR users. In this network, each CR user sends its sensing data to the base station periodically via the common control channels [2] while the base station combines the sensing data from different CR users and makes a decision on the presence or absence of the primary user. For simplicity, we assume the sensing data is sent from the CR users to the base station free of error throughout this letter.

A. Primary Signal Model

Consider a CR network with N cooperative users. Suppose M samples are utilized for energy detection [10], [11] at each CR user. The received signal at the ith sample of the jth CR user, $r_{ji}, 1 \le j \le N, 1 \le i \le M$, is given by

$$r_{ji} = \begin{cases} n_{ji}, & \mathcal{H}_0, \\ \sqrt{\gamma_j} s_{ji} + n_{ji}, & \mathcal{H}_1, \end{cases} \tag{1}$$

where $\sqrt{\gamma_j} s_{ji}$ denotes the received primary signal with the average power γ_j, and n_{ji} denotes the white noise. In (1), $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the hypotheses corresponding to the absence and presence of the primary signal, respectively; the goal of energy detection is to decide between the two hypotheses.

Throughout this letter, we assume that s_{ji}'s, for different i's and j's, are *independently and identically distributed* (i.i.d.)

Manuscript received August 23, 2007; revised January 24, 2008; accepted April 27, 2008. The associate editor coordinating the review of this letter and approving it for publication was X. Wang. This work was supported in part by the National Science Foundation under Grant No. 0721580, and the Research Gift from Huawei Technologies Co., Ltd.

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Digital Object Identifier 10.1109/T-WC.2008.070941

[1] Note that the secondary and primary networks are not using the same base station.

Gaussian random variables with zero mean and unit variance. While the Gaussian primary signal model facilitates the analysis of soft combination in Section III, it is actually reasonable since usually there is no *line-of-sight* (LOS) path between a CR user and the primary transmitter, and as a result the received primary signal is a superposition of several *non-line-of-sight* (NLOS) signals and hence approximates Gaussian according to the central limit theorem. In [14], we have analyzed soft combination under another primary signal model wherein the total energy of the transmitted primary signal within each observation period is assumed constant.

Without loss of generality, we assume that the noise at each sample is Gaussian with zero mean and unit variance, independent of the primary signal under $\mathcal{H}_1$. Thus γ_j also represents the instantaneous SNR of the jth CR user within the current observation period. We further assume γ_j varies from (observation) period to period while its *probability distribution function* (PDF) is determined by the fading characteristic of the channel that the CR users experience.

According to the above assumptions, the received signal, r_{ji}, is Gaussian with

$$r_{ji} \sim \begin{cases} \mathcal{N}(0,1), & \mathcal{H}_0, \\ \mathcal{N}(0,1+\gamma_j), & \mathcal{H}_1. \end{cases} \tag{2}$$

B. Local Detection Performance of Energy Detector

Throughout this letter, we assume that energy detection [10] is applied at each CR user. According to (2), the observed energy at the jth CR user is given by

$$Y_j = \sum_{i=1}^{M} r_{ji}^2 = \begin{cases} b_{j_0}, & \mathcal{H}_0, \\ (1+\gamma_j) b_{j_1}, & \mathcal{H}_1, \end{cases} \tag{3}$$

where random variables b_{j_0} and b_{j_1} follow a central chi-square distribution with M degrees of freedom. Since different CR users are at different locations, we assume that Y_j's are independent for a given hypothesis.

Let λ be the local decision threshold for each CR user, then the local false alarm probability, P_F, and detection probability, P_D, can be obtained from (3) as [11],

$$P_F(M,\lambda) = P(Y_j > \lambda | \mathcal{H}_0) = \frac{\Gamma\left(\frac{M}{2}, \frac{\lambda}{2}\right)}{\Gamma(\frac{M}{2})}, \tag{4}$$

and

$$P_D(M,\lambda,\gamma_j) = P(Y_j > \lambda | \mathcal{H}_1) = \frac{\Gamma\left(\frac{M}{2}, \frac{\lambda}{2(1+\gamma_j)}\right)}{\Gamma(\frac{M}{2})}, \tag{5}$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ denote the gamma function and upper incomplete gamma function [3], respectively.

Assume that the CR users experience independent Nakagami fading channels [4] with the same average SNR, $\bar{\gamma}$, then the PDF of the instantaneous SNR, γ, is given by

$$f_\gamma(\gamma, m) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}}}, \ \gamma \geq 0, \tag{6}$$

where m is the Nakagami parameter. Assuming M is even, which is always true when it comes to the detection of complex baseband primary signal consisting of a pair of real signals, the average local detection probability under Nakagami fading channel can be obtained by Equation (7), which will be used to evaluate $\overline{P}_{D,Nak}(\bar{\gamma}, m, M, \lambda)$ numerically in the subsequent discussion.

III. Soft Combination

In soft combination, CR users send their original sensing information to the base station without any local processing and the decision is made at the base station by combining them appropriately. In this section, we will find the soft combination scheme that optimizes the detection performance.

A. Optimal Soft Combination Scheme

There is a pair of conflicting probabilities involved in binary hypothesis testing: the detection probability and the false alarm probability. Without loss of generality, we are concerned with maximizing the detection probability for a given false alarm probability in this letter. Therefore, the Neyman-Pearson criterion [12] is applied here, which is equivalent to the *likelihood ratio test* (LRT).

Let $\mathbf{Y} = (Y_1, Y_2, \cdots, Y_N)$, then the corresponding likelihood ratio between hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$ is expressed as $LR(\mathbf{Y}) = \frac{Pr(\mathbf{Y}|\mathcal{H}_1)}{Pr(\mathbf{Y}|\mathcal{H}_0)}$, and the decision is given by

$$LR(\mathbf{Y}) \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \eta, \tag{8}$$

where η is the threshold determined by the given false alarm probability. Since Y_j's are independent for a given hypothesis, $LR(\mathbf{Y})$ can be decomposed as

$$LR(\mathbf{Y}) = \prod_{j=1}^{N} \frac{Pr(Y_j|\mathcal{H}_1)}{Pr(Y_j|\mathcal{H}_0)}, \tag{9}$$

where $Pr(Y_j|\mathcal{H}_0)$ and $Pr(Y_j|\mathcal{H}_1)$ can be obtained based on (3) as

$$Pr(Y_j|\mathcal{H}_0) = \frac{(\frac{1}{2})^{\frac{M}{2}}}{\Gamma(\frac{M}{2})} Y_j^{\frac{M}{2}-1} e^{-\frac{1}{2}Y_j}, \tag{10}$$

and

$$Pr(Y_j|\mathcal{H}_1) = \frac{1}{1+\gamma_j} \frac{(\frac{1}{2})^{\frac{M}{2}}}{\Gamma(\frac{M}{2})} \left(\frac{Y_j}{1+\gamma_j}\right)^{\frac{M}{2}-1} e^{-\frac{1}{2}\frac{Y_j}{1+\gamma_j}}, \tag{11}$$

respectively. Thus LR($\mathbf{Y}$) can be expressed as

$$LR(\mathbf{Y}) = \left(\prod_{j=1}^{N} \frac{1}{1+\gamma_j}\right)^{\frac{M}{2}} e^{\frac{1}{2}\sum_{j=1}^{N} \frac{\gamma_j}{1+\gamma_j} Y_j}. \tag{12}$$

Therefore, the original decision criterion given in (8) is equivalent to

$$\sum_{j=1}^{N} \frac{\gamma_j}{1+\gamma_j} Y_j \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\gtrless}} \mu, \tag{13}$$

where $\mu = 2\ln\eta + M\sum_{j=1}^{N}\ln(1+\gamma_j)$ is the new decision threshold determined by the given false alarm probability. Thus we obtain an *optimal soft combination* (OC) scheme, in which the decision is based on the weighted summation of the observed energies from different CR users, $Y_{OC} =$

$$\begin{aligned}
\overline{P}_{D,Nak}(\bar{\gamma}, m, M, \lambda) &= \int_0^{+\infty} P_D(M, \lambda, \gamma) \cdot f_\gamma(\gamma, m) d\gamma \\
&= \int_0^{+\infty} e^{-\frac{\lambda}{2(1+\gamma)}} \sum_{k=0}^{M/2-1} \frac{1}{k!} \left(\frac{\lambda}{2(1+\gamma)} \right)^k \cdot f_\gamma(\gamma, m) d\gamma \\
&\overset{t=\frac{\lambda}{2(1+\gamma)}}{=} \frac{\lambda m^m e^{\frac{m}{\overline{\gamma}}}}{2\Gamma(m)\overline{\gamma}^m} \sum_{k=0}^{M/2-1} \frac{1}{k!} \int_0^{\frac{\lambda}{2}} \left(\frac{\lambda}{2t} - 1 \right)^{m-1} t^{k-2} e^{-\left(t + \frac{m\lambda}{2\overline{\gamma}} \frac{1}{t}\right)} dt
\end{aligned} \tag{7}$$

$\sum_{j=1}^N w_{OC_j} Y_j$, where $w_{OC_j} = \frac{\gamma_j}{1+\gamma_j}$ is the weight corresponding to the jth CR user with the instantaneous SNR γ_j.

Like in systems with multiple receive antennas, we may apply the *equal gain combination* (EGC) and *maximal ratio combination* (MRC) schemes here with the corresponding weights, $w_{EGC_j} = 1$ and $w_{MRC_j} = \gamma_j$ for $1 \leq j \leq N$, respectively. Apparently, when $\gamma_j \gg 1$, $w_{OC_j} \approx w_{EGC_j}$; when $\gamma_j \ll 1$, $w_{OC_j} \approx w_{MRC_j}$. In other words, the OC scheme reduces to the EGC scheme in high SNR region, and reduces to the MRC scheme in low SNR region. In [14], we have proved that the MRC soft combination scheme is nearly optimal in low SNR region by using the central limit theorem. Here we have arrived at the same conclusion.

For a soft combination scheme with weights $w_j, 1 \leq j \leq N$, the weighted summation of the observed energies can be obtained from (3) as

$$Y = \sum_{j=1}^N w_j Y_j = \begin{cases} \sum_{j=1}^N w_j b_{j_0}, & \mathcal{H}_0, \\ \sum_{j=1}^N w_j (1+\gamma_j) b_{j_1}, & \mathcal{H}_1, \end{cases} \tag{14}$$

where b_{j_0}'s (or b_{j_1}'s) follow an i.i.d. central chi-square distribution with M degrees of freedom for a given hypothesis, $\mathcal{H}_0$ (or $\mathcal{H}_1$). In [13], a method has been presented to evaluate the detection and false alarm probabilities numerically based on an accurate approximation of the *cumulative distribution probability* (CDF) of a weighted sum of independent central chi-square random variables. This method will be used in this letter to determine the thresholds of soft combination schemes so that the given false alarm probability is met exactly.

B. Simulation Results

Figure 1 shows the corresponding detection probability curves of different soft combination schemes under i.i.d. Rayleigh and Nakagami fading channels when the given false alarm probability is 10^{-2}. Corresponding curves of the conventional one-bit hard combination scheme are also plotted for comparison. The thresholds for these schemes are obtained numerically to meet the given false alarm probability exactly. For the conventional hard combination scheme, the 1-*out-of-*N rule [8] is applied, i.e., the primary user will be declared present if any one of the N CR users detects locally the presence of the primary signal.

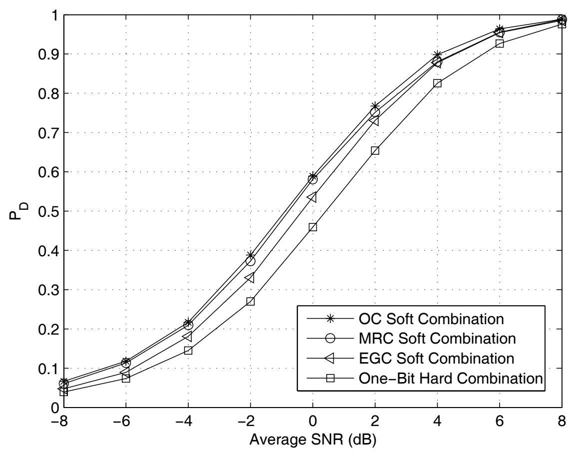
We observe from Figure 1 that the OC scheme does exhibit the best detection performance. The EGC scheme does not require any channel state information of the CR users, but still exhibits much better performance than the conventional hard combination scheme. Figure 1 also indicates that the performance gap between the EGC and OC schemes diminishes gradually as the average SNR increases, and, in contrast, the gap between the MRC and OC schemes diminishes as the average SNR decreases, both of which verify the above analysis. Comparison between Figures 1(a) and 1(b) indicates that, the larger the number of cooperative CR users is, the greater the performance improvement of soft combination over hard combination is, and the greater the performance improvement of the OC scheme over the EGC and MRC schemes is. On the other hand, comparison between Figures 1(a)[2] and 1(c) indicates that, the larger the Nakagami parameter (m) is, the smaller the performance gap between the OC and EGC schemes is. This is reasonable since a larger m means smaller variance of the instantaneous SNR and, hence, smaller differences between γ_j's. Therefore, both the OC and MRC schemes reduce to the EGC scheme gradually as m increases.

Figure 2 shows the contrastive detection probability curves of the OC and the conventional one-bit hard combination schemes with different M's and N's under i.i.d. Rayleigh fading channels when the given false alarm probability is 10^{-2}. To ensure fair comparison, the multiplication of M and N is fixed at 24, that is, the total number of samples utilized by cooperative CR users for energy detection is 24. Figure 2 indicates that for the conventional hard combination, in low SNR region, the smaller N is, the better the detection performance is, while in high SNR region, the larger N is, the better the performance is. This reflects a tradeoff involved in hard combination between multiuser diversity and information loss caused by local hard decisions. The larger N is, the higher the multiuser diversity order is, but the more information is lost. In low SNR region, information loss plays a more critical role, so a smaller N has a better performance; in high SNR region, multiuser diversity plays a more critical role, so a larger N has a better performance. In contrast, the detection performance of the OC scheme is always improved as N increases no mater how much the average SNR is. This is reasonable since for the OC scheme, no information is lost and more cooperative CR users mean higher order multiuser diversity.

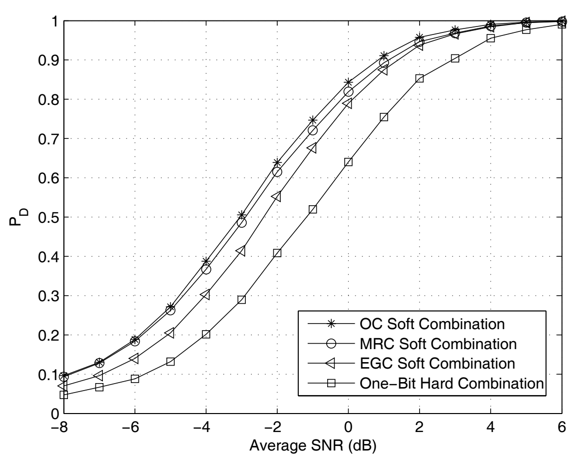
IV. Softened Two-Bit Hard Combination

Although the OC scheme has the best detection performance, it is based on the instantaneous SNR's of CR users and, hence, may be impractical in certain environments. Moreover,

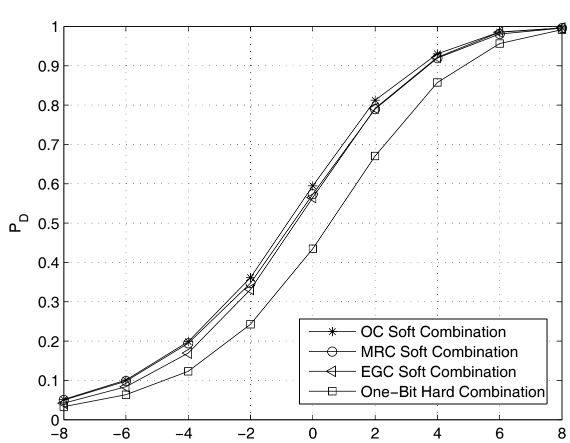
[2]Note that Rayleigh fading channel corresponds to a special type of Nakagami fading channel with $m = 1$.



(a) Rayleigh fading channel, M=6, and N=4



(b) Rayleigh fading channel, M=6, and N=8



(c) Nakagami fading channel (m=2), M=6, and N=4

Fig. 1. Detection probability curves of soft combination schemes under i.i.d. Rayleigh and Nakagami fading channels

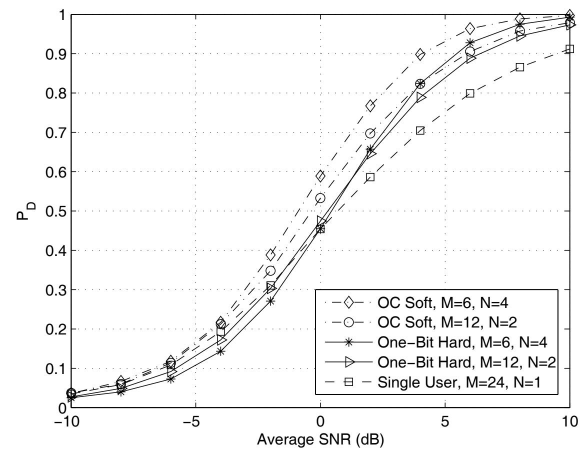


Fig. 2. Detection probability curves of the OC and one-bit hard combination schemes with different M's and N's under i.i.d. Rayleigh fading channels

soft combination schemes require lots of overhead for each CR user to feedback observation periodically. In contrast, the conventional hard combination scheme requires only one bit of overhead for each CR user, but suffers performance degradation because of information loss caused by local hard decisions. In this section, we will propose a new *softened* hard combination scheme with two-bit overhead for each CR user, which achieves a good tradeoff between detection performance and complexity.

A. Principle of Two-Bit Hard Combination Scheme

We know from Section III that the optimal detection performance of the OC scheme is obtained by allocating different weights to different CR users according to their respective instantaneous SNR. In the conventional one-bit hard combination scheme, there is only one threshold dividing the whole range of the observed energy into two regions. As a result, all of the CR users above this threshold are allocated the same weight regardless of the possible significant differences in their observed energies. Intuitively, a better detection performance can be achieved if we divide the whole range of the observed energy into more regions, and allocate larger weights to the upper regions and smaller weights to the lower regions. Based on the above heuristic, we develop a *softened* two-bit hard combination scheme which we describe below.

Figure 3 shows the principle of the two-bit hard combination scheme. Different from the conventional one-bit scheme with only one threshold, three thresholds in the two-bit scheme, λ_1, λ_1 and λ_3, divide the whole range of the observed energy into 4 regions. Therefore, each CR user needs to feedback two-bit information to indicate which region its observed energy falls in. The primary signal will be declared present if any one of the observed energies falls in region 3, or L ones of them fall in region 2, or L^2 [3] ones fall in region 1, where L is a design parameter to be optimized. This decision criterion is equivalent to allocating the 4 regions different

[3] While the optimal detection performance can be achieved if we use a general function of L, $f(L)$, here and try to optimize it, we simplify the design and use suboptimal L^2 to facilitate the analysis in this letter.

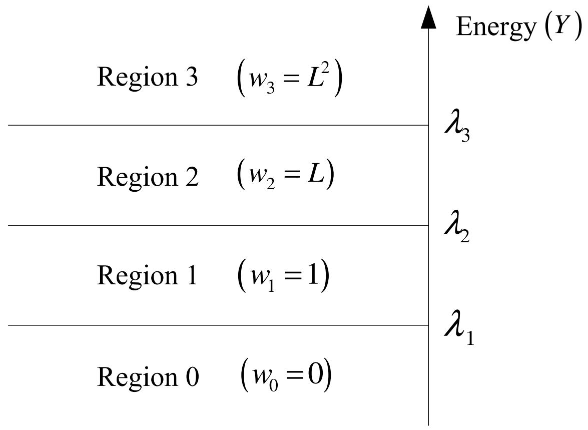


Fig. 3. Principle of two-bit hard combination scheme

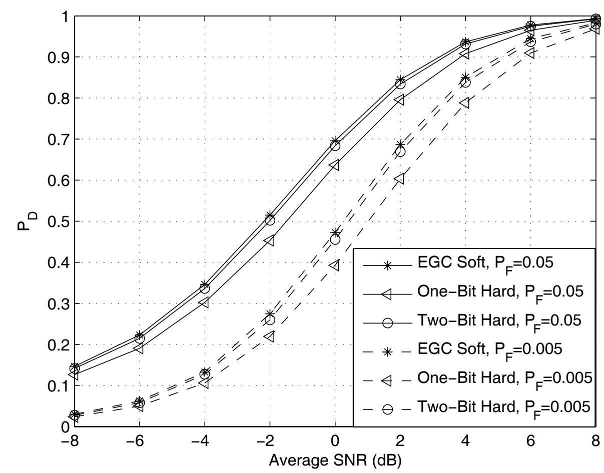


Fig. 4. Detection probability curves of hard combination schemes under i.i.d. Rayleigh fading channels

weights, $w_0 = 0, w_1 = 1, w_2 = L$, and $w_3 = L^2$, and the weighted summation is given by $N_c = \sum_{i=0}^{3} w_i N_i$, where N_i denotes the number of observed energies falling in region i. If $N_c \geq L^2$, the primary signal is declared present; otherwise, it is declared absent.

For the two-bit hard combination scheme, thresholds λ_1, λ_2, and λ_3 need to be determined to meet the target overall false alarm probability of the N-user CR network, Q_F, exactly, and also to optimize the detection performance. Suppose the primary signal is currently absent. To avoid false alarm, there must be no CR user in region 3. Assume there are j users in region 2, $i-j$ users in region 1, and all of the rest $N-i$ users fall in region 0, i.e., $N_3 = 0, N_2 = j, N_1 = i-j$, and $N_0 = N-i$. Then the weighted summation, $N_c = (i-j)w_1 + jw_2$, needs to be less than L^2 so as to avoid false alarm. As a result, it is required that $i \leq L^2-1$ and $j \leq \min\left\{\left\lfloor \frac{L^2-1-iw_1}{w_2-w_1}\right\rfloor, i\right\}$, where $\lfloor\cdot\rfloor$ denotes the largest integer no greater than the argument. Therefore, the probability of the successful detection of $\mathcal{H}_0$, $1-Q_F$, can be obtained by summing all of the possibilities of i and j that avoid false alarm, as demonstrated in Equation (15), where $I = L^2 - 1$, $J_i = \min\left\{\left\lfloor \frac{L^2-1-iw_1}{w_2-w_1}\right\rfloor, i\right\}$, and $P_{F_l} = P(Y > \lambda_l|\mathcal{H}_0)$ denotes the local false alarm probability at each CR user corresponding to threshold $\lambda_l, 1 \leq l \leq 3$.

Define $\beta_1 = \frac{P_{F_2}}{P_{F_1}}$, $\beta_2 = \frac{P_{F_3}}{P_{F_2}}$, where β_1 and β_2 are design parameters to be optimized, and $\rho = \frac{P_{F_1}}{1-P_{F_1}}$, then Equation (15) can be rewritten as (16), which is an Nth-order equation with respect to ρ. When N, Q_F, L, β_1, and β_2 are given, ρ can be uniquely determined based on (16), from which P_{F_1}, P_{F_2} and P_{F_3} can be obtained. Afterwards, thresholds λ_1, λ_2, and λ_3 can be determined based on (4).

Assume that all cooperative CR users experience i.i.d. fading channels, then, in a similar manner, the average overall detection probability of the CR network can be obtained by Equation (17), where I and J_i are defined as earlier, and $\overline{P}_{D_l} = P(Y > \lambda_l|\mathcal{H}_1)$ denotes the average local detection probability at each CR user corresponding to threshold $\lambda_l, 1 \leq l \leq 3$. Since the average local detection probability under Nakagami fading channel has been obtained in (7) in Section II, Equation (17) can be used to numerically find the optimal L, β_1, and β_2 that maximize the average overall detection probability of the CR network for a given overall false alarm probability. Although the exhaustive search of the optimal L, β_1, and β_2 involves significant computational complexity, it can be performed offline and, hence, does not impose any difficulty on the implementation of the two-bit hard combination scheme.

B. Simulation Results

Figure 4 shows the the average overall detection probability curves of the conventional one-bit hard combination, two-bit hard combination, and EGC soft combination schemes under i.i.d. Rayleigh fading channels when $M = 6$ and $N = 4$. In the two-bit hard combination scheme, we let $L = 2$, $\beta_1 = 0.25$ and $\beta_2 = 0.1$ when $Q_F = 0.05$, or $\beta_1 = 0.1$ and $\beta_2 = 0.05$ when $Q_F = 0.005$, the values of which are obtained numerically to maximize $\overline{Q}_{D,2B}$ given in (17).

Figure 4 indicates that the proposed two-bit hard combination scheme exhibits much better performance than the conventional one-bit scheme at the expense of only one more bit of overhead for each CR user. In fact, the two-bit hard combination scheme exhibits even comparable performance with the EGC soft combination scheme despite that it has much less complexity and overhead. Therefore, the *softened* two-bit hard combination scheme achieves a good tradeoff between detection performance and complexity.

V. Conclusion and Future Work

We have discussed cooperative spectrum sensing based on energy detection in CR networks. Soft combination of the observed energies from different CR users has been investigated. Based on the Neyman-Pearson criterion, we have obtained the optimal soft combination (OC) scheme that maximizes the detection probability for a given false alarm probability. We have further proposed a *softened* hard combination scheme with two-bit overhead for each CR user. Simulation results have demonstrated that the proposed two-bit hard combination scheme exhibits comparable performance with the EGC

$$\begin{aligned} 1 - Q_F &= \sum_{i=0}^{I} \sum_{j=0}^{J_i} Pr\left(N_0 = N - i, N_1 = i - j, N_2 = j, N_3 = 0 | \mathcal{H}_0\right) \\ &= \sum_{i=0}^{I} \left(\begin{array}{c} N \\ i \end{array} \right) \left(1 - P_{F_1}\right)^{N-i} \left\{ \sum_{j=0}^{J_i} \left(\begin{array}{c} i \\ j \end{array} \right) \left(P_{F_1} - P_{F_2}\right)^{i-j} \left(P_{F_2} - P_{F_3}\right)^{j} \right\} \end{aligned} \tag{15}$$

$$(1 - Q_F)(1+\rho)^N = \sum_{i=0}^{I} \left(\begin{array}{c} N \\ i \end{array} \right) \left\{ \sum_{j=0}^{J_i} \left(\begin{array}{c} i \\ j \end{array} \right) \times (1-\beta_1)^{i-j} (\beta_1 - \beta_1\beta_2)^j \right\} \rho^i \tag{16}$$

$$\begin{aligned} \overline{Q}_{D,2B} &= 1 - \sum_{i=0}^{I} \sum_{j=0}^{J_i} Pr\left(N_0 = N - i, N_1 = i - j, N_2 = j, N_3 = 0 | \mathcal{H}_1\right) \\ &= 1 - \sum_{i=0}^{I} \left(\begin{array}{c} N \\ i \end{array} \right) \left(1 - \overline{P}_{D_1}\right)^{N-i} \left\{ \sum_{j=0}^{J_i} \left(\begin{array}{c} i \\ j \end{array} \right) \left(\overline{P}_{D_1} - \overline{P}_{D_2}\right)^{i-j} \left(\overline{P}_{D_2} - \overline{P}_{D_3}\right)^{j} \right\} \end{aligned} \tag{17}$$

soft combination scheme and thus achieves a good tradeoff between performance and complexity.

It will be our future work to develop a static suboptimal soft combination scheme that is based on the static average SNR's of CR users. Obviously this scheme will be more practical than the OC scheme given in this letter since the instantaneous SNR's of CR users are not required. Also, we will try to develop a general K-bit ($K \geq 2$) hard combination scheme to further improve the performance of hard combination.

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