Optimization for Weighed Cooperative Spectrum Sensing in Cognitive Radio Network

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Abstract **─** In this paper, an optimal weighed cooperative spectrum sensing strategy based on data fusion is investigated in cognitive radio network. Cognitive radios sense the channels by energy detection independently and send their results to a fusion center, in which the observed data are fused by the specific weighing. The optimal sensing problem, which seeks to minimize interference and maximize throughput by keeping the probabilities of false alarm and detection within the allowable limit, is formulated. In particular, both the cooperative detections in single channel and multi-channels are analyzed, and the optimal weighed factors are obtained by Cauchy-inequality. Based on the weighing, we transform the non-convex optimal problem of multi-channel sensing with double parameters and nonlinear constraints into a convex problem with single parameter and linear constraints, which can be easily solved. The simulation shows that the proposed algorithm can achieve lower interference and higher throughput with less computing complexity, and the detected performance of each sub-channel can also be guaranteed. It also indicates that there is a conflict between improving throughput and decreasing interference, and the proposed algorithm can make better use of spectrum by balancing the conflict.

Index Terms **─** Cognitive radio, cooperative spectrum sensing, data fusion, energy detection, signal processing.

I. INTRODUCTION

Since wireless technologies continue to grow, more and more spectrum resources will be needed. Within the current spectrum allocation, all of the frequency bands are allocated to the legal user authorized by the government, which is called primary user (PU), and the unlicensed user is not permitted to access to the spectrum [1]. A survey of spectrum utilization made by the Federal Communications Commission (FCC) has indicated that 70% of the allocated spectrum in US has not been well-utilized, and in New York City, only 13.1% of the spectrum source from 30 MHz to 3 GHz is well used [2]. Moreover, the spectrum usage varies significantly in various time, frequency, and geographic locations, so it is difficult to reuse the spectrum according to the previous allocation principle [3].

Spectrum utilization can be improved significantly by allowing an unlicensed user to utilize a licensed band when the PU is absent, and therefore, a new intelligent unlicensed wireless communication system named cognitive radio (CR) is proposed to promote the efficient use of the spectrum [4]. A CR based on software radio, can reuse the temporarily unused radio spectrum allocated to PU, which is called idle spectrum, by sensing and adapting to the environment. Since the chief principle for CR to operate in the idle channel is that CR can't cause harmful interference to the PU, the CR must continuously sense the idle frequency band used by it, in order to detect the presence of the PU. Once the PU appears, CR should immediately vacate this band to search a new idle spectrum [5].

Presently, three schemes (namely, matched filter detection, energy detection and cyclo-stationary feature detection) have been presented for the single-user detection in CR networks. Matched filter detection can achieve high processing gain while cyclo-stationary feature detection can distinguish the primary signal under

Submitted On: May 14, 2011
Accepted On: October 13, 2011

low SNR. However, both of them need the prior information about the primary signal, which is difficult to get in the actual case [6]. Energy detection has been put forward as an optimal method for the occasion where CR cannot gather sufficient information about the primary signal [7]. However, unfortunately, the performance of energy detection could be degraded in the fading and shadow environment. In order to cope with this problem, the cooperative spectrum sensing has been proposed [8].

It has been proved that compared to the single-user detection, by allowing multiple CRs to cooperatively sense spectrum, the detected performance in the fading and shadow environment can be improved greatly [9]. In cooperative spectrum sensing, each CR makes a local decision by energy detection, and then reports its decision result to a fusion center in order to obtain the final decision on the presence of PU [10]. The fusion rule of the cooperative detection includes decision fusion and data fusion, and in this paper, we focus on data fusion which can achieve higher performance while more CRs are in deep fading [11].

Light-weight cooperative detection based on decision fusion is proposed in [12] to increase the detection probability under a specific false alarm probability. By its predominant nature as a data fusion scheme, an optimal linear cooperative spectrum sensing for CR network based on weighed data fusion is proposed by [13]. In [13], the detected performance is improved through the optimum weight vector obtained by the global solution of the objective function. However, the complexity brought by the solution of non-convex optimization problem is high. The linear combination weights for a global fusion center that together maximize global probability of detection [14]. However, the probability of false alarm which needs to be decreased for improving the spectrum utilization is lack of consideration. The researches in [12-14] are all about the cooperative detection in the single channel. An optimal multi-band joint detection for spectrum sensing in CR network is proposed in [15], and the spectrum sensing problem is formulated as a class of optimization problems which maximize the throughput of CR. However, the objective function and constraints in [15] are all nonlinear functions, and the interior-point method adopted to solve the problem is complex.

In this paper, the weighed cooperative detection based on data fusion is researched further and both the cooperative detections in single channel and multi-channel are considered. Our technical contributions are summarized as follows: (1) We respectively obtain the optimal weighed factors of the cooperative detection in single channel from the two aspects: minimizing interference and maximizing throughput, and the optimal problem can be further expressed as maximizing probability of detection and minimizing probability of false alarm subject to the constraints of throughput and interference respectively. The solution of the proposed optimal problem is based on the Cauchy-inequality which has less complexity. (2) By the research result of the detection in single channel, the non-convex optimal problem of the cooperative detection in multi-channel with double parameters and nonlinear constraints can be transformed into a convex optimal problem with single parameter and linear constraints, which can be solved easily. (3) Our simulation proves that there is an obvious conflict between improving throughput and decreasing interference, however the proposed algorithms can balance the conflict better.

The rest of the paper is organized as follows. In Section II, we describe the single-user energy detection. In Section III, we develop the weighed cooperative detection in single channel in order to minimize interference to PU and maximize throughput of CR. Based on the research result in Section III, the optimization of the cooperative detection in multi-channel is proposed and solved in Section IV. The advantages of the proposed cooperative spectrum sensing algorithm are then illustrated by the simulations in Section V, and lastly the conclusions are drawn in Section VI.

II. SINGLE USER DETECTION

A. Primary signal assumption

Suppose that there are N users in the CR network, and the received signal of CRi can be denoted by the binary assumption defined as (1). Hypothesis H_1 denotes the presence of PU while hypothesis H_0 denotes the absence of PU.

$$\begin{aligned} &H_0: x_i(l) = n(l) && i = 1,2,\ldots,N \\ &H_1: x_i(l) = h_i s(l) + n(l) && l = 1,2,\ldots,M \end{aligned}, \tag{1}$$

where $x_i(l)$ is the received signal of CRi, and l is the sampling node of the received signal. $s(l)$ is the primary signal which is assumed to be a uniform random process with zero mean and variance σ_s^2, while the noise $n(l)$ is assumed to be Gaussian random process with zero mean and variance σ_n^2, and $s(l)$ and $n(l)$ are completely independent. h_i is the channel gain between the PU and CRi.

B. Energy detection

If prior knowledge of the primary signal is unknown, the energy detection method is optimal for detecting any zero-mean constellation signals.

In the energy detection approach, the radio-frequency (RF) energy in the channel or the received signal strength indicator is measured by CR to determine the presence of the PU. Firstly, the received signal is filtered through a band-pass filter to select the preferable bandwidth. The output signal is then squared and integrated over the observed interval. Finally, the output of the integrator is compared to a pre-set threshold for deciding the vacancy of the channel. The energy detection model is shown in Fig. 1.

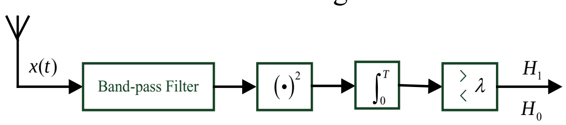

Fig. 1. Energy detection model.

Over an observed interval of M samples, each CR calculates an energy statistic T_i which is given by

$$T_i = \frac{1}{M}\sum_{l=1}^{M} x_i^2(l) \quad i = 1,2,\ldots,N. \tag{2}$$

By comparing T_i to the threshold λ_i, the presence of the PU can be estimated by

$$T_i \underset{H_0}{\overset{H_1}{\gtrless}} \lambda_i. \tag{3}$$

If M is large enough, according to the center limit theorem (CLT), the probability distribution function (PDF) of T_i can be approximated by a Gaussian distribution whose mean $u_{i,j}$ and variance $\sigma_{i,j}^2$ under the hypothesis H_j (j=0,1) are calculated respectively as follows

$$H_0 \begin{cases} u_{i,0} = \sigma_n^2 \\ \sigma_{i,0}^2 = \dfrac{2}{M}\sigma_n^4 \end{cases} \quad H_1 \begin{cases} u_{i,1} = (1+\gamma_i)\sigma_n^2 \\ \sigma_{i,1}^2 = \dfrac{2}{M}(2\gamma_i + 1)\sigma_n^4 \end{cases}, \tag{4}$$

where the received SNR by CRi is $\gamma_i = h_i^2\sigma_s^2 / \sigma_n^2$. Therefore, according to (4), for a single CR, the probabilities of false alarm and detection are given respectively as follows

$$P_{f,i} = Q\left((\frac{\lambda_i}{\sigma_n^2} - 1)\sqrt{\frac{M}{2}} \right), \tag{5}$$

$$P_{d.i} = Q\left((\frac{\lambda_i}{\sigma_n^2} - \gamma_i - 1)\sqrt{\frac{M}{4\gamma_i + 2}} \right), \tag{6}$$

where function $Q(x) = \int_x^\infty \exp(-t^2/2)\mathrm{d}t \Big/ \sqrt{2\pi}$.

Probabilities of false alarm and detection represent the different characters of CR. The high probability of false alarm, which means the high error probability of deciding the presence of the PU, decreases the spectrum utilization, while the low probability of detection, which means the high error probability of deciding the absence of the PU, increases the interference to PU. The probability of miss detection is obtained by

$$P_{m,i} = 1 - P_{d,i}. \tag{7}$$

By setting the threshold λ_i for a desired probability of false alarm $\tilde{P}_{f,i}$, according to (5) and (6), we obtain the probability of detection as

$$P_{d,i} = Q\left(\frac{Q^{-1}(\tilde{P}_{f,i})}{\sqrt{2\gamma_i + 1}} - \gamma\sqrt{\frac{M}{4\gamma_i + 2}} \right), \tag{8}$$

while by setting the threshold λ_i for a desired probability of detection $\tilde{P}_{d,i}$, we can obtain the probability of false alarm as

$$P_{f,i} = Q\left(Q^{-1}(\tilde{P}_{d,i})\sqrt{2\gamma_i + 1} + \gamma_i\sqrt{M/2} \right). \tag{9}$$

III. COOPERATIVE DETECTION IN SINGLE CHANNEL

A. Cooperative detection generalization

The critical challenging issue in spectrum sensing of CR is the hidden terminal problem, which occurs when the CR is shadowed or in severe multipath fading. Figure 2 shows that CR3 is shadowed by a high building over its sensing channel, and therefore CR3 may falsely decide the absence of the PU because of the weak primary signal power received by it. Thus, CR3 may access to the channel in spite of the interference to PU. To solve this problem, multiple CRs can be designed to collaborate in spectrum sensing. When one CR is in deep fading, the received signal may be too weak to be detected. However, by employing a CR located near by the PU as an assistant, the primary signal can be detected reliably by the infirm CR.

In this paper, we consider a cooperative spectrum sensing scenario where multiple CRs can be coordinated to enhance the performance of spectrum sensing as a whole, and by cooperative spectrum sensing, the probability of detection in fading channel can be greatly increased.

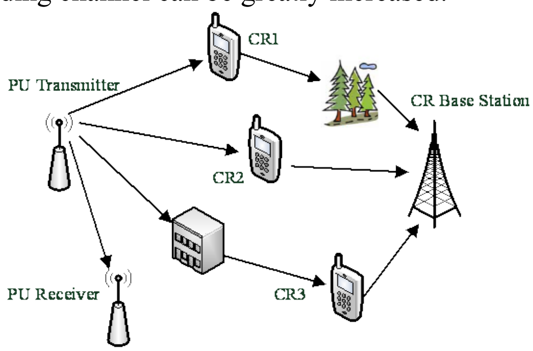

Fig. 2. Causes of unreliable detection.

In this subsection, we assume that one CR can only detect a single channel at one time and the CR network is composed of N CRs, and a fusion center which manages the CR network and all the associated N CRs.

In the network, cooperative detection can be defined by the following four steps

(1) Each CR performs local spectrum sensing by observing the primary signal independently, and its sensing result may be a 1-bit binary decision 0/1 which denotes H_0 / H_1 or an energy statistic of the primary signal.

(2) All the CRs transmit their sensing results to the fusion center through one dedicated control channel in an orthogonal manner.

(3) The fusion center fuses all the sensing results from the CRs in order to make the final decision to infer the presence of the PU.

(4) After getting the fusion decision, the fusion center reports its final decision to all the CRs through the dedicated control channel.

The cooperative detection model is showed in Fig. 3. It shows that cooperative spectrum sensing goes through two successive channels: the sensing channel (observed channel from PU to CR) and the reporting channel (dedicated control channel from CR to the fusion center).

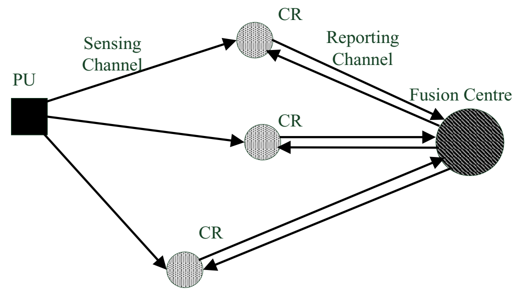

Fig. 3. Cooperative detection model in CR.

The fusion fashion by the fusion center includes the following two kinds

(1) Decision fusion: each CR makes a binary decision based on the local observation and then forwards 1-bit decision to the fusion center. At the fusion center, all the 1-bit decisions are combined together to make the final decision by a fusion rule such as OR logic, AND logic and K-OUT-N logic.

(2) Data fusion: instead of transmitting the 1-bit decision to the fusion center in the decision fusion, here each CR can just send its observed value directly to the fusion center. At the fusion center, all the observed values from CRs are accumulated and then compared to a global decision threshold for getting the final decision.

Compared to the 1-bit transmission of decision fusion, data fusion needs CR to transmit larger observed information, however, data fusion which gets less influence of the single CR, outperforms decision fusion while more CRs are shadowed or in deep fading.

B. Cooperative detection based on weighing

Since the single detected performance of each CR is different, and the CRs with low detected performance can decrease the cooperative detected performance while those with high detected performance can increase the cooperative detected performance, in this paper, weighed factor is used to represent the contribution of the single CR to the cooperative detection. A weighed cooperative detection model based on data fusion is showed in Fig. 4.

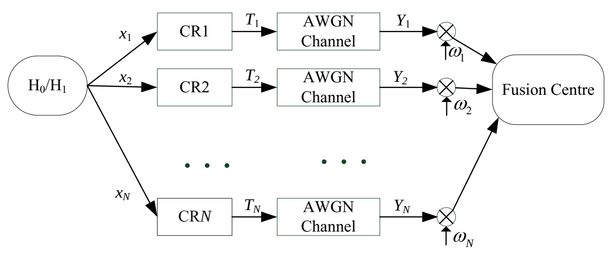

Fig. 4. Weighed cooperative detection model.

In Fig. 4, each CR sends its energy statistic T_i for i=1, 2,…, N to the fusion center which together combines all the statistics by the specific weighed factors, and gives the final decision by comparing the fusion statistic to the global threshold. The statistic received from CRi by the fusion center is obtained as follows

$$Y_i = g_i T_i + v, \quad i = 1, 2, ..., N , \tag{10}$$

where g_i is the channel gain between CRi and the fusion center, and v is AWGN with the variance σ_v^2. The fusion statistic is given by

$$Z = \sum_{i=1}^{N} \omega_i Y_i , \tag{11}$$

where the weight vector $\boldsymbol{\omega}=[\omega_1,\omega_2,\ldots,\omega_N]^T$ satisfies $\|\boldsymbol{\omega}\|=1$. According to (4), the mean $u_{z,j}$ and variance $\sigma_{Z,j}^2$ under H_j (j=0,1) are given by

$$H_0 \begin{cases} u_{Z,0} = \sum_{i=1}^{N} \omega_i g_i \sigma_n^2 \\ \sigma_{Z,0}^2 = \frac{2}{M} \sum_{i=1}^{N} \omega_i^2 g_i^2 \sigma_n^4 + \sigma_v^2 \end{cases}$$
$$H_1 \begin{cases} u_{Z,1} = \sum_{i=1}^{N} \omega_i g_i (1+\gamma_i)\sigma_n^2 \\ \sigma_{Z,1}^2 = \frac{2}{M} \sum_{i=1}^{N} \omega_i^2 g_i^2 (1+2\gamma_i)\sigma_n^4 + \sigma_v^2 \end{cases} . \tag{12}$$

Similar with (5-6), the cooperative probabilities of false alarm and detection are obtained as (13-14).

$$Q_f = Q\left(\frac{\lambda_g / \sigma_n^2 - \sum_{i=1}^{N} \omega_i g_i}{\sqrt{\frac{2}{M} \sum_{i=1}^{N} \omega_i^2 g_i^2 + \tilde{\sigma}_v^2}} \right), \tag{13}$$

$$Q_d = Q\left(\frac{\lambda_g / \sigma_n^2 - \sum_{i=1}^{N} \omega_i g_i (1+\gamma_i)}{\sqrt{\frac{2}{M} \sum_{i=1}^{N} \omega_i^2 g_i^2 (1+2\gamma_i) + \tilde{\sigma}_v^2}} \right), \tag{14}$$

where λ_g is the global detection threshold of cooperative spectrum sensing, and $\tilde{\sigma}_v^2 = \sigma_v^2 / \sigma_n^4$. By supposing that the channel state between the CR and fusion center is much better than that between the PU and CR, we have $\tilde{\sigma}_v^2 \approx 0$ and $\gamma_i << 1$ for i=1, 2,…, N.

From (9), we know that the probability of detection improves with the increasing of the received SNR, and therefore, a larger weighed factor should be allocated to the CR with high SNR in order to improve the cooperative probability of detection. A simple method proposed in [16] is to obtain the weighed factors according to the SNR ratio of the CRs, which can be defined as

$$\omega_i = \gamma_i \Big/ \sqrt{\sum_{i=1}^{N} \gamma_i^2} . \tag{15}$$

The weight vector obtained by (15) can improve the cooperative detected performance; however, the channel gain between the CR and fusion center isn't considered by (15), and the detected performance may be decreased when the channel is worse.

The two basic communication characters of CR are defined as follows

(1) Decrease the interference to PU in order to guarantee the communication quality of PU.

(2) Improve the throughput of CR in order to improve the spectrum utilization.

So we can propose the optimal cooperative spectrum sensing scheme from the two aspects mentioned above.

C. Weighing based on minimizing interference

Since the CR and PU coexist in the same channel, the communication of CR can undergo the four states defined as follows

(1) While the PU is present in the channel and the CR can detect the presence of the PU exactly, the CR can't use the channel in order to avoid disturbing the PU with the probability Q_d.

(2) While the PU is absent and the CR detects

the vacancy of the channel exactly, the CR can use this channel without disturbing the PU with the probability 1-Q_f and rate C_0.

(3) While the PU is present in the channel and the CR falsely detects the vacancy of the channel, the CR can use the channel and disturb the PU with the probability 1-Q_d and rate C_1.

(4) While the PU is absent, and the CR falsely detects the presence of the PU, the CR can vacate the idle channel and waste the spectrum utilization with the probability Q_f.

The CR communicates mainly at the scene (2) and (3) with the rates C_0 and C_1, which are obtained as follows

$$\begin{aligned} C_0 &= W\log_2\left(1+\frac{\sigma_R^2}{\sigma_n^2}\right) \\ C_1 &= W\log_2\left(1+\frac{\sigma_R^2}{\sigma_s^2+\sigma_n^2}\right) \end{aligned}, \quad (16)$$

where W is the bandwidth of the primary channel, and σ_R^2 is the transmission power of the CR. Observably, we can have $C_0 > C_1$.

The transmission capacity of the CR at the scene (2) and (3) can be respectively obtained as

$$R_C = P_{H0}(1-Q_f)C_0, \quad (17)$$

$$R_I = P_{H1}(1-Q_d)C_1, \quad (18)$$

where P_{H_0} and P_{H_1} denote the probabilities of the hypotheses H_0 and H_1 respectively, and the transmission capacities R_C and R_I can be named communication throughput and interference capacity respectively. From (17) and (18), we know low Q_f can increase the throughput of CR while high Q_d can decrease the interference to PU.

The optimal problem in this subsection can be defined as to minimize the interference capacity in scene (3) subject to the constraint that guarantees the communication throughput in scene (2) and the spectrum utilization in scene (4). Therefore, the optimal problem can be defined as

$$\begin{aligned} &\min_{\boldsymbol{\omega}} R_I \\ &s.t.\ R_C \geq \varepsilon \\ &\quad Q_f \leq \alpha \\ &\quad \|\boldsymbol{\omega}\| = 1 \end{aligned}, \quad (19)$$

where ε and α are the constraint values, and generally we make $0 \leq \alpha < 0.5$. According to (17-18), the optimal problem (19) can be modified as

$$\begin{aligned} &\max_{\boldsymbol{\omega}} Q_d \\ &s.t.\ Q_f \leq \eta, \\ &\quad \|\boldsymbol{\omega}\| = 1 \end{aligned} \quad (20)$$

where $\eta = \min(1-\varepsilon / P_{H_0}C_0, \alpha)$ which denotes that if $\varepsilon \geq P_{H_0}C_0(1-\alpha)$, $\eta = 1-\varepsilon / P_{H_0}C$ and otherwise $\eta = \alpha$.

Since function $Q(x)$ is the decreasing function, according to (13-14), Q_d improves with the increasing of Q_f, and when Q_f reaches the upper band, Q_d can also reach the maximum. Letting Q_f $=\eta$ and substituting it into (13-14), similar with (8), Q_d can be denoted by η as

$$Q_d \approx Q\left(\frac{Q^{-1}(\eta)}{\sqrt{1+2\bar{\gamma}}} - \sqrt{\frac{M}{2}}\frac{\sum_{i=1}^{N}\omega_i g_i \gamma_i}{\sqrt{\sum_{i=1}^{N}\omega_i^2 g_i^2(1+2\gamma_i)}}\right), \quad (21)$$

where $\bar{\gamma} = \sum_{i=1}^{N}\gamma_i / N$ is the average SNR of N CRs. Since $Q(x)$ is the decreasing function, the optimal problem of (20) can be further modified by

$$\begin{aligned} &\max_{\boldsymbol{\omega}}\ f(\boldsymbol{\omega}) = \frac{\left(\sum_{i=1}^{N}\omega_i g_i \gamma_i\right)^2}{\sum_{i=1}^{N}\omega_i^2 g_i^2 (1+2\gamma_i)}. \\ &s.t.\quad \|\boldsymbol{\omega}\| = 1 \end{aligned} \quad (22)$$

By substituting $d_i = \omega_i g_i \sqrt{1+2\gamma_i}$ into (22), we get

$$f(\boldsymbol{\omega}) = \left(\sum_{i=1}^{N} d_i \frac{\gamma_i}{\sqrt{1+2\gamma_i}}\right)^2 \Bigg/ \sum_{i=1}^{N} d_i^2. \quad (23)$$

According to the Cauchy-inequality, we can get

$$\left(\sum_{i=1}^{N} d_i \frac{\gamma_i}{\sqrt{1+2\gamma_i}}\right)^2 \leq \sum_{i=1}^{N} d_i^2 \sum_{i=1}^{N}\frac{\gamma_i^2}{1+2\gamma_i}. \quad (24)$$

When $d_i = \rho\gamma_i / \sqrt{1+2\gamma_i}$ where the constant $\rho > 0$, the equation of (24) which denotes that $f(\boldsymbol{\omega})$ reaches the maximum, can be obtained as

$$f_{\max}(\boldsymbol{\omega}) = \sum_{i=1}^{N}\frac{\gamma_i^2}{1+2\gamma_i}, \quad (25)$$

where the corresponding weighed factors satisfy

$$\omega_i^* = \frac{\gamma_i}{g_i(1+2\gamma_i)} \Bigg/ \sum_{i=1}^{N} \frac{\gamma_i^2}{g_i^2(1+2\gamma_i)^2},\ i=1,2,...,N. \quad (26)$$

By substituting (25) into (21) and (18), the minimum of interference capacity is obtained as

$$R_I = P_{H_1} C_1 \left(1 - Q\left(\frac{Q^{-1}(\eta)}{\sqrt{1+2\overline{\gamma}}} - \sqrt{\frac{M}{2}\sum_{i=1}^{N}\frac{\gamma_i^2}{1+2\gamma_i}}\right)\right). \quad (27)$$

From (27), we can know that with the increasing of the number and SNR of the cooperative CRs, the interference to the PU can be decreased.

D. Weighing based on maximizing throughput

Another purpose to research on the CR is to improve its communication throughput. Since the channel used by CR is allocated to the PU, and while the PU appears in the channel, the CR must vacate this channel and wait to search a new idle spectrum, it is important to improve the throughput of CR during the transmission time. It is also necessary to keep the interference to the PU below the specific tolerance, while the throughput is improved [17]. The optimal problem in this section can be defined as to maximize the communication throughput in scene (2) subject to the constraint that makes the interference in scene (3) and (4) below the tolerance. Therefore, the optimal problem can be defined as

$$\begin{aligned} &\max_{\boldsymbol{\omega}}\ R_C \\ &s.t.\ \ R_I \le \xi \\ &\qquad Q_d \ge \beta \\ &\qquad \|\boldsymbol{\omega}\| = 1 \end{aligned}, \quad (28)$$

where ξ and β are the constraint values, and generally we make $0.5 < \beta \le 1$. According to (17-18), the optimal problem in (28) is modified by

$$\begin{aligned} &\min_{\boldsymbol{\omega}}\ Q_f \\ &s.t.\ Q_d \ge \mu, \\ &\qquad \|\boldsymbol{\omega}\| = 1 \end{aligned} \quad (29)$$

where $\mu = \max(1-\xi / P_{H_1}C_1, \beta)$ which denotes that if $\xi \le P_{H_1}C_1(1-\beta)$, $\mu = 1-\xi / P_{H_1}C_1$ and otherwise $\mu = \beta$.

As mentioned above, Q_f increases with the increasing of Q_d, and when Q_d reaches the lower band, Q_f can reach the minimum. By substituting $Q_d = \mu$ into (13-14), Q_f could be denoted by μ as

$$Q_f \approx Q\left(Q^{-1}(\mu)\sqrt{1+2\overline{\gamma}} + \sqrt{\frac{M}{2}}\frac{\sum_{i=1}^{N}\omega_i g_i \gamma_i}{\sqrt{\sum_{i=1}^{N}\omega_i^2 g_i^2}}\right). \quad (30)$$

Similar with (22), the optimal problem in (29) can be equivalent as

$$\begin{aligned} &\max_{\boldsymbol{\omega}}\ \phi(\boldsymbol{\omega}) = \frac{\left(\sum_{i=1}^{N}\omega_i g_i \gamma_i\right)^2}{\sum_{i=1}^{N}\omega_i^2 g_i^2}. \quad (31) \\ &s.t.\quad \|\boldsymbol{\omega}\| = 1 \end{aligned}$$

According to the Cauchy-inequality, the maximum of $\phi(\boldsymbol{\omega})$ can be obtained as

$$\varphi_{\max}(\boldsymbol{\omega}) = \sum_{i=1}^{N}\gamma_i^2, \quad (32)$$

where the corresponding $\boldsymbol{\omega}$ is given by

$$\omega_i^* = \frac{\gamma_i}{g_i} \Bigg/ \sqrt{\sum_{i=1}^{N}\frac{\gamma_i^2}{g_i^2}}\quad i=1,2,...,N. \quad (33)$$

By substituting (32) and (33) into (30) and (17), the maximum of communication throughput is obtained as

$$R_C = P_{H_0} C_0 \left(1 - Q\left(Q^{-1}(\mu)\sqrt{1+2\overline{\gamma}} + \sqrt{\frac{M}{2}\sum_{i=1}^{N}\gamma_i^2}\right)\right). \quad (34)$$

According to (26) and (23), if $\gamma_i << 1$, it can be given that $\omega_i^* \sim \gamma_i / g_i$, and compared to (15), the proposed optimal algorithm in this paper can allocate a larger weighed factor to the CR whose channel gain to the fusion center is lower in order to compensate the lost information brought by the fading of the reporting channel, besides that increases the weighed factor of the CR with high SNR in order to improve its contribution to the cooperative detection.

IV. COOPERATIVE DETECTION IN MULTI-CHANNEL

A. Minimizing interference

Consider a primary communication system (multi-carrier modulation based) operating over a wideband channel which is divided into L non-overlapping narrowband sub-bands. In a particular geographical region and within a particular time interval, some of the sub-bands might not be used by the PUs and are available for opportunistic spectrum access. Compared to the detection in single channel, the detection in multi-channel must consider the total detected performance of all the sub-channels. Since the fading of each channel is different, the thresholds and probabilities of false alarm and detection of each sub-channel should also be different in order to make the best use of the spectrum.

In this subsection, we present the multi-channel cooperative detection framework for wideband spectrum sensing. Since the sensing about wideband experiences different channel conditions, it is difficult to distinguish the channel fading. As mentioned in Section 3, the weighed cooperative detection can compensate the lost information brought by the channel fading, and therefore it is necessary to apply the weighed cooperation in the multi-channel detection.

The design objective is to find the optimal global threshold vector $\boldsymbol{\lambda}_g=[\lambda_{g,1},\lambda_{g,2},\ldots,\lambda_{g,L}]$ and the optimal weight vectors $\boldsymbol{\omega}^{(j)}=[\omega_1^{(j)},\omega_2^{(j)},...,\omega_N^{(j)}]$ for $j = 1, 2,\ldots, L$, so that the CR system can make the efficient use of the unused idle sub-channels without causing harmful interference to the PU. For the given threshold vectors $\boldsymbol{\lambda}_g$ and $\boldsymbol{\omega}^{(j)}$, the probabilities of false alarm and detection can be compactly represented as follows

$$\begin{aligned}\boldsymbol{Q}_f(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)})&=[Q_f^{(1)}(\lambda_{g,1},\boldsymbol{\omega}^{(1)}),...,Q_f^{(L)}(\lambda_{g,L},\boldsymbol{\omega}^{(L)})]\\ \boldsymbol{Q}_d(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)})&=[Q_d^{(1)}(\lambda_{g,1},\boldsymbol{\omega}^{(1)}),...,Q_d^{(L)}(\lambda_{g,L},\boldsymbol{\omega}^{(L)})]\\ \boldsymbol{Q}_m(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)})&=[Q_m^{(1)}(\lambda_{g,1},\boldsymbol{\omega}^{(1)}),...,Q_m^{(L)}(\lambda_{g,L},\boldsymbol{\omega}^{(L)})]\end{aligned} \quad . (35)$$

The vector $\boldsymbol{Q}_m$ can be obtained by $\boldsymbol{Q}_m=\boldsymbol{I}-\boldsymbol{Q}_d$, where $\boldsymbol{I}$ denotes the all one vector.

All the N CRs detect the L sub-channels independently, and the received SNR of CRi in the channel j is defined as γ_{ij} for i=1,2,…,N and j=1, 2,…,L. We also denote the CR rates of the L sub-channels at scene (2) and (3) as the two vectors $\boldsymbol{C}_0=[C_{0,1},C_{0,2},...,C_{0,L}]$ and $\boldsymbol{C}_1=[C_{1,1},C_{1,2},...,C_{1,L}]$ where $\boldsymbol{C}_0>\boldsymbol{C}_1$ respectively. Therefore, the total communication throughput and interference capacity of the CR in L sub-channels can be respectively obtained as follows

$$R_C=P_{H_0}\sum_{j=1}^{L}C_{0,j}\left(1-Q_f^{(j)}(\lambda_{g,j},\boldsymbol{\omega}^{(j)})\right), \quad (36)$$

$$R_I=P_{H_1}\sum_{j=1}^{L}C_{1,j}\left(1-Q_d^{(j)}(\lambda_{g,j},\boldsymbol{\omega}^{(j)})\right). \quad (37)$$

Similar with the detection in single channel, one of our objectives is to find the optimal thresholds $\boldsymbol{\lambda}_{g,j}$ and weight vectors $\boldsymbol{\omega}^{(j)}$ for j=1, 2,…, L in the L sub-bands in order to collectively minimize the total interference to PU subject to the constraint that guarantees the communication throughput and spectrum utilization of the CR in each sub-channel. As such, the optimal problem of cooperative detection in multi-channel can be formulated as

$$\begin{aligned}&\min_{\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)}} R_I\\ &s.t.\ R_C\ge\varepsilon\\ &\quad \boldsymbol{Q}_f(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)})\le\boldsymbol{\alpha}\\ &\quad \boldsymbol{Q}_d(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)})\ge\boldsymbol{\beta}\end{aligned}, \quad (38)$$

where ε, $\boldsymbol{\alpha}=[\alpha_1,\alpha_2,...,\alpha_L]$ and $\boldsymbol{\beta}=[\beta_1,\beta_2,...,\beta_L]$ are respectively the constraints of the throughput and probabilities of false alarm and detection.

The objective function and constraints in (38) are the non-convex functions with double parameters and nonlinear constraints, and therefore, the optimal problem in (38) is usually NP-hard to be solved directly. In order to solve the problem in (38), we resort to transformation of the problem into a sub-problem with low complexity, in which the conclusions obtained in Section 3 are also used.

According to (26), by choosing $\boldsymbol{\omega}^{(j)}$ as the optimal weight vector, we can define R_I by $Q_f^{(j)}$ as (27). Since $Q_d^{(j)}$ increases with the increasing of $Q_f^{(j)}$, R_I can reach the minimum when R_C reaches its lower band. Since there is the only $Q_f^{(j)}$ corresponding to the given $\lambda_{g,j}$ and $\boldsymbol{\omega}^{(j)}$, the optimal solution of λ_g can be substituted by optimizing $\boldsymbol{Q}_f$.

Therefore the optimal problem of (38) can be further modified as follows

$$\min_{\boldsymbol{Q}_f} \sum_{j=1}^{L} C_{1,j}\left(1-Q\left(\frac{Q^{-1}(Q_f^{(j)})}{\sqrt{1+2\overline{\gamma}_j}}-\sqrt{\frac{M\theta_j}{2}}\right)\right)$$
$$s.t.\ \sum_{j=1}^{L} C_{0,j}Q_f^{(j)} = \sum_{j=1}^{L} C_{0,j} - \varepsilon' / P_{H_0}$$
$$Q\left(Q^{-1}(\beta_j)\sqrt{1+2\overline{\gamma}_j}+\sqrt{(0.5+\overline{\gamma}_j)M\theta_j}\right) \le Q_f^{(j)} \le \alpha_j \tag{39}$$

where the lower band of communication throughput $\varepsilon' = \max\left(\varepsilon, P_{H_0}\sum_{j=1}^{L} C_{0,j}(1-\alpha_j)\right)$ which denotes that if $\varepsilon \ge P_{H_0}\sum_{j=1}^{L} C_{0,j}(1-\alpha_j)$, $\varepsilon' = \varepsilon$ and otherwise $\varepsilon' = P_{H_0}\sum_{j=1}^{L} C_{0,j}(1-\alpha_j)$. The average SNR of the channel j is $\overline{\gamma}_j = \sum_{i=1}^{N}\gamma_{ij}/N$. The substituted variable $\theta_j = \sum_{i=1}^{N}\gamma_{ij}^2/\left(1+2\gamma_{ij}\right)$.

In this way, the original nonlinear constraints are transformed into the linear constraints, and the optimal global thresholds can be obtained by $\boldsymbol{Q}_f$ through (13). In order to solve the optimal problem in (39), firstly, we must prove that the objective function is convex in $\boldsymbol{Q}_f$, and in order to prove this problem, we define

$$s_j(Q_f^{(j)}) = 1-Q\left(\frac{Q^{-1}(Q_f^{(j)})}{\sqrt{1+2\overline{\gamma}_j}}-\sqrt{\frac{M\theta_j}{2}}\right), \tag{40}$$

and the objective function can be defined as

$$S(\boldsymbol{Q}_f) = \sum_{j=1}^{L} C_{1,j}s_j(Q_f^{(j)}). \tag{41}$$

Lemma 1: Subject to the conditions $\boldsymbol{\alpha} < 0.5$ and $\boldsymbol{\beta} > 0.5$, the function $s_j(Q_f^{(j)})$ is convex in $Q_f^{(j)}$.

Proof: Let $Q^{-1}(Q_f^{(j)}) = \tau_j$, and according to (40) it is obtained that $Q_f^{(j)} = Q(\tau_j)$ and $s_j(Q_f^{(j)}) = 1-Q\left(\tau_j/\sqrt{1+2\overline{\gamma}_j}-\sqrt{0.5M\theta_j}\right)$. By taking the second derivative of $Q_f^{(j)}$ and $s_j(Q_f^{(j)})$ in τ_j , we can obtain

$$\frac{\partial^2 Q_f^{(j)}}{\partial^2\tau_j} = \frac{\tau_j}{\sqrt{2\pi}}\exp\left(-\frac{\tau_j^2}{2}\right), \tag{42}$$

$$\frac{\partial^2 s_j(Q_f^{(j)})}{\partial^2\tau_j} = -\frac{\tau_j-\sqrt{(0.5+\overline{\gamma}_j)M\theta_j}}{\sqrt{2\pi}(1+2\overline{\gamma}_j)^{3/2}}\times \exp\left(-0.5\left(\frac{\tau_j}{\sqrt{1+2\overline{\gamma}_j}}-\sqrt{0.5M\theta_j}\right)^2\right). \tag{43}$$

According to the inequality constraint of (39), the range of τ_j is obtained by

$$Q^{-1}(\alpha_j) \le \tau_j \le Q^{-1}(\beta_j)\sqrt{1+2\overline{\gamma}_j} + \sqrt{(0.5+\overline{\gamma}_j)M\theta_j}. \tag{44}$$

Since $\alpha_j < 0.5$, we get $\tau_j > 0$ and $\partial^2 Q_f^{(j)}/\partial^2\tau_j > 0$. According to (42-43), while $\beta_j > 0.5$, we can have that $\tau_j < \sqrt{(0.5+\overline{\gamma}_j)M\theta_j}$ and $\partial^2 s_j(Q_f^{(j)})/\partial^2\tau_j > 0$. Finally we can obtain

$$\frac{\partial^2 s_j(Q_f^{(j)})}{\partial^2 Q_f^{(j)}} = \frac{\partial^2 s_j(Q_f^{(j)})}{\partial^2\tau_j}\bigg/\frac{\partial^2 Q_f^{(j)}}{\partial^2\tau_j} > 0, \tag{45}$$

which implies that $s_j(Q_f^{(j)})$ is convex in $Q_f^{(j)}$.

Lemma 2: The objective function $S(\boldsymbol{Q}_f)$ is also convex in $\boldsymbol{Q}_f$.

Proof: By supposing that both the two vectors $\boldsymbol{Q}_{fa} = [Q_{fa}^{(1)}, Q_{fa}^{(2)}, ..., Q_{fa}^{(L)}]$ and $\boldsymbol{Q}_{fb} = [Q_{fb}^{(1)}, Q_{fb}^{(2)}, ..., Q_{fb}^{(L)}]$ satisfy the linear constraints of (39), for any $\zeta \in [0, 1]$, we define that

$$\boldsymbol{Q}_{fc} = \zeta\boldsymbol{Q}_{fa} + (1-\zeta)\boldsymbol{Q}_{fb}, \tag{46}$$

where the vector $\boldsymbol{Q}_{fc} = [Q_{fc}^{(1)}, Q_{fc}^{(2)}, ..., Q_{fc}^{(L)}]$. It is easy to know that $\boldsymbol{Q}_{fc}$ also satisfies the constraints of (39). Since according to Lemma 1, $s_j(Q_f^{(j)})$ is convex in $Q_f^{(j)}$, it can be obtained that

$$s_j\left(Q_{fc}^{(j)}\right) = s_j\left(\zeta Q_{fa}^{(j)} + (1-\zeta)Q_{fb}^{(j)}\right) \ge \zeta s_j(Q_{fa}^{(j)}) + (1-\zeta)s_j(Q_{fb}^{(j)}) \tag{47}$$

By substituting (47) into (41), we have

$$S(\boldsymbol{Q}_{fc}) = \sum_{j=1}^{L} C_{1,j}s_j(Q_{fc}^{(j)}) \ge \zeta\sum_{j=1}^{L} C_{1,j}s_j(Q_{fa}^{(j)}) + (1-\zeta)\sum_{j=1}^{L} C_{1,j}s_j(Q_{fb}^{(j)}) = \zeta S(\boldsymbol{Q}_{fa}) + (1-\zeta)S(\boldsymbol{Q}_{fb}) \tag{48}$$

which means that function $S(\boldsymbol{Q}_f)$ is convex in $\boldsymbol{Q}_f$.

So the optimal problem (39) takes the form of minimizing a convex function subject to the linear constraints, and thus a local optimum is also the global optimum. Efficient numerical search algorithms such as the Graded Newton method can be used to find the optimal solution. In this subsection, the non-convex optimal problem with double parameters and nonlinear constraints is transformed into a convex optimal problem with single parameter and linear constraints, which can be solved easily.

B. Maximizing throughput

Alternatively, we can formulate the cooperative detection in multi-channel into another optimization problem that maximizes the throughput of CR subject to the constraint of the interference to PU. This optimal problem is defined as follows

$$\begin{aligned} &\max_{\lambda_g,\boldsymbol{\omega}^{(j)}} R_C \\ s.t.\quad & R_I \le \xi \\ & \boldsymbol{Q}_f(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)}) \le \boldsymbol{\alpha} \\ & \boldsymbol{Q}_d(\boldsymbol{\lambda}_g,\boldsymbol{\omega}^{(j)}) \ge \boldsymbol{\beta} \end{aligned} \quad . \tag{49}$$

For getting the sub-problem of (49), the weighed factors obtained by (33) are adopted, and R_I can be denoted by $\boldsymbol{Q}_d$ according to (34). By transforming the objective function into the minimal problem, similar with (39), the optimal problem of (49) can be modified as

$$\begin{aligned} &\min_{\boldsymbol{Q}_d} \sum_{j=1}^{L} C_{0,j} Q\left(Q^{-1}(Q_d^{(j)})\sqrt{1+2\overline{\gamma}_j} + \sqrt{\frac{M\varphi_j}{2}} \right) \\ s.t.\quad & \sum_{j=1}^{L} C_{1,j} Q_d^{(j)} = \sum_{j=1}^{L} C_{1,j} - \xi' / P_{H_1} \quad , \\ & \beta_j \le Q_d^{(j)} \le Q\left(\frac{Q^{-1}(\alpha_j) - \sqrt{0.5M\varphi_j}}{\sqrt{1+2\overline{\gamma}_j}} \right) \end{aligned} \tag{50}$$

where the upper band of the interference capacity $\xi' = \min\left(P_{H_1}\sum_{j=1}^{L} C_{1,j}(1-\beta_j), \xi\right)$ which denotes that if $\xi \le P_{H_1}\sum_{j=1}^{L} C_{1,j}(1-\beta_j)$, $\xi' = \xi$ and otherwise $\xi' = P_{H_1}\sum_{j=1}^{L} C_{1,j}(1-\beta_j)$. The substituted variable $\varphi_j = \sum_{i=1}^{N} \gamma_{ij}^2$.

The optimal problem of (50) is also a convex optimal problem with single parameter and linear constraints, which can be proved to have solution similar with Lemma 1 and 2. The global detection threshold $\boldsymbol{\lambda}_g$ can be obtained by $\boldsymbol{Q}_d$ through (14).

V. SIMULATION AND ANALYSIS

A. Simulation of detection in single channel

In this subsection, we numerically evaluate the proposed weighed cooperative detection based on data fusion. Consider the single channel used by the PU, and the achievable rates $C_0 = 10$kbps and $C_1 = 5$kbps in the primary channel. There are N=5 CRs in the network, and their SNRs are $\gamma = [-15, -10, -8, -5, -3]$ dB. The number of the sampling nodes M=100, and the hypothesis probabilities satisfy $P_{H_0} = P_{H_1} = 0.5$. The sensing channel and reporting channel obey Rayleigh distribution.

Figures 5 and 6, respectively, illustrate the interference capacity and communication throughput of the three cooperative detection algorithms: the proposed weighed algorithm based on minimizing interference or maximizing throughput, the algorithm without weighing and the weighed algorithm based SNR. From Fig. 5, we can see that the proposed weighed algorithm based on minimizing interference can achieve lower interference than the other two subject to the constraint on the communication throughput. While communication throughput R_C improves, the interference capacity R_I also increases, that is because the probability Q_d can decrease with the decreasing of Q_f .

Figure 6 shows that the proposed weighed algorithm based on maximizing throughput also achieves higher communication throughput than the other two subject to the constraint on the interference capacity. While the interference capacity increases, the communication throughput also improves, and therefore there is a conflict between improving throughput and decreasing interference. So the limit probabilities of false alarm and detection should be chosen appropriately according to the requirement of CR.

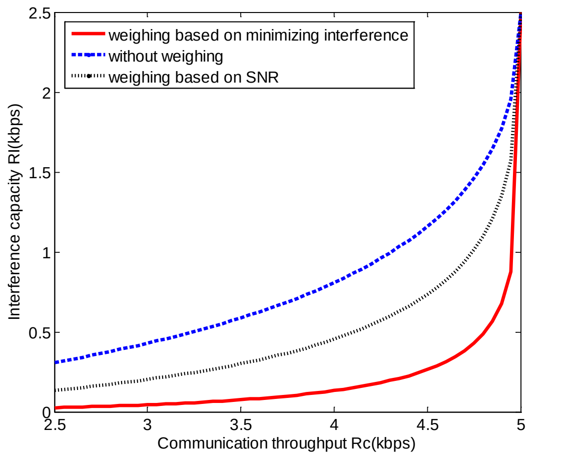

Fig. 5. Interference capacity R_I versus communication throughput R_C.

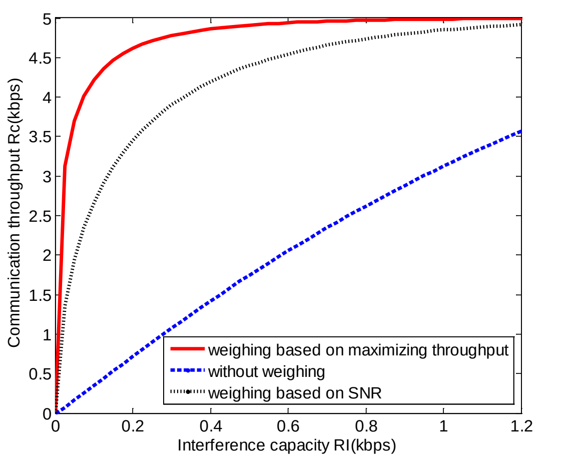

Fig. 6. Communication throughput R_C versus interference capacity R_I.

Figures 7 and 8, respectively, reflect the interference capacity and communication throughput of the three algorithms versus the average channel gain between CRs and the fusion center. Here, the channel gains obey random Rayleigh distribution, and the average channel gain which is given by $g=\sum_{i=1}^{N} g_i \big/ N$ increases from 0dB to 10dB. The proposed algorithm cannot be affected by the channel gain, while the other two have the obvious fluctuation with the changing of the channel gain. In addition, compared to the other algorithms, the proposed weighed algorithm based on minimizing interference always keeps the lower interference capacity, while the proposed weighed algorithm based on maximizing throughput always keeps higher communication throughput. That is because, according to (26) and (33), the weighed factors obtained by the proposed algorithm satisfy $\omega_i \sim 1/g_i$ for i=1, 2,…, N, and the larger factor can be allocated to the CR with lower channel gain in order to compensate the sensing loss brought by the channel fading.

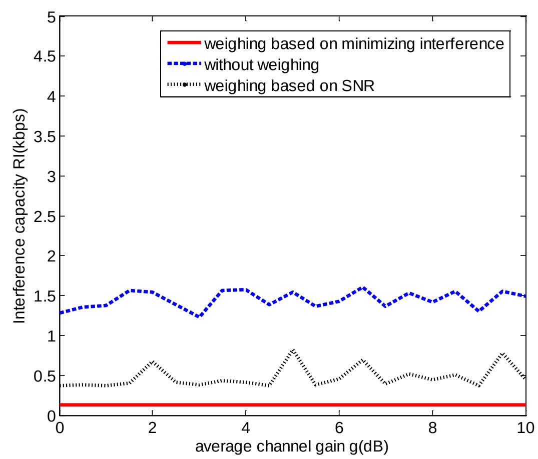

Fig. 7. Interference capacity R_I versus the average channel gain g from CRs to fusion center.

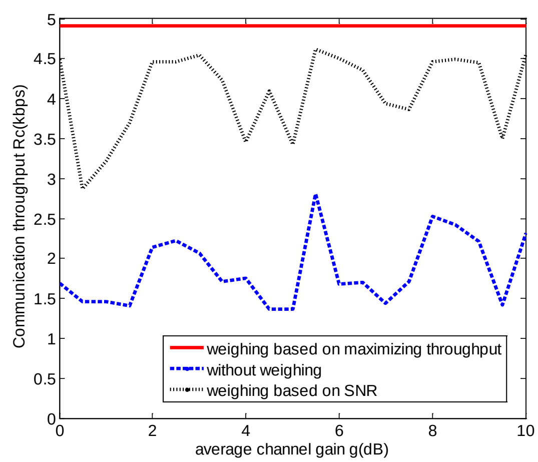

Fig. 8. Communication throughput R_C versus the average channel gain g from CRs to fusion center.

B. Simulation of detection in multi-channel

In this section, the performance of the proposed cooperative detection in multi-channel is analyzed. We assume that there is L=5 sub-channels, and the average SNRs of these channels are $\bar{\gamma}$ =[-15,-13,-12,-10,-8] dB. The CR rates in L sub-channels are $\boldsymbol{C}_0$ =[12, 10, 8, 6, 4] and $\boldsymbol{C}_1$ = [6, 4, 3, 2, 1], and the upper band of probability of false alarm and the lower band of probability of detection are $\alpha = 0.4$ and $\beta = 0.6$ respectively.

Figure 9 illustrates the comparative interference capacity R_I of the proposed multi-channel cooperative detection based on (39), the weighed algorithm with the uniform threshold and the weighed factors obtained by (26), and the algorithm with uniform threshold but without weighing versus the communication throughput R_C. Differing from the uniform threshold adopted by the other two algorithms, the optimal thresholds shown in Fig. 10 which are different and adaptive to the status change of the sub-channels (channel with higher SNR has larger threshold), are adopted by the proposed algorithm, and therefore the proposed algorithm which can produce lower interference to the PU, can make better use of the wide frequency band by balancing the conflict between improving spectral utilization and decreasing interference.

Figures 11 and 12, respectively, show the probabilities of false alarm and detection of each sub-channel in the proposed algorithm and the weighed algorithm with uniform threshold when $R_C = 13.2\text{kbps}$. Obviously, the proposed algorithm can keep the sensing probabilities within the limits, and the probabilities of false alarm are all below 0.4 while the probabilities of detection are all above 0.6. However in the weighed algorithm with uniform threshold, the probabilities of false alarm are higher in some channels, while the probabilities of detection are lower in the other channels, and only the sensing probabilities of channel 3 satisfy the limits.

Figure 13 illustrates the comparative communication throughput R_C of the proposed multi-channel cooperative detection based on (50), the weighed algorithm with the uniform threshold and the weighed factors obtained by (33), and the algorithm with uniform threshold but without weighing versus the interference capacity R_I. From this figure we can see that the proposed algorithm can achieve higher throughput than the other two.

From Figs. 14 and 15, we can see that similar with the optimal problem of (39), the optimal sub-channel probabilities of false alarm and detection obtained by (50) can respectively keep below 0.4 and above 0.6, when $R_I = 2.4\text{kbps}$. Compared to the probabilities in Figs. 11 and 12, in order to improve the throughput, the probabilities of false alarm are decreased, however, the probabilities of detection are synchronously decreased and therefore, the interference to PU is increased. That is, the conflict between improving throughput and decreasing interference is ineluctable.

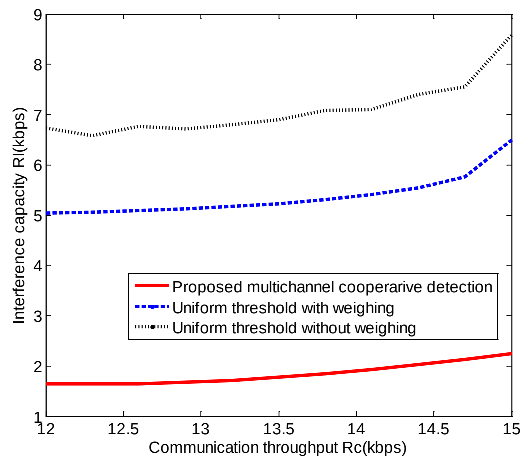

Fig. 9. Interference capacity R_I versus communication throughput R_C.

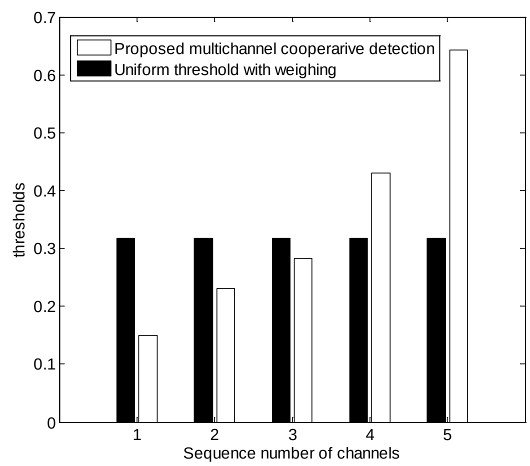

Fig. 10. Threshold of each sub-channel.

We illustrate the computational complexity of the proposed multi-channel cooperative detection. The number of iterations to reach the optimal solution is taken as the measure of complexity. Figure 16 shows the computational complexity versus the number of CRs N when the number of channels L=10, while Fig. 17 shows the computational complexity versus different L when N=10. We can see that compared to the conventional non-convex optimization scheme with double parameters, the computational complexity of the proposed scheme is much lower.

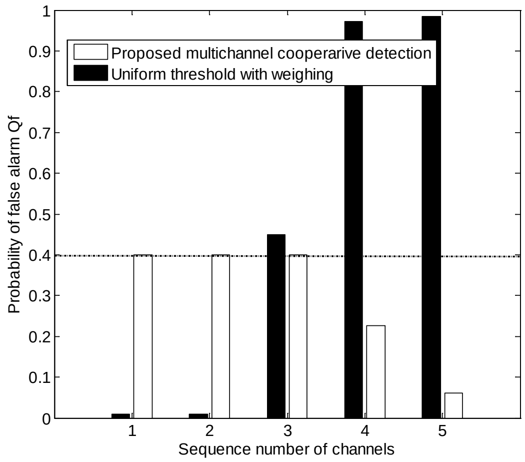

Fig. 11. Probability of false alarm in each sub-channel.

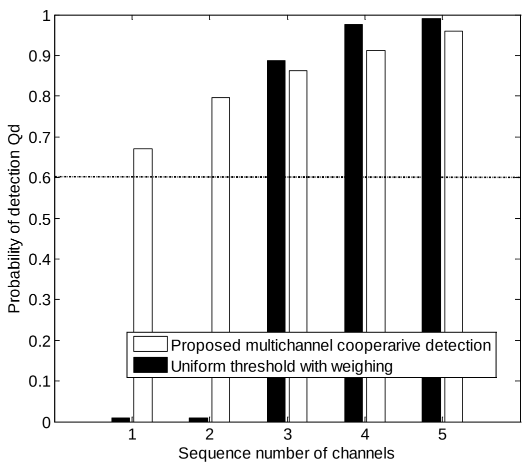

Fig. 12. Probability of detection in each sub-channel.

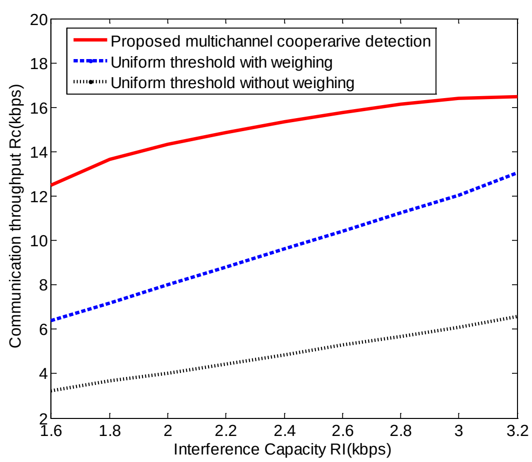

Fig. 13. Communication throughput R_C versus interference capacity R_I.

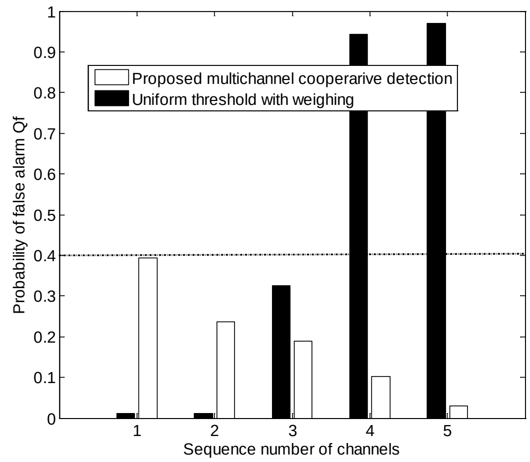

Fig. 14. Probability of false alarm in each sub-channel.

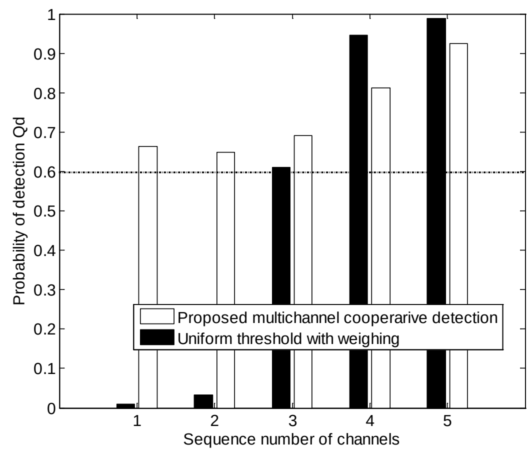

Fig. 15. Probability of detection in each sub-channel.

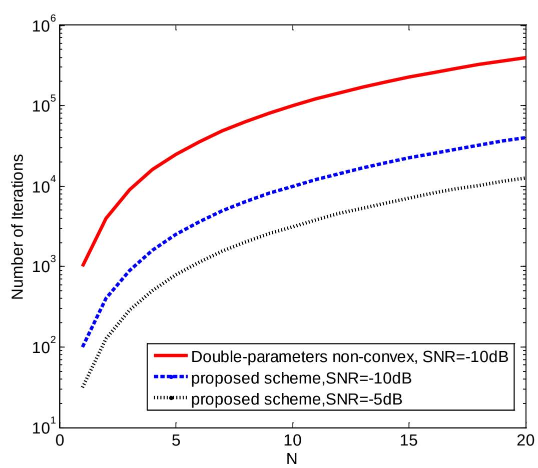

Fig. 16. Number of iterations versus the number of CRs N.

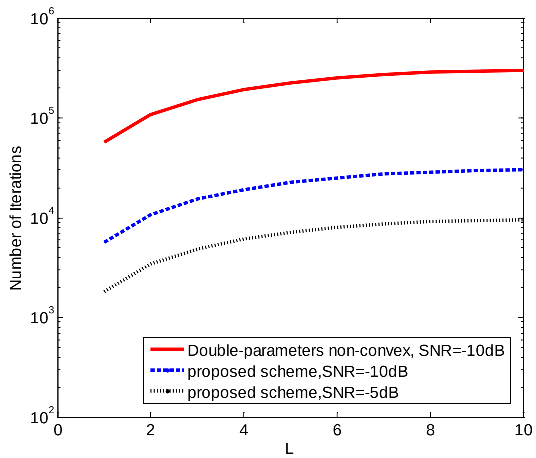

Fig. 17. Number of iterations versus the number of the sub-channels *L*.

VI. CONCLUSION

In this paper, we have explored both the optimal cooperative spectrum sensing strategies for cognitive radio networks in single channel and multi-channel. We have studied the problem how to choose the optimal weighed factors to minimize interference and maximize throughput in the weighed cooperative detection model based on data fusion. We obtain the optimal weighed factors of the single-channel cooperative detection by the Cauchy-inequality, and by the research results of the single-channel cooperative detection, we have transformed the non-convex optimal problem of multi-channel cooperative detection with double parameters and nonlinear constraints into the convex optimal problem with single parameter and linear constraints, which can be solved easily.

In our algorithm, the weighed factors are proportional to the received SNRs by CRs and inversely proportional to the channel gains between CRs and the fusion center. Therefore compared to the conventional weighed algorithm, the proposed algorithm can allocate a larger weighed factor to the CR with higher SNR and lower gain in order to increase its decision strength in the cooperative detection and compensate the lost information brought by the channel fading. By the obtained weighing, the sensing performance of the cooperative detection can be improved greatly.

The simulation shows that there is a conflict between improving throughput and decreasing interference, however, the proposed algorithm can make better use of spectrum by balancing the conflict. The proposed algorithm can also keep the probabilities of false alarm and detection within the limits in order to guarantee the effective utilization of each sub-channel. In this paper, from the two aspects: minimizing interference and maximizing throughput, we develop our problems, however, these two aspects are conflictive and contrary, so how to find the uniform weighing to obtain a better tradeoff between the two aspects is an interesting research topic for further investigation.

ACKNOWLEDGMENT

This paper is supported by National Natural Science Foundation of China (61071104). It also gets the supports of Communication Research Center of Harbin Institute of Technology.

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