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Cooperative spectrum sensing with imperfect feedback channel in the cognitive radio systems

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SUMMARY

The primary object of cognitive radio is to increase spectral efficiency, while causing limited interference to primary users who are using the spectrum. Hence, an essential part of cognitive radio is a spectrum sensing that determines whether a particular spectrum is occupied or not by a primary user. However, the sensing decision of a local secondary user alone may not be reliable enough due to shadowing and multipath fading of wireless channels. Recently, cooperative spectrum sensing has emerged as a remedy to the problems of local sensing. To sense the spectrum in a cooperative manner, secondary users report their local decisions to a cognitive base station through a feedback channel that is subject to fading and shadowing. Therefore, though the local sensing result is obtained accurately, it might not be suitable for making a cooperative decision due to feedback error. To alleviate this problem, we propose a hard decision combining-based cooperative spectrum sensing scheme in the presence of a feedback error caused by imperfect channel condition. In the proposed scheme, only the most favorable secondary users, those whose reporting channel conditions are peak, are allowed for cooperation. Through the proposed scheme, we can maximize the detection probability while guaranteeing that the desired false alarm probability is maintained. The simulation results show that the proposed scheme provides better spectrum sensing performance than the conventional scheme. Copyright © 2010 John Wiley & Sons, Ltd.

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KEY WORDS: cognitive radio; cooperative spectrum sensing; imperfect feedback channel; reporting error; user scheduling

1. INTRODUCTION

As the demand for ubiquitous wireless services has increased during the last decade, broader spectrum resources are needed. However, spectrum resources are limited and are allocated according to a fixed spectrum assignment policy. As a result, spectrum resources for future wireless networks are extremely limited [1, 2]. To alleviate this problem, the Federal Communications Commission

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has proposed a policy of frequency allocation that allows an unlicensed system, called a secondary user, to operate opportunistically in the frequency band allocated to a licensed system, or the primary user [3]. However, operating opportunistically in licensed band is risky since interference among the users degrades system performance. Cognitive radio has been suggested as a way to alleviate this problem due to its ability to rapidly and autonomously adapt its operating parameters to changing environments [2–5]. One of the important tasks for realizing cognitive radio is spectrum sensing since the secondary user needs to detect the primary user's signal prior to the use of the frequency [2].

Spectrum sensing requires the detection of possibly weak signals of unknown types with high reliability [6]. However, the sensing decision of the local secondary user alone may not be reliable enough due to the shadowing, multipath fading, and time-varying nature of wireless channels between secondary and primary users. Recently, cooperative spectrum sensing has been investigated to improve the spectrum sensing performance, and is performed in two successive stages sensing and fusion [7–13]. In the sensing stage, each secondary user performs local spectrum sensing and then reports the results to a cognitive base station (BS). In the fusion stage, the cognitive BS makes a spectrum allocation decision by fusing the local sensing results from all of the secondary users. Therefore, a practical feedback channel is needed in order to sense the spectrum cooperatively. Infinite bits are required if all the secondary users report the real value of their sensing observations. To minimize the feedback overhead, secondary users should each make their own sensing decisions and report their one-bit decisions (i.e. busy or idle) to the cognitive BS for fusion [10–13].

Most previous cooperative spectrum sensing schemes rely upon a perfect feedback channel between the cognitive BS and the secondary users. As the number of cooperative users increases in a perfect feedback channel environment, the detection probability asymptotically approaches a value of one while maintaining the false alarm probability at a desired level [11]. However, since the feedback channel is in reality imperfect, it is difficult to achieve the desired sensing performance although many secondary users are involved in the cooperative spectrum sensing. To cope with an imperfect feedback channel, the use of a maximum a posteriori (MAP) detector in the cognitive BS has been considered [12]. When the feedback channel is deeply faded, however, the use of a MAP detector cannot guarantee the reliability of the reported local decision value, resulting in degradation of the sensing performance. A cluster-based cooperative spectrum sensing scheme can alleviate this problem, but it requires direct communication among the secondary users, which is impractical [13].

To alleviate the problems of previous schemes, we investigate a new cooperative spectrum sensing scheme. In the proposed scheme, the cognitive BS first estimates the feedback channel conditions between the cognitive BS and the secondary users by means of uplink sounding (or probing) signals. Based on the condition of the feedback channel, the cognitive BS schedules secondary users with good feedback channel condition to satisfy the desired spectrum sensing requirement and then broadcasts the scheduling results to the secondary users. After receiving the scheduling results, only the scheduled secondary users perform local spectrum sensing and report their local binary decisions (i.e. busy or idle) to the cognitive BS. By using the local spectrum sensing results of only the scheduled users, the cognitive BS makes a final decision by means of a decision fusion rule. Under the proposed scheme, the detection probability can be maximized while guaranteeing that the false alarm probability remains at a desired level, even when the channel between the cognitive BS and the secondary user is imperfect. In addition, the proposed scheme can reduce the amount of the feedback signaling burden since only the scheduled users are allowed to report their local sensing results.

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The remainder of this paper is organized as follows. Section 2 describes the system model and Section 3 describes the proposed spectrum sensing scheme. Section 4 verifies the performance of the proposed scheme by computer simulation. Finally, conclusions are given in Section 5.

2. SYSTEM MODEL

The cognitive radio-based IEEE 802.16m WiMAX network is examined, where the macro-cell and the femto-cell operate as the primary and the secondary systems, respectively. We assume that the femto-cell system is composed of one cognitive BS and M secondary users. In the cognitive femto-cell system, each frame is divided into two parts sensing and data transmission, as shown in Figure 1. Secondary users perform local spectrum sensing for downlink (DL) and uplink (UL) channels during the DL and UL sensing duration, respectively, and report the results to the cognitive BS. As spectrum sensing for the DL and UL channels is performed in a similar manner, we only consider the DL spectrum sensing environment for simplicity.

In cooperative spectrum sensing, the received signal sample of the secondary user k at each hypothesis $\mathcal{H}_0$ (idle state) and $\mathcal{H}_1$ (busy state) can be represented as

$$y_k(n)=\begin{cases} w(n), & \mathcal{H}_0,\\ h_k(n)s(n)+w(n), & \mathcal{H}_1, \end{cases} \tag{1}$$

where n is sample index, $h_k(n)$ is impulse response of the channel between secondary user k and primary user (i.e. macro BS), $s(n)$ is a signal of primary user, and $w(n)$ is zero-mean circular-symmetric complex Gaussian noise with unit variance (i.e. $w(n)\sim\mathcal{CN}(0,1)$). For ease of analysis, we assume that the channel $h_k(n)$ is unchanged during the sensing process, say $h_k(n)=h_k$.

For the spectrum band of interest, the test statistic of the energy detection can be represented as

$$R_k(N_s)=\frac{1}{N_s}\sum_{n=1}^{N_s}|y_k(n)|^2, \tag{2}$$

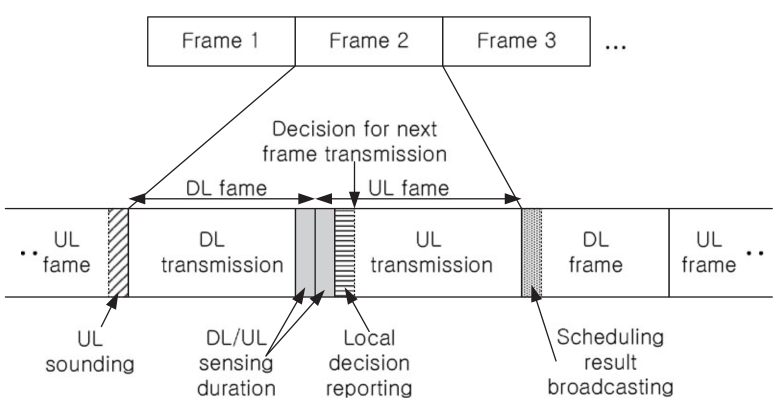

Figure 1. Cooperative spectrum sensing procedure.

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where N_s is the number of samples, which is the same as two times the time-bandwidth product (i.e. $N_s \triangleq 2TW$) [14, 15].

Based on the test statistic, the secondary user k makes a local decision on the existence of the primary user as

$$u_k = \begin{cases} 1, & R_k(N) > \lambda, \\ 0, & R_k(N) < \lambda, \end{cases} \tag{3}$$

where λ is the threshold level to be determined.

For the cooperation, each secondary users report their binary decision result u_k to the cognitive BS through the feedback channel with instantaneous channel signal-to-noise power ratio (SNR) η_k. The cognitive BS combines the local decisions with weight $w_k \in \{0, 1\}$ based on the feedback channel condition, and makes a final decision as [13]

$$D = \begin{cases} \mathscr{H}_1, & \sum_{k=1}^{M} w_k u_k \geqslant 1, \\ \mathscr{H}_0, & \text{otherwise.} \end{cases} \tag{4}$$

It can be shown that the use of binary weight $w_k \in \{0, 1\}$ implies that the cognitive BS schedules the secondary user whose weight is one based on the feedback channel condition which is measured by means of the uplink sounding (or probing) signal.

The considered cooperative spectrum sensing scheme requires an additional UL sounding phase and it, therefore, takes a longer time than the conventional cooperative spectrum sensing scheme. However, since the UL sounding signal is transmitted at the final three OFDM symbols of the UL frame, the additional latency is no longer than approximately 300 µs [16]. In addition, since the sounding and cooperative user-scheduling information is transmitted through the legacy WiMAX control signal, there is no need to change the legacy WiMAX frame structure other than the insertion of the sensing duration.

Assuming that the cognitive BS assigns the spectrum resource to the user having the highest channel SNR for data transmission in order to exploit the multi-user diversity gain, the upper bound of the average spectral efficiency of the secondary network at each hypothesis can be represented as [17]

$$\begin{aligned} \bar{C}_0 &= \log_2\left(1+\eta_0\left(1+\sum_{i=2}^{K}\frac{1}{i}\right)\right), \quad \mathscr{H}_0, \\ \bar{C}_1 &= \log_2\left(1+\frac{\eta_0}{\gamma_0+1}\left(1+\sum_{i=2}^{K}\frac{1}{i}\right)\right), \quad \mathscr{H}_1, \end{aligned} \tag{5}$$

where η_0 and γ_0 are the average SNR and interference-to-noise power ratio (INR), respectively, K is the number of scheduled secondary users, and $\sum_{i=2}^{K}\frac{1}{i}$ is an additional gain due to multi-user diversity [18].

The upper bound of the normalized achievable network throughput can be represented as [7]

$$\bar{R} = (1-p(\mathscr{H}_1))\left(\frac{T_{\mathrm{DL}}-\tau}{T_{\mathrm{DL}}}\right)(1-Q_{\mathrm{F}})\bar{C}_0 + p(\mathscr{H}_1)\left(\frac{T_{\mathrm{DL}}-\tau}{T_{\mathrm{DL}}}\right)(1-Q_{\mathrm{D}})\bar{C}_1, \tag{6}$$

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where $p(\mathscr{H}_1)$ is the probability that the primary user is active in the spectrum band, T_{DL} and τ are the DL transmission and sensing duration, respectively, and Q_{F} and Q_{D} are final false alarm and detection probabilities of fusing the local sensing results at the cognitive BS, which will be discussed in more detail below.

3. PROPOSED COOPERATIVE SPECTRUM SENSING SCHEME

In this section, we consider the user scheduling of the cooperative spectrum sensing scheme in the presence of a feedback error in order to maximize detection probability while guaranteeing that the false alarm probability is at a desired level.

3.1. Local spectrum sensing

When the primary user's signal is absent (i.e. hypothesis $\mathscr{H}_0$), the test statistic can be modeled as a central Chi-square distributed random variable divided by constant N_{s} with $2N_{\mathrm{s}}$ degree of freedom [19]. On the other hand, when the signal of primary user is present (i.e. hypothesis $\mathscr{H}_1$), the test statistic can be modeled as a non-central Chi-square distributed random variable divided by a constant N_{s} with $2N_{\mathrm{s}}$ degree of freedom and a non-centrality parameter γ_k, which is defined as the instantaneous INR of secondary user k [19].

Therefore, the probability density function (pdf) for each hypothesis can be represented as

$$\begin{aligned} f_{R_k}(r_k|\mathscr{H}_0) &= \frac{N_{\mathrm{s}}}{\Gamma(N_{\mathrm{s}})}(N_{\mathrm{s}}r_k)^{N_{\mathrm{s}}-1}\exp(-N_{\mathrm{s}}r_k),\\ f_{R_k}(r_k|\mathscr{H}_1) &= N_{\mathrm{s}}\left(\frac{r_k}{\gamma_k}\right)^{\frac{N_{\mathrm{s}}-1}{2}}\exp(-N(\gamma_k+r_k))I_{N_{\mathrm{s}}-1}(2N_{\mathrm{s}}\sqrt{\gamma_k r_k}), \end{aligned} \tag{7}$$

where $\Gamma(\cdot)$ and $I_v(\cdot)$ are a gamma function and the vth order modified Bessel function of the first kind, respectively [20].

According to energy detection theory [14], the false alarm, detection, and miss probability of secondary user k can be represented as [21]

$$\begin{aligned} P_{f,k}(\lambda) &= \Pr(u_k=1|\mathscr{H}_0)\\ &= \int_{\lambda}^{\infty}\frac{N_{\mathrm{s}}}{\Gamma(N_{\mathrm{s}})}(N_{\mathrm{s}}r_k)^{N_{\mathrm{s}}-1}\exp(-N_{\mathrm{s}}r_k)dr_k\\ &= \frac{\Gamma(N_{\mathrm{s}},N_{\mathrm{s}}\lambda)}{\Gamma(N_{\mathrm{s}})}\\ &\simeq Q((\lambda-1)\sqrt{N_{\mathrm{s}}}), \qquad (8)\\ P_{d,k}(\lambda,\gamma_k) &= \Pr(u_k=1|\mathscr{H}_1)\\ &= \int_{\lambda}^{\infty}N_{\mathrm{s}}\left(\frac{r_k}{\gamma_k}\right)^{\frac{N_{\mathrm{s}}-1}{2}}\exp(-N(\gamma_k+r_k))I_{N_{\mathrm{s}}-1}(2N_{\mathrm{s}}\sqrt{\gamma_k r_k})\,\mathrm{d}r_k\\ &= Q_{N_{\mathrm{s}}}(\sqrt{2N_{\mathrm{s}}\gamma_k},\sqrt{2N_{\mathrm{s}}\lambda}) \end{aligned}$$

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$$= Q\left((\lambda-\gamma_k-1)\sqrt{\frac{N_s}{2\gamma_k+1}}\right), \tag{9}$$

$$P_{m,k}(\lambda,\gamma_k)=1-P_{d,k}(\lambda,\gamma_k), \tag{10}$$

where $\Gamma(\cdot,\cdot)$ is incomplete gamma function, and $Q(\cdot)$ and $Q_u(\cdot,\cdot)$ are the Q-function and generalized Marcum Q-function, respectively [22].

3.2. Cooperative spectrum sensing

Cooperative spectrum sensing is coordinated by the cognitive BS. After receiving authorization from the cognitive BS, all secondary users independently initiate spectrum sensing and then report their observations to the cognitive BS. If the feedback channels between the secondary users and the cognitive BS are perfect and decision fusion is employed at the cognitive BS, the false alarm, detection, and missing probabilities can be represented as [7]

$$Q_F = 1-\prod_{k=0}^{M}(1-P_{f,k}(\lambda)), \tag{11}$$

$$Q_D = 1-\prod_{k=0}^{M}(1-P_{d,k}(\lambda,\gamma_k)), \tag{12}$$

and

$$Q_M = \prod_{k=0}^{M} P_{m,k}(\lambda,\gamma_k), \tag{13}$$

where M is the number of secondary users and $P_{f,k}(\lambda)$, $P_{d,k}(\lambda,\gamma_k)$, and $P_{m,k}(\lambda,\gamma_k)$ are the false alarm, detection, and missing probabilities, respectively, for local spectrum sensing of the secondary user k.

It is desirable to make the detection probability higher than or equal to the desired detection probability (i.e. $Q_d \geqslant \bar{Q}_d$) and to make the false alarm probability lower than or equal to the desired false alarm probability (i.e. $Q_f \leqslant \bar{Q}_f$). In order to achieve the desired sensing performance, two approaches, the constant detection rate (CDR) and the constant false-alarm rate (CFAR), have been considered [7, 11]. The use of a CDR detector minimizes the false alarm probability when the detection probability is fixed at a desired level. On the other hand, the use of a CFAR detector maximizes the detection probability while guaranteeing that the false alarm probability remains at a desired level. As there is no information about the primary user's signal (actually, we even do not know whether the signal of primary user exists), the use of a CFAR detector is usually considered [7, 23].

To achieve the desired false alarm probability $\bar{Q}_f$ in a perfect feedback channel environment, the secondary user's local target false alarm probability $\bar{P}_{f,k}$ can be represented as

$$\bar{P}_{f,k} = 1-\sqrt[M]{1-\bar{Q}_F}, \tag{14}$$

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and with the $\bar{P}_{f,k}$, the detection probability of the secondary user k can be represented as [7]

$$P_{d,k} \simeq Q\left\{\frac{1}{\sqrt{2\gamma_k+1}}\left(Q^{-1}\left(1-\sqrt[M]{1-\bar{Q}_{\mathrm{F}}}\right)-\gamma_k\sqrt{N_{\mathrm{s}}}\right)\right\}. \tag{15}$$

As the detection probability is less than or equal to one (i.e. $p_{d,k} \leqslant 1$), it can be shown from (12) that as the number of cooperative users increases and the threshold level is set to satisfy the local target false alarm probability in (14), the detection probability increases. Therefore, in a perfect feedback channel environment as the number of cooperative users increases the detection probability asymptotically approaches one while maintaining the false alarm probability at the desired level [11].

Owing to imperfect feedback channel conditions in practice, although the local sensing result is accurately obtained it might not be suitable for making a cooperative decision. By letting η_k be the instantaneous channel SNR of the secondary user k the reporting bit-error probability (BER) can be represented as [24]

$$p_{e,k}(\eta_k) = Q(\sqrt{2\eta_k}). \tag{16}$$

Assuming that all the secondary users are involved in the cooperation and that the decision of secondary user k is transmitted to the cognitive BS at a BER of $p_{e,k}(\eta_k)$, the false alarm and detection probabilities can be, respectively, represented as

$$Q_{\mathrm{F}} = 1-\prod_{k=1}^{M}[\{1-P_{f,k}(\lambda)\}\{1-p_{e,k}(\eta_k)\}+P_{f,k}(\lambda)p_{e,k}(\eta_k)], \tag{17}$$

$$Q_{\mathrm{D}} = \prod_{k=1}^{M}[P_{d,k}(\lambda,\gamma_k)\{1-p_{e,k}(\eta_k)\}+\{1-P_{d,k}(\lambda,\gamma_k)\}p_{e,k}(\eta_k)]. \tag{18}$$

Owing to the feedback error, the false alarm probability is bounded in the presence of the feedback error as

$$\begin{aligned}\hat{Q}_{\mathrm{F}} &= \lim_{\lambda\to\infty} Q_{\mathrm{F}} \\ &= 1-\prod_{k=1}^{M}\{1-p_{e,k}(\eta_k)\}.\end{aligned} \tag{19}$$

This means that the detector cannot work properly when the desired false alarm probability $\bar{Q}_{\mathrm{F}}$ is lower than the bound $\hat{Q}_{\mathrm{F}}$. Therefore, to maximize the detection probability while guaranteeing the desired false alarm probability (i.e. optimize CFAR performance), the cognitive BS schedules secondary users whose feedback channel is good enough to satisfy the target CFAR requirements.

Let K be the number of scheduled secondary users. To achieve the desired CFAR requirement (i.e. $Q_{\mathrm{F}} = \bar{Q}_{\mathrm{F}}$) in the presence of feedback error, the target local false alarm probability $\bar{P}_{f,k}$ of secondary user k should be given by

$$\bar{P}_{f,k} = \frac{1-\sqrt[K]{1-\bar{Q}_{\mathrm{F}}}-p_{e,k}(\eta_k)}{1-2p_{e,k}(\eta_k)}, \tag{20}$$

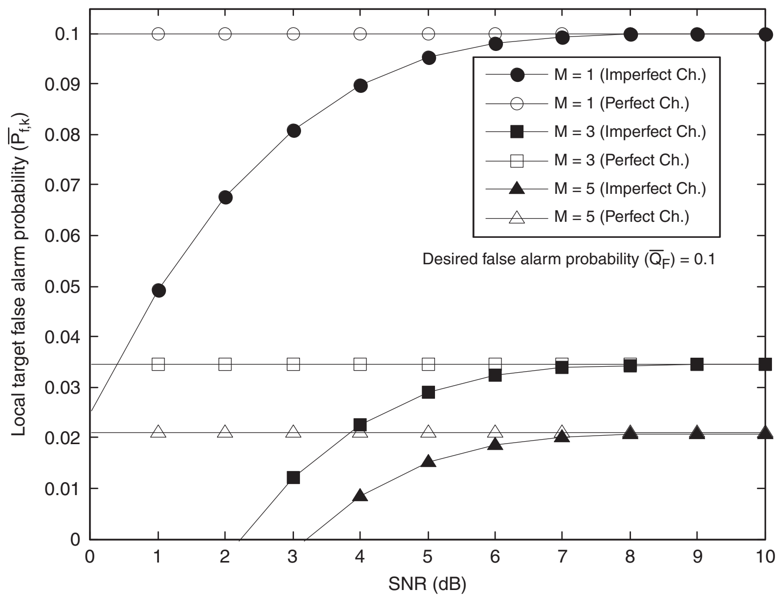

Figure 2. Local target false alarm probability according to channel SNR.

and the decision threshold level to achieve the target local false alarm probability $\bar{P}_{f,k}$ can be represented from (8) as

$$\lambda = \frac{Q^{-1}(\bar{P}_{f,k})}{\sqrt{N_s}} + 1. \tag{21}$$

By comparing (14) with (20), the target local false alarm probability is affected by the presence of feedback error. Figure 2 depicts the target local false alarm probability for secondary user according to channel SNR when $\bar{Q}_f = 0.1$ and the feedback channel is either perfect or imperfect. It can be seen that the target local false alarm probability in an imperfect feedback channel environment is smaller than it is in an error-free environment.

From (20), when $p_{e,k}(\eta_k) \geqslant 1 - \sqrt[K]{1 - \bar{Q}_F}$ the local sensing result should not be used in forming the cooperative decision and as the number of cooperative secondary users increases, the requirement for the target local false alarm probability $\bar{P}_{f,k}$ becomes strict (i.e. $\bar{P}_{f,k}$ decreases as the number of scheduled secondary users K increases). Therefore, it might be required to give priority to the secondary user with a lower reporting error probability (i.e. a higher channel SNR) while excluding the secondary user whose BER $p_{e,k}(\eta_k)$ is greater than or equal to $1 - \sqrt[K]{1 - \bar{Q}_F}$. The cooperative secondary users are scheduled as follows.

[A1] Initialize secondary user set Φ, scheduled secondary user set Ω, and the number of scheduled secondary users K as

$$\Phi = \{1, 2, \ldots, M\}, \quad \Omega = \{\cdot\}, \quad K = 0. \tag{22}$$

[A2] Schedule the secondary user with minimum BER value

$$\pi = \arg\min_{k \in \Phi} p_{e,k}(\eta_k). \tag{23}$$

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[A3] Check if the secondary user π satisfies the following condition

$$p_{e,\pi}(\eta_\pi) < 1 - \sqrt[K+1]{1-\bar{Q}_{\mathrm{f}}}. \tag{24}$$

[A4] If $p_{e,\pi}(\eta_\pi) < 1 - \sqrt[K+1]{1-\bar{Q}_{\mathrm{f}}}$, update the scheduled secondary user set as

$$\Phi \leftarrow \Phi - \{\pi\}, \quad \Omega \leftarrow \Omega \cup \{\pi\}, \quad K = K+1, \tag{25}$$

and go to [A2]. Else stop.

After scheduling the secondary users, the cognitive BS broadcasts only the number of scheduled secondary users K, and not the index of each scheduled secondary user. The secondary user k also estimates the BER $p_{e,k}(\eta_k)$ by means of a DL pilot signal [16]. Based on the estimated BER, the secondary user can detect whether it is scheduled for the cooperation simply by checking the scheduling condition $p_{e,k}(\eta_k) < 1 - \sqrt[K]{1-\bar{Q}_{\mathrm{F}}}$. After receiving the scheduling result, only the scheduled secondary users perform local spectrum sensing and report their local binary decisions (i.e. busy or idle) to the cognitive BS. The cognitive BS makes a final decision by fusing the local spectrum sensing results reported from only the scheduled users. The cognitive BS can, respectively, yield the false alarm and detection probability as

$$Q_{\mathrm{F,pro}} = 1 - \prod_{k=1}^{K} [\{1 - P_{f,\Omega(k)}(\lambda)\}\{1 - p_{e,\Omega(k)}(\eta_{\Omega(k)})\} + P_{f,\Omega(k)}(\lambda)\, p_{e,\Omega(k)}(\eta_{\Omega(k)})], \tag{26}$$

$$Q_{\mathrm{D,pro}} = \prod_{k=1}^{K} [P_{d,\Omega(k)}(\lambda, \gamma_{\Omega(k)})\{1 - p_{e,\Omega(k)}(\eta_{\Omega(k)})\} + \{1 - P_{d,\Omega(k)}(\lambda, \gamma_{\Omega(k)})\} p_{e,\Omega(k)}(\eta_{\Omega(k)})], \tag{27}$$

and the achievable network throughput can be represented as

$$R_{\mathrm{pro}} = (1 - p(\mathscr{H}_1)) \left(\frac{T_{\mathrm{DL}} - \tau}{T_{\mathrm{DL}}} \right) (1 - Q_{\mathrm{F,pro}}) \bar{C}_0 + p(\mathscr{H}_1) \left(\frac{T_{\mathrm{DL}} - \tau}{T_{\mathrm{DL}}} \right) (1 - Q_{\mathrm{D,pro}}) \bar{C}_1. \tag{28}$$

By using the proposed scheme, the detection probability can be maximized while guaranteeing that the false alarm probability remains at a desired level, even when the channel between the cognitive BS and the secondary user is imperfect. In addition, the proposed scheme can reduce the amount of feedback signaling burden since only the scheduled users are allowed to report their local sensing results to the cognitive BS.

Assuming that the channel between secondary user k and the primary user, as well as channel between secondary user k and the cognitive BS, have Rayleigh fading, the pdf of the channel SNR and INR of secondary user k can be, respectively, represented as [19]

$$f_{\gamma_k}(\gamma) = \frac{1}{\gamma_0} \exp\left(-\frac{\gamma}{\gamma_0} \right), \tag{29}$$

$$f_{\eta_k}(\eta) = \frac{1}{\eta_0} \exp\left(-\frac{\eta}{\eta_0} \right), \tag{30}$$

where η_0 and γ_0 are the average channel SNR and INR, respectively.

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Then, the average detection probability of the secondary user k can be represented as [21]

$$
\begin{aligned}
E\{P_{d,k}\} &= \int_0^\infty Q_{N_s}(\sqrt{2N_s\gamma_k}, \sqrt{2N_s\lambda_k})\frac{1}{\gamma_0}\exp\left(-\frac{\gamma_k}{\gamma_0}\right)\mathrm{d}\gamma_k \\
&= Q((\lambda-1)\sqrt{N_s}) + \exp\left(\frac{1}{2\lambda^2\gamma_0^2 N_s} - \frac{\lambda-1}{\lambda\gamma_0}\right) Q\left(\frac{1}{\lambda\gamma_0\sqrt{N_s}} - (\lambda-1)\sqrt{N_s}\right). \qquad (31)
\end{aligned}
$$

By letting $\eta_{\Omega(k)}$ be the channel SNR between the kth scheduled user and the cognitive BS, it can be modeled as the kth largest element of $\{\eta_1, \eta_2, \ldots, \eta_M\}$, represented as

$$\eta_{\Omega(k)} = OS_k^M\{\eta_1, \eta_2, \ldots, \eta_M\}, \qquad (32)$$

where $OS_k^M\{\cdot\}$ denotes the order statistic filtering with rank k. Assuming that all the secondary users have the same average SNR, the pdf of $\eta_{\Omega(k)}$ can be represented as [22]

$$f_{\eta_{\Omega(k)}}(\eta) = \frac{M-k+1}{\eta_0}\exp\left(-\frac{\eta}{\eta_0}\right)\left[1-\exp\left(-\frac{\eta}{\eta_0}\right)\right]^{M-k}. \qquad (33)$$

When the local sensing result is reported by means of the BPSK modulation, the average BER can be represented as

$$
\begin{aligned}
\bar{p}_{e,\Omega(k)} &= \int_0^\infty Qt(\sqrt{2\eta}) f_{\eta_{\Omega(k)}}(\eta)\mathrm{d}\eta \\
&= \sum_{m=1}^{M-k}\binom{M-k}{m}(-1)^{M-k-m}\frac{M-k-1}{2(M-k+1-m)}\left(1-\sqrt{\frac{\eta_0}{M-k+1-m+\eta_0}}\right). \qquad (34)
\end{aligned}
$$

Therefore, for a given number of scheduled user K, the expected spectrum sensing performance $E\{Q_{\mathrm{F,pro}}\}$ and $E\{Q_{\mathrm{D,pro}}\}$ of the proposed scheme can be analyzed by substituting (8), (31), and (34) into (26) and (27).

4. PERFORMANCE EVALUATION

The performance of the proposed scheme is verified by computer simulation. We assume that the feedback channel between cognitive BS and secondary user is Rayleigh faded and the common simulation parameters are summarized in Table I. We assume that when no secondary user satisfies the desired CFAR condition (i.e. $K=0$), the cognitive BS makes final decision based on its own local decision. To verify the validation of the proposed scheme, we compare the performance of the proposed scheme with the conventional cooperative spectrum sensing scheme (i.e. all of the secondary users are involved in cooperation).

Figure 3 depicts the difference between the desired and the actual false alarm probability (i.e. $|Q_{\mathrm{F}} - \bar{Q}_{\mathrm{F}}|$) of the proposed scheme according to the desired false alarm probability $\bar{Q}_{\mathrm{F}}$ when the average SNR is 5 dB. It can be seen that the false alarm difference of the conventional scheme is

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Table I. Common simulation parameters.

Parameters	Setting
Channel bandwidth (W)	262.5 kHz
Sampling frequency (f_S)	262.5 MHz
Frame duration (T_{DL})	5 ms
Sensing time (τ)	200 µs
Average SNR $(\bar{\eta})$	5, 10 dB
Average INR $(\bar{\gamma})$	−10, −5 dB
Number of secondary users (M)	5, 10, 100
Channel between secondary and primary users	Rayleigh faded

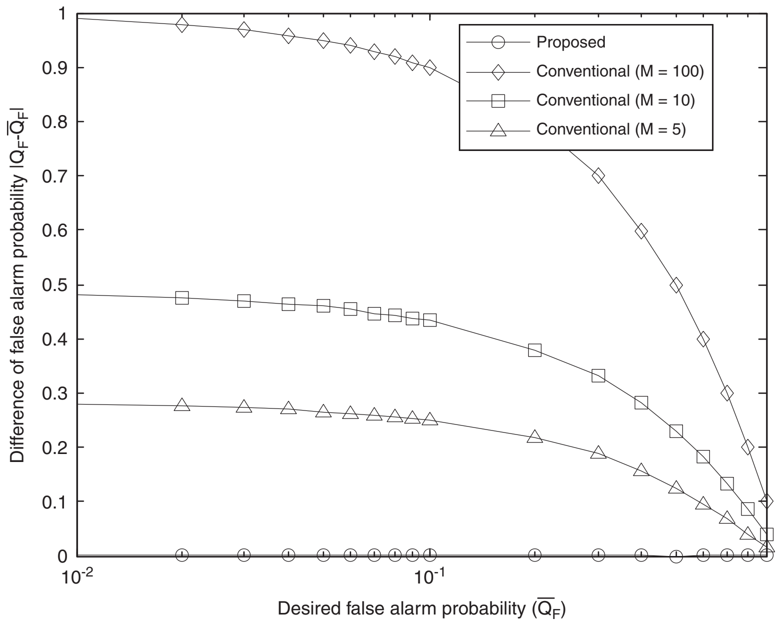

Figure 3. Difference of desired and actual false alarm probability.

considerably large especially when the number of secondary users is large and the desired false alarm probability is low. This is due to the fact that the false alarm probability of the conventional scheme is bounded due to the feedback error, and the bound value is increased, as the number of users increases as shown in (19). On the other hand, the false alarm difference does not occur in the proposed scheme for any desired false alarm probability. This is mainly because the proposed scheme schedules secondary users in such a way as to guarantee the desired false alarm probability.

Figure 4 depicts the complementary receiver operating characteristic (ROC) curve of the proposed scheme for different numbers of secondary users (i.e. $M=5$ and 10) when the average SNR and INR are 5 and -10 dB, respectively. It can be seen that for a certain low false alarm probability, miss detection probability $Q_M(\triangleq 1-Q_D)$ of the proposed scheme decreases compared

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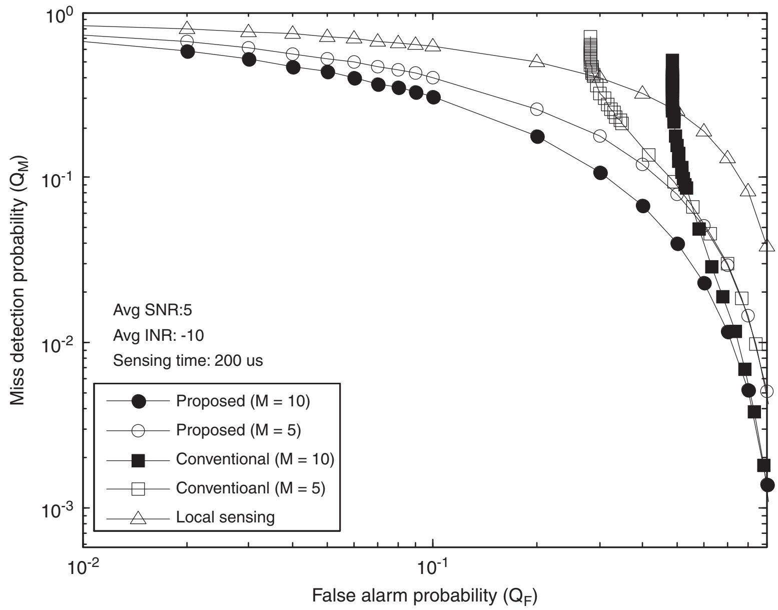

Figure 4. The complementary ROC curve of the proposed scheme when $M=5$ and 10.

with that of the conventional scheme. This is due to the fact that the proposed scheme schedules secondary users based on the condition of the feedback channel in order to maximize the detection probability while guaranteeing a desired false alarm probability. On the other hand, the conventional scheme is bounded at a certain false alarm probability due to the feedback error. It can also be seen that the sensing performance of the proposed scheme improves as the number of secondary users increases. This is mainly because as the number of secondary users increases, the number of scheduled $K\,(\leqslant M)$ secondary users whose feedback channel condition satisfies the CFAR requirement (i.e, $Q_{\mathrm{F}}=\bar{Q}_{\mathrm{F}}$) increases due to multi-user diversity [18]. On the other hand, as the number of secondary users increases, the bound of Q_{F} for the conventional scheme becomes larger.

Figure 5 depicts the complementary ROC curve of the proposed scheme for the different value of INR (i.e. $\gamma_0=-10$ and -5 dB) when the number of secondary users is 10 and the average SNR is 5 dB. It can be seen that when the average INR is high, all the spectrum sensing schemes provide better sensing performances. This is due to the fact that when the INR is high, the strength of the primary signal is stronger than the noise power, and it is therefore easy to discriminate between the primary signal and noise. It can also be seen that the bound of Q_{F} for the conventional scheme is the same regardless of INR. This is mainly because as seen in (19), the bound of Q_{F} is only related to the channel SNR. Therefore, although the local sensing result is accurately obtained, it might not be appropriate for making a cooperative decision due to the feedback error. On the other hand, by adjusting the number of scheduled secondary users, the proposed scheme maximizes the detection probability while guaranteeing the desired false alarm probability, regardless of the INR environment.

Figure 6 depicts the complementary ROC curve of the proposed scheme for the different value of SNR (i.e. η_0 = 5 and 10 dB) when the number of secondary users is 10 and the average INR

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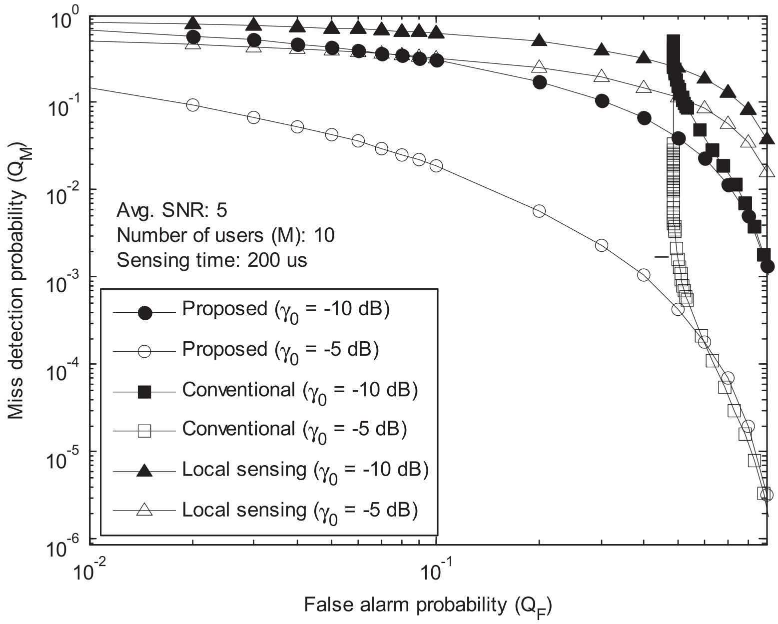

Figure 5. The complementary ROC curve of the proposed scheme when $\gamma_0 = -10$ and -5 dB.

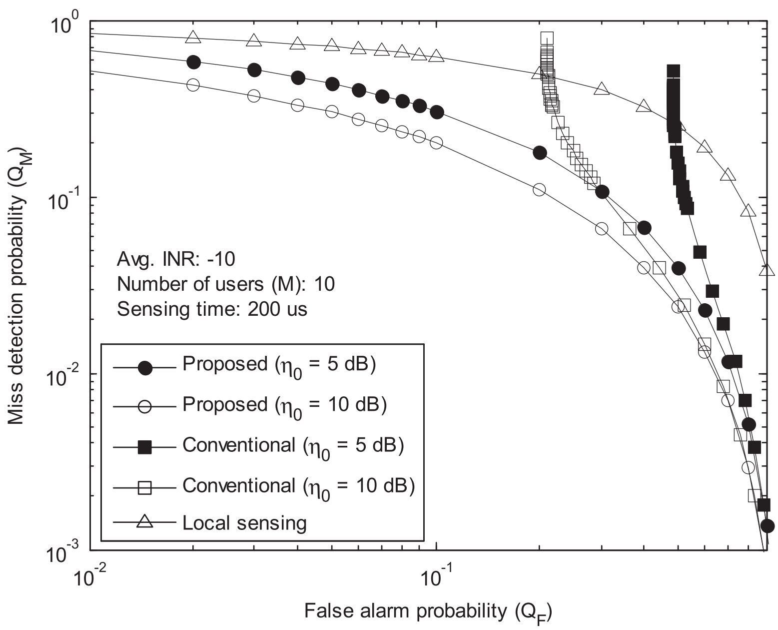

Figure 6. The complementary ROC performance of the proposed scheme when $\eta_0 = 5$ and 10 dB.

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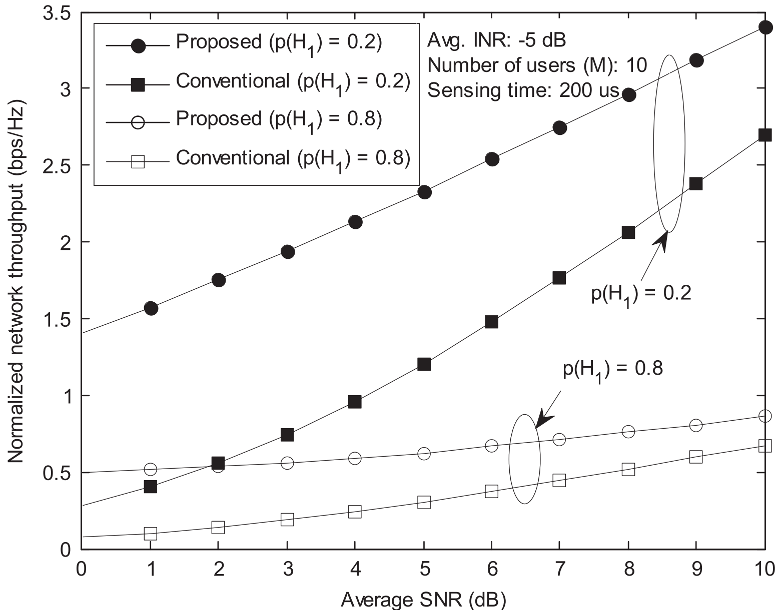

Figure 7. Normalized network throughput according to the average SNR.

is -10 dB. It can be seen that the proposed scheme provides better sensing performance than the conventional scheme in a high SNR environment. This is due to the fact that in the high SNR environment, the number of scheduled users satisfying the CFAR requirement (i.e. $Q_{\mathrm{F}} = \bar{Q}_{\mathrm{F}}$) increases. It can also be seen that the bound of false alarm probability of the conventional scheme decreases. This is mainly because as the SNR increases, the value of $p_{e,k}(\eta_k)$ in (19) decreases, reducing the bound of the false alarm probability.

Figure 7 depicts the normalized network throughput in terms of the average SNR when the average INR is -5 dB, the number of users is 10, the desired false alarm probability is 0.1, and the active probability of the primary user is 0.2 and 0.8, respectively. It can be seen that the proposed scheme outperforms the conventional cooperative spectrum sensing scheme. This is due to the fact that the proposed scheme accurately detects the unoccupied spectrum band by using secondary user scheduling based on the feedback channel condition. It can be also seen that as the average SNR increases, the performance gain of the proposed scheme is reduced. This is due to the fact that as the average SNR increases, the bound of the false alarm probability of the conventional scheme decreases. As the active probability of the primary user increases, the normalized network throughput decreases since the opportunity to access the spectrum band of interest is reduced.

Figure 8 depicts the average number of scheduled secondary users according to the desired false alarm probability $\bar{Q}_{\mathrm{F}}$ when the average SNR and INR are 5 and -10 dB, respectively. It can be seen that the proposed scheme adjusts the number of secondary users to maximize the detection probability while guaranteeing that the desired false alarm requirements are maintained according to the operating conditions. As the amount of feedback signaling burden is minimized as the number of secondary users decreases, the proposed scheme can satisfy the spectrum sensing requirement with a minimal signaling burden.

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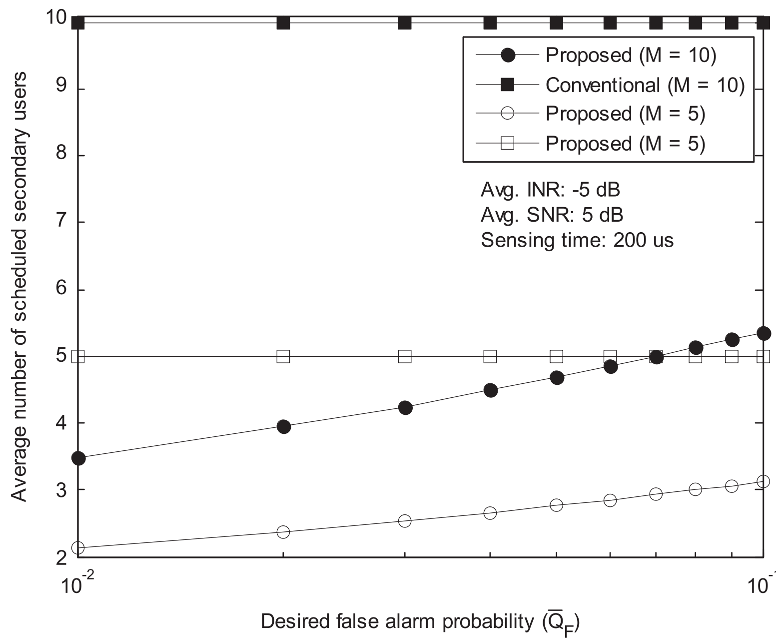

Figure 8. Average number of cooperative secondary users according to the desired false alarm probability.

5. CONCLUSIONS

We have investigated a hard decision combining-based cooperative spectrum sensing scheme in cognitive radio systems. By considering imperfect feedback channel condition between cognitive BS and secondary user, the proposed scheme schedules the secondary user involving cooperative spectrum sensing. Through the secondary user scheduling, the proposed scheme can maximize the detection probability as much as possible while guaranteeing a desired false alarm probability in the presence of feedback error. The simulation results show that the proposed scheme provides better spectrum sensing performance compared to the conventional cooperative spectrum sensing scheme.

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