무선 인지 시스템에서 궤환 오류를 고려한 협력 스펙트럼 센싱 기법에 관한 연구

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Cooperative Spectrum Sensing with Feedback Error in the Cognitive Radio Systems

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요 약

본 논문에서는 무선인지 시스템에서 궤환 오류를 고려한 협력 스펙트럼 센싱 기법에 대해서 제안한다. 협력 센싱에서는 각 부사용자의 자체 센싱 결과를 결합하여 최종 판정을 내리게 되는데, 부사용자가 정확한 자체 센싱 결과를 내리더라도 궤환 채널의 상태가 좋지 않은 경우 이를 협력 센싱을하는데 직접적으로 사용할 수 없게 된다. 본 논문에서는 궤환 채널 상태가 좋은 사용자만 선택하여 협력 센싱에 참여하도록 함으로써 목표 오검출 확률을 만족하면서 정검출 확률을 최대화 시키는 협력 센싱 기법에 대해 제안한다.

Key Words : Cognitive radio, Spectrum Sensing, User Scheduling

ABSTRACT

In this paper, we propose a cooperative channel sensing scheme in the presence of feedback errors. Accurate local sensing results may not directly be applied to cooperative sensing due to feedback errors. We consider the cooperative channel sensing that utilizes local sensing results in good feedback channel condition. Finally, simulation results show that the proposed scheme can maximize the detection probability while guaranteeing desired false alarm probability.

Ⅰ. Introduction

The demand for ubiquitous wireless service has requested the use of more wireless resources. To alleviate the spectrum scarcity problem, the Federal Communications Commission (FCC) has proposed the use of licensed spectrum by secondary users, without hampering the operation of primary users.

Cognitive radio is an intelligent technology that can rapidly and autonomously adapt operating parameters in response to the change of operation environments[1,2]. For coexistence with primary systems, cognitive radio (CR) network employs a cooperative spectrum sensing scheme where the CR base station makes a final decision by fusing local sensing decisions reported from each secondary user [1,2].

Most of previous spectrum sensing works assumed that the reporting channel between the cognitive BS and the secondary user is perfect. As the number of cooperative secondary users increases,

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the detection probability asymptotically approaches to one while maintaining the false alarm probability at a desired level in the presence of perfect reporting channel[3,4]. However, since the reporting channel is not perfect in practice, the use of maximum a posteriori (MAP) detector has been considered[5]. When the reporting channel experiences deep fading, it cannot provide desired performance. The use of cluster based cooperative spectrum sensing can alleviate this problem, but it needs information sharing among the secondary users, making it impractical[6,7].

To mitigate the reporting error, we consider the estimation of the reporting channel condition by exploiting uplink sounding signal. The cognitive BS allows secondary users to report their sensing results only when their reporting channel is in good condition. The proposed scheme can maximize the detection probability while keeping the false alarm probability at a desired level even in the presence of reporting channel errors. In addition, the proposed scheme can reduce the amount of feedback signaling burden since only scheduled users are allowed to report their local sensing results.

The rest of this paper is organized as follows. Section II describes the system model and Section III describes the proposed spectrum sensing scheme. Section IV verifies the performance of the proposed scheme by computer simulation. Finally, conclusions are given in Section V.

Ⅱ. System Model

Consider the CR network that comprises one CR base station and M secondary users. In the cooperative spectrum sensing, the received signal sample of the secondary user k at each hypothesis H_0 (idle state) and H_1 (busy state) can be represented as

$$y_k = \begin{cases} w(n); & H_0 \\ h_k(n)s(n) + w(n); & H_1 \end{cases} \tag{1}$$

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., $w(n) \sim CN(0,1)$). 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

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

where N_s is the number of samples which is same as 2 times time-bandwidth product (i.e., $N_s = 2TW$)[8].

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

$$u_k = \begin{cases} 1; R_k(N_s) > \lambda \\ 0; R_k(N_s) < \lambda \end{cases} \tag{3}$$

where λ is the threshold level to be determined.

For the cooperation, the secondary users report their binary decision result to the CR base station. The CR base station combines the local decisions with weight $w_k \in \{0,1\}$ based on the condition of reporting channel, and makes a final decision as[6]

$$D = \begin{cases} H_1; \sum_{k=1}^{M} w_k u_k > \zeta \\ H_0; otherwise \end{cases} \tag{4}$$

where ζ is the global threshold level. We assume that the cognitive BS makes final decision by means of well-known OR-fusion rule where ζ is set to be one[3,6]. It can be shown that the use of binary weight $w_k \in \{0,1\}$ implies that the cognitive BS schedules secondary users whose weight is one based on reporting channel condition which is measured by means of uplink sounding signal [9].

Ⅲ. Proposed Cooperative Sensing

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

According to energy detection theory[8], the false alarm, detection, and miss probability of secondary user k can be represented as [12]

$$P_{f,k}(\lambda)=Q\left((\lambda-1)\sqrt{N_s}\right) \quad (5)$$

$$P_{d,k}(\lambda,\gamma_k)=Q\left((\lambda-\gamma_k-1)\sqrt{\frac{N_s}{2\gamma_k+1}}\right) \quad (6)$$

$$P_{m,k}(\lambda,\gamma_k)=1-P_{d,k}(\lambda,\gamma_k) \quad (7)$$

where $Q(\cdot)$ are Q-function.

In the spectrum sensing, it is desirable to make the detection probability higher than or equal to the target detection probability (i.e., $Q_d \geq \overline{Q_d}$) and to make the false alarm probability lower than or equal to the target false alarm probability (i.e., $Q_f \leq \overline{Q_f}$). 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[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. Since there is no information on the primary user' signal (actually, we even do not know if the signal of primary user exists or not), we consider the use of a CFAR detector.

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. In practice, the reporting channel condition is imperfect. Therefore, although the local sensing result is accurately obtained, it might not be suitable for making a cooperative decision. By assuming local decision u_k is reported by means of BPSK modulation with instantaneous channel SNR η_k, the reporting bit-error probability (BER) of the secondary user k can be represented as[12]

$$p_{e,k}(\eta_k)=Q\left(\sqrt{2\eta_k}\right) \quad (8)$$

Note that cognitive BS can estimate η_k by means of an uplink sounding signal[9].

Assuming that all of 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

$$Q_f=1-\prod_{k=1}^{M}\left[\begin{array}{l}\{1-P_{f,k}(\lambda)\}\{1-p_{e,k}(\eta_k)\}\\+P_{f,k}(\lambda)p_{e,k}(\eta_k)\end{array}\right] \quad (9)$$

$$Q_d=1-\prod_{k=1}^{M}\left[\begin{array}{l}P_{d,k}(\lambda,\gamma_k)\{1-p_{e,k}(\eta_k)\}\\+\{1-P_{d,k}(\lambda,\gamma_k)\}p_{e,k}(\eta_k)\end{array}\right] \quad (10)$$

where $P_{f,k}(\lambda)$ and $P_{d,k}(\lambda,\gamma_k)$ are the local false alarm and detection probability of the secondary user k, respectively [11].

Due to the reporting error, the false alarm probability is bounded in the presence of the reporting error as

$$\begin{aligned}\widehat{Q_f}&=\lim_{\lambda\to\infty}Q_f\\&=1-\prod_{k=1}^{M}\{1-p_{e,k}(\eta_k)\}\end{aligned} \quad (11)$$

This means that the detector cannot work properly when the desired false alarm probability $\overline{Q_f}$ is lower than the bound $\widehat{Q_f}$. Therefore, to maximize the detection probability while guaranteeing the target false alarm probability (i.e., optimize CFAR performance), the cognitive BS schedules secondary users whose reporting channel is sufficient to satisfy the target CFAR requirements.

Let K be the number of scheduled secondary users. To achieve the desired CFAR requirement (i.e., $Q_f = \overline{Q_f}$) in the presence of reporting errors, the target local false alarm probability $\overline{P_{f,k}}$ of secondary user k should be given by

$$\overline{P_{f,k}} = \frac{1 - \sqrt[K]{1-\overline{Q_f}} - p_{e,k}(\eta_k)}{1 - 2p_{e,k}(\eta_k)} \quad (12)$$

and the decision threshold level to achieve the target local false alarm probability $\overline{P_{f,k}}$ can be represented as[11]

$$\lambda = \frac{Q^{-1}(\overline{P_{f,k}})}{\sqrt{N_s}} + 1 \quad (13)$$

It can be also shown from (13) that when $p_{e,k}(\eta_k) \geq 1 - \sqrt[K]{1-\overline{Q_f}}$, 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 $\overline{P_{f,k}}$ becomes strict (i.e., $\overline{P_{f,k}}$ decreases as the number of scheduled secondary users K increases). Therefore, it might be required to give priority to secondary user with a lower reporting error probability (i.e., a higher channel SNR) while excluding secondary user whose BER $p_{e,k}(\eta_k)$ is greater than or equal to $1 - \sqrt[K]{1-\overline{Q_f}}$. The cooperative secondary users are scheduled as follows.

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

$$\Phi = \{1,2,...,M\}; \Omega = \{\bullet\}; K = 0 \quad (14)$$

Schedule the secondary user with minimum BER value

$$\pi = \arg\min_{k \in \Phi} p_{e,k}(\eta_k) \quad (15)$$

Check if the secondary user π satisfies the following condition

$$p_{e,k}(\eta_k) < 1 - \sqrt[K+1]{1-\overline{Q_f}} \quad (16)$$

If $p_{e,k}(\eta_k) < 1 - \sqrt[K+1]{1-\overline{Q_f}}$, update the scheduled secondary user set as

$$\Phi \leftarrow \Phi - \{\pi\}; \Omega \leftarrow \Omega \cup = \{\pi\}; K = K+1 \quad (17)$$

and go to step 2. Else stop.

After scheduling the secondary users, the cognitive BS broadcasts only the number of scheduled secondary users K, 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 downlink pilot signal [9]. Based on the estimated BER, the secondary user can detect whether it is scheduled for the cooperation simply by checking the scheduling condition $p_{e,\pi}(\eta_\pi) < 1 - \sqrt[K]{1-\overline{Q_f}}$. 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 the scheduled users. The cognitive BS can respectively yield the false alarm and detection probability as

$$Q_{f,\mathrm{Pro}} = 1 - \prod_{k=1}^{K} \left[\begin{matrix} \{1 - P_{f,\Omega(k)}(\lambda)\}\{1 - p_{e,\Omega(k)}(\eta_{\Omega(k)})\} \\ + P_{f,\Omega(k)}(\lambda) p_{e,\Omega(k)}(\eta_{\Omega(k)}) \end{matrix} \right]$$

$$Q_{d,\mathrm{Pro}} = 1 - \prod_{k=1}^{K} \left[\begin{matrix} P_{d,\Omega(k)}(\lambda, \gamma_{\Omega(k)})\{1 - p_{e,\Omega(k)}(\eta_{\Omega(k)})\} \\ + \{1 - P_{d,\Omega(k)}(\lambda, \gamma_{\Omega(k)})\} p_{e,\Omega(k)}(\eta_{\Omega(k)}) \end{matrix} \right]$$

IV. Simulation Results

The performance of the proposed scheme is verified by computer simulation. We assume that when any secondary user cannot satisfy CRAR constraint (i.e., $K=0$), the cognitive BS makes final decision based on its own local decision. The common simulation parameters are summarized in Table I, and to verify the validation of the proposed scheme, we compare the performance of the proposed scheme with the conventional cooperative

Table 1. Common simulation parameters

Parameters	Setting
Channel bandwidth	262.5kHz
Sampling frequency	262.5kHz
Sensing time	200 us
Average SNR	5, 10 dB
Average INR	-10, -5 dB
Number of secondary users	5, 10

spectrum sensing scheme (i.e., all of the secondary users are involved in cooperation).

Fig. 1 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 is 5 and -10 dB, respectively. It can be seen that for a certain low false alarm probability, miss detection probability $Q_m(=1-Q_d)$ of the proposed scheme decreases compared 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 reporting channel in order to maximize the detection probability while guaranteeing a desired false alarm probability. On the other hand, conventional scheme is bounded at a certain false alarm probability due to the reporting 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 $K(\leq M)$ secondary users whose reporting channel condition satisfies the CFAR requirement (i.e, $Q_f=\overline{Q_f}$) increases due to multi-user diversity. On the other hand, as the number of secondary users increases, the bound of Q_f for the conventional scheme becomes larger.

Fig. 2 depicts the complementary ROC curve of the proposed scheme for the different value of INR (i.e., $\bar{\gamma}$ = -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 of the spectrum sensing schemes provide better sensing performance. 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 same regardless of INR. This is mainly because as seen in (12), 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 reporting error. On the other hand, by adjusting the number of scheduled secondary users, the proposed scheme maximizes the detection probability while

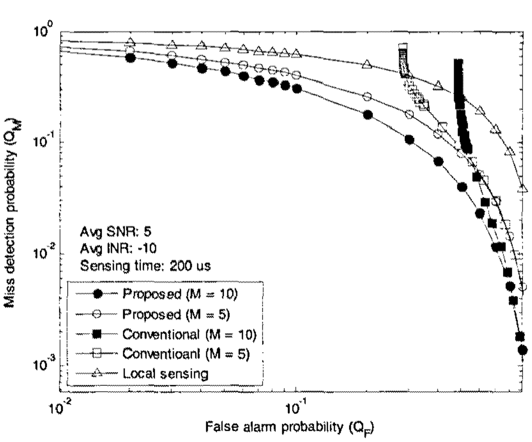

그림 1. M = 5, 10일 때 제안 기법의 ROC
Fig. 1. The complementary ROC curve of the proposed scheme when M = 5 and 10

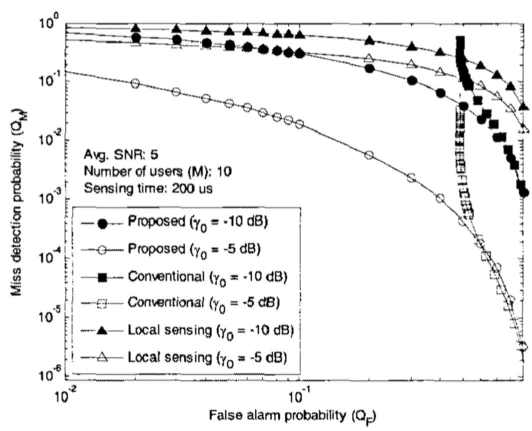

그림 2. $\bar{\gamma}$ = -10, -5 dB일 때 제안 기법의 ROC
Fig. 2. The complementary ROC curve of the proposed scheme when $\bar{\gamma}$ = -10 and -5 dB

guaranteeing the desired false alarm probability, regardless of the INR environment.

Fig. 3 depicts the complementary ROC curve of the proposed scheme for the different value of SNR (i.e., $\bar{\eta}$= 5 and 10 dB) when the number of secondary users is 10 and the average INR is -0 dB. It can be seen that the proposed scheme provides better sensing performance than do 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, $Q_f = \overline{Q_f}$) 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 (12) decreases, reducing the bound of the false alarm probability.

Fig. 4 depicts the average number of scheduled secondary users according to the target false alarm probability $\overline{Q_f}$ 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 target false alarm requirements are maintained according to the operating conditions. Since the amount of reporting 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.

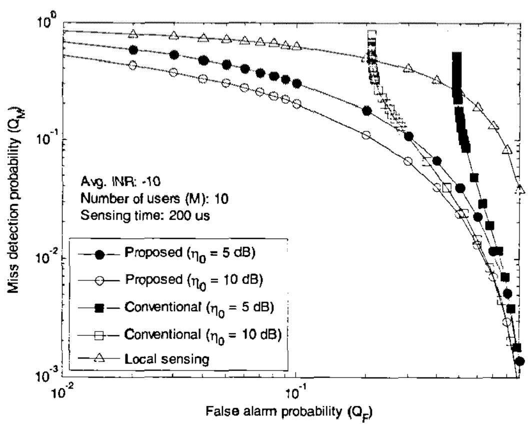

그림 3. $\bar{\eta}$ = 5, 10 dB일 때 제안 기법의 ROC
Fig. 3. The complementary ROC curve of the proposed scheme when $\bar{\eta}$ = 5 and 10 dB

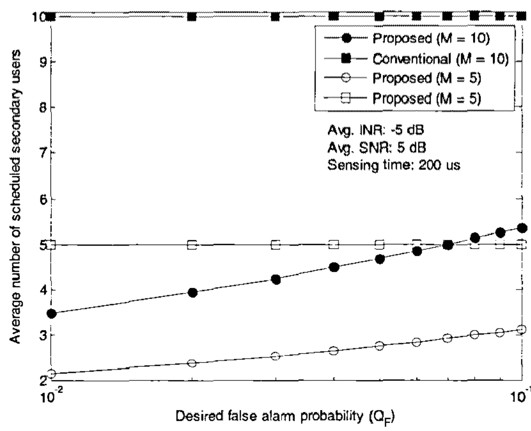

그림 4. 목표 오검출 확률에 따른 평균 협력 부사용자 수.
Fig. 4. Average number of cooperative secondary users according to the desired false alarm probability

V. Coclusions

We have investigated a hard decision combining-based cooperative spectrum sensing scheme in cognitive radio systems. By considering imperfect reporting 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 target false alarm probability in the presence of reporting 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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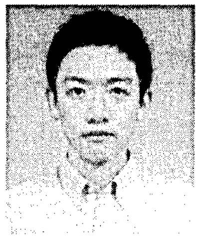

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