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인지 무선 센서 네트워크에서 에너지 효율적인 협력 스펙트럼 센싱을 위한 센싱 노드 선택 기법

(A Sensing Node Selection Scheme for Energy-Efficient Cooperative Spectrum Sensing in Cognitive Radio Sensor Networks)

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요 약 인지 무선 기술은 보조 사용자가 (SUs) 주 사용자 (PUs)에 간섭을 주지 않고 기회주의적 방식으로 라이선스 스펙트럼을 사용할 수 있는 기술이다. 인지 라디오의 핵심 기술은 스펙트럼 센싱이다. 그러나 인지 무선 센서 네트워크에서 에너지 효율적인 스펙트럼 센싱 기법에 대한 연구는 많지 않다. 본 논문에서는 클러스터 기반의 인지 무선 센서 네트워크를 위한 에너지 효율적인 협력 스펙트럼 센싱 노드 선택 기법을 제안한다. 제안하는 기법에서, 허위 경보 확률 및 에너지 소비를 최적화하기 위하여 클러스터 내 스펙트럼 센싱 노드들의 수를 최소화하게 된다. 시뮬레이션 결과를 통하여 본 논문에서 제안한 최적의 스펙트럼 센싱 노드 수를 적용하므로 스펙트럼 센싱 효율성이 향상되었고, 또한 네트워크의 에너지 효율성도 보장된 것을 검증하였다.

키워드: 인지 무선 센서 네트워크, 클러스터링, 스펙트럼 센싱, 네트워크 수명

Abstract Cognitive radio technology can allow secondary users (SUs) to access unused licensed spectrums in an opportunistic manner without interfering with primary users (PUs). Spectrum sensing is a key technology for cognitive radio (CR). However, few studies have examined energy-efficient spectrum sensing in cognitive radio sensor networks (CRSNs). In this paper, we propose an energy-efficient cooperative spectrum sensing nodes selection scheme for cluster-based cognitive radio sensor networks. In our proposed scheme, false alarm probability and energy consumption are considered to minimize the number of spectrum sensing nodes in a cluster. Simulation results show that by applying the proposed scheme, spectrum sensing efficiency is improved with a decreased number of spectrum sensing nodes. Furthermore, network energy efficiency is guaranteed and network lifetime is substantially prolonged.

Keywords: cognitive radio sensor network, clustering, spectrum sensing, network lifetime

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1. Introduction

Due to spectrum scarcity, cognitive radio technology is proposed by Mitola in 1999 [1] to relieve scarcity of spectrum resources. Cognitive radio can make primary users (PUs) and secondary users (SUs) or SUs and other SUs share limited radio resource under the premise of collision-free. Concretely, cognitive radio technology can improve spectral efficiency by opportunistic accessing the licensed bands which is not occupied by PUs; therefore cognitive radio technology has been widely applied in various wireless networks [2,3].

Spectrum sensing is a key technology for cognitive radio. SUs can efficiently access spectrum resources in interference-free manner according to spectrum sensing results. There are two ways for spectrum sensing: individual spectrum sensing and cooperative spectrum sensing (CSS). Individual spectrum sensing suffers from shadowing and hidden terminal problem; therefore, its sensing performance is not satisfactory. CSS can efficiently solve these problems by cooperation of multiple spectrum sensing nodes with more energy consumption cost and the overhead of control messages. There are many works on CSS in Cognitive Radio Networks (CRNs). In [4], Shengliang et al. propose a relay based CSS method. Concretely, a SU with higher Signal-to-Noise Ratio (SNR) takes a part of sensing time as a relay to help other SUs whose SNR is low to enhance the accuracy of spectrum sensing. In [5], in order to improve the detection probability, Msumba et al. present a CSS scheme for multi-user. These spectrum sensing schemes proposed for CRNs cannot be directly applied in CRSNs, because they do not consider energy restriction which is the most important characteristic of CRSNs. In CRSNs, energy is the most important because in general, it is hard or even impossible to recharge or change the battery for sensor nodes due to application environments. However, there are few solutions specific to CRSNs to design energy efficient CSS schemes.

In this paper, a CSS nodes selection scheme is proposed for a large scale of cluster-based CRSN. Since not all of sensing nodes can be helpful to the final sensing result, in our proposed scheme, some sensor nodes which have the highest SNR sense the spectrum to detect PUs and others can keep in sleep state for a certain time. In other words, a cooperative sensing nodes selection is proposed to improve energy efficiency of spectrum sensing. In this way, not only the good sensing performance can be achieved by nodes with highest SNR, energy consumption can be decreased by less cooperative sensing nodes. Another contribution of this paper is that, meanwhile, energy consumption caused by new added sensing node is also considered, and the number of sensing nodes is optimized further. The number of sensing nodes in a cluster can be obtained by optimizing detection probability, false alarm probability and energy consumption. Furthermore, through a set of simulation, the performance of the proposed scheme is verified that a better sensing performance with less sensor nodes is achieved.

The rest of the paper is organized as follows. Section 2 explains the related works which are specific to CRSNs. We propose our scheme with mathematical analysis in Section 3. We evaluate the performance of the proposed scheme through simulations in Section 4. Finally Section 5 concludes this paper.

2. Related work

Cognitive radio technology enables SUs temporarily occupy the licensed spectrum band when the spectrum band is not utilized by PU. The combination of cognitive radio technology and wireless sensor network explores more opportunities. Spectrum sensing is crucial to identify the presence of PU. There are many works on energy efficient spectrum sensing for CRNs. On the other hand, there are few works specific to CRSNs, especially in terms of CSS.

Wei et al. [6], authors propose a CSS for OFDM based MIMO CRSN. The sensor nodes should be equipped with multiple antennas. In addition, because all nodes participate in CSS, large amount of energy will be exhausted. Maryam et al. propose a node selection criterion for spectrum sensing [7]. KKT conditions are used to find the optimal sensing nodes which operate CSS and prolong the network lifetime. An energy-based sensor selection method is proposed by Maryam et al. [8] to guarantee the fairness among different sensors and balance the network energy consumption. The sensors are assumed to experience the same SNR and sensing thresholds in the same cluster, but it is rarely practical in reality. In addition, the process of sensing nodes selection is irrelevant to SNR. Compared with our scheme, our scheme can provide a better sensing performance from the view of intuition. In [9] and [10], the nodes which local sensing results agree with FC's decision are preferred to be selected for CSS. However, if majority of sensing nodes are in the case of poor sensing quality, FC will be misguided by the received wrong local sensing results.

3. Proposed scheme

In this section, an energy-efficient CSS nodes selection scheme is introduced. A large scale of cluster-based CRSN is assumed, and we focus on one cluster and optimize the number of sensing nodes in terms of false alarm probability and energy consumption. Because the objective is to select most appropriate number of cooperative sensing nodes, the proposed scheme can be applied for various cluster-based CRSNs.

3.1 System model

A large scale of cluster-based CRSN is assumed in this paper. The network consists of one PU and several clusters. Each cluster is composed of one cluster head (CH) and a certain amount of SUs which represent cluster members. The frame of SUs contains two parts: sensing phase and data transmission phase. At first, selected cooperative sensing nodes operate local sensing and send the local sensing results to CH. CH will make the final decision according to fusion rule and broadcast it to all SUs. If PU is absent, SUs will transmit data.

3.2 Proposed scheme

For proposed CSS nodes selection scheme, the main contribution is to solve two problems: how many nodes and which nodes should be selected. The detail process of proposed scheme is presented as follows.

In this paper, energy detector is employed as the spectrum sensing scheme, because it is simple and do not need priori knowledge of PUs. We can use a binary hypothesis testing problem to formulate spectrum sensing as follows:

$$H_0\text{: } y(n)=u(n), \tag{1}$$

$$H_1\text{: } y(n)=x(n)+u(n), \tag{2}$$

where hypothesis H_0 indicates that a PU is inactive and the noise is denoted by $u(n)$. $u(n)$ is assumed to be an independent and identically distributed Gaussian random process with zero mean and variance σ_y^2. The hypothesis H_1 indicates that a PU is transmitting and $x(n)$ is denoted by received PU's signal.

The test statistic can be calculated as below:

$$\mathrm{T}(\mathrm{y})=\sum_{n=1}^{N}\left|y(n)\right|^2, \tag{3}$$

where N is the number of sample times. The test statistic follows the central and non-central chi-square distribution with $2N$ degrees of freedom under hypothesis H_0 and H_1, respectively. The test statistic can be approximated as a Gaussian distribution, because central limit theorem can be utilized for it if N is large.

$$\mathrm{T}(\mathrm{y})\sim \begin{cases} \mathcal{N}\left(N\sigma_y^2, 2N\sigma_y^4\right), & H_0 \\ \mathcal{N}\left(N\left(\sigma_x^2+\sigma_y^2\right), 2N\left(\sigma_x^2+\sigma_y^2\right)^2\right), & H_1 \end{cases}, \tag{4}$$

where σ_x^2 is the received signal power. And we focus on detection probability p_d and false alarm probability p_f to calculate the optimal number of cooperative sensing nodes.

$$p_d = p\left(H_1 \middle| H_1\right), \tag{5}$$

$$p_f = p\left(H_1 \middle| H_0\right). \tag{6}$$

We can get the following p_d and p_f based on the statistics of $\mathrm{T}(\mathrm{y})$.

$$\begin{aligned} p_d &= p\left(\mathrm{T}(y)>\lambda \middle| H_1\right) \\ &= Q\left(\sqrt{\frac{N}{2}}\left(\frac{\lambda}{N\sigma_y^2(\gamma+1)}-1\right)\right), \end{aligned} \tag{7}$$

$$\begin{aligned} p_f &= p(\mathrm{T}(y)>\lambda|H_0) \\ &= Q\left(\sqrt{\frac{N}{2}}\left(\frac{\lambda}{N\sigma_y^2}-1\right)\right), \end{aligned} \tag{8}$$

where λ is the sensing threshold and γ is the received SNR of PU, and Q(·) is Q-function. If the sensing result is bigger than threshold λ, we consider that PU exists; otherwise, we consider PU is inactive. In this paper, we take the OR rule as the fusion scheme of CSS, which means we can consider PU exists when at least one sensor node detects PUs. The global detection probability $p_{d,G}$ and the global false alarm probability $p_{f,G}$ can be calculated as follows:

$$p_{d,G} = 1 - \prod_{i=1}^{k}\left(1 - p_{d,i}\right), \tag{9}$$

$$p_{f,G} = 1 - \prod_{i=1}^{k}\left(1 - p_{f,i}\right). \tag{10}$$

We want to fix $p_{d,G}$ and calculate the optimum p_f and energy consumption. From Eq. (10), we can know that the value of $p_{f,G}$ will increase with the increasing number of cooperative sensing nodes k. Therefore, we set a threshold for global false alarm probability $p_{f,G}$ to meet the requirement of networks (such as $p_{f,G} \leq 0.05$). Under this condition, the relationship between false alarm probability p_f and energy consumption can be optimized.

Firstly, according to Eq. (9), p_d can be calculated. Secondly, we substitute p_d into Eq. (7), and threshold λ can be figured out. Finally, the calculated threshold λ is put into Eq. (8), p_f can be achieved as

$$p_f = Q\left(\left(\gamma+1\right)Q^{-1}\left(p_d\right) + \sqrt{\frac{N}{2}}\gamma\right). \tag{11}$$

According to Eq. (11), larger value of γ will result in smaller value of p_f. Therefore, we pick the node which has the largest value of γ first. In this way, the problem which node should be selected can be solved.

Due to the important place of energy consumption in CRSNs, we also take it into our consideration. In the proposed scheme, if the rate of descent of p_f is less than the rate of rise of energy consumption, the new sensing node will be not added, even this new sensing node has lower p_f. Therefore, the energy consumption model is defined as below:

$$E = E_s + E_t + E_r\ , \tag{12}$$

where E is the total energy consumed by the spectrum sensing, and E_s, E_t, and E_r represent the energy consumed by the spectrum sensing, packet transmission and packet reception, respectively. And for k cooperative sensing nodes, the total energy consumption is

$$E_{coo} = k * E\ . \tag{13}$$

Here, we suppose the energy consumption of each sensing node is the same. Then, we analyze p_f and E_{coo} to find the optimal k, given the preset threshold for global false alarm probability $p_{f,G}$. The objective function is expressed as

$$W = \log p_f + \log E_{coo}\ . \tag{14}$$

In general, the value of p_f varies between [0, 0.1] and according to Eq. (13), we can get that the variation of E_{coo} is from hundreds to thousands. The logarithmic function can balance the weight between p_f and E_{coo} in some ways. Therefore the objective function is represented as Ep. (14). We can apply exhaustive search method to add the node one by one into CSS nodes, and the sensing node with the highest SNR has a higher priority. The k which can minimize W is the optimal number of CSS nodes. Therefore, the problem how many nodes should be selected can also be solved.

4. Performance evaluation

In this section, we show the performance of the proposed CSS nodes selection scheme. The simulation for the performance evaluation is implemented in MATLAB, and parameters are setting as follows.

We assume a large scale of cluster-based CRSN which consists of one PU and C clusters, and each cluster consists with M SUs. We set the value of M as 30, 50 and 100, respectively. The global detection probability $p_{d,G}$ is set to 0.99, and the threshold of global false alarm probability $p_{f,G}$ can be set according to the requirement of the network. The energy that each node consumes for the periodic spectrum sensing is assumed as the same normalized value of 1. Each sensor is randomly distributed in a circular cluster with radius 50m. When the number of SUs in a cluster is large, we might assume that the SNR received by SUs in descending order can be approximated to arithmetic progression.

Fig. 1 shows the optimal number of cooperative sensing nodes under different values of M when the sample time N is set to 10 for local energy detection. When the value of M is set to 30, 50 and 100, the optimal number of cooperative sensing nodes k is 9, 12 and 20, respectively. Therefore, by comparing with the traditional cooperative sensing which all of

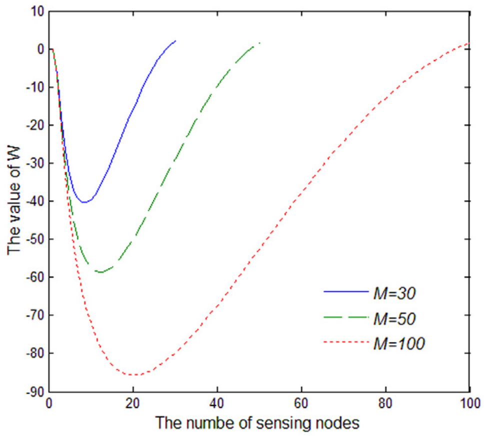

그림 1 $N=10$ 때 M에 따른 W의 값
Fig. 1 The value of W according to M when N is 10

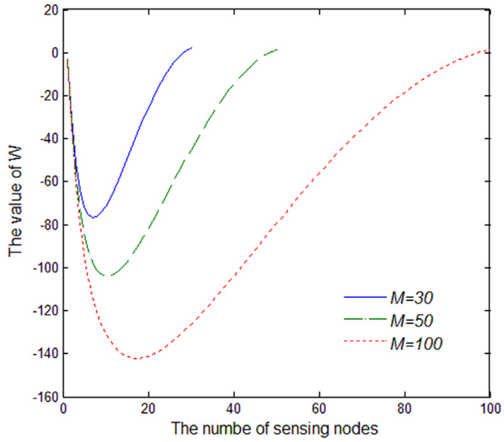

그림 2 $N=20$ 때 M에 따른 W의 값
Fig. 2 The value of W according to M when N is 20

nodes operate the spectrum sensing, our proposed scheme can save about 70%, 76% and 80% energy consumption, respectively. The simulation results verify that the optimal number of cooperative sensing nodes k indeed exists, and our proposed scheme is feasible with the optimization of false alarm probability and energy consumption to promote the performance of CRSNs.

Fig. 2 shows the optimal number of cooperative sensing nodes under different values of M when the sample time N is set to 20. The optimal number of cooperative sensing nodes k is 7, 10, 17, respectively, when the value of M is 30, 50 and 100, respectively. The optimal number of cooperative sensing nodes is less than the previous one which N is set to 10. The reason is that if the sample time N is bigger, which also means that the sensing time is longer. The longer sensing time will bring a better sensing performance; accordingly, less sensing nodes can also achieve the same sensing performance.

Fig. 3 shows the false alarm probability of new added sensing node. The false alarm probability p_f will decrease at first due to the detection probability. The rate of descent of p_f is bigger than the rate of rise of energy consumption. Therefore, the value of W will decrease. However, with decreasing SNR, false alarm probability p_f will increase again when after a certain point. The low SNR can make false alarm probability increase significantly according to Eq. (11). Furthermore, increasing sensing nodes will bring more energy consumption. That is the reason why the value of W will increase again.

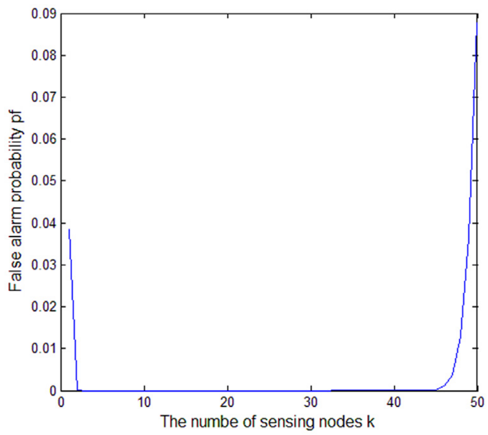

그림 3 k에 따른 허위 경보 확률
Fig. 3 The variation of false alarm probability with increasing sensing nodes k

Fig. 4 shows the comparison of normalized energy consumption for proposed scheme and traditional cooperative sensing scheme which proposed in [6] under the situation of different values of M. In the traditional scheme, all of sensor nodes included in cluster have to sense the spectrum and send local sensing results to CH. CH will make final decision with OR rule. In traditional scheme, each node is also assumed to have the same energy consumption; therefore, the total energy consumption will follow the approximate linear increase with the increasing total number of

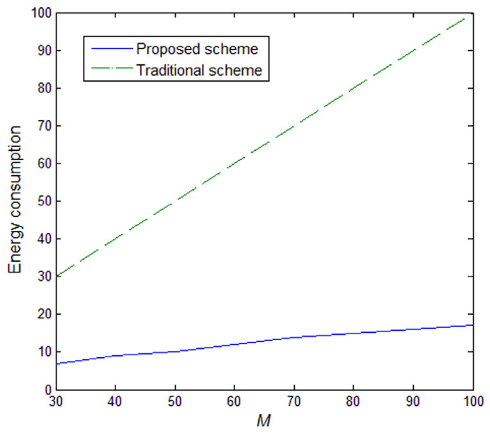

그림 4 정규화된 에너지 소모의 비교

Fig. 4 Comparison of normalized energy consumption according to various M

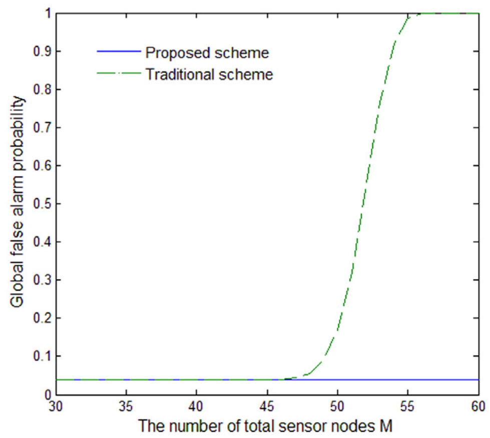

그림 5 글로벌 허위 경보 확률의 비교

Fig. 5 Comparison of global false alarm probability

sensor nodes M. On the contrary, through the proposed spectrum sensing scheme, the number of spectrum sensing nodes is optimized; therefore, the energy consumption is efficiently reduced. Furthermore, the simulation results show that more energy can be saved if there are more sensor nodes in a cluster by comparison with traditional cooperative sensing method. It benefits from that less sensing nodes are used with the increasing M in our proposed scheme.

Fig. 5 compares the global false alarm probability between the proposed scheme and the traditional cooperative sensing scheme. According to Eq. (10), we can observe that $p_{f,G}$ will always increase with the increasing k in terms of the OR rule (where $0 \leq 1 - p_{f,i} \leq 1$). In the proposed scheme, the number of nodes which used for spectrum sensing is much less than the traditional cooperative sensing scheme. We can get that the false alarm probability of new added sensing node is very small when the number of spectrum sensing node is less than 40. Therefore, our proposed scheme can remain global false alarm probability in a small value. For traditional scheme, even though it has a similar sensing performance when the number of total sensor nodes M is small, the global false alarm probability will increase very fast if the value of M becomes big. The main reason is that the high false alarm probability of new added sensing node affects the global false alarm probability significantly. Hence, a smaller global false alarm probability can be achieved with our proposed scheme by comparison with the OR rule based traditional cooperative sensing scheme.

5. Conclusion and future work

In this paper, an energy-efficient CSS nodes selection scheme is proposed for cluster-based CRSNs. The number of spectrum sensing nodes is optimized by optimizing detection probability, false alarm probability and energy consumption in a cluster. Since less sensor nodes operate CSS, we can save more energy by comparison with traditional cooperative sensing scheme. Finally, our simulation shows that the proposed scheme has a better sensing performance even though less sensing nodes are used for the spectrum sensing. In the future, we will pay more attention to prolong network lifetime further, and take the influence of the number of clusters on the proposed scheme into consideration from a global perspective.

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