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ADAPTIVE CLUSTER COOPERATIVE SPECTRUM SENSING SCHEME

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Abstract. *For optimizing the white space, we proposed a fast cluster head election scheme based on the minimum spanning tree theory and an adaptive cooperation spectrum detection scheme. Here the adaptive cluster thresholds were deduced based on the fixed cluster threshold and the global detection metrics in previous period. Then, the detection system could select the cooperative cluster heads and matched fusion rules according to the adaptive cluster threshold to expand the available detection region under the minimum performance requirements. The energy consumption analysis shows that the proposed scheme has an optimal tradeoff between the total energy consumption and the global detection performance. Simulations show that the proposed scheme can expand available detection region by about 20% and have stable energy consumption in Rayleigh fading channels.*

Keywords: Minimum performance requirement, Available region, Adaptive cluster cooperation, Minimum spanning tree, Cooperative spectrum detection

1. **Introduction.** To improve the global detection performance, cooperative spectrum sensing (CSS) scheme has been employed to solve the multi-path fading, shadow effect and hidden terminal problems in a cognitive radio (CR) network by using user diversity in the same band and period. The local detection results are reported to fusion center (FC) only by the cluster head (CH) in distributed cluster cooperative detection model. Thus, the reported channel bandwidth, computing complexity and energy consumption of detection nodes are decreased in the cluster model [1]. However, the detection metrics of the CSS based on fixed threshold and fusion rule is uncertain in time-variation channels. The nodes in bad channels still participate in the spectrum detection and report their results, which utilize more bandwidth and degrade the global detection performance [2].

The exact probability distribution of total received signal energy is difficult to be derived in fast-fading channel, which leads to the high probability of missed detection [3]. In fact, there are both large-scale and small-scale fading in time-variation channels. The conventional cluster CSS scheme would degrade the global detection performance [4]. Smitha and Vinod proposed an improved frequency divisional cluster using location information to reduce the average number of sensing bits sent to the FC so as to reduce the bandwidth of reporting channels [5]. And the total transmission power of the secondary users (SUs) was reduced in turn, which could improve the SU battery life. However, an additional block is necessary to compute the location information of SUs. An objection-based CSS scheme had been proposed for decreasing the reporting SUs [6]. However, the energy efficiency influence of some harmful factors, as the local detection accuracy for broadcasting, and the transmission range of selected broadcasting SU, had not been analyzed in fading channel.

For the consensus-based decentralized cluster scheme, the node information was exchanged on the basis of interactions among one-hop neighbors. And the nodes in high quality channels were selected for CSS [7]. Sobron et al. have used a defined cost-function to adapt the detection threshold to the channel status. This method could improve the detection performance in both single node and CSS model [8]. Lee proposed an adaptive collection period of detection results in an unequal signal-to-noise ratio (*SNR*) case by random access method to optimize the number of SUs participating in the cooperative sensing [9]. In our previous work [10], we employed an optimal cooperative model according to fusion rule for improving the global metrics. The SUs in the channels with high *SNR* were selected to participate in the CSS scheme. The others only received the decision from FC. However, it is important that the system gets the maximum white space for some purposes. In this paper, the proposed scheme can expand the available sensing region for maximizing the throughput under the minimum performance requirements by adapting cluster model. For grouping a cluster rapidly, a fast clustering method is proposed based on the minimum spanning tree theory. The contributions include the fast cluster head election scheme and adaptive cooperative threshold method, see in Section 3.

2. Adaptive Cluster Cooperative Scheme.

Given a cooperative CR network with M SUs and K licensed channels, SUs with heterogeneous detection ability will cooperatively detect the licensed channels using the cluster CSS scheme to find the idle channels.

2.1. Problem formulation.

Assume that all SUs in different fading channels detect the dedicated licensed channel in the same period. Cooperative SUs will be clustered into L clusters according to their location and power information. The detection results of L clusters are reported to the FC which makes the global decision for the licensed channel. Under the minimum performance requirements, the cluster heads only take part in cooperative spectrum detection for decreasing communication cost and power consumption. However, the different fusion rules have different *SNR* threshold requirements to the cluster heads and bring different available detection regions.

To protect PUs, they should be detected within 2 seconds with detection probability $Q_d \geq 0.9$ and false alarm probability $Q_f \leq 0.1$ regarding to IEEE 802.22 standard. Thus, we define the available detection region as the *SNR* region under the minimum performance requirements. This is given as Equation (1).

$$D_R = \{SNR \geq \gamma\} \tag{1}$$

where γ is the *SNR* threshold under specified fusion rule. Our optimization problem is formulated as follows:

$$\max_{\gamma, E_k, \eta_k} D_R$$

Subject to

$$\text{C1}: \ Q_d \geq 0.9 \text{ and } Q_f \leq 0.1; \tag{2}$$

$$\text{C2}: \ \min\left(\sum_{k=1}^{L} E_k\right), \ 1 \leq k \leq L; \tag{3}$$

$$\text{C3}: \ \min\left(\sum_{k=1}^{L} \eta_k\right), \ \eta_k = \frac{n_k}{N_i} \cdot T_s, \ 1 \leq i \leq M, \ 1 \leq k \leq L; \tag{4}$$

where for the kth cluster, E_k and n_k are the energy consumption and number of SUs that take part in spectrum detection, respectively. η_k is the overhead for reporting the results to FC. N_i is the total of SUs. Constraint C1 can ensure the minimum global detection performance requirements. Constraints C2 and C3 are to ensure the least SUs to take part in spectrum sensing in each period as far as possible.

2.2. **Fast clustering method.** All SUs are grouped into several clusters in different channels. The clusters are formed and maintained based on the cluster head. Suppose V denotes the vertex set constituted by all SUs in the targeted channel, and E denotes the set of edges constituted by the connection between SUs. They form a connected weighted graph $G = (V, E)$. Assume that all SUs cache weight parameters, such as Signal-to-Noise Ratio, the remaining energy and the distance from FC. And the neighbor SUs can communicate with each other. Let e be an edge of graph G and $w(e)$ be the weight of that edge. We define the graph G as a weighted graph when all of edges are weighted. A minimum spanning tree of the graph G represents a spanning tree T that satisfies:

$$w(T) = \min_{T} \sum_{e \in T} w(e) \tag{5}$$

For all spanning trees, T can be computed from G.

Here we denote W as the weight of the edge, N as the number of SUs in a cluster, and the CH can be elected as follows in detail.

Step 1. We can select an SU randomly as candidate CH denoted by $\{H\}$. And the sub-set V_{r-1} is the vertex set $\{H\}$, $r = 1, \ldots, N$.

Step 2. Compare W between $\{H\}$ and the vertex set $\{V - V_{r-1}\}$. The SU with larger W is elected as new candidate CH. Then, a "member" message is sent to the SU with smaller W from the new candidate CH. To confirm the new candidate CH, the SUs that receive the "member" message reply to the "head" message. And update V_{r-1} to be V_r.

Step 3. IF $r < N$, then return to Step 2; if $r = N$, the cluster head is the candidate CH.

Considering the system with M SUs, the time complexity of grouping all SUs into several parallel clusters is $o(M)$ by the minimum clique partition method. Time complexity of searching the maximum weight SU as candidate CH is $o(N \log N)$ in a cluster. Thus, the time complexity is equal to $o(M + N \log N)$ for the proposed CH election scheme in a period. From Hassan [11], the time complexity of constructing a cluster based on the position is $o(M)$. Under the comparison of the reporting channel status between each other, the time complexity of electing the CH is $o(N^2)$. In another CH election algorithm, the time complexity of constructing several parallel clusters after the selection of CHs from M nodes is $o(N^2 \log N)$.

2.3. **Adaptive cooperative threshold.** Different from improving the detection metrics in conventional CSS scheme, the proposed scheme will find the maximum idle licensed channels by expanding the detection region under the minimum performance requirement for maximizing throughput. We define the global performance index as $I = Q_d/Q_f$. Here Q_d and Q_f are the global detection probability and global false alarm probability, respectively. The index, I, could not be less than 9 in an available detection region as described in Section 2.1. An adaptive cooperative *SNR* threshold, γ_T, is defined as Equation (6) under the minimum performance requirements.

$$\gamma_T = \frac{9}{I}\gamma, \quad \gamma = \gamma_{or} \text{ or } \gamma_{and} \tag{6}$$

where γ is the fixed cooperative *SNR* threshold. And γ can be computed according to fusion rule. The spectrum detection system adapts to select the cooperative detection model as Figure 1 according to γ_T to achieve a tradeoff between the bandwidth efficiency and global detection performance. For all SUs with $SNR < \gamma_{Tor}$, the system only employs the OR rule to improve the global performance. However, the bandwidth efficiency is decreased and energy consumption is increased. For CHs with $SNR \in [\gamma_{Tor}, \gamma_{Tand})$, the system employs the cluster cooperative model and only CHs report the local detection results to FC which employs the OR rule. In this scenario, the bandwidth and energy efficiency are enhanced. For all CHs with $SNR \geq \gamma_{Tand}$, the system employs the AND

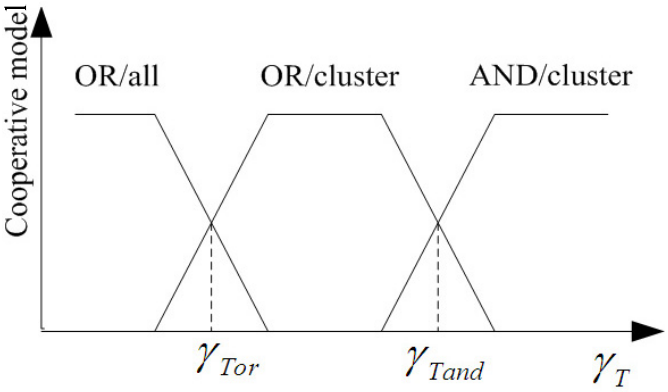

FIGURE 1. Adaptive cooperative model

rule for the cluster cooperative model to decrease global false alarm probability. And the bandwidth and energy efficiency can also be enhanced.

Here we use the available detection region to estimate the number of idle licensing channels. Let $P_{d,Ray}$ and $P_{f,Ray}$ be as the detection probability and false alarm probability using the energy detection in a Rayleigh fading channel, respectively. Let N_i be as the number of SUs in the kth cluster of L clusters. The $\overline{P_d^{or}}$ and $\overline{P_f^{or}}$ are average detection probability and false alarm probability of CH under OR rule. They are shown as Equation (7).

$$\overline{P_f^{or}} = 1 - \sqrt[L]{1 - Q_f}; \quad \overline{P_d^{or}} = 1 - \sqrt[L]{1 - Q_d} \tag{7}$$

The cluster detection threshold, λ_{or}, can be computed by $P_{f,Ray} = \overline{P_f^{or}}$. According to equation $P_{d,Ray} = \overline{P_d^{or}}$, the SNR threshold, γ_{or}, can be deduced as $\gamma_{or} = f_{or}\left(\lambda_{or}, \mu, P_d^{or}\right)$. Thus, the available detection region can be expressed by

$$D_R^{or} = \{SNR \geq \gamma_{or}\} \tag{8}$$

Let $\overline{P_d^{and}}$ and $\overline{P_f^{and}}$ be average detection probability and false alarm probability of CH under AND rule, respectively. Then they can be shown as follows:

$$\overline{P_f^{and}} = \sqrt[L]{Q_f}; \quad \overline{P_d^{and}} = \sqrt[L]{Q_d} \tag{9}$$

The cluster detection threshold, λ_{and}, can be computed by $P_{f,Ray} = \overline{P_f^{and}}$. According to equation $P_{d,Ray} = \overline{P_d^{and}}$, the SNR threshold, γ_{and}, can be deduced as $\gamma_{and} = f_{and}\left(\lambda_{and}, \mu, P_d^{and}\right)$. The available detection region can be expressed by

$$D_R^{and} = \{SNR \geq \gamma_{and}\} \tag{10}$$

The available detection region of adaptive cooperative model under the minimum performance requirements can be expressed as $D_{RT} = \{SNR \geq \gamma_T\}$. Thus, we defined the expanded available detection region of the white space as:

$$\varepsilon_r = D_{RT} - D_R = \{\gamma_T - \gamma\} = \gamma\left(\frac{9}{I} - 1\right) \tag{11}$$

where D_R is the D_R^{or} under $\gamma = \gamma_{or}$ or the D_R^{and} under $\gamma = \gamma_{and}$. Thus, the proposed scheme is a tradeoff between the available spectrum region and the global detection accuracy by dynamically adjusting the cooperative SNR threshold.

3. Energy Consumption Analysis and Performance Evaluation.

3.1. **Energy consumption analysis.** In the spectrum detection period, the total energy consumption of the fixed cluster CSS under $SNR_{CH} \geq \gamma$ can be given as follows

$$E_F = N_{CH}(E_S + E_R) \tag{12}$$

where E_S, and E_R are the energy consumed in local detection and reporting the result to the FC, respectively, by one SU. N_{CH} and γ are the number and *SNR* threshold of CHs.

The total energy consumption based on objection CSS under the cluster model can be given as follows

$$E_O = N_{CH}E_S + E_{BC} + N_i^* E_R \tag{13}$$

where E_{BC} is the energy consumed in broadcasting and N_i^* is the number of the objecting CHs given that the kth CH is broadcasting.

The total energy consumption of the proposed CSS under $SNR_{CH} \geq \gamma$ can be given as follows

$$E_A = P_A N_{CH}(E_S + E_R) + (1 - P_A)\left[N'_{CH}(E_S + E_R) + N_i(E_S + E_R)\right] \tag{14}$$

where P_A is the clustering probability of the proposed CSS completely. N'_{CH} is the number of CHs in incomplete cluster scheme. N_i is the number of SUs in kth cluster with $SNR_{CHi} < \gamma_T$. And the clustering probability P_A depends on the global performance index, I, in previous period and can be given as follows

$$P_A = \begin{cases} 1 & I \geq 9 \\ I/9 & I < 9 \end{cases} \tag{15}$$

3.2. **Performance evaluation.** In this section, we compared the global detection performance of the proposed algorithm with the fixed cluster CSS scheme and the adaptive CSS scheme in [8] in i.i.d. Rayleigh fading channels. The detection threshold $\lambda = 12$ and the time-bandwidth product of energy detector μ equals 5. The adaptive detection threshold came from Equation (20) in [8]. Assumed that $M = 25$SUs were grouped into 5 clusters. We set the minimum global detection performance metrics as the global false alarm probability, Q_f, to be 0.1 and the global detection probability, Q_d, to be 0.9. In this case, the fixed cluster thresholds were $\gamma_{or} = 1.3$dB and $\gamma_{and} = 6.2$dB, respectively, resulting from Equations (7) and (9). The fixed cluster CSS employed the cooperation model and fusion rule according to the fixed cluster threshold, γ. The proposed CSS employed the cooperation model and fusion rule according to Equation (6).

In the channels with low *SNR*, *SNR* of SUs in five clusters were random values within $[-4, 6]$dB. However, *SNR* of four in five CHs belonged to $[\gamma_{or}, \gamma_{and})$ at least. The system employed OR rule with cluster cooperative model. The global detection performance was shown in Figure 2. In the channels with high *SNR*, *SNR* of SUs in five clusters were random values within $[0, 10]$dB. However, SNR of four in five CHs were better than γ_{and} at least. The system employed AND rule in FC with cluster cooperative model. The global detection performance was shown in Figure 3.

Figure 2 showed that the proposed and the adaptive CSS had hypothetical performance in the area of $Q_d \geq 0.9$ and $Q_f \leq 0.1$. The proposed CSS enhanced the Q_d by about 5.34% and expanded the available detection region by about 25% than the fixed cluster CSS. We supposed that *SNR* of all SUs in a cluster are random values in simulations. When *SNR* of all SUs were smaller than γ_{Tor}, the cluster could not take part in the cooperative detection in this period in the proposed CSS. When SNR of all CHs were around the threshold, $\gamma_{or} = 1.3$dB, the Q_f was larger than 0.1 and the detection system ran out of the available detection region. The proposed CSS could put off switching the cluster model in order to keep the system in the available detection region.

Figure 3 showed that the proposed CSS expanded the available detection region about 20% and 17.6% than the fixed cluster CSS and adaptive CSS, respectively. When *SNR*

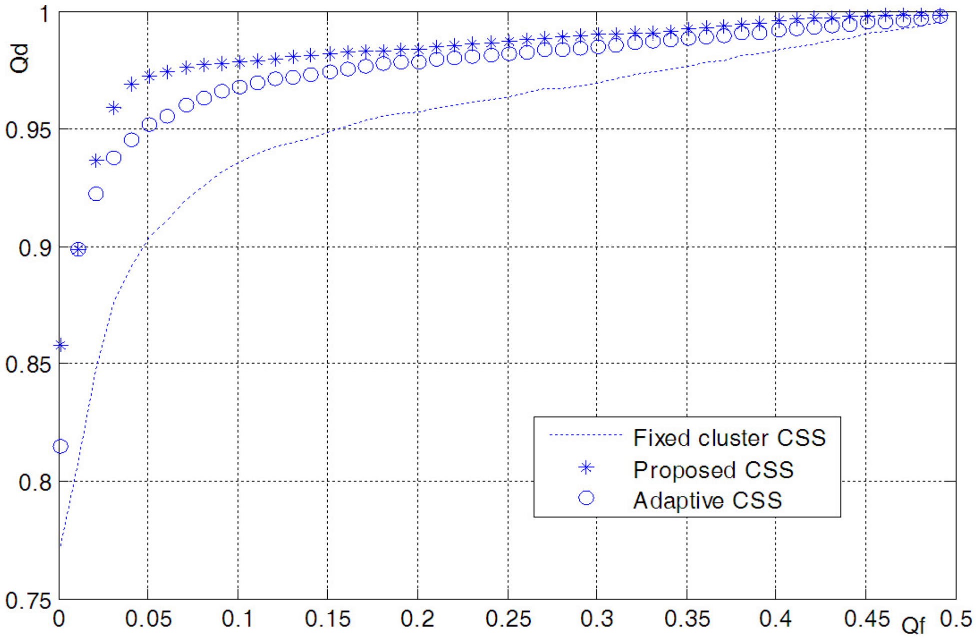

Figure 2. Available detection region under low *SNR*

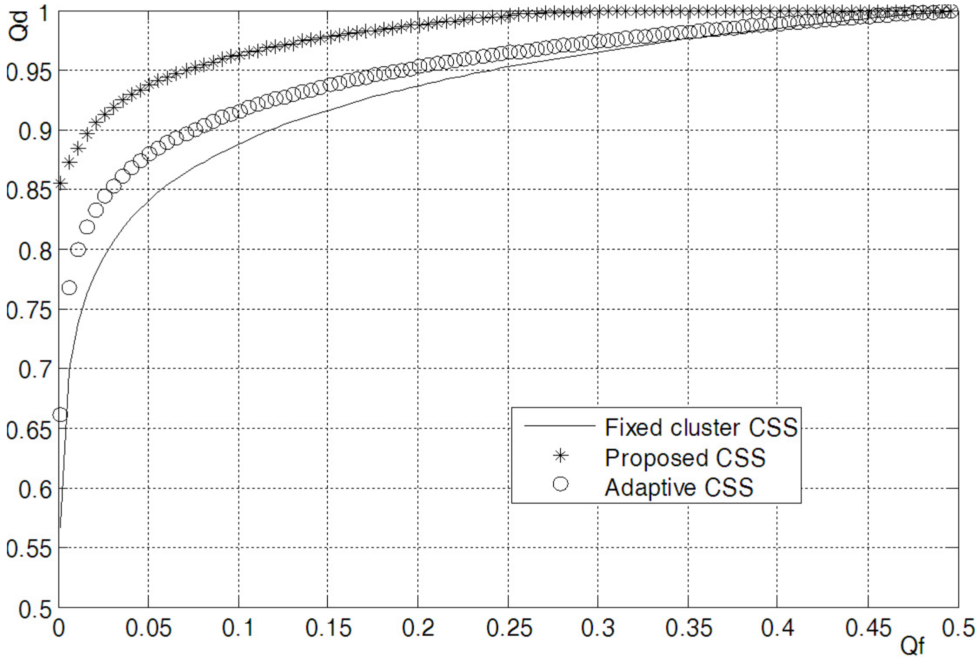

Figure 3. Available detection region under high *SNR*

of all CHs were around the threshold, $\gamma_{and} = 6.2$dB, Q_f and Q_d were both decreased and the detection system ran out of the available detection region. The proposed CSS could keep the system in the available region by selecting cooperative nodes and fusion rule in FC using adaptive cluster threshold, γ_T. The adaptive CSS could select the nodes in high quality channels to detect cooperatively, but some nodes with low *SNR* was also forced to be selected under all nodes in bad channels for adaptive detection threshold.

Assume that $E_{BC} = 2E_S = 2E_R = 2E$ for simplification. In the channels with low *SNR*, the energy consumption of three schemes was shown in Figure 4. In cluster model, the objected based CSS had the best energy efficiency. Here the cluster with $SNR_{CH} < \gamma_{or}$ could not take part in local sensing and reporting decision in the proposed CSS. And the CH with $SNR_{CH} < \gamma_{or}$ became an objector in objected based CSS. However, in

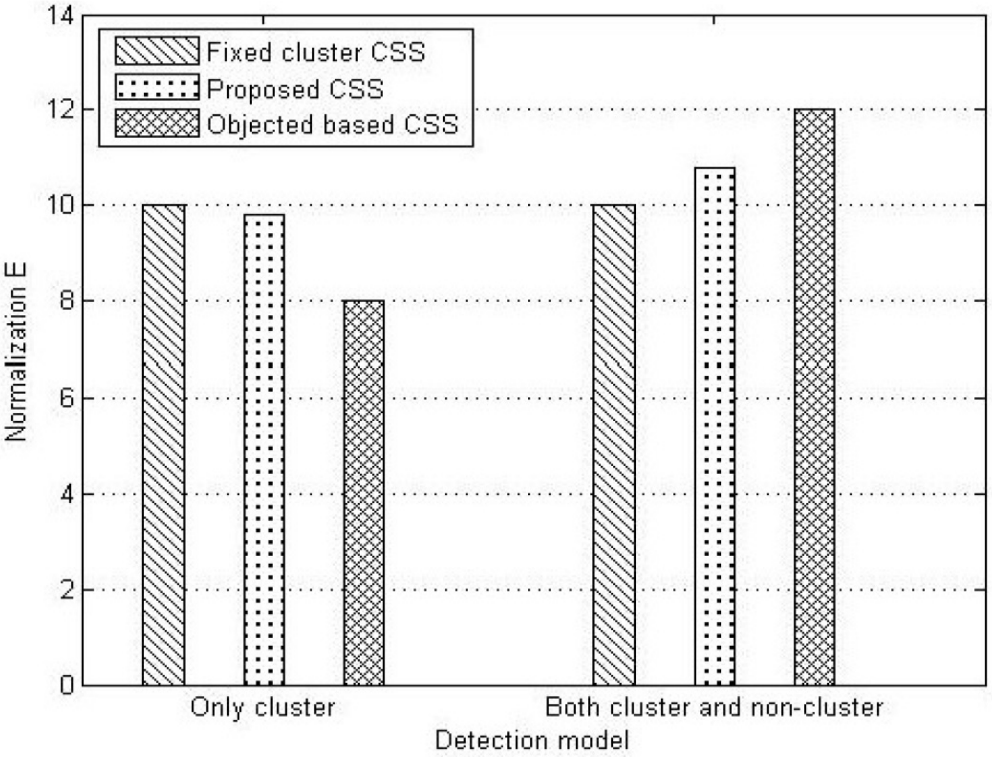

Figure 4. Total energy consumption

incomplete cluster model, the objected based CSS had the worst energy efficiency. The SUs in the cluster with $SNR_{CH} < \gamma_{or}$ would take part in cooperative detection by no-cluster way. These SUs became the objectors because of poor SNR. It was worth noting that the proposed CSS had an optimal tradeoff between the energy consumption and the global detection performance. In the channels with high SNR, the objected based CSS had the best energy efficiency. The energy efficiency of fixed cluster CSS was the same as the proposed CSS. However, there was not always high SNR in time-variation channels.

From the simulation results, the proposed CSS increased the available idle licensed channels (Area belong to $Q_d \geq 0.9$ and $Q_f \leq 0.1$) and decreased the energy efficiency as much as possible under the minimum global detection performance requirements.

4. **Conclusions.** In this paper, the proposed CSS can employ an optimal cooperation strategy under the constraints from the channel quality, the minimum performance requirements, and the energy consumption. The scheme can select the cooperative SUs and matched fusion rule adaptively according to the status in fading channel in detection period. For grouping all SUs into several clusters quickly, the cluster head election method based on the minimum spanning tree theory is proposed to improve the stability of cluster and decrease the time complexity of clustering. The proposed CSS scheme can expand the available detection region by about 20% to find more idle channels for maximizing the throughput. In practice, the idle channels with various available bandwidths and stabilities are not suited to all SUs with diversity quality of service requirements. Thus, the idle channels should be managed and allocated for different access applications according to the spectrum characteristics. An service awareness adaptive cooperative spectrum detection and allocation algorithm should be investigated in the future.

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