A Censored and Ordered Sequential Collaborative Spectrum Sensing Scheme based on Evidence Theory for CRAHN

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***Abstract*—This paper proposes a censored and ordered sequential collaborative spectrum sensing scheme for cognitive radio ad hoc network (CRAHN). The scheme uses the ordered of the sensing data reliability for enabling the Dempster Shafer theory of evidence sequential combination. A preceding censored process removes the nodes having insignificant sensing data to the broadcasting sensing result process. The advantage of ordered sequential and censored mechanism will help to reduces communication resources (the energy consumption, the coordination and overhead in control channel and the sensing result collecting time) while keeping the same sensing performance compared with the conventional centralized cooperative spectrum sensing.**

***Index Terms*—cognitive radio, spectrum sensing, collaborative, sequential fusion, censoring, Dempster Shafer theory**

I. Introduction

In recent years, Cognitive Radio (CR) which enables opportunistic access to underutilized licensed spectrum band has been considered as a promising technology. Spectrum sensing (SS) plays an essential role in CR. Among various spectrum sensing techniques, energy detection is an engaging method due to its easy implementation and admirable performance. However, its major disadvantage is that the receiver signal strength can be seriously weakened at a particular geographical location due to multi-path fading and shadow effect [1]. In order to overcome the hidden node problem in which a single sensing node cannot distinguish between an idle or a deep fade band, the collaborative SS scheme has been considered in many literatures (see [2]-[8] for examples).

By utilizing the diversity of distributed sensing data resources based on a fusion rule such as “And rule,” “Or rule,” “k out of n,” etc. [2][3], cooperative spectrum sensing (CSS) can simultaneously decrease both the miss detection and the false-alarm probability of a single sensing node. A data fusion scheme for CR network based on Dempster-Shafer theory of evidence (D-S theory) was first proposed in [4]. This scheme shows a significant improvement in the detection probability as well as considerable reduction in the false alarms probability without any requirement of prior primary system’s activity information. Nguyen Thanh and Koo [5] enhanced the D-S theory based fusion scheme in [4] to obtain a very high gain of combination by utilizing available primary signal’s SNR. However, such above advantages of data fusion schemes are at the cost of overhead traffic of control signaling and sensing results transmission, which consumes more communication resources such as reporting time delay, control channel bandwidth and transmission energy. The requirement resources will be extremely large when the number of CR User (CU) increases. However, only a few works have considered this problem. Yeelin and Su [6] proposes a sequential test for CSS to control the average number of the reporting bits and reduce the mean detection time and bandwidth. In [7], a data fusion scheme which utilizes a D-S theory based ordered sequential test for higher efficiency (i.e, lower reporting resources requirement) and faster detection is proposed. However, all of these sequential fusion schemes not only do not take advantage of removing the low reliability data from reporting by a censoring method as proposed in [8] but also can be only applied for centralized CR networks which require a data fusion center to control the process of sequential test.

For the case of CR ad hoc network (CRAHN), due to the lack of central controller, each CU is responsible for determining its actions based on its local observation. Since the CU cannot predict the influence of its actions on the entire network only with its local observation, collaboration schemes, in which the observed information can be exchanged among devices are essential [9]. Therefore, it is necessary to consider an effective mechanism for sequential fusion in such the case.

In this paper, we propose a collaborative SS scheme for CRAHN based on censored and ordered sequential D-S theory combination. The censored and ordered collaborative mechanism enables the sensing data sequentially to be combined in a descending sequence of reliability. This will help to reduce the number of reporting data and the sensing time.

The rest of the paper is organized as follows. Section 2 describes the system model. Section 3 introduces the collaborative spectrum sensing based on D-S theory. Section 4 proposes the censored and ordered collaborative mechanism. Section 5 develops the censored and ordered sequential D-S

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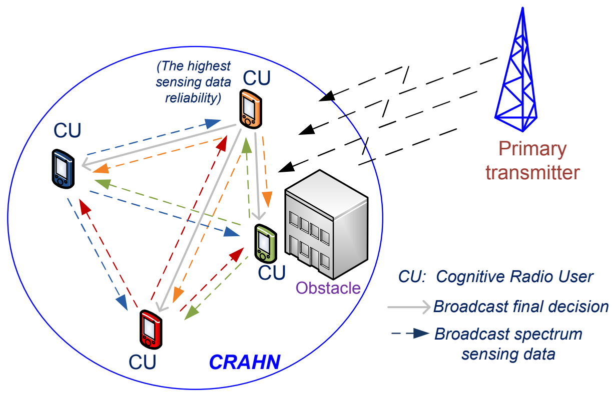

Fig. 1. System model

theory based collaborative SS scheme. Section 5 shows the simulation results. Finally, Section 6 concludes the paper.

II. System Description

We consider a single-hop CRAHN with a dedicated common control channel (CCC) and multiple CUs sharing the same frequency band with a licensed system as shown in Fig. 1. In order to increase the reliability of the licensed user (LU) protection, the CUs, after sensing the spectrum band, exchange their SS information each other. Therefore, the collaborative SS model which does not require a central controller will be adopted into our CRAHN. As a result, the whole process of SS includes two phase: the individual SS phase and the collaborative phase. The individual SS for detecting the LUs signal is essentially a binary hypotheses testing problem as follows:

$$\begin{cases} H_0 : x\left(t\right) = n\left(t\right) \\ H_1 : x\left(t\right) = h\left(t\right) s\left(t\right) + n\left(t\right) \end{cases} \tag{1}$$

where H_0 and H_1 are the hypotheses of the absence and presence of the LU's signal, respectively, $x\left(t\right)$ represents the received data at the CU, $h\left(t\right)$ denotes the gain of the channel between LU and CU, $s\left(t\right)$ is the signal transmitted from the primary user and $n\left(t\right)$ is the additive white Gaussian noise. The spectrum sensing method is energy detection. The output of energy detector is the received signal power which is given by

$$x_E = \sum\nolimits_{n=1}^{N} \left|x_n\right|^2 \tag{2}$$

where x_n is the n-th sample of the received signal and $N = 2TW$. T and W denote the detection time and signal bandwidth, respectively. When N is relatively large (e.g. $N > 200$), x_E can be well approximated as a Gaussian random variable under both hypotheses H_1 and H_0, with mean μ_1, μ_0 and variance σ_1^2, σ_0^2, respectively [10], such that

$$\begin{cases} \mu_0 = N & \sigma_0^2 = 2N \\ \mu_1 = N\left(\gamma+1\right) & \sigma_1^2 = 2N\left(2\gamma+1\right) \end{cases} \tag{3}$$

where γ is the SNR of the LU's signal at the CU.

III. The D-S theory based collaborative spectrum sensing

A. Basic probability assignment estimation

In order to apply D-S theory of evidence to the collaborative spectrum sensing scheme, the frame of discernment A is defined as $\{H_1, H_0, \Omega\}$, where Ω, called ignorance hypothesis, denotes either hypotheses is true. After sensing time, each CU will estimate its self-assessed decision credibility which is equivalent to Basic Probability Assignment (BPA) for these hypotheses. The BPA function is defined as a form of the cumulative density function similar to those in [5] as follows:

$$m_i\left(H_0\right) = \int_{x_{E_i}}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_{0i}} \exp\left(-\frac{\left(x-\mu_{0i}\right)^2}{2\sigma_{0i}^2}\right) dx \tag{4}$$

$$m_i\left(H_1\right) = \int_{x_{E_i}}^{+\infty} \frac{1}{\sqrt{2\pi}\sigma_{1i}} \exp\left(-\frac{\left(x-\mu_{1i}\right)^2}{2\sigma_{1i}^2}\right) dx \tag{5}$$

$$m_i\left(\Omega\right) = 1 - m_i\left(H_1\right) - m_i\left(H_0\right) \tag{6}$$

where $m_i\left(H_0\right)$, $m_i\left(H_1\right)$ and $m_i\left(\Omega\right)$ are the BPA of hypotheses H_0, H_1 and Ω of the i-th CU, respectively. Using these functions, the BPA of hypotheses H_0 and H_1 are unique for each test statistics value x_{E_i} and vary in such a way that the larger x_{E_i} is the larger $m_i\left(H_1\right)$ and the smaller $m_i\left(H_0\right)$ are and vice versa. These values are broadcasted from various CUs and combined at each CUs to obtain a final decision.

B. D-S theory based combination

According to the D-S theory of evidence, the combination of the BPAs from n sources can be obtained via the following equations [11]:

$$m\left(H_0\right) = \sum_{A_1 \cap A_2 \cap . A_n = H_0} \prod_{i=1}^{n} m_i\left(A_i\right) \Big/ \left(1-K\right) \tag{7}$$

$$m\left(H_1\right) = \sum_{A_1 \cap A_2 \cap . A_n = H_1} \prod_{i=1}^{n} m_i\left(A_i\right) \Big/ \left(1-K\right) \tag{8}$$

where

$$K = \sum_{A_1 \cap A_2 \cap \ldots A_n = \emptyset} \prod_{i=1}^{n} m_i\left(A_i\right)$$

and A_i can be one element of the set $\{H_1, H_0, \Omega\}$.

A simple decision strategy is chosen; and the global decision is made while considering the following numerical relationships:

$$\log\left(\frac{m\left(H_1\right)}{m\left(H_0\right)}\right) \underset{H_1}{\overset{H_0}{\lessgtr}} 0 \tag{9}$$

where the ratio $\frac{m(H_1)}{m(H_0)}$ is considered as the global combination ratio.

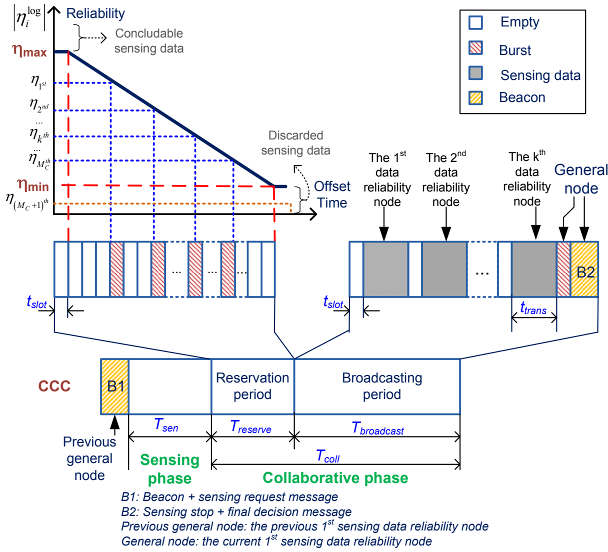

Fig. 2. The censored and ordered collaborative mechanism

IV. The Censored and Ordered Collaborative Mechanism

As mentioned above, the main problem of D-S theory based collaborative spectrum sensing as well as other schemes is the large communication resource requirement for reporting sensing results, particularly, in a large cognitive radio network. For this reason, in order to reduce the overhead, the total processing time and the energy consumption for spectrum sensing, we propose an censored and ordered sensing data reliability broadcasting mechanism in which nodes with higher current sensing datas reliability will broadcast earlier and nodes with sensing datas reliability lower than a censored threshold will not report as shown in Fig. 2. The highest sensing data reliability node, which is free after first broadcasting its sensing data, becomes the general node and makes the final decision.

The proposed ordered collaborative mechanism includes the reservation period and the broadcasting period. In the first period, the CUs make a reservation by utilizing a short burst signal according to a reservation timeslot R_T. Since every CU can listen to the CCC, the broadcasting time slot position can be determined according to the reservation burst order.

In details, the reservation period $T_{reserve}$ is divided into κ reservation timeslots ($\kappa \geq M$, i.e., number of CUs). Each timeslot length t_{slot} is equal to a slot time, i.e., the time required by the radio layer for functioning carrier sensing.

After sensing the spectrum band, each CU estimates its data reliability and conducts a censored process. This means that the CU will take no action if the sensing data reliability is smaller than a minimum reliability threshold η_{min}. The selection of the minimum threshold has to guarantee that the discarded, i.e. lower reliability than η_{min}, sensing data have less significant in the contribution to final decision if it is used.

After the censored process, the CU whose sensing data reliability is larger than η_{min} will calculate the reservation timeslot R_T according to the data reliability as follows:

$$R_T = \left\lfloor \frac{\eta_{\max} - \eta_i^{\log}}{\eta_{\max} - \eta_{\min}} \kappa \right\rfloor \tag{10}$$

where $\lfloor . \rfloor$ is a round-down operator and η_{max} is the maximum reliability threshold. The η_{max} is selected large enough such that a reliable final decision can immediately be concluded if the data reliability is a larger than that value.

In broadcasting period, CUs will transmit their sensing data at the corresponding reserved data timeslot if the first part of the data timeslot, equivalent to a slot time, is empty. In contrast, if the first part of the data timeslot is occupied by a burst signal, the nodes have to wait for the followed beacon message which includes the stop broadcasting request and final decision result from the general node.

V. The Censored and Ordered Sequential D-S Theory Based Collaborative Spectrum Sensing Scheme

For broadcasting the sensing result in the sequence of the data reliability, the i-th CU will make its self-assessed credibility ratio which is defined by:

$$\eta_i^{\log} = \left| \log \frac{m_i(H_1)}{m_i(H_0)} \right|. \tag{11}$$

At the general node, the broadcasted BPA is immediately combined in the sequence as follows:

$$m_{combined}^k(H_j) = m_{combined}^{k-1}(H_j) \oplus m_k(H_j) \quad j = 0, 1 \tag{12}$$

where $k = 1, ..., M_C$, $m_{combined}^{k-1}(H_j)$ and $m_{combined}^k(H_j)$ are the $(k-1)$-th and (k)-th combined BPA of hypothesis H_j, respectively, M_C is the total number of CUs joined in the broadcasting process after censoring and $\oplus$ is the combination operator defined based on DS-theory as follows:

$$m_a \oplus m_b(H_j) = \frac{m_a(H_j)m_b(\Omega)+m_a(H_j)m_b(H_j)+m_a(\Omega)m_b(H_j)}{1-[m_a(H_j)m_b(H_{1-j})+m_a(H_{1-j})m_b(H_j)]}, \tag{13}$$

$$m_a \oplus m_b(\Omega) = 1 - m_a \oplus m_b(H_1) - m_a \oplus m_b(H_0), \tag{14}$$

where $j = 0, 1$, and a and b denote the two arbitrary combining sources.

Due to the commutative and associative properties of the D-S theory combination operator $\oplus$, the combined result of the sequential CSS scheme will be equal to that of the non-sequential one as in (7) and (8) when all nodes' sensing data are combined as the same time. Therefore, instead of using the 0 as a threshold for the final decision making as in (9), the general node adopts a couple thresholds $\pm\delta$ where $\delta > 0$ for comparing the combination ratio. The value of δ is selected large enough so that the cooperative gain is equivalently maintained though the number of combined sensing data is lower. The proposed sequential fusion scheme is based on the following final decision making strategy:

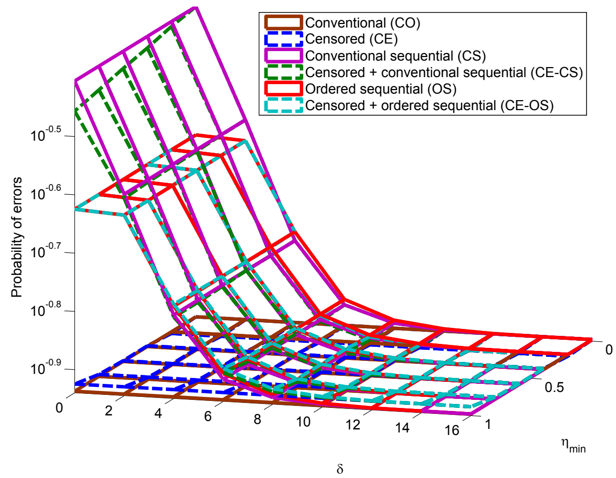

Fig. 3. The error probabilities of different fusion schemes vs. both the censoring threshold η_{min} and the sequential test's threshold δ under the LUs signal SNR = -15 dB at all 20 CUs.

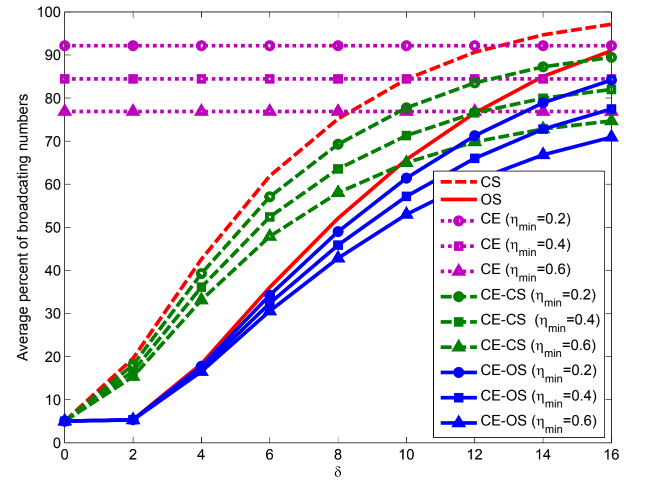

Fig. 4. The average percent of broadcasting number of different fusion schemes vs. the threshold value of sequential test δ with different values of censoring threshold η_{min} under the LUs signal SNR = -15 dB at all 20 CUs.

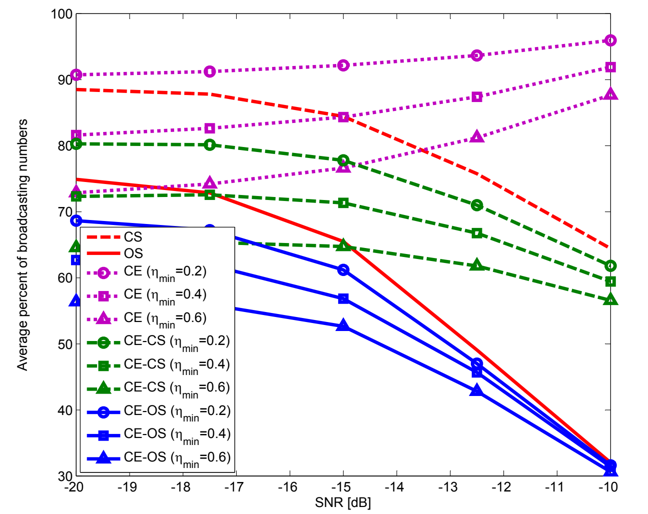

Fig. 5. The average percent of broadcasting number of different fusion schemes vs. the LU's signal SNR values with different values of censoring threshold η_{min} under the sequential test's threshold δ = 10.

- If $k < M_C$ then

$$D_{final} = \begin{cases} H_1 & \text{if } \eta^k_{combined} > \delta \\ \text{no decision} & \text{if } -\delta < \eta^k_{combined} < \delta \\ H_0 & \text{if } \eta^k_{combined} < -\delta \end{cases}$$

where D_{final} denotes the global decision, M is the total number of CUs in the network and $\eta^k_{combined}$ represents the global decision credibility ratio at the k-th report which is given by:

$$\eta^k_{combined} = \log \frac{m^k_{combined}(H_1)}{m^k_{combined}(H_0)}. \quad (15)$$

In the case that $-\delta < \eta^k_{combined} < \delta$ the general node will wait for the next data report.

- If $k = M_C$ then the truncated process is applied as follows:

$$D_{final} = \begin{cases} H_1 & \text{if } \eta^k_{combined} > 0 \\ H_0 & \text{if } \eta^k_{combined} < 0 \end{cases}.$$

VI. Simulation Results

For simulation, we assume that the LU signal is DTV signal whose bandwidth is 6 MHz. 20 sensing nodes with the same LU signals SNR are in the network. The local sensing time is 50 μs. Firstly, we consider the influence of the censoring threshold η_{min} and the sequential test's threshold δ on the collaborative SS performance, i.e. the global error probability as shown in Fig.3. In the figure, the *conventional* (CO), the *conventional sequential* (CS), the *censored* (CE), the *censored and conventional sequential* (CE-CS), the *ordered sequential* (OS) and the *censored and ordered sequential* (CE-OS) DS-theory based data fusion are simulated under the same LUs signal SNR as -15 dB at all 20 CUs. As shown in the figure, the error probabilities of all others fusion scheme are converged to that of CO DS-theory based one when the value threshold δ is adequate enough (i.e. $\delta \geq 8$). Furthermore, when the threshold δ is large the increasing of threshold η_{min} in the range [0, 1] softly reduces the sensing performance.

Fig. 4 shows the average percent of broadcasting number of CS, CE, OS, CE-CS and CE-OS fusion schemes according to δ with different values of η_{min} under the LU's signal SNR = -15 dB at all 20 CUs. The figure indicates that the number of broadcasting nodes is low when the threshold δ is low. Therefore, the selection of threshold δ is a tradeoff between performance and network overhead. Beside, as shown in the Fig.4, the average percent of broadcasting number for the same fusion scheme will decrease when we increase the value of η_{min}. In the case of our proposed CE-OS scheme, at $\delta = 10$, for example, the average percent of broadcasting number is 65% for η_{min} = 0 (i.e., OS scheme), 60% for η_{min} = 0.2 and 52% for η_{min} = 0.6. This result is fully significant if we note that the SS performance is almost unaffected in the range from 0.2 to 0.6 of the threshold η_{min} at δ = 10 in Fig. 3. Above all, compared with other schemes, our proposed CE-OS

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fusion outperforms the other schemes in the same threshold condition. Indeed, as shown in the Fig. 4, at δ = 10 and η_{min} = 0.6, the average broadcasting number percent is 77% for CE fusion, 62% for CE-CS fusion and 52% for our proposed CE-OS fusion.

For further consideration, the five above schemes are simulated with different SNR conditions and different threshold η_{min} values while keeping δ =10. As shown in the Fig.5, for CE fusion, the broadcasting number increases when the SNR increases. This can be explained by the fact that the sensing data reliability will be improved when the SNR increases. For both CE-CS and CE-OS fusion, however, the broadcasting numbers is reduced when the SNR value increases. Similarly to previous results the same best performance is obtained by our proposed CE-OS scheme.

VII. Conclusions

In this paper, a censored and ordered sequential D-S theory based collaborative SS scheme for CRAHN has been proposed. The preceding censored process and the followed ordered sequential fusion not only mantain the same sensing performance compared with the conventional cooperative centralized spectrum sensing scheme but also strongly reducing the collaborative resource requirements such as the overhead of control channel, the energy and the collecting sensing data time. For future works, the detail protocol for coordination between CUs and the timming for making the proposed scheme precisely work in practice require more research.

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