Sensing-throughput Tradeoff in Cluster-based Cooperative Cognitive Radio Networks: A Novel Frame Structure

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Abstract— **In cooperative cognitive radio networks (CCRNs), the reporting time is consumed by all secondary users (SUs) for reporting the sensing results to the central node or fusion center. Intuitively, the performance of CCRNs will be degradation, since the more SUs for cooperation, the more reporting time for reporting sensing results. However, most previous studies have not considered this point. In this paper, a cluster-based cooperative spectrum sensing model is proposed in order to reduce the reporting time. Based on a novel frame structure, a sensing-throughput tradeoff problem considering the reporting time is formulated for two scenarios. The optimal clustering rule is obtained by maximizing the transmission time of all SUs. Then, a low-complexity solution is proposed to solve the tradeoff problem, which shows close-to-optimal performance by simulation.**

I. INTRODUCTION

The rapid development of new wireless devices and services has lead to a growing demand for wireless radio spectrum [1]. Cognitive radio is an enabling technology for future communications and networking since it can utilize the limited spectrum resources in a much more efficient and flexible manner [2]. Spectrum sensing, which is used to detect the state of primary users (PU), is the first step in cognitive radio. In cognitive radio networks (CRNs), the sensing performance is greatly influenced by shadowing and multipath. To overcome this problem, cooperative spectrum sensing scheme [3], which fuses the sensing results of all secondary users (SUs) distributed in the whole CRN, is proposed. In cooperative CRNs, the more SUs for cooperation, the better performance of spectrum sensing. However, when the number of cooperative SUs is large, too much time is needed for reporting the sensing results, which reduces the time left for data transmission. Recently, a cluster-based cooperative spectrum sensing model [4] is proposed to release the crowded reporting channel. By dividing all SUs in the CRN into some clusters and selecting a proper SU in each cluster as the head user for reporting to the fusion center (FC), the cluster-based cooperative spectrum sensing reduces the reporting time consumption of SUs significantly.

Some previous work has studied the cluster-based cooperative CRN. [4] introduces the general steps that cluster-based cooperative spectrum sensing performs. Two fusion rules in each cluster is proposed to improve the sensing performance. [5] and [6] focus on the optimization of the cluster-based cooperative spectrum sensing system. Considering the tradeoff between efficiency and reliability, [5] obtains the optimal number of clusters in CRN assuming that the reporting channel is perfect. [6] proposes a new multi-cluster multi-group based cooperative spectrum sensing scheme, which obtains the optimal number of groups to minimize the error rate of each cluster.

However, all of these work aforementioned only consider the performance of sensing scheme, while ignoring optimization of throughput of CRN which is related to the data transmission time and user reporting time consumption. Specifically, high sensing performance ensures more opportunities for SUs to use licensed spectrum. While longer data transmission time guarantees the efficient use of PU's resource by SUs. In this paper, a novel frame structure is used, where the sensing, reporting and data transmission operate periodically. A sensing-throughput tradeoff problem is proposed by jointly considering the sensing performance and data transmission. The optimal clustering rule is obtained by maximizing the transmission time of all SUs. Then, a low-complexity solution is proposed to solve the tradeoff problem, which shows close-to-optimal performance by simulation. Without the loss of generality we use the energy detection [7] method to conduct the spectrum sensing.

II. SYSTEM MODEL AND FRAME STRUCTURE

Fig.1 shows the system model of cluster-based cooperative CRN. There is a PU in the primary user network (PUN). We assume that there are K SUs in the CRN, who are divided into L clusters. The ith cluster has N_i (N_i is an integer) SUs, which satisfies

$$\sum_{i=1}^{L} N_i = K. \tag{1}$$

The SU that has the best reporting channel quality to the FC is selected as a head user. The FC only processes the sensing information from the head users. The novel frame structure is shown in Fig.2. The total frame length is fixed to T, in which sensing and decision time τ_s and data transmission time

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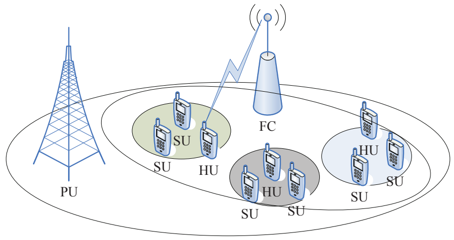

Fig. 1. System model

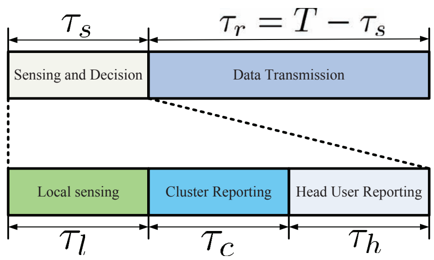

Fig. 2. Frame structure for cluster-based cooperative spectrum sensing system

$\tau_r = T - \tau_s$ are two main parts. τ_s consists of local sensing time τ_l, cluster reporting time τ_c and head user reporting time τ_h. For each SU in this paper, τ_l is also fixed.

The following five steps are conducted in the cluster based CRN.

1) Clustering and local sensing. All SUs are divided into a few clusters based on proper clustering rules. Then, during τ_l, SUs sense the state of PU independently with their energy detectors. Each SU uses the hard decision method [8].

2) Cluster reporting. During τ_c, each SU (except the head user) reports the sensing result to the head user in the way of time division multiplex access (TDMA). Due to clustering, SUs in different cluster can use the same time slot to send the results to their head users. Head user uses a certain fusion rule to fuse the sensing results of other SUs in its cluster.

3) Head user reporting. During τ_h, all head users will send the fused sensing results to the FC in the way of TDMA.

4) Final decision. The FC fuses the reporting information of all head users and makes the final decision.

5) Data transmission. If the final decision is that the PU is active, all the SUs will keep silent until the next frame to start local sensing again. Otherwise, the SUs start data transmission with the frequency of PU during the left time of the current frame.

III. Optimal Clustering Rule for Data Transmission Time Maximization

In this section we obtain the optimal rule to maximize the data transmission time. From the frame structure we can get

$$\tau_s = \tau_l + \tau_c + \tau_h. \tag{2}$$

We assume that each SU consumes one fixed time slot δ to report its sensing result. Time consumption of cluster reporting is

$$\tau_c = \max_{i=1,2,\ldots,L} N_i * \delta - \delta. \tag{3}$$

The head user reporting consumes

$$\tau_h = L * \delta. \tag{4}$$

Intuitively, the sensing and decision time depends on the quantity of cluster L. Since the total frame length is fixed, the transmission time maximization is equal to the sensing and decision time minimization. The sensing and decision time minimization problem can be described below:

$$\min_L \ \tau_s \tag{5}$$

$$s.t.\textbf{equation}(1)(2)(3)(4)$$

As we know $\max\limits_{i=1,2,\ldots,L} N_i$ is not smaller than the average value K/L (we assume that K/L is an integer). So we get

$$\min_L \tau_s = \tau_l + \min_L[\max_i N_i\delta - \delta + L\delta] \geq \tau_l + \min_L[(K/L)\delta + L\delta - \delta]. \tag{6}$$

Use the monotonicity of function $f(x) = K/x + x(x > 0, K > 0)$ and (6) is rewritten as

$$\min_L \tau_s \geq \tau_l + \min_L[(K/L)\delta + L\delta - \delta] = \tau_l + 2\sqrt{K}\delta - \delta. \tag{7}$$

When $L = \sqrt{K}$, the equal sign of (7) is satisfied and the time for sensing and detection is the smallest for each frame. This is the optimal clustering rule for transmission time maximization. This rule is used in the suboptimal solution for the formulated sensing-throughput problems in the next section.

IV. Sensing-Throughput Tradeoff

In this section the sensing-throughput tradeoff problem for two different scenarios in cluster-based cooperative CRNs is formulated. A suboptimal solution for these sensing-throughput trade off problems is proposed.

A. Scenario I

Scenario I is based on the assumptions below.

- The cluster-based cooperative CRN is small compared to the PUN. The whole CRN has almost the same path-loss.
- The reporting channel quality between SU and its head user or between the head user and FC is perfect.
- Each cluster has the same quantity of SUs.

In scenario I, clustering can be simply based on the locations of SUs. SUs that are close to each other will be divided into the same cluster. For a cluster, any SU is selected as the head user will make no difference. The cluster-based cooperative CRN for scenario I conducts below.

1) Local sensing. The received signals of each SU are

$$\mathcal{H}_1 : y(n) = s(n) + u(n), \tag{8}$$

$$\mathcal{H}_0 : y(n) = u(n), \tag{9}$$

where $\mathcal{H}_1$/ $\mathcal{H}_0$ represents the active/ inactive state of PU, $s(n)$ is the signal received by the SU, $u(n)$ is the noise with zero mean and variance σ^2. The test statistic for the energy detector is

$$T(y) = \frac{1}{N}\sum_{n=1}^{N}|y(n)|^2, \tag{10}$$

where $N = f_s * \tau_l$ is the total sample size, f_s is the sample frequency. Using the Central Limit Theorem the test statistic can be approximated by a Gaussian distribution. With the first assumption of scenario I the false alarm probability p_f and detection probability p_d of each SU can be obtained in [9].

2)Sensing result fusion. K-out-of-N fusion rule is adopted in the head user and 'OR' fusion rule is adopted in the FC [10]. With the third assumption of scenario I, we know that each cluster has K/L SUs, the global detection probability and false alarm probability are

$$Q_d = 1 - (1 - \sum_{k=l}^{K/L}\binom{(K/L)}{k}(p_d)^k(1-p_d)^{\frac{K}{L}-k})^L, \tag{11}$$

$$Q_f = 1 - (1 - \sum_{k=l}^{K/L}\binom{(K/L)}{k}(p_f)^k(1-p_f)^{\frac{K}{L}-k})^L. \tag{12}$$

3) Data transmission. There are two cases in which SUs will transmit data.

Case 1 PU is active but the FC fails to detect the active state of PU. The throughput of all SUs in case 1 is

$$R_1 = \frac{T-\tau_s}{T}\sum_{i=1}^{K}\log_2(1+SNR_{1,i}), \tag{13}$$

where $SNR_{1,i}$ is the signal to noise ratio of the ith SU during τ_r under the hypothesis $\mathcal{H}_1$.

Case 2 PU is inactive and the FC succeeds in detecting the absence of the PU. The throughput of all SUs in case 2 is

$$R_0 = \frac{T-\tau_s}{T}\sum_{i=1}^{K}\log_2(1+SNR_{0,i}), \tag{14}$$

where $SNR_{0,i}$ is the signal to noise ratio of the ith SU during τ_r under the hypothesis $\mathcal{H}_0$. The total throughput of CRN is

$$\mathcal{C} = R_1(1-Q_d)\mathcal{P}(\mathcal{H}_1) + R_0(1-Q_f)\mathcal{P}(\mathcal{H}_0), \tag{15}$$

where $\mathcal{P}(\mathcal{H}_1)$/$\mathcal{P}(\mathcal{H}_0)$ is the probability of the state that the PU is active/inactive. In practice, we have $\mathcal{P}(\mathcal{H}_0) > \mathcal{P}(\mathcal{H}_1)$ in CRN. A high protection to the PU is necessary, which means that the Q_d should be high enough. So the first part of (15) can be negligible. The throughput can be approximated as

$$\mathcal{C} \approx R_0(1-Q_f)\mathcal{P}(\mathcal{H}_0). \tag{16}$$

The sensing-throughput optimization problem can be described below:

$$\max_{L,l}\mathcal{C} \tag{17}$$

subject to

$$Q_d \geq \overline{Q_d}, \tag{18}$$

where $\overline{Q_d}$ is the lowest needed global detection probability.

When the CRN detects the resource of PU is available, the CRN operates as a normal wireless system by using the resource of PU. From the view of the CRN, more opportunities to fully use the resource of PU can surely lead to the throughput maximization. So we can ignore the SNR part of (17) and just focus on optimizing the opportunities to fully use the PU's resource. From (14) and (16) We define

$$\overline{\mathcal{C}} = \frac{\mathcal{C}}{\mathcal{P}(\mathcal{H}_0)\sum_{i=1}^{K}\log_2(1+SNR_{0,i})} = \frac{T-\tau_s}{T}(1-Q_f) \tag{19}$$

as the factor of capacity (FoC). Then the optimal problem is simplified to relying on the data transmit time and the false alarm probability. From (19) we can get the upper bound of FoC. When the false alarm probability is equal to zero and data transmission time is the maximum, the upper bound of FoC is obtained. The sensing and detection time in scenario I is

$$\tau_s = \tau_l + (K/L)*\delta - \delta + L*\delta \tag{20}$$

Due to the positive correlation between Q_d and Q_f, the minimum false alarm probability is obtained when $Q_d = \overline{Q_d}$. So the simplified optimal problem can be rewritten as

$$\max_{L,l}\overline{\mathcal{C}} \tag{21}$$

subject to

$$Q_d = \overline{Q_d}, \tag{22}$$

where $L(1 \leq L \leq K)$ and $l(l = 1, 2, \ldots K/L)$ are all integers. Then, the optimal solution can be found by comparing all the possible set (L, l).

B. Scenario II

The main assumptions that Scenario II different from scenario I are given below.

- Each SU experiences fading. The reporting channels among SUs in the same cluster are not perfect. The reporting channels between head users and the FC are also not perfect.

Based on the above assumptions, the cluster-based cooperative CRN for scenario II is conducted below.

1) Clustering and local sensing. We perform clustering operations according to the rules below. First, sort all the SUs' channel gains in ascending order. Then, based on the order, divide the K SUs into L clusters, so that each cluster has the the same quantity of SUs and SUs in the same cluster have the most likely channel gains. In each cluster, the SU that has the best report channel gain to the FC will be selected as the head user. During the sensing stage, the received signals of the ith SU in the jth cluster are

$$\mathcal{H}_1 : y_{i,j}(t) = h_{i,j} * s(t) + n_{i,j}(t), \tag{23}$$

$$\mathcal{H}_0 : y_{i,j}(t) = n_{i,j}(t), \tag{24}$$

where $h_{i,j}$ is the channel gain between the PU and the SU, $n_{i,j}$ is the noise with zero mean and variance $E[|n_{i,j}|] = \sigma_u^2$, $s(t)$ is the transmitted signal of the PU.

The detection probability $\overline{p}_{d,i,j}$ and false alarm probability $p_{f,i,j}$ of the ith SU in the jth cluster that experiences Rayleigh fading can be obtained in [5].

2) Sensing results fusion. The detection probability and false alarm probability of each cluster are

$$\overline{p}_{d,i} = \sum_{k=l_i}^{N_i} \binom{N_i}{k} (\overline{p}_{d,i,j} * (1 - p_{e,c,i}) + (1 - \overline{p}_{d,i,j}) * p_{e,c,i})^k * \\ (1 - (\overline{p}_{d,i,j} * (1 - p_{e,c,i}) + (1 - \overline{p}_{d,i,j}) * p_{e,c,i})^k)^{N_i - k}, \tag{25}$$

$$\overline{p}_{f,i} = \sum_{k=l_i}^{N_i} \binom{N_i}{k} (p_{f,i,j} * (1 - p_{e,c,i}) + (1 - p_{f,i,j}) * p_{e,c,i})^k * \\ (1 - (p_{f,i,j} * (1 - p_{e,c,i}) + (1 - p_{f,i,j}) * p_{e,c,i})^k)^{N_i - k}, \tag{26}$$

where $p_{e,c,i}$ is the ith cluster reporting error rate due to the interference from other SUs. In the FC, the global detection probability and false alarm probability are

$$Q_d = 1 - \prod_{i=1}^{L} (1 - ((1 - \overline{p}_{d,i}) * (1 - p_{e,i}) + \overline{p}_{d,i} * p_{e,i})), \tag{27}$$

$$Q_f = 1 - \prod_{i=1}^{L} (1 - ((1 - p_{f,i}) * (1 - p_{e,i}) + p_{f,i} * p_{e,i})), \tag{28}$$

where $p_{e,i}$ is the head user reporting error rate of the ith cluster due to fading.

3) Data transmission. The throughput of the system is the same as equation (15), but the corresponding probabilities of the equation belong to scenario II. The sensing-throughput optimization problem of scenario II can be described below:

$$\max_{L, N_i, l_i (i=1,2,\ldots,L)} \mathcal{C} \tag{29}$$

$$s.t. Q_d \geq \overline{Q}_d. \tag{30}$$

Since L, N_i, and l_i are all integer, the optimal solution can be found through the brute-force method.

C. Suboptimal solution to scenario I and scenario II

There are many similarities in the formulated sensing-throughput problems. First, a high detection probability is necessary to ensure sufficient protection to PU. Second, we tend to use the resource of PU in case 2 rather than case 1. Third, a brute-force method is adopted to solve the sensing-throughput tradeoff problem. As we know the complexity of brute-force method can be huge especially when K is large. In order to reduce the complexity, a suboptimal solution to the formulated problems above is proposed. The suboptimal solution describes below.

Step 1: Obtain the proper cluster number L. Considering the optimal clustering rule in section III, we divide all the K SUs into $L = \sqrt{K}$ clusters. If $\sqrt{K}$ is not an integer, then choose $L = b$ or $L = a$, where b is the minimum positive factor of K that satisfies $b > \sqrt{K}$ and a is the maximum positive factor of K that satisfied $a < \sqrt{K}$. SU that has the best reporting channel to the FC is selected as the head user.

Step 2: Obtain the proper probability. In scenario I, we adjust the threshold of each energy detector so that the global detection probability is satisfied. In scenario II, in order to give the PU sufficient protection and a relative satisfying low false alarm probability, we adjust the threshold of each energy detector to minimize the $p_{f,i} + 1 - p_{d,i}$ for each cluster.

Based on the above steps we can solve the problems by just choosing the optimal value of l in k-out-of-N rule.

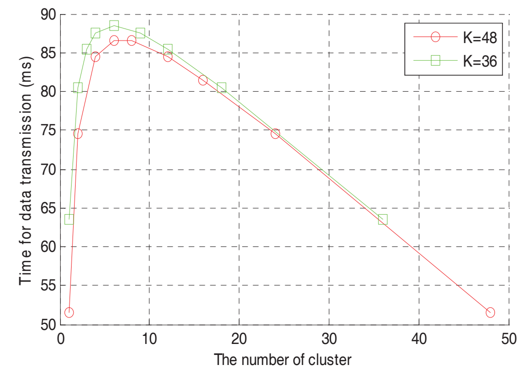

Fig. 3. Data transmission time of different clustering methods

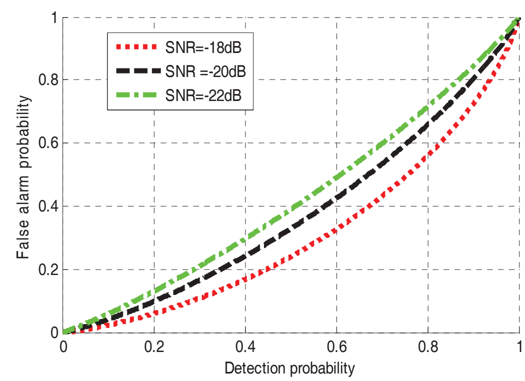

Fig. 4. Positive correlation between the detection probability and false alarm probability

V. Simulation Results

In this section, numerical simulation results are given. In the simulation of optimal clustering rule for data transmission time maximization, $K = 48$ and $K = 36$ are both considered. In both cases, $T = 100ms$, $\tau_l = 0.5ms$, $\delta = 1ms$ are assumed. Besides we assume that there are same quantity of SUs in each cluster.

In Fig.3 we can see that the longest data transmission time is obtained when the cluster number is $\sqrt{K}$. When $\sqrt{K}$ is not an integer, we can get two clustering methods to make the transmission time maximum.

We assume that the $SNR(dB) = -18, -20, -22$, $f_s = 4MHz$, $\tau_l = 0.5ms$ in the simulation for the relationship between detection probability and false alarm probability. In

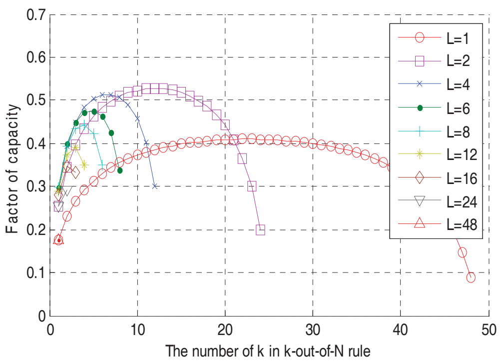

Fig. 5. Factor of capacity (FoC) in each cluster

TABLE I
SIMULATION RESULTS OF SCENARIO II

Cluster		1	2	3	4
The cluster sensing SNR when PU is active(dB)		-17.3336	-14.1986	-13.7589	-10.0988
Optimal false alarm probability of each user		0.2635	0.1029	0.1029	0.02889
Optimal detection probability of each user		0.6090	0.6198	0.6454	0.7435
False alarm probability of the cluster	l=1	0.7058	0.2848	0.0587	0.0048
	l=2	0.3525	0.0552	0.0040	0.0001
	l=3	0.3525	0.0552	0.0040	0.0001
	l=4	0.1106	0.0048	0.00009	0.0000006
Detection probability of the cluster	l=1	0.9766	0.8311	0.4910	0.1376
	l=2	0.9791	0.8429	0.5097	0.1476
	l=3	0.9842	0.8691	0.5549	0.1735
	l=4	0.9957	0.9455	0.7273	0.3056
Global false alarm probability	l=1	0.8907			
	l=2	0.3865			
	l=3	0.1025			
	l=4	0.044			
Global detection probability	l=1	0.999999			
	l=2	0.9997			
	l=3	0.9691			
	l=4	0.5907			
Optimal global false alarm probability and detection probability		(0.1025 0.9691)			

Fig.4 we can see the positive correlation between detection probability and false alarm probability of one SU. We can also see that higher SNR can improve the accuracy of detection. Besides, we can now explain the reason why equation (22) is used in scenario I.

In simulation of scenario I, we assume that $K = 48$, $Q_d = 0.95$, $\tau_l = 0.5ms$, $f_s = 4MHz$, the $SNR = -20dB$. Fig.5 shows the FoC of all possible clustering methods under scenario I. In Fig.5 we can see that the longest data transmission time $L = 6$ or $L = 8$ cannot ensure the largest capacity. But the capacity of the longest transmission time clustering method, is closely to the maximum capacity.

Simulation parameters of scenario II is described below. We assume $K = 16$, $L = 4$, $\tau_l = 1ms$, $T = 20ms$, $\delta = 0.5ms$, $f_s = 4MHz$, the average SNR of SUs in the same cluster is the same. The reporting error of each cluster is equal to 0.05 and the reporting error of each head user is equal to 0.01. The average sensing SNR in the four clusters are $-17.3336dB$, $-14.1986dB$, $-13.7589dB$, $-10.0988dB$. The simulation result of scenario II is shown in table I. The last row of table I shows the suboptimal solution. We can see that the global detection probability of suboptimal solution is almost to 1 while the false alarm probability is 0.1025. Using the definition of FoC in scenario I, total FoC of the simulation in scenario II only has ten percent off compared to the upper bound. The suboptimal solution has a satisfying performance.

VI. CONCLUSION

In this paper, we propose a new frame structure of cluster-based cooperative CRNs and the optimal clustering rule to make the transmission time maximum is obtained. We formulate the sensing-throughput tradeoff problems of two scenarios in cluster-based cooperative CRNs based on the novel frame structure. A suboptimal scheme is proposed to solve these problems. Simulation results show that the optimal cluster rule for transmission time maximization may not lead to the throughput maximization, but the suboptimal solution to these formulated problems has a satisfying performance.

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