An Objection-based Collaborative Spectrum Sensing for Cognitive Radio Networks

Saud Althunibat, Student Member, IEEE and Fabrizio Granelli, Senior Member, IEEE

University of Trento, Trento, Italy
E–Mail: althunibat@disi.unitn.it, granelli@disi.unitn.it

Abstract—Cognitive radio transmission relies on the awareness of the instantaneous spectrum utilization. Such awareness can be gained by spectrum sensing process. To this end, collaborative spectrum sensing (CSS) is preferred as it yields more reliable results than individual sensing. However, CSS requires collaboration among all the cognitive users (CUs), which leads to a high energy consumption. This letter provides a new energy-efficient CSS scheme. The proposed scheme implies that only a CU will broadcast its local decision among the whole network. Will be informed by all local decision of the CUs, and will make a global decision. An analytical study on how to select the broadcasting CU such that energy efficiency is maximized is provided. Simulation and analytic results explore the energy efficiency gain compared to the literature.

I. INTRODUCTION

Spectrum regulatory bodies in each country divide the spectrum into bands. Only licensed users for each band can freely use the spectrum band. However, due to spectrum scarcity problem, unlicensed users have been allowed to exploit the temporarily unused portions of some bands. This concept is called cognitive radio (CR) [1]. Unlicensed users, also called cognitive users (CUs), should sense the spectrum individually or collaboratively in order to identify the unused portions and avoid the collision with licensed users.

Collaborative spectrum sensing (CSS) is performed by reporting the individual sensing results to a fusion center (FC) that is in charge of making a global decision regarding the spectrum availability [2]. CSS can mitigate multi-path fading and shadowing that degrade individual sensing [3]. On the other hand, CSS requires extra energy expenditure and imposes additional security challenges [4].

Many works in the literature handle reducing the energy consumption in CSS. In [5] a censoring technique is proposed, where each CU should not report its sensing result if it is within a specific range. A similar approach, called confidence voting, is presented in [6]. In confidence voting, each CU compares its local result to the global decision, and accordingly, updates its confidence level. Each CSS round, the CU will report its result only if its confidence level exceeds a predefined threshold. Clustering is another popular approach for reducing the energy consumption in CSS [7]. The reader should note that, in all of the above mentioned schemes, not all the individual sensing results will be present at the FC due to excluding some of the CUs in the reporting process. Hence, the overall detection accuracy will be influenced, leading to degraded throughput which, in turn, affects the global energy efficiency that is defined as the ratio of the achievable throughput to the consumed energy.

In this letter we propose a novel CSS scheme, called objection-based CSS scheme. The proposed scheme includes that one of the CUs will broadcast its local decision. Accordingly, the other CUs should object/agree with the announced decision. Each objecting CU will send an objection report to the FC on its reporting time slot, while the agreeing CUs will stay silent on their time slots. Doing so, the energy consumed in CSS should be less, while the detection accuracy is kept unaffected. A practical method for selecting the broadcasting CU, which is a key factor in the overall performance, is presented. Moreover, a mathematical framework and intensive analysis have been made in order to investigate the performance of the proposed scheme.

II. SYSTEM MODEL

A cognitive radio network (CRN) of N CUs is considered. A single-channel spectrum is assumed with occupancy probability denoted by $P_1$, $(P_0 = 1 - P_1)$. CSS is started at the beginning of each time frame by performing individual local spectrum sensing. Each CU issues a local decision $u_i \{1, 0\}$ about the channel availability. Free channel is denoted by $u_i = 0$, while $u_i = 1$ refers to occupied channel. The reliability of the local decision of each CU is evaluated by two probabilities: local detection probability $(P_d)$ and local false-alarm probability $(P_f)$. The former is defined as the probability of identifying the channel as occupied given that is occupied, whereas the latter is the probability of identifying the channel as occupied given that it is free.

Following the CSS procedure, the next step is to share all the local decisions at the FC. We consider that the reporting phase is performed based on a TDMA approach, where each CU has its own time slot. At the FC, a specific fusion rule (FR) is employed to process these reported decisions in order to make a global decision. The general FR is called $K$-out-of-$N$ rule [8], where $K$ is a predefined threshold on the number of CUs who detect a user on the spectrum, i.e., the users that provide a local decision of 1 ($1 \leq K \leq N$). According to this rule, the number of users that report 1 is compared to $K$. If it is less than $K$, then the spectrum is decided to be free. Otherwise, the spectrum is considered as occupied. If the spectrum has been decided as free, one of the CUs will

*This work is funded by the Research Project GREENET (PITN-GA-2010-264759).
be scheduled to transmit its data during the rest of the frame, denoted by $T$.

The global sensing accuracy is assessed by the global detection probability ($P_D$) and the global false-alarm probability ($P_F$). Both are similar to the metrics used at the local level but related the global decision made by the FC. It is worth mentioning that high $P_D$ values help to limit the induced interference at the licensed users, while low values of $P_F$ improve the efficient usage of the channel vacancy.

III. OBSESSION-BASED COLLABORATIVE SPECTRUM SENSING

In the conventional CSS scheme, all CUs should report their local decisions to the FC, each on its time slot. This implies extra energy consumption that is continuous as long as the CRN lasts. The total energy consumption in one round by the whole CRN can be formulated as follows

$$E_{\text{conv}} = NE_S + NE_R + P_{free}ET$$  \hspace{1cm} (1)

where $E_S$, $E_R$ and $E_T$ are the energy consumed in local spectrum sensing, reporting the decision to the FR, and in data transmission, respectively, by one CU. Notice that $E_S$ and $E_R$ are always exist, while $E_T$ is conditioned by making a global decision of free channel. $P_{free}$ is the probability of making a global decision of “0”, expressed as follows

$$P_{free} = P_0(1 - P_D) + P_1(1 - P_F)$$  \hspace{1cm} (2)

According to (1), the energy consumption increases as $N$ increases, which may result in a huge energy expenditure in case of high number of CUs. To this end, we propose a novel CSS that is able to limit the number of reporting CUs, and to reduce the total energy consumption without affecting the global detection accuracy achieved by the CRN.

Following our proposal, only one CU will broadcast its local decision to the whole network on the first time slot in the reporting phase. As the other CU have heard the broad-casted local decision, the CUs that agree with it will stay silent during their time slots, while those CU who have different local decision should object and inform the FC during their time slots. Therefore, the number of reporting CUs should be less than $N$, and consequently, the energy consumption decreases. The total energy consumption based on the proposed CSS scheme can be given as follows

$$E_{\text{prop}} = NE_S + E_{BC} + N_i^*E_R + P_{free}ET$$  \hspace{1cm} (3)

where $E_{BC}$ is the energy consumed in broadcasting and $N_i^*$ is the number of the objecting CUs given that the $i^{th}$ users is broadcasting. The energy consumed in receiving the broadcasted decision is considered to be included in the reporting energy ($E_R$).

It is worth noting that all the local decisions will be available at the FC by the end of the CSS process. Thus, the proposed scheme will not degrade the detection accuracy, and it still provides the same detection accuracy as in the conventional CSS scheme.

From (3), the total energy consumption depends on the number of objecting CUs. The probability that the $i^{th}$ CU will send an objection report given that the $j^{th}$ CU is the broadcasting CU can be expressed as follows

$$P_{obj_i} = P_0(P_{fj}(1 - P_{fi}) + (1 - P_{fj})P_{fi}) + P_1(P_{dj}(1 - P_{di}) + (1 - P_{dj})P_{di})$$  \hspace{1cm} (4)

The four terms that appear in (4) represent the four probable cases of sending an object by the $j^{th}$ CU, as follows: (i) The broadcasting CU makes a false-alarm while the $j^{th}$ CU does not, (ii) The broadcasting CU correctly identifies a free channel while the $j^{th}$ CU makes a false-alarm, (iii) The broadcasting CU correctly detects a licensed user while the $j^{th}$ CU does not, and (iv) The broadcasting CU miss-detects a licensed user while the $j^{th}$ CU correctly detects it.

The average number of the objecting CUs given that the $i^{th}$ CU is broadcasting can be derived as follows

$$N_i^* = \sum_{n=1}^{N-1} nP(N_i^* = n)$$  \hspace{1cm} (5)

where

$$P(N_i^* = n) = \sum_{k=1}^{N-1} \left( P_0P_{fj} \prod_{l \in A_k} (1 - P_{fl}) \prod_{l \notin A_k} P_{fl} \right) + \left( P_1P_{dj} \prod_{l \in A_k} (1 - P_{dl}) \prod_{l \notin A_k} P_{dl} \right)$$  \hspace{1cm} (6)

where $A_k (k = 1, 2, \ldots (N-1))$ represents the whole possible combinations of $n$ CUs out of the total number of $N$ CUs.

A. The selection of the broadcasting CU

The selection of the broadcasting CU is a key factor in the performance of the proposed scheme. Specifically, the local sensing accuracy of the broadcasting CU, i.e., $P_{da}$ and $P_{df}$, determines the amount of the saved energy obtained by the proposed scheme. A tricky point is that the broadcasting CU is not necessary to be the one that achieves the best sensing accuracy. On the contrary, the broadcasting CU should be selected so that its decision will most likely agree with the majority of the other CUs in the network.

The selection of the broadcasting CU should be performed in order to minimize the total energy consumption, which is attained by reducing the number of objecting CUs. Thus, the optimal broadcasting CU should be the CU that more accords with the majority of the other CUs. Notice that the majority decision can be different from the global decision taken at the FC. For example, if the FC employs AND rule or OR rule,
it is likely that the global decision does not agree with the
majority decision.

A practical algorithm to select the broadcasting CU is to
initiate a counter for each CU at the FC. This counter is
updated each CSS round based on the accordance with the
majority decision. Specifically, if the local decision of a CU
agrees with the majority decision, its corresponding counter
will be incremented by one. If we denote the agreement
counter of the $i^{th}$ CU at the $k^{th}$ CSS round by $\alpha_{i,k}$, then
$\alpha_{i,k}$ should be updated as follows

$$\alpha_{i,k} = \begin{cases} 
\alpha_{i,k-1} + 1, & \text{if } u_{i,k} = M_k \\
\alpha_{i,k-1}, & \text{if } u_{i,k} \neq M_k
\end{cases}$$

(7)

where $M_k$ is the majority decision, and $\alpha_{i,0} = 0$.

Each CSS round, the FC will select the broadcasting CU
based on the current state of the counters, where the broad-
casting probability of the $i^{th}$ CU is given as follows

$$P_{bc,i} = \frac{\alpha_{i,k}}{\sum_{i=1}^{N} \alpha_{i,k}}$$

(8)

The selected CU will act as a broadcasting CU on the first time
slot. This implies that the FC should update the reporting order
in each round to avoid any probable collision during reporting
the local decisions.

B. Throughput Reward

The broad-casted decision should be transmitted to the
whole CRN, while in normal reporting, the decision is sent
only to the FC. Hence, broadcasting consumes more energy
than normal reporting since it is adjusted to cover a wider area.
Thus, those CUs that have high values at their $\alpha$ counters will
suffer from high energy expenditure, while the others will save
energy due to not even reporting the local decision. Motivated
by this, the proposed scheme offers a throughput reward to
the CUs broadcasting more often. Particularly, the scheduling
policy adopted is not equally probable among CUs. Instead,
the scheduled CU for data transmission in each frame, if any,
will be based on a new metric that is based on the contribution
in the broadcasting process. Doing so, those CUs that lose
their energy in broadcasting will be compensated by achieving
higher throughput. According to this throughput reward, a
proportional fairness can be attained among CUs in their
achievable energy efficiency in bit/Joule.

The scheduling probability for a specific CU is equal to the
broadcasting probability given as follows

$$P_{sch,i} = P_{bc,i} = \frac{\alpha_{i,k}}{\sum_{i=1}^{N} \alpha_{i,k}}$$

(9)

Notice that (9) does not imply that the broadcasting CU in a
specific round is the scheduled CU on the corresponding data
transmission frame.

The individual performance of each CU can be represented
by the individual energy efficiency defined as the ratio between
the achievable throughput to the consumed energy.

$$\mu_i = \frac{D_i}{E_i}$$

(10)

The average individual energy consumed by the $i^{th}$ CU can
be expressed as follows

$$E_i = E_S + P_{bc,i}E_{bc} + (1 - P_{bc,i})P_{obj,i}E_R + P_{sch,i}P_{free}E_T$$

(11)

The individual achievable throughput can be given as follows

$$D_i = P_0(1 - P_F)P_{sch,i}RT$$

(12)

where the transmitted data are considered successfully delivered
only if the free channel has been correctly identified as free, represented by factor $P_0(1 - P_F)$ in (12).

From (11) and (12), increasing the broadcasting probability
increases the individual energy expenditure, but it also
increases the individual achievable throughput, leading to a
balance in the achievable energy efficiency among CUs.

The flow charts shown in Fig. 1 depict the procedure of the
proposed objection-based CSS at FC side and CU side.

![Flow chart of the proposed objection-based CSS](image)

Fig. 1. A flow chart of the proposed objection-based CSS

IV. NUMERICAL ANALYSIS AND SIMULATION RESULTS

In this section, the performance of the proposed CSS
scheme is proved by numerical and simulation results. All the
necessary parameters regarding detection performance, energy
consumption and network specifications are summarized in
Table I.

<table>
<thead>
<tr>
<th>Table I: Simulation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>$P_0$</td>
</tr>
<tr>
<td>$FR$</td>
</tr>
<tr>
<td>$E_{obj}$</td>
</tr>
<tr>
<td>$E_{RT}$</td>
</tr>
</tbody>
</table>

Numerical results for a CRN that consists of 5 CUs are
shown in Table II and Table III. The first two columns in
Table II list the individual sensing performance of each CU,
which are selected randomly. The employed FR is considered
majority rule ($K = N/2$). The individual energy consumption,
achievable throughput and energy efficiency are shown in
Table II for both the proposed scheme and the conventional
scheme. The conventional CSS scheme refers to the scheme where all CUs sense and report their results to the FC, and the scheduled CU is randomly chosen where all CUs are equal probable.

Table II: Numerical Results - Individual Performance

<table>
<thead>
<tr>
<th></th>
<th>$P_d$</th>
<th>$P_f$</th>
<th>$S_{EC}$</th>
<th>$E_{report}$</th>
<th>$D_{KK}$</th>
<th>$D_{MM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUS</td>
<td>0.5</td>
<td>0.1</td>
<td>21.30</td>
<td>1.38</td>
<td>1.96</td>
<td>10.61</td>
</tr>
<tr>
<td>CUS</td>
<td>0.5</td>
<td>0.1</td>
<td>25.30</td>
<td>1.41</td>
<td>1.96</td>
<td>10.30</td>
</tr>
<tr>
<td>CUS</td>
<td>0.5</td>
<td>0.1</td>
<td>18.74</td>
<td>1.49</td>
<td>1.96</td>
<td>10.21</td>
</tr>
<tr>
<td>CUS</td>
<td>0.5</td>
<td>0.1</td>
<td>21.37</td>
<td>1.61</td>
<td>1.96</td>
<td>10.70</td>
</tr>
<tr>
<td>CUS</td>
<td>0.5</td>
<td>0.1</td>
<td>20.30</td>
<td>1.56</td>
<td>1.96</td>
<td>10.80</td>
</tr>
</tbody>
</table>

Regarding the individual energy consumption shown in Table II, the results show that all CUs have saved different amounts of energy compared to the conventional scheme. However, the different individual energy consumption among CUs refers to the different broadcasting and objecting probabilities. The distribution of the transmitted data is almost identical in the conventional scheme, whereas in the proposed scheme, the transmission opportunity is distributed based on the contribution in the broadcasting phase. Consequently, the individual energy efficiency for each CU has been improved in the proposed scheme compared to the conventional scheme.

A primary note on the global performance shown in Table III is that the global detection accuracy is equal in both schemes. Not effecting the detection accuracy is an interesting property that usually does not exist in most of the proposed schemes in the literature. The proposed scheme results in 17.5% saved energy for the whole CRN, leading to 21% energy efficiency improvement for the whole CRN.

For the purpose of comparison to other schemes, we choose the confidence voting scheme (CV) that is presented in [6]. Briefly, CV scheme implies that each CU has a confidence counter which is updated each CSS round as follows. If the local decision matches the global decision, the confidence counter is incremented by one, while if the local decision mismatches the global decision, it is decreased by one. When the confidence counter is below a specific threshold, the corresponding CU will not report its local decision. CV scheme attempts to reduce the energy consumption in reporting phase by limiting the number of reporting CUs. However, unlike our proposed scheme, CV scheme influences the global detection accuracy since not all the decisions will be present at the FC.

The global energy efficiency versus the total number of CUs for the three schemes is shown in Fig.2. The detection and false-alarm probabilities for the CUs are selected uniformly from the periods [0.4 0.95] and [0.05 0.6], respectively. The voting threshold of CV scheme is set to zero. The global energy efficiency has been opted as a comparison base since it incorporates all the performance aspects, see (10)-(12).

Generally, the global energy efficiency of all schemes decreases due to the increase in the energy consumed in local sensing. However, the objection-based scheme still achieves higher energy efficiency than the other schemes. This is a result of reducing the number of reporting CUs without degrading the detection accuracy nor the global achievable throughput.

V. CONCLUSIONS

In this paper a novel collaborative spectrum sensing scheme for cognitive radio networks is proposed. The proposed scheme implies that one of the CUs broadcasts its local decision about the spectrum availability to the whole network. The other CUs that have a different local decision should send an objection to the FC, each on its corresponding reporting time slot, while the CUs that agree with the announced decision should stay silent. The amount of the saved energy refers to limiting the number of reporting CUs without affecting the overall detection accuracy. A practical algorithm to select the broadcasting CU in each round is presented. Simulation and analytic results show the superiority of the proposed scheme compared to the conventional scheme and the confidence voting scheme.

As a future work, the broad-casted decision can be made by the FC itself based on an optimization technique using statistical data about the activity of the licensed users.

REFERENCES