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COOPERATIVE SPECTRUM SENSING IN COGNITIVE RADIO

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Abstract— In cognitive radio (CR) networks, cooperative spectrum sensing is utilized to improve the sensing performance to avoid potential interference to primary users (PUs) and increase spectrum access opportunities for secondary users (SUs). The problem of how to collect sensing data should be solved for the implementation of the cooperative sensing. A cooperative spectrum sensing process is divided into three phases: individual sensing/detection, reporting/fusion, and data transmission. In the reporting phase, one or more reporting channels are needed to transmit individual sensing results to a fusion center (FC), and global spectrum sensing results are determined at the FC. The number of required reporting channels depends on the number of spectrum sensors or SUs, which relates to reporting channel efficiency and channel scheduling complexity. In the proposed scheme, random access is used to collect the spectrum sensing data of the secondary users during collection period and the length of the collection period is determined adaptively based on the sensing data collected so far. Thus, complex slot management for the collection of the sensing data is not necessary. Also we design a reporting channel scheme based on random access protocols, including slotted Aloha and reservation-Aloha. Performance evaluations in terms of PU detection probabilities and false alarm probabilities considering the proposed reporting channels are presented.

Index Terms- Backward induction, Cognitive Radio, Cooperative spectrum sensing, Random access.

I. INTRODUCTION

To accommodate the ever increasing wireless service demand, cognitive radio (CR) technology is introduced, in which secondary users (SUs) share spectrum with primary users (PUs) through the detection of spectrum holes .

CR is designed to sense the changes in its surroundings. Thus it learns from its environment and performs functions that best serve its users. This is a very crucial feature of CR networks which allow users to operate in licensed bands without a license. Though the above technologies promise tremendous gain, practical systems are yet to be developed that allow multiple users to share the spectrum in a smart way. There are three phases in cooperative spectrum sensing, individual sensing/detection, reporting/fusion and data transmission. In individual sensing/detection, spectrum sensing algorithms are used at individual SUs. In data transmission, SU utilizes detected spectrum holes and, to improve transmission performance, cooperative relays can also be implemented. In the reporting/fusion phase, there are two challenging issues, reporting channel design and fusion algorithm selection.

II. RELATED WORK

Many techniques have been proposed in the literature to improve energy efficiency of CSS. These techniques can be classified into three classes. In the first class, the techniques in address the energy efficiency by optimally selecting the set and the number of sensing nodes. For example, the authors in and formulated the minimum number of sensing cognitive users that satisfy predefined constraints on detection and false alarm probabilities. They only studied the energy consumed in sensing stage only. The technique in determines how many CR nodes must sense each spectrum band in a wideband sensing manner. In , the authors reduced sensing energy consumption by dividing the cognitive users into several subsets and activating only one subset during any period of time. The optimal number of sensing users was also determined in through an iterative algorithm that considered maximizing energy efficiency. The analysis was based on limited time resources assumption and fixed transmission time. This implies that the time resources dedicated for CSS process are limited and shared between spectrum sensing and results reporting. The authors of investigated the sensing time for individual sensing systems. They presented an adaptive sensing time based on the past spectrum occupancy pattern. However, none of these techniques considered selecting the CR sensing nodes and the FC since it was assumed that the sensing time and energy is the same for all CR nodes. Additionally, they did not specify how to find the optimal FC.

In the second class, the problem of reducing the consumed energy is approached through clustering the CR nodes such that each cluster has a cluster head . For example, the authors of suggested an energy efficient low-energy adaptive clustering hierarchy (i.e. energy efficient LEACH), which is a variation of the LEACH protocol. Specifically, the cluster heads are selected with predetermined probability and energy drain. Then, the nodes join their nearest cluster heads. On the other hand, the techniques in and select the cluster such that the network life time is maximized, where the life time is defined as the time for the first node to die. One more method is to select the cluster head that has more residual energy and more neighbors. In, the authors proposed an alternative approach which foresees that each group of users selects a cluster head to process their results and to report just one decision on behalf of all of them. In, given a cluster-based cognitive radio network, the authors optimize the number of spectrum sensing nodes in each cluster.

However, none of the techniques in performed the selection of the FC node and the set of nodes that should perform sensing jointly. Basically, they selected the cluster head based on its residual energy together with other factors without considering the energy of other nodes. After selecting the cluster head node, they selected the nodes that will be in the cluster. This is unlike the algorithms that we present in this paper where we determine the FC, the sensing nodes and sensing parameters jointly in order to specify the required sensing times for each node. We also take into consideration the variable sensing energies, variable reporting energies and sensing performance.

As for the third class, the techniques in this class focused on reducing the reporting energy as it contributes to significant portion of the total energy in the sensing phase. The authors in optimized the censoring thresholds to decrease the energy consumption. Censoring is a technique that can reduce the reporting cognitive users such that a node reports its decision to the FC only when its energy is above certain threshold. Lee and Wolf introduced a confidence-voting scheme, where each user sends its sensing result only if it has a given confidence level that is computed from the history of the local result compared with the final result. Similarly in, cognitive users perform coarse sensing that is basically an initial short sensing stage. If the sensing result stays in the predefined range, then the cognitive user does not report the local decision to the FC. Otherwise, the cognitive user reports the local decision to the FC. However, all cognitive users still sense the spectrum, which consumes large amount of energy.

To the best of our knowledge, the only work that selects the number of sensing nodes as well as the FC for the sake of enhancing energy efficiency is the approach presented in. In this approach, they assumed that part of the nodes performs the sensing for the benefit of all CR nodes. They suggested that the nodes that have the highest SNR to PU and have higher residual energy levels must perform sensing. The optimal number of cooperating sensing CR nodes is obtained by optimizing energy consumption subject to minimizing the detection and false alarm probabilities. However, their approach has several drawbacks: (i) The FC is selected to be the node with the highest residual energy without considering the fact that other nodes, with lower energy levels, may consume more energy in sensing and reporting when the FC is the node with highest energy. (ii) The sensing nodes are selected as the nodes that are closer to the FC. However, these nodes may have low SNR to the PU, which may demand more sensing energy. (iii) The reporting, sensing and transmitting energies are assumed to be equal. However, the reporting energy is actually variable and dependent on the locations of the nodes with respect to the FC.

III. System Model

We detect the activity of a PU on a single spectrum band. We also assume that each CR node receives the PU signal with different SNRs.

These N_T nodes can share the channel; however, not all the N_T nodes are required to perform the sensing. The required number of sensing nodes is $NS$and the set of nodes that will perform the sensing is referred as $\hat{S}$. Each of the cooperative CRs in $\hat{S}$ is supposed to employ some energy detection mechanism, in which the CR node measures the received energy $y(t)$ over the sensing period. The received energy is given by

$$y(t) = \begin{cases} x(t) + n(t), & \text{if the channel is busy, H1} \\ n(t), & \text{if the channel is free, H0} \end{cases}$$

where n(t)n(t) is additive white Gaussian noise with variance σ2nσn2 and x(t)x(t) is the received signal of the PU which is assumed to be distributed Circularly Symmetric Complex Gaussian with variance σ.

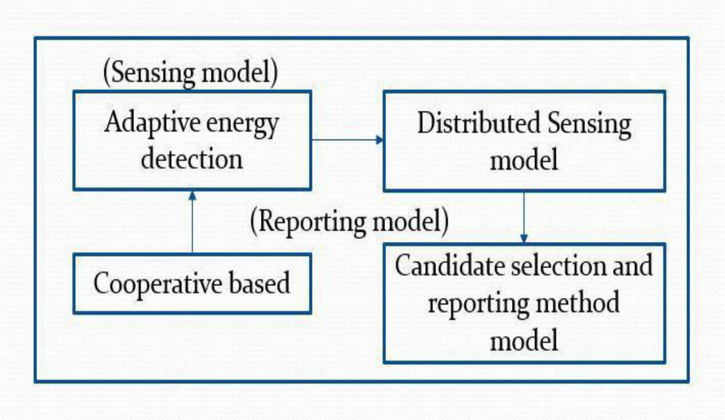
After local sensing, each node decides whether it sees the channel as idle (H_0) or busy (H_1) such that

$$\text{Decision}\begin{cases} H_1(\text{busy}), Av \geq \lambda \\ H_0(\text{free}), Av < \lambda \end{cases}$$

where Av is the sum of the received energy on the channel during the sensing time and is computed using

$$Av = \sum_{j=1}^{si} y_j(t)$$

where SiSi is the number of samples taken by the ith CR node, while λ is the energy detection threshold. Assuming that each CR node can take energy samples from the PU signal with sampling frequency.



The number of samples for each CR node is supposed to be different for each CR node due to differences in the SNR. Also, the number of samples is assumed to sufficient to achieve specific sensing performance as we will discuss later.

The final decision on spectrum status is cooperatively made by reporting the local decisions to the FC. We use Time Division Multiple Access (TDMA) for reporting the local decisions to the FC. It is assumed that the hard decision fusion scheme is employed where each CR node sends its 1-bit decision to the FC. The FC decides on the channel's availability by ORing the CRs' decisions. Effectively, the decision is either the channel is in busy state H_1 when at least one of the nodes identified the channel as busy, or the channel is in free state H_0 if none of the nodes reported the channel as busy. Alternatively, the FC may use a more general rule such as K-out-of-N_S rule, in which the channel is considered busy if K or more nodes reported the channel as busy.

We assume that each CR node is provided with single transceiver. Therefore, the CR node cannot transmit and sense at the same time, and thus they need periodic spectrum sensing. Figure 2 shows the frame structure that each node uses for different operations. The duration of the frame T is divided into three time slots, which are the following:

- The sensing slot (T_S) in which the CR nodes can sense the spectrum. During this slot, no CR is allowed to transmit on the same channel due to source uncertainty where any sensed energy is considered as PU signal.
- The reporting slot (T_r) in which each CR node reports its decision to the FC. The CR nodes cannot report to the FC at the same time over one channel because the receiver is the FC which is common. Thus, we consider TDMA scheme, where each CR node has its own reporting time slot τ.
- The transmission slot (T_t) is utilized when the channel is free and one or more CR nodes (out of the N_T nodes) can be scheduled for data transmission.

As a consequence, the frame duration is basically

$$T=TS+Tr+Tt$$

If we consider τ as the reporting time for each CR node, then the total reporting time for all CR nodes that perform sensing is

$$Tr=NS\times\tau$$

During energy detection, if one CR node is performing sensing, then none of the other CR nodes can transmit at the same time. Therefore, there is a period called 'quiet period' during which the N_S nodes can perform the sensing and none of the N_T nodes is allowed to transmit. Due to the differences of the SNR perceived by different sensing nodes, the sensing period may vary. Thus, the quiet period whose length is the same as the sensing period T_S is determined by

$$TS=\max\{TiS,\forall CRi\in\hat{\mathcal{S}}\}$$

IV.PROPOSED METHODOLOGY:

A. Local Spectrum Sensing Analysis

In a sensing period, the received signal strength at ith SU in nth slot is represented as

$$H0 : y_i\ (n) = w_i\ (n)$$
$$H1 : y_i\ (n) = h_i s(n) + (w_i\ n)$$

where s(n) is the PU transmitted signal power and hi is the corresponding channel coefficience for i^{th} SU. w_i (n) is the additive white Gaussian noise with distribution (CN0,σ2i) H 0/H1 denotes the PU status (absent/present).

The sensing results for i^{th} SU considering energy detection are given as

$$N = 1/Ns \sum_{n=1}^{Ns} j\ yi\ (n)\ j2$$

Ns is the number of spectrum sensing slots for each sensing period .When Ns is sufficiently large ,according to central limit theory the ith SU local sensing result Yi is asymptotically normally distributed as Yi ~N[E(Yi),Var(Yi)] [26]. E(Yi) and Var(Yi) are as follows,

$$E(Yi) = \begin{cases} Ns\sigma & H0 \\ (Ns + \rho i)\sigma 2 & H1 \end{cases}$$

And

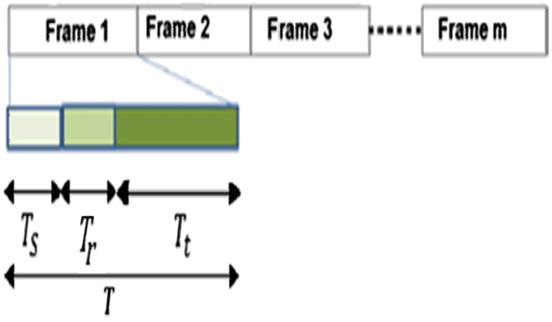
$$Var(Yi)=\begin{cases} 2Ns\sigma 4 & H0 \\ 2\ (Ns + 2\rho i) & H1 \end{cases}$$

where ρi represents ith SU's SNR. ith SU determines the PU status based on a predefined threshold ωi and the detection probability Pi d and false alarm probability Pi f are given as follows,

$$P = P\ (Yi > \omega i\,|\,H1)\left(\frac{\omega i - E(Yi\,|\,H1)}{\sqrt{Var\ (Yi\,j\,H1)}}\right)$$

Q(.) is the complementary cumulative distribution function.

B. Cooperative Spectrum Sensing Analysis



Within the framework of soft combining with r successfully received local sensing results, a global sensing result Yc is calculated as follows,

$$Y_c = \sum_{i=1}^{r} w_i Y_i = \mathbf{w}^{\mathrm{T}} \mathbf{y}$$

where w = [w1,w2,··· ,wr]T is a weight vector assigned to SUs based on MRC and y = [Y1,Y2,··· ,Yr]T is the received signal vector. If Yc is larger than a predefined global threshold, the FC claims that PU is present; Otherwise, PU is absent. When the MRC method is considered, the cooperative false alarm probability Qf for a given specific cooperative detection probability Qd with known SU channel gains can be found as

$$Q_f = \mathrm{Q}\left(\sqrt{N_s}\sum_{i=0}^{r}\rho_i + \mathrm{Q}^{-1}\left(Q_d\right)\sqrt{1+2\sum_{i=0}^{r}\rho_i}\right)$$

[Notice that, in cognitive radio networks, the miss detection probability,

Pmd = 1−Pd,

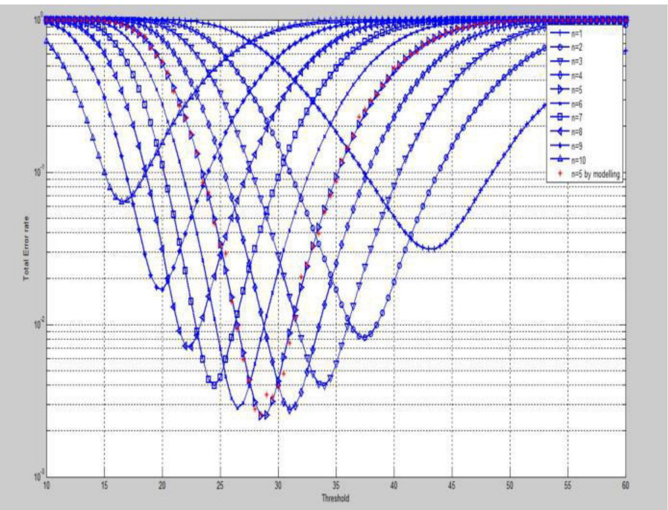
should be smaller than a certain specified value in order to avoid severe interference to PU. In our following numerical evaluations, the required miss detection probability is set as 10%. Since the number of slots in one frame is fixed (N = Ns + Nr + Nt), there is a tradeoff between better sensing performance and higher transmission load. The sensing performance can be improved with more reporting slots .However, this leads to fewer slots for data transmissions. Following [14], the normalized expected revenue, which is defined as the percentage of slots used for PU or SU data transmissions, can be represented as

$$\mathrm{ER}\left(N_t\right) = \frac{\left(1-Q_f\right) N_t \bar{P}_0 + Q_d N_t \bar{P}_1}{N_r + N_t}$$

where Nt is the number of transmission slots, ¯ P0 is the probability that PU is absent and ¯ P1 is the probability that PU is present. Both ¯ P0 and ¯ P1 can be estimated/obtained in advance. Notice that the tradeoff between Nr and Nt is considered in (48). While the normalized expected revenue is evaluated in [14] and in this paper, a related performance measure, throughput, was considered.

V. THEORETICAL AND SIMULATION RESULTS

In this section, we present the theoretical and simulation results for the proposed reporting channel design and S-Aloha and R-Aloha are implemented. Both hard and soft decision fusion are considered. For the hard decision fusion, SUs send their binary (+1/−1) individual detection reports and FC implements K out of N as the fusion rule .For the soft decision fusion, SUs send the unquantized energy detection results and FC applies MRC as the fusion rule. Simulation results are obtained with running 10,000 frames. In the following, Fig. 3–5 present results based on the hard fusion rule. Fig. 6–7 evaluate the impact of the unquantized detector and the soft fusion rule, and Fig. 8 presents the impact of the malicious users.



VI.CONCLUSION

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