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Capacity Optimization in Cooperative Cognitive Radio Networks

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***Abstract*—**Cooperative spectrum sensing is a crucial challenge in cognitive radio networks. Cooperative sensing can increase the reliability of spectrum hole detection, optimize sensing time and reduce delay in cooperative networks. In this paper, an efficient central capacity optimization algorithm is proposed to minimize cooperative sensing time in a homogenous sensor network using OR decision rule subject to the detection and false alarm probabilities constraints. The evaluation results reveal significant improvement in the sensing time and normalized capacity of the cognitive sensors.

***Keywords*—**Cooperative networks, normalized capacity, sensing time.

I. Introduction

THE anticipated growth and proliferation of wireless devices with multifarious network's standards require advanced algorithms and intelligence to overcome the challenges of spectrum scarcity, power consumption, interoperability, users' demands for higher data rates and better quality of service. Cognitive Radio (CR) is an advanced technology to enhance better spectrum utilization by enabling secondary users (SU) have access to intermittently available unoccupied spectrum band referred to as spectrum holes without interfering with the operations of the primary or licensed users [1], [2]. Spectrum sensing is an important functionality in cognitive radio. Its main objectives are to detect transmissions by licensed users and identify any unused portions in the frequency bands thereby avoiding interference between licensed users and SUs. Spectrum sensing process can be categorized into two mechanisms namely: non-cooperative and cooperative sensing. In the former, each cognitive user senses its radio environment, and makes an independent decision based on collected radio information. In the later, cognitive users observe their radio environment, collects radio state information and share their information to make a cooperative decision using either the central or distributed strategies [3]-[5] In cooperative centralized decision, different fusion techniques such as hard decision (i.e. OR, AND and majority scheme) and soft decision such as: square-law combining (SLC) and maximal ratio combining (MRC) can be applied. Cooperative sensing has the benefit of overcoming the hidden node problem and hardware simplicity, as each node does not need much computational processing capacity [6].

The frame structure of any cognitive radio system that employs spectrum sensing studied so far consists of a sensing time slot and a data transmission slot as shown in Fig. 1. Therefore, an inherent tradeoff exists between the sensing time, the data transmission time and the throughput of the cognitive radio network. The problem of the sensing-throughput tradeoff for an opportunistic spectrum access cognitive radio network that employs energy detection for spectrum sensing is addressed in [7] for a single frequency band. In [7], the authors studied the problem of finding the optimal sensing time that maximizes the throughput under a constraint on the probability of detection of the primary users.

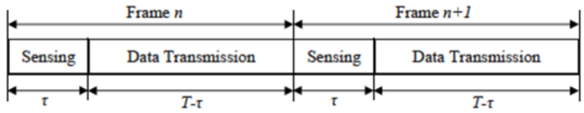

Fig. 1 Framework structure of the conventional opportunistic spectrum access cognitive radio networks

In this paper, we study and focus on the design of the optimal sensing time that maximizes the ergodic throughput of a cooperative cognitive radio network which operates under opportunistic spectrum access. Different from the work in [8], we take into consideration the probability of false alarm and the probability of detection constraints while maximizing throughput of the cognitive users. In the proposed scheme, the fusion center collects local sensing decision of secondary users and makes the final decision on the availability of the monitored spectrum employing the OR technique. The rest of this paper is organized as follows: Section II presents the system model. Signal detection and cooperative model are described in Section III. The numerical evaluation of the proposed scheme is presented in Section IV. Finally, the conclusions are drawn in Section V.

II. System Model

This paper considers an open licensed spectrum network consisting of several static wireless nodes communicating with each other using N licensed channels, while a multi-user cognitive radio network is located within the licensed coverage area. The coverage area of the secondary network is small compared to the distance between the secondary users and the primary transmitter such that the effect of primary signal at the secondary user can be ignored (see Fig. 2). In the considered cooperative sensing scenario, each cognitive user

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detects primary signal energy and sends the local sensing results to the fusion centre via the reporting channels [3], [4].

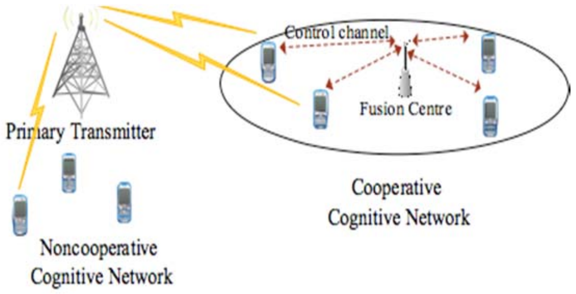


Fig. 2 Network topology; secondary users report sensing information to the fusion centre

At the fusion center, OR rule is employed to determine the appropriate unoccupied licensed channels, which can be assigned to the cognitive users. The proposed scheme at the fusion centre employs a throughput maximization algorithm to find optimal sensing time under detection and false alarm probabilities constraints. The common notations used throughout this paper are summarized in Table I.

TABLE I
NETWORK NOTATION

Parameter	Description	Parameter	Description
Q_{fa}	Cooperative false alarm probability	$\overline{Q_f}$	Upper limit of false alarm probability
Q_d	Cooperative detection probability	$\overline{Q_d}$	Lower limit of detection probability
T	Secondary user time slot	P_{fa}	False alarm probability
W	Bandwidth	P_d	Detection probability
τ	Local sensing time	γ	Received SNR of primary user
λ	Threshold detection level at fusion centre	τ_{co}	Optimized sensing time
K	Number of SU	f_s	Sampling frequency
σ_w^2	AWGN variance	g_{ss}	Secondary user channel gain
δ^i	Threshold detection level of sensor i	g_{ps}	Primary user to secondary user channel gain

A. Spectrum Sensing and Cooperation Mechanism

Each cognitive device performs spectrum sensing independently and the sensing outcomes are sent to the fusion centre. According to the collected information received at the fusion centre, the OR rule can be employed to determine unoccupied licensed channels (spectrum hole) in a cooperative manner. Assuming licensed channels are identical and independent, the received signals at the SU node i during sensing period of time slot (n) can be given by;

$$Y_i(n) = \begin{cases} \omega_i(n) \\ h_i(n)S_i(n) + \omega_i(n) \end{cases} \tag{1}$$

where $Y_i(n)$ is the received signal by the i^{th} secondary user. The signal $S_i(n)$ is distorted by the channel gain $h_i(n)$, which is assumed to be constant during the detection interval and is further corrupted by the zero-mean Additive White Gaussian Noise (AWGN). ω_i is the receiver noise for the i^{th} secondary user, which is assumed to be an i.i.d random process with zero mean and variance σ^2. Each secondary user calculates a summary statistic over observation time, $E_i = \sum_{n=0}^{N-1}|y_i(n)|^2$, i=1, 2, 3…K. where N represents the number of observed samples in the observation time interval τ. Let $\gamma_i = \frac{1}{N}\sum_{k=1}^{N} S_{ik}^2$, be the instantaneous received SNR of the primary signal at the i^{th} sensor.

$$E_i \sim \begin{cases} \Upsilon_{2\upsilon}^2 & ,H_0 \\ \Upsilon_{2\upsilon}^2(2\gamma_i) & ,H_1 \end{cases} \tag{2}$$

The random variable E follows a central chi-square distribution with $2\tau W$ degree of freedom if the licensed user signal is absent. Otherwise a non-central chi-square distribution with $2\tau W$ degree of freedom and a non-centrality parameter $2\tau W\gamma_i$. The parameter υ denotes time bandwidth product. In the case of hard decision, cognitive users make one bit local decision based on comparing the received energy of the primary signal with a threshold level (δ). Therefore, the local probability of detection (P_d^i) and probability of false alarm (P_{fa}^i) of the detector can be approximated as;

$$P_d^i = P(E_i > \delta^i|H_1) = Q\left(\frac{\delta^i - \tau f_s(|h|^2\sigma_s^2 + \sigma_\omega^2)}{\sqrt{2\tau f_s}(|h|^2\sigma_s^2+\sigma_\omega^2)}\right) \tag{3}$$

$$P_{fa}^i = P(E_i > \delta^i|H_0) = Q\left(\frac{\delta^i - \tau f_s\sigma_\omega^2}{\sqrt{2\tau f_s}\sigma_\omega^2}\right) \tag{4}$$

where $Q(.)$ denotes the right-tail probability of a normalized Gaussian distribution $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-t^2}{2}}dt$, f_s is the sampling frequency and τ represents the sensing time slot. The equations above show that the probability of detection and probability of false alarm are related to the detection threshold, sensing time, SNR and sampling frequency. From (4) and (5), the minimum required sensing time on secondary user i to satisfy desired P_{fa} and P_{md} is given by:

$$\tau^i = \frac{2}{f_s{\gamma_i}^2}[Q^{-1}(p_{fa}^i) - Q^{-1}(1-p_{md}^i)\sqrt{1+2\gamma_i}]^2 \tag{5}$$

The equations above show that the probability of detection and the probability of false alarm affect the sensing time and throughput of the cognitive users. It also shows that increasing the sensing time duration reduces the throughput and increases delay at the secondary user.

B. Fusion Centre Decision

Hard decision and soft decision are two prominent decision mechanisms at the fusion center. In the former, each cognitive user detects the primary signal and makes an individual binary decision about spectrum occupancy. The binary decisions are then transmitted to the fusion centre via common control channel. The final decision is made employing OR, AND and majority voting schemes at the fusion centre [3]. In soft data fusion, cognitive users report the sensing result E_i to the fusion centre without making local decisions. The final decision is made by using appropriate combining rules such as: square law combining (SLC), maximal ratio combining (MRC) and selection combining (SC).

The probability of detection and probability of false alarm of the SUs network under OR-rule, Q_d and Q_{fa} respectively can be mathematically written as [9];

$$Q_d = 1 - \prod_{i=1}^{N}\left(1 - P_d^i\right) \tag{6}$$

$$Q_{fa} = 1 - \prod_{i=1}^{N}\left(1 - P_f^i\right) \tag{7}$$

In the case of a homogeneous network, Q_d and Q_{fa} can be simplified by $Q_d = 1 - (1 - P_d)^K$ and $Q_{fa} = 1 - \left(1 - P_f\right)^K$ where K represents number of secondary users participating in the sensing task.

C. Average Throughput

The instantaneous transmission rate of the secondary user, denoted by r_0 for the case of absence of primary user ($\mathcal{H}_0$) and by r_1 for the case of existence of the primary user ($\mathcal{H}_1$), is given by

$$r_0 = \log_2\left(1 + \frac{g_{ss}P_s}{N_0}\right) \tag{8}$$
$$r_1 = \log_2\left(1 + \frac{g_{ss}P_s}{g_{ps}P_p + N_0}\right)$$

where P_p denotes the transmit power of the primary user. The secondary user transmits using P_s during the data transmission slot. Thus, the average throughput of the jth secondary user using the probability of the false alarm and the probability of detection can be formulated as:

$$C_j = P(H_0)\left(1 - Q_{fa}\right)r_{j0} + P(H_1)(1 - Q_d)r_{j1} \tag{9}$$

where $P(H_0)$ denotes the probability that the channel is idle and $P(H_1)$ denotes the probability that the channel is active. Thus, the optimization problem that maximizes the ergodic throughput of a spectrum sharing cognitive radio network, under sensing time and the probability of false alarm and detection constraint is

$$\begin{gathered} Maximize\ \frac{T-\tau}{KT}\sum_{j=1}^{K} C_j \\ \text{Subject to } 0 \le \tau \le T \\ Q_{fa} \le \overline{Q_{fa}} \\ Q_d \ge \overline{Q_d} \end{gathered} \tag{10}$$

Therefore, the above problem can be rewritten by;

$$\begin{gathered} Maximize\ \frac{T-\tau}{KT}\sum_{j=1}^{K}\left[P(H_0)\left(1 - Q_{fa}\right)r_{j0} + P(H_1)(1 - Q_d)r_{j1}\right] \\ \text{Subject to } 1 - \left(1 - P_f\right)^K \le \overline{Q_{fa}} \\ 1 - (1 - P_d)^K \ge \overline{Q_d} \\ 0 \le \tau \le T \end{gathered} \tag{11}$$

III. Proposed Algorithm

This section considers an optimal sensing time algorithm, which results in the maximum average secondary user throughput. In this scenario, each SU observes PU's target channel independently during local sensing period and the local sensing results will be reported to the fusion centre. The fusion centre makes a central cooperative decision based on the received results on the occupancy and idleness of channels. The average throughput of the secondary users is evaluated under sensing time and the probabilities of false alarm and detection constraints. The proposed algorithm is located at the fusion centre and the optimal sensing time is broadcasted to the secondary users.

Algorithm Exploring optimal sensing time

Begin
1: Initial parameters; $K, \lambda, \bar{Q}_D, \bar{Q}_f, P_d, P_f, W$
2: Sensing request flag $\leftarrow 1$
3: Local sampling using local sensing time slot
4: $E_i = \sum_{n=0}^{N-1}|y_i(n)|^2$; for each user
5: $Report\ sensing\ results\ (0,1)_i\ i = 1, \ldots K$ to Fusion Centre
6: For $\tau = 0\ to\ T$
7: Evaluate $Q_{fa}, Q_d, \sum C_j$
8: If $Q_D \ge \bar{Q}_D\ or\ Q_f \le \bar{Q}_f$
9: $[\tau] \leftarrow \tau$ and $[C] \leftarrow \sum C_j$
10: $\tau_{co} = argmax([C])$
11: Assign τ_{co} to sensors
. End

IV. Numerical Analysis

This section presents the performance of the proposed scheme through its complementary Receiver Operating Characteristic (ROC) curves (Q_d versus Q_f) for different situations of the network. The channels are assumed to be block faded and their power gains ergodic, stationary and exponentially distributed with unit mean. The frame duration of the secondary networks is fixed and set to T = 100ms. Suppose that the sampling frequency f_s= 1kHz, the upper limit of false alarm probability 0.1, the lower limit of detection probability 0.9. The transmit power of the primary user on all channels is assumed to be P_p= 10dB, whereas the noise variance equal to N_0= 1.

Fig. 3 shows the sensing time versus received SNR of the primary user at the SU. The results show that low level SNR forces the SU to spend more time on the sensing phase which will result to its associated increase in energy consumption and delay within the network.

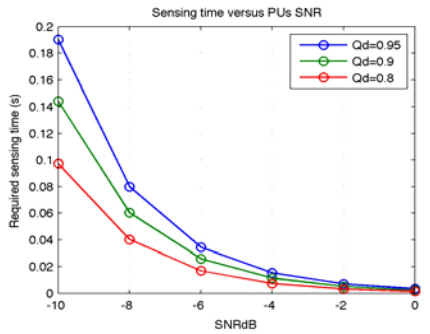
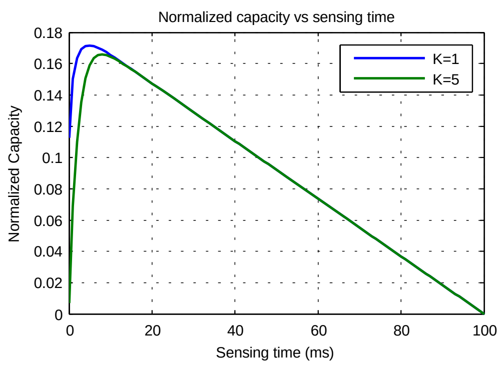
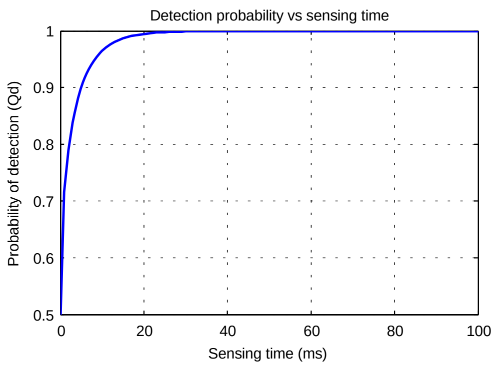


Fig. 3 Sensing time versus primary user SNR ($\bar{Q}_d = 0.95$, $\bar{Q}_f = 0.1$)

Fig. 4 (a) presents the normalized capacity of secondary users versus sensing time within our experimental cognitive network (in this case; one user and five users). The results show that optimized sensing time equals to 5ms when normalized capacity reaches 0.172 for one user. It is also observed from this figure that sensing time is 8ms in cognitive radio network of five users. Fig. 4 (b) reveals the probability of detection versus sensing time. The results depict that the increase of sensing time improves probability of detection of the primary signal.



(a)



(b)

Fig. 4 Normalized capacity versus sensing time. b) The probability of detection versus sensing time

Fig. 5 depicts the normalized capacity of the cognitive network versus probability of detection. The increase of probability of detection results to reduction in normalized capacity. The outcomes show that the proposed scheme improves the sensing interval time of a cooperative cognitive network.

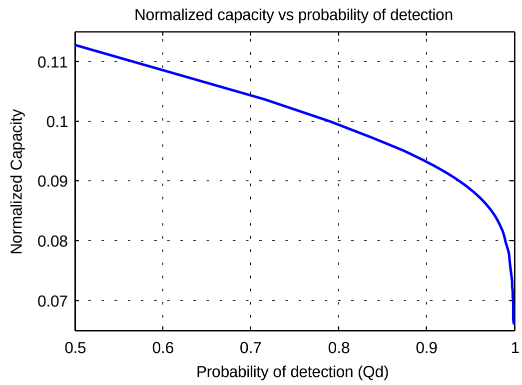


Fig. 5 Normalized capacity versus probability of detection in cooperative cognitive network

The simulation results are summarized in Tables II and III for a cooperative cognitive network consisting of 1, 5, 10, 15 and 20 users. Table II shows normalized capacity (NC) and required sensing time of cognitive network using sampling frequency equal to 6MHz while Table III shows the normalized capacity and required sensing time of the cognitive network using sampling frequency equal to 1MHz. It is observed from these two tables that the decrease in sampling frequency causes increment to the sensing time (see Table II).

TABLE II
MAXIMUM NORMALIZED CAPACITY VERSUS NUMBER OF SUS ($F_s = 6$MHz)

K	1	5	10	15	20
NC	0.172	0.166	0.163	0.162	0.161
τ (ms)	5	8	9	10	11

TABLE III
MAXIMUM NORMALIZED CAPACITY VERSUS NUMBER OF SUS ($F_s = 1$MHz)

K	1	5	10	15	20
NC	0.147	0.119	0.107	0.099	0.094
τ (ms)	11	25	31	35	38

V. CONCLUSION

This paper has considered a homogenous cooperative cognitive radio network with cooperative sensing where cognitive users' sense licensed spectrum bands and report the local decision to the fusion centre. Each cognitive user reports a 0 and 1 for the primary users' signals. The final decision is made by employing the OR fusion rule at the fusion centre. Our proposed scheme results in the sensing time to be optimized and also an improvement in the normalized capacity of the cognitive network by optimization programming. The simulation results showed that there is a significant improvement on sensing time and normalized capacity with our proposed optimized sensing time algorithms. To this end, sensing time allocation and optimization is a crucial challenge in cooperative cognitive radio networks and needs to be considered in cooperative cognitive radio networks.

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