# General Analytical Framework for Cooperative Sensing and Access Trade-off Optimization

Le Thanh Tan and Long Bao Le

Abstract—In this paper, we investigate the joint cooperative spectrum sensing and access design problem for multi-channel cognitive radio networks. A general heterogeneous setting is considered where the probabilities that different channels are available, SNRs of the signals received at secondary users (SUs) due to transmissions from primary users (PUs) for different users and channels can be different. We assume a cooperative sensing strategy with a general a-out-of-b aggregation rule and design a synchronized MAC protocol so that SUs can exploit available channels. We analyze the sensing performance and the throughput achieved by the joint sensing and access design. Based on this analysis, we develop algorithms to find optimal parameters for the sensing and access protocols and to determine channel assignment for SUs to maximize the system throughput. Finally, numerical results are presented to verify the effectiveness of our design and demonstrate the relative performance of our proposed algorithms and the optimal ones.

Index Terms—MAC protocol, cooperative spectrum sensing, throughput maximization, channel assignment, cognitive radio.

#### I. INTRODUCTION

Design and analysis of MAC protocols for cognitive radio networks is an important research topic. There has been growing literature on this topic over the last few years [1] and [12] (see [1] for a survey of recent works). However, most existing works either assume perfect spectrum sensing or do not explicitly model the sensing imperfection in their design and analysis. In [2], we design and optimize the sensing and MAC protocol parameters where each SU is assumed to perform parallel sensing on all channels and it can use all available channels for data transmission. This can be considered as an extension of throughput-sensing optimization framework of [4] from the single-user to the multi-user setting. In [3], we consider a scenario where each SU can exploit at most one channel for transmission. All these works do not consider cooperative sensing and its design issues.

Cooperative spectrum sensing has been shown to improve the sensing performance [5]–[10]. In a cooperative sensing strategy, each SU performs sensing independently and then sends its sensing results to an access point (AP). The AP then makes decisions on the idle/busy status of each channel by using certain aggregation rule. In [6], weighted data based fusion is proposed to improve sensing performance. In [7]-[9], the optimization of cooperative sensing using an aout-of-b rule is performed. In [8], the game-theoretic based method is taken to develop a cooperative spectrum sensing strategy. However, these works only focus on design and

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optimization of cooperative sensing without considering the spectrum access problem (i.e., how SUs share the available spectrum). Furthermore, these sensing optimization works are performed for a single channel and homogeneous scenario where channel parameters such as SNRs, probabilities that different channels are available are the same. In [10], the authors investigate a multi-channel scenario where each SU simultaneously senses all channels using one receiver per channel and calculates the log-likelihood ratio of observed measurement. Then AP collects these statistics to decide when to terminate the process. All of these existing works do not consider the joint cooperative sensing and access design under the heterogeneous setting.

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In this paper, we propose the general cooperative sensingaccess framework for the non-homogeneous scenario where a general a-out-of-b aggregation rule is assumed at the AP. Specifically, the contributions of this paper can be summarized as follows: i) we design joint cooperative sensing and synchronized MAC protocols for a multi-channel cognitive radio network. We derive the spectrum sensing performance for a-out-of-b aggregation rule and we perform the throughput analysis of our proposed sensing and access design. ii) we propose solutions for two parameter optimization problems of our proposed design. Specifically, given a channel assignment, we study how to determine the sensing time and contention window of the MAC protocol. Moreover, we consider the channel assignment problem for throughput maximization where we present both brute-force search optimal algorithm and the low-complexity greedy algorithm. iii) we present numerical results to illustrate the performance of the proposed MAC protocols and the throughput gains due to optimized design compared to the non-optimized one.

The remaining of this paper is organized as follows. Section II describes the system model, sensing, and access design. Throughput analysis, optimization of spectrum sensing, access, and channel assignment are performed in Section III. Section IV presents numerical results followed by concluding remarks in Section V.

# II. SPECTRUM SENSING AND ACCESS DESIGN

In this section, we describe the system model, spectrum sensing, and access design for the cognitive radio networks.

#### A. System Model

We consider a network setting where N pairs of secondary users (SUs) opportunistically exploit available frequency bands in M channels for data transmission. For simplicity, we refer

#### Collocated network

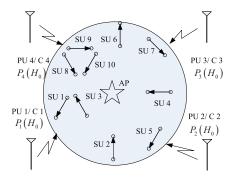


Fig. 1. Network model (PU: primary user, SU: secondary user)

to pair i of SUs simply as SU i. We assume that each SU can exploit multiple available channels for transmission (e.g., by using OFDM technology). We will design a synchronized MAC protocol for channel access. We assume that each channel is either in the idle or busy state for each predetermined periodic interval, which is called a cycle in this paper.

We further assume that each pair of SUs can overhear transmissions from other pairs of SUs (i.e., collocated networks). There are M primary users (PUs) each of which may or may not use one corresponding channel for its data transmission in any cycle. In addition, it is assumed that transmission from any pair of SUs on a particular channel will affect the primary receiver which receives data on that channel. The network setting under investigation is shown in Fig. 1.

## B. Cooperative Spectrum Sensing

We assume that each SU i is assigned in advance a set of channels  $S_i$  where it senses all channels in this assigned list at beginning of each cycle. Optimization of such channel assignment will be considered in the next section. Upon completing the channel sensing, each SU i sends the idle/busy states of all channels in  $S_i$  to the access point (AP) for further processing. The AP upon collecting sensing results from all SUs will decide idle/busy status for all channels. Then, the AP broadcasts the list of available channels to all SUs. SUs are assumed to rely on a distributed MAC protocol to perform access resolution where the winning SU transmits data by using all available channels. Detailed MAC protocol design will be elaborated later.

Let  $\mathcal{H}_0$  and  $\mathcal{H}_1$  denote the events that a particular PU is idle and active, respectively (i.e., the corresponding channel is available and busy, respectively) in a cycle. In addition, let  $\mathcal{P}_j(\mathcal{H}_0)$  and  $\mathcal{P}_j(\mathcal{H}_1) = 1 - \mathcal{P}_j(\mathcal{H}_0)$  be the probabilities that channel j is available and not available for all SUs, respectively. We assume that SUs employ an energy detection scheme and let  $f_s$  be the sampling frequency used in the sensing period for all SUs. There are two important performance measures, which are used to quantify the sensing performance, namely detection and false alarm probabilities. In particular, detection event occurs when a SU successfully senses a busy channel and false alarm represents the situation when a spectrum sensor returns a busy status for an idle channel (i.e., a transmission opportunity is overlooked).

Assume that transmission signals from PUs are complexvalued PSK signals while the noise at the SUs is independent and identically distributed circularly symmetric complex Gaussian  $\mathcal{CN}\left(0,N_0\right)$  [4]. Then, the detection and false alarm probabilities for the channel j at SU i can be calculated as [4]

$$\mathcal{P}_d^{ij}\left(\varepsilon^{ij}, \tau^{ij}\right) = \mathcal{Q}\left(\left(\frac{\varepsilon^{ij}}{N_0} - \gamma^{ij} - 1\right)\sqrt{\frac{\tau^{ij}f_s}{2\gamma^{ij} + 1}}\right), \quad (1)$$

$$\mathcal{P}_{f}^{ij}\left(\varepsilon^{ij}, \tau^{ij}\right) = \mathcal{Q}\left(\left(\frac{\varepsilon^{ij}}{N_{0}} - 1\right)\sqrt{\tau^{ij}f_{s}}\right)$$

$$= \mathcal{Q}\left(\sqrt{2\gamma^{ij} + 1}\mathcal{Q}^{-1}\left(\mathcal{P}_{d}^{ij}\left(\varepsilon^{ij}, \tau^{ij}\right)\right) + \sqrt{\tau^{ij}f_{s}}\gamma^{ij}\right), \quad (2)$$

where  $i \in [1,N]$  is the index of a SU link,  $j \in [1,M]$  is the index of a channel,  $\varepsilon^{ij}$  is the detection threshold for an energy detector,  $\gamma^{ij}$  is the signal-to-noise ratio (SNR) of the PU's signal at the SU,  $f_s$  is the sampling frequency,  $N_0$  is the noise power,  $\tau^{ij}$  is the sensing interval of SU i on channel j, and  $\mathcal{Q}(.)$  is defined as  $\mathcal{Q}(x) = \left(1/\sqrt{2\pi}\right)\int_x^\infty \exp\left(-t^2/2\right)dt$ .

We assume that a general cooperative sensing scheme, namely a-out-of-b rule, is employed by the AP to determine the idle/busy status of each channel based on reported sensing results from all SUs. Under this scheme, the AP will declare that a channel is busy if a or more SUs out of b SUs report that the underlying channel is busy. The a-out-of-b rule covers different other rules including OR, AND and Majority rules as special cases. In particular, when a=1, it is OR rule; when a=b, it is AND rule; and when  $a=\lceil b/2 \rceil$ , it is Majority rule. Let consider channel j. Let  $\mathcal{S}_j^U$  denote the set of SUs that sense channel j and  $b_j=\left|\mathcal{S}_j^U\right|$  be the number of SUs sensing channel j. Then the AP's decision on the status of channel j will result in detection and false alarm probabilities for this channel, which can be calculated as, respectively [8]

$$\mathcal{P}_d^j\left(\vec{\varepsilon}^j, \vec{\tau}^j, a_j\right) = \sum_{l=a_j}^{b_j} \sum_{k=1}^{C_{b_j}^l} \prod_{i_1 \in \Phi_k^k} \mathcal{P}_d^{i_1 j} \prod_{i_2 \in \mathcal{S}_a^U \setminus \Phi_k^k} \bar{\mathcal{P}}_d^{i_2 j} \tag{3}$$

$$\mathcal{P}_f^j\left(\vec{\varepsilon}^j, \vec{\tau}^j, a_j\right) = \sum_{l=a_j}^{b_j} \sum_{k=1}^{C_{b_j}^l} \prod_{i_1 \in \Phi_f^k} \mathcal{P}_f^{i_1 j} \prod_{i_2 \in \mathcal{S}_i^U \setminus \Phi_f^k} \bar{\mathcal{P}}_f^{i_2 j} \tag{4}$$

where  $\Phi_l^k$  in (3) and (4) are particular sets with l SUs whose sensing outcomes indicate that channel j is busy given that this channel is indeed busy and idle, respectively;  $\vec{\varepsilon}^j = \left\{ \varepsilon^{ij} \right\}$ ,  $\vec{\tau}^j = \left\{ \tau^{ij} \right\}$ ,  $i \in \mathcal{S}_j^U$ . For brevity,  $\mathcal{P}_d^j \left( \vec{\varepsilon}^j, \vec{\tau}^j, a_j \right)$  and  $\mathcal{P}_f^j \left( \vec{\varepsilon}^j, \vec{\tau}^j, a_j \right)$  are written as  $\mathcal{P}_d^j$  and  $\mathcal{P}_f^j$  in the following.

# C. MAC Protocol Design

We assume that time is divided into fixed-size cycles and it is assumed that SUs can perfectly synchronize with each other (i.e., there is no synchronization error) [12]. We propose a synchronized multi-channel MAC protocol for dynamic spectrum sharing as follows. The MAC protocol has three phases in each cycle utilizing one control channel, which is assumed to be always available, as illustrated in Fig. 2. In the first phase, namely the sensing phase of length  $\tau$ , all SUs simultaneously perform spectrum sensing on their assigned

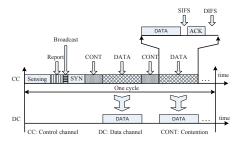


Fig. 2. Timing diagram of the proposed multi-channel MAC protocol

channels. Here, we have  $\tau = \max_i \tau_i$ , where  $\tau_i = \sum_{j \in \mathcal{S}_i} \tau_{ij}$  is total sensing time of SU i,  $\tau_{ij}$  is the sensing time of SU i on channel j, and  $\mathcal{S}_i$  is the set of channels assigned for SU i. All SUs exchange beacon signals on the control channel to achieve synchronization in the second phase. Then, each SU reports its sensing results to the AP on the control channel. The AP collects sensing results from all SUs; decide idle/status for all channels; and broadcast this information to all SUs on the control channel.

In the third phase, SUs participate in the contention and the winning SU will transmit data on all vacant channels. We assume that the length of each cycle is sufficiently large so that SUs can transmit several packets during the data transmission phase. During the data transmission phase, we assume that active SUs employ a standard contention technique to capture the channel similar to that in the CSMA/CA protocol. Exponential backoff with minimum contention window W and maximum backoff stage  $m_0$  [13] is employed in the contention phase. For brevity, we refer to W simply as contention window in the following. Specifically, suppose that the current backoff stage of a particular SU is i then it starts the contention by choosing a random backoff time uniformly distributed in the range  $[0, 2^iW - 1]$ ,  $0 \le i \le m_0$ . This user then starts decrementing its backoff time counter while carrier sensing transmissions from other SUs on vacant channels.

Let  $\sigma$  denote a mini-slot interval, each of which corresponds one unit of the backoff time counter. Upon hearing a transmission from any SU, each SU will "freeze" its backoff time counter and reactivate when the channel is sensed idle again. Otherwise, if the backoff time counter reaches zero, the underlying SU wins the contention. Here, two-way handshake will be employed to transmit one data packet on the available channel. After sending the data packet the transmitter expects an acknowledgment (ACK) from the receiver to indicate a successful reception of the packet. Standard small intervals, namely DIFS and SIFS, are used before backoff time decrements and ACK packet transmission as described in [13].

# III. PERFORMANCE ANALYSIS, DESIGN, AND OPTIMIZATION

#### A. Throughput Analysis

We assume that all SUs transmit data packets of the same length. Let  $\mathcal E$  denote the average number of vacant channels that are correctly detected by the AP. Suppose  $\mathcal T(\tau,W)$  denote the throughput achieved by all N SUs on an imaginary single-channel network where the channel is always available. Then,

the normalized throughput per one channel achieved by our MAC protocol can be calculated as

$$\mathcal{N}\mathcal{T} = \mathcal{T}\left(\tau, W\right) \frac{1}{M} \mathcal{E} \tag{5}$$

Here,  $\mathcal{E}$  can be calculated as follows:

$$\mathcal{E} = \sum_{m=1}^{M} \sum_{i=1}^{C_M^m} \prod_{j_1 \in \Psi_m^i} \mathcal{P}_{j_1} \left( \mathcal{H}_0 \right) \prod_{j_2 \in \mathcal{S} \setminus \Psi_m^i} \mathcal{P}_{j_2} \left( \mathcal{H}_1 \right)$$
 (6)

$$\times \sum_{n=1}^{m} \sum_{i_{1}=1}^{C_{m}^{n}} n \prod_{j_{3} \in \Theta_{n}^{i_{1}}} \bar{\mathcal{P}}_{f}^{j_{3}} \prod_{j_{4} \in \Psi_{m}^{i} \setminus \Theta_{n}^{i_{1}}} \mathcal{P}_{f}^{j_{4}}$$
 (7)

where  $\mathcal{S}$  is the set of all M channels. The quantity (6) represents the probability that there are m available channels, which may or may not be correctly detected by SUs and the AP. Here,  $\Psi^i_m$  denotes a particular set of m available channels whose index is i. The second quantity (7) describes the product of n and the probability that there are n available channels according to the sensing decision of the AP (so the remaining available channels are overlooked due to sensing errors) where  $\Theta^{i_1}_n$  denotes the  $i_1$ -th set with n available channels.

In the following, we describe how to calculate  $\mathcal{T}(\tau,W)$  by using the technique developed by Bianchi in [13]. In particular, we approximately assume a fixed transmission probability  $\phi$  in a generic slot time. Bianchi shows that this transmission probability can be computed from the following two equations [13]

$$\phi = \frac{2(1-2p)}{(1-2p)(W+1) + Wp(1-(2p)^{m_0})},$$
 (8)

$$p = 1 - (1 - \phi)^{n-1}, \tag{9}$$

where  $m_0$  is the maximum backoff stage, p is the conditional collision probability (i.e., the probability that a collision is observed when a data packet is transmitted on the channel). For our system, there are N SUs participating in contention in the third phase, the probability that at least one SU transmits its data packet can be written as

$$\mathcal{P}_t = 1 - (1 - \phi)^N \,. \tag{10}$$

However, the probability that a transmission occurring on the channel is successful given there is at least one SU transmitting can be written as

$$\mathcal{P}_s = \frac{N\phi \left(1 - \phi\right)^{N-1}}{\mathcal{P}_t}.\tag{11}$$

The average duration of a generic slot time can be calculated as

$$\bar{T}_{sd} = (1 - \mathcal{P}_t) T_e + \mathcal{P}_t \mathcal{P}_s T_s + \mathcal{P}_t (1 - \mathcal{P}_s) T_c, \tag{12}$$

where  $T_e = \sigma$ ,  $T_s$  and  $T_c$  represent the duration of an empty slot, the average time the channel is sensed busy due to a successful transmission, and the average time the channel is sensed busy due to a collision, respectively. These quantities can be calculated under the basic access mechanism as [13]

$$\begin{cases} T_{s} = T_{s}^{1} = H + PS + SIFS + 2PD + ACK + DIFS \\ T_{c} = T_{c}^{1} = H + PS + DIFS + PD \\ H = H_{PHY} + H_{MAC} \end{cases}, (13)$$

where  $H_{PHY}$  and  $H_{MAC}$  are the packet headers for physical and MAC layers, PS is the packet size in transmission time, which is assumed to be fixed in this paper, PD is the propagation delay, SIFS is the length of a short interframe space, DIFSis the length of a distributed interframe space, ACK is the length of an acknowledgment. Recall that these parameters are measured in units of bits or  $\mu s$  due to bit rate = 1 Mbps. Based on these quantities, we have

$$\mathcal{T}(\tau, W) = \left| \frac{T - \tau - T_R}{\bar{T}_{sd}} \right| \frac{\mathcal{P}_s \mathcal{P}_t PS}{T}, \tag{14}$$

where  $T_R = Nt_r + t_b$ ,  $t_r$  is the report time from each SU to the AP,  $t_b$  the broadcast time from the AP to all SUs. Recall that  $\tau = \max_i \tau^i$  is the total the sensing time. |.| denotes the floor function and recall that T is the duration of a cycle. Note that  $\frac{T-\tau-T_R}{T_{sd}}$  denotes the average number of generic slot times in one particular cycle excluding the sensing and reporting phase. Here, we omit the length of the synchronization phase, which is assumed to be negligible.

#### B. Cooperative Sensing and Access Optimization

We discuss optimization of cooperative sensing and access parameters to maximize the normalized throughput under sensing constraints for PUs. In particular, the throughput maximization problem can be stated as follows:

$$\max_{\tau^{ij} W} \quad \mathcal{NT}(\tau, W) \tag{15}$$

$$\text{s.t.} \ \ \mathcal{P}_{d}^{j}\left(\bar{\varepsilon}^{j},\vec{\tau}^{j},a_{j}\right)\geq\widehat{\mathcal{P}}_{d}^{j},j\in\left[1,M\right] \tag{16}$$

$$0 < \tau^{ij} < T, \quad 0 < W < W_{\text{max}},$$
 (17)

where  $\mathcal{P}_d^j$  is the detection probability for channel j at the AP,  $W_{\mathsf{max}}$  is the maximum contention window and recall that Tis the cycle interval.

## Algorithm 1 Sensing and Access Optimization

- 1: Assume we have the sets of all SU i,  $\{S_i\}$ . Initialize  $\tau^{ij}$ ,
- 2: For each integer value of  $W \in [1, W_{\text{max}}]$ , find  $\bar{\tau}^{ij}$  as
- 3: for i=1 to N do
- Fix all  $\tau^{i_1j}$ ,  $i_1 \neq i$ . Find optimal  $\bar{\tau}^{ij}$  as  $\bar{\tau}^{ij} = \underset{0 < \tau^{ij} \leq T}{\operatorname{argmax}} \mathcal{NT}(\tau^{ij}, W)$ .
- 6: end for
- 7: The final solution  $(\bar{W}, \bar{\tau}^{ij})$  is determined as  $(\bar{W}, \bar{\tau}^{ij}) =$  $\operatorname{argmax} \mathcal{NT}(\bar{\tau}^{ij}, W).$  $W, \bar{\tau}^{ij}$

We propose a low-complexity algorithm (Alg. 1) to find an efficient solution for the optimization problem (15, 16, 17). In particular, for each potential value of  $W \in [1, W_{\text{max}}]$ , we search for the best  $\tau^{ij}$  to maximize the total throughput. This is done by a sequential search technique. Then, the final solution is determined by the best combination of  $\tau^{ij}$ , W for different values of W. Numerical results reveal that Alg. 1 can always find the optimal solution of the underlying problem.

# C. Channel Assignment for Throughput Maximization

So far we have assumed a fixed channel assignment based on which SUs perform sensing. In this section, we attempt to determine an efficient channel assignment solution by solving the following problem

$$\max_{\{S_i\}} \mathcal{N}\mathcal{T}\left(\bar{\tau}^{ij}, \bar{W}, \{S_i\}\right) \tag{18}$$

# Algorithm 2 CHANNEL ASSIGNMENT ALGORITHM

- 1: Run Alg. 1 for temporary assignments  $S_i = S$ ,  $i \in [1, N]$ to get  $(\bar{W}, \bar{\tau}^{ij})$ . Employ Hungarian algorithm [14] to determine the first channel assignment for each SU so that each channel is assigned to exactly one SU where the cost of assigning channel j to SU i is  $\bar{\tau}^{ij}$ . This results in initial channel assignment sets  $\{S_i\}$  for different SU i.
- 2: continue := 1, k := 1.
- 3: **while** continue = 1 do
- Calculate the normalized throughput with optimized parameter setting by using Alg. 1 as  $\mathcal{NT}_{th}$  =  $\mathcal{NT}(\bar{\tau}^{ij}, \bar{W}, \mathcal{S}_i).$
- Each SU i calculates the increase of throughput if it is assigned one further potential channel j as  $\Delta T_{ij} =$  $\mathcal{NT}(\bar{\tau}^{ij}, \bar{W}, \mathcal{S}_i^1) - \mathcal{NT}_{th}$  where  $\mathcal{S}_i^1 = \mathcal{S}_i \cup j$  and  $\bar{\tau}^{ij}$ ,  $\hat{W}$  are determined by using Alg. 1 for assignment sets  $S_i^1$  and  $S_l$ ,  $l \neq i$ .
- Find the "best" assignment  $(\bar{i}, \bar{j})$  as  $(\bar{i}, \bar{j}) =$  $\operatorname{argmax} \Delta T_{ij}$ .
  - $\inf^{i,j\in\mathcal{S}\setminus\mathcal{S}_i}\Delta T_{\overline{i}\overline{j}}>\delta \ \ \text{then}$
- Assign channel  $\bar{j}$  to SU  $\bar{i}$  ( $S_i = S_i^1$ ). 8:
- k = k + 1. 9:
- else 10:
- continue := 0
- end if
- end while 13:
- 14: **if** k > 1 **then**
- Return to step 2.
- else 16:
- 17: STOP Alg.
- 18: **end if**

1) Brute-force Search Algorithm: Since the possible number of channel assignments is finite, we can employ the bruteforce search to determine the optimal channel assignment solution and its protocol parameters. This can be done by determining the best configuration parameters under each channel assignment (i.e., using Alg. 1) then comparing the throughput achieved by different channel assignments to find the best one.

We now quantify the complexity of this optimal brute-force search algorithm. The number of possible assignments is equal to the following: How many ways are there to fill 1/0 to the elements of an NxM matrix. It can verify that the number of ways is  $2^{MN}$ . Therefore, the complexity of the optimal brute-force search algorithm is  $\mathcal{O}(2^{MN})$ . Moreover, for each case, we must run Alg. 1 to determine the sensing and access parameters.

2) Low-complexity Algorithm: We propose a lowcomplexity algorithm to find an efficient channel assignment solution, which is described in Alg. 2. In step 1, we run Hungarian algorithm to perform the first channel assignment for each SU i. The complexity of this operation can be upper-bounded by  $\mathcal{O}(M^2N)$  (see [14] for more details). In each assignment in the loop (i.e., Steps 2-13), each SU i calculates the increases of throughput due to different potential channel assignments, and selects the one resulting in the maximum increase. Hence, the complexity involved in these assignments is upper-bounded by MN since there are at most M channels to choose for each of N SUs. Also, the number of assignments to perform is upper bounded by MN. Therefore, the complexity of this loop is upper-bounded by  $M^2N^2$ . Suppose we run these assignments for r times before the algorithm terminates. Therefore, the complexity of Alg. 2 can be upper-bounded by  $\mathcal{O}(M^2N + rM^2N^2) = \mathcal{O}(rM^2N^2)$ , which is much lower than that of the brute-force search algorithm.

#### IV. NUMERICAL RESULTS

To obtain numerical results, we take key parameters for the MAC protocols from Table II in [13]. Other parameters are chosen as follows: cycle time is T = 100ms; minislot (i.e., generic empty slot time) is  $\sigma = 20 \mu s$ ; sampling frequency for spectrum sensing is  $f_s = 6MHz$ ; bandwidth of PUs' QPSK signals is 6MHz;  $t_r = 80\mu s$  and  $t_b = 80\mu s$ . The target detection probabilities for channel j  $\widehat{\mathcal{P}}_d^j$  in (16) are chosen randomly in the intervals [0.95, 0.99]. In order to calculate  $\mathcal{E}$  in (6)-(7), we need to determine  $\mathcal{P}_f^j$  for different j, which can be done as follows. We set the equality for (16), i.e.,  $\mathcal{P}_{d}^{j}\left(\vec{\varepsilon}^{j},\vec{\tau}^{j},a_{j}\right)=\widehat{\mathcal{P}}_{d}^{j}$  (see [2] for detailed explanation) and assume that detection probabilities  $\mathcal{P}_d^{ij}=\mathcal{P}_d^{j*}$  are equal to each other from which we can calculate  $\mathcal{P}_d^{j*}$  by using (3). Then, we can determine  $\mathcal{P}_f^j$  by using (4) and (2). The signal-to-noise ratio of PU signals at SUs  $\gamma^{ij} = SNR_n^{ij}$ are chosen randomly in the range [-15, -20]dB and the maximum backoff stage is  $m_0 = 3$ .

We first compare the throughput performance achieved by the brute-force search and low-complexity algorithms (i.e., Alg. 2) for channel assignment. In particular, in Table I we show the normalized throughput  $\mathcal{NT}$  versus probabilities  $\mathcal{P}_j\left(\mathcal{H}_0\right)$  for these two algorithms. Here, the probabilities  $\mathcal{P}_j\left(\mathcal{H}_0\right)$  for different channels j are chosen to be the same and we choose M=4 channels and N=4 SUs. This figure confirms that the throughput gaps between our greedy algorithm and the brute-force optimal search algorithm are quite small, which is about 1% in all cases. These results confirm that our proposed greedy algorithm works well for small systems (i.e., small M and N).

We now investigate the performance of our proposed algorithm for larger systems. In Figs. 3, 4, 5, and 6, we consider the network setting with N=10 and M=4. We divide SUs into 2 groups where SUs have received SNRs due to PU i's signal equal to  $\gamma^{ij}=-15dB$  and  $\gamma^{ij}=-10dB$  in the two groups, respectively. We use a combination  $\{i,j\}$  to represent

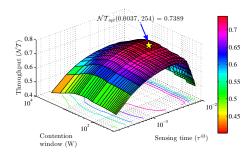


Fig. 3. Normalized throughput versus contention window W and sensing time  $\tau$  for  $m=3,\ N=10,\ M=4.$ 

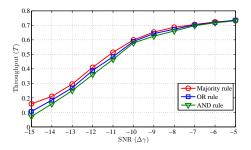


Fig. 4. Normalized throughput versus SNR shift  $\Delta\gamma$  for m=3,~N=10,~M=4 under 3 aggregation rules.

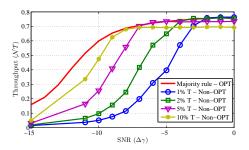


Fig. 5. Normalized throughput versus SNR shift  $\Delta \gamma$  for m=3,~N=10,~M=4 for optimized and non-optimized scenarios.

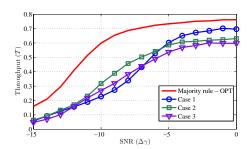


Fig. 6. Normalized throughput versus SNR shift  $\Delta\gamma$  for m=3,~N=10,~M=4 for optimized and RR channel assignments.

the scenario where channel j is assigned to and sensed by SU i. The following combinations are set corresponding to  $\gamma^{ij}=-10dB$ : channel 1:  $\{1,1\}$ ,  $\{2,1\}$ ,  $\{3,1\}$ ; channel 2:  $\{2,2\}$ ,  $\{4,2\}$ ,  $\{5,2\}$ ; channel 3:  $\{4,3\}$ ,  $\{6,3\}$ ,  $\{7,3\}$ ; and channel 4:  $\{1,4\}$ ,  $\{3,4\}$ ,  $\{6,4\}$ ,  $\{8,4\}$ ,  $\{9,4\}$ ,  $\{10,4\}$ . The remaining combinations correspond to the SINR value  $\gamma^{ij}=-15dB$ . To obtain results for different values of SNRs, we shift both SNRs (-10dB and -15dB) by  $\Delta\gamma$ . For example, when  $\Delta\gamma=-10$ , the resulting SNR values are  $\gamma^{ij}=-25dB$  and

TABLE I THROUGHPUT VS PROBABILITY  $\mathcal{P}_{i}\left(\mathcal{H}_{0}\right)$  (MXN=4X4)

		$\mathcal{P}_{j}\left(\mathcal{H}_{0} ight)$									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
	Greedy	0.0838	0.1677	0.2515	0.3353	0.4191	0.5030	0.5868	0.6707	0.7545	0.8383
$\mathcal{N}\mathcal{T}$	Optimal	0.0846	0.1692	0.2544	0.3384	0.4239	0.5082	0.5935	0.6769	0.7623	0.8479
	Gap (%)	1.0090	0.9187	1.1293	0.9142	1.1294	1.0261	1.1266	0.9159	1.0261	1.1266

TABLE II ROUND-ROBIN CHANNEL ASSIGNMENT (X DENOTES AN ASSIGNMENT)

	Case 1				Case 2				Case 3			
	1	2	3	4	1	2	3	4	1	2	3	4
1	X				X	X			X	X	X	
2		X				X	X			X	X	X
3			X				X	X			X	X
4				X				X				X
5	X				X	X			X	X	X	
6		X				X	X			X	X	X
7			X				X	X			X	X
8				X				X				X
9	X				X	X			X	X	X	
10		X				X	X			X	X	X

 $\gamma^{ij} = -20dB.$ 

Fig. 3 presents the normalized throughput  $\mathcal{NT}$  versus contention window W and sensing time  $\tau^{ij}$  for the combination  $\{4,3\}$  and  $\Delta\gamma=-5$  (the parameters of other combinations are set at optimal values). Therefore, this figure shows the normalized throughput  $\mathcal{NT}$  versus W and only  $\tau^{43}$ . We show the optimal configuration  $(\bar{\tau}^{43},\bar{W})$ , which maximizes the normalized throughput  $\mathcal{NT}$  of the proposed MAC protocol. It can be observed that the normalized throughput  $\mathcal{NT}$  is less sensitive to the contention window W while it decreases significantly as the sensing time  $\tau^{43}$  deviates from the optimal value.

In Fig. 4, we compare the throughput performance as the AP employs there different aggregation rules, namely AND, OR, and Majority rules. The three throughput curves in this figure represent the optimized normalized throughputs (i.e., by using Algs. 1 and 2). It can be seen that The Majority rule achieves the highest throughput among the three. In Fig. 5, we compare the throughput performances under the optimized and the non-optimized scenarios. For the non-optimized scenario, we also employ Alg. 2 for channel assignment; however we do not use Alg.1 to choose optimal sensing/access parameters. Instead,  $\tau^{ij}$  is chosen from the following values: 1%T, 2%T, 5%T and 10%T, where T is the cycle time. Again, the optimized normalized throughput is higher than that due to non-optimized scenarios. Finally, Fig. 6 demonstrates the relative throughput performance of our proposed algorithm and the round-robin (RR) channel assignment strategies. For RR channel assignments, we allocate channels for users, which is described in Table II. For all RR channel assignments, we employ Alg. 1 to determine optimal sensing/access parameters. Again, the optimized design achieve much higher throughput than those due to RR channel assignments.

#### V. CONCLUSION

We propose a general analytical framework for cooperative sensing and access design and optimization in cognitive radio networks. We analyze the throughput performance of the proposed design, and develop an algorithm to find its sensing/access parameters. Moreover, we present both optimal brute-force search and low-complexity algorithms to determine efficient channel assignments. Then, we analyze the complexity of different algorithms and evaluate their throughput performance via numerical studies.

#### REFERENCES

- C. Cormiob and K. R. Chowdhurya, "A survey on MAC protocols for cognitive radio networks," *Elsevier Ad Hoc Networks*, vol. 7, no. 7, pp. 1315-1329, Sept. 2009.
- [2] L. T. Tan and L. B. Le, "Distributed mac protocol for cognitive radio networks: Design, analysis, and optimization," *IEEE Transactions on Vehicular Technology*, vol.60, no.8, pp. 3990-4003, 2011.
- [3] L. T. Tan and L. B. Le, "Channel assignment with access contention resolution for cognitive radio networks," *IEEE Transactions on Vehicular Technology*, vol.61, no.6, pp. 2808-2823, 2012.
- [4] Y.-C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks", *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326-1337, April 2008.
- [5] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio. Part I: Two user networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 22042213, Jun. 2007
- [6] Z. Quan, S. Cui, and A. H. Sayed, "Optimal linear cooperation for spectrum sensing in cognitive radio networks," *IEEE J. Sel. Topics Signal Process.*, vol. 2, no. 1, pp. 2840, Feb. 2008.
- [7] E. C. Y. Peh, Y.-C. Liang and Y. L. Guan, "Optimization of cooperative sensing in cognitive radio networks: A sensing-throughput tradeoff view," in *Proc. IEEE International Conf. Commun.*, pp. 3521–3525, 2009
- [8] Y. Wei, H. Leung, C. Wenqing and C. Siyue, "Optimizing voting rule for cooperative spectrum sensing through learning automata," *IEEE Transactions on Vehicular Technology*, vol.60, no.7, pp. 3253–3264, 2011.
- [9] Z. Wei, R. Mallik and K. Letaief, "Optimization of cooperative spectrum sensing with energy detection in cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol.8, no.12, pp. 5761–5766, 2009
- [10] K. Seung-Jun, and G. B. Giannakis, "Sequential and cooperative sensing for multi-channel cognitive radios," *IEEE Transactions on Signal Processing*, vol. 58, no. 8, pp. 4239–4253, 2010.
- [11] J. Park, P. Pawelczak and D. Cabric, "Performance of joint spectrum sensing and mac algorithms for multichannel opportunistic spectrum access ad hoc networks," *IEEE Transactions on Mobile Computing*, vol.10, no.7, pp. 1011-1027, 2011.
- [12] Y.R. Kondareddy, and P. Agrawal, "Synchronized MAC protocol for multi-hop cognitive radio networks," in *Proc. IEEE ICC* 2008.
- [13] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.
- [14] H.W. Kuhn, "The Hungarian method for the assignment problem," Naval Research Logistic Quarterly, 2 (1955), pp. 83–97, 1955.