A Cooperative MAC with Efficient Spectrum Sensing Algorithm for Distributed Opportunistic Spectrum Networks

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***Abstract*—The spectrum scarcity has led to rethink in the current frequency spectrum usage and develop a new concept of wireless networking. Opportunistic Spectrum Networks (OSNs) have been considered as a promising solution to the problem of spectrum shortage. In this paper, in order to compensate for the need of complex hardware, a novel and efficient Medium Access Control (MAC) framework that integrates a kind of cooperative spectrum sensing method at the physical layer into a cooperative MAC protocol is developed for distributed OSNs considering the requirements of both the primary and secondary users. For the MAC framework, an innovative deterministic sensing policy called Allocated-group Sensing Policy (ASP) is proposed to identify the spectrum opportunities based on a dynamic ID numbering approach, and its effectiveness is demonstrated by comparison with two random sensing policies. Moreover, a computationally simple but efficient sensing algorithm is developed to assist each sensing user to identify the optimal number of channels to sense and the optimal sensing duration. It is demonstrated that the proposed cooperative MAC framework can efficiently achieve the ultimate goal of the OSNs even with only a small number of sensing users each equipped with a single cognitive radio transceiver.**

***Index Terms*—Opportunistic Spectrum Networks (OSNs), Medium Access Control (MAC), Dynamic ID Numbering, Sensing Policy.**

I. Introduction

In the last two decades, the world has witnessed rapid increasing applications of wireless networks; however, with the past and current fixed spectrum allocating regulations, the natural resource of the frequency spectrum is running out. This has led to what so-called spectrum scarcity [1]. Since the spectrum is the lifeblood of wireless communications, it should be used efficiently, or the emerging wireless applications would not be supported any more. In this paper, we are interested in a kind of wireless networks that is considered as a promising solution to the spectrum scarcity. These networks are known as Opportunistic Spectrum Networks (OSNs). It is worth mentioning that Cognitive Radio Networks (CRNs), Dynamic Spectrum access Networks (DSNs), and Opportunistic Spectrum access Networks (OSNs) terminologies are often used interchangeably in the literature to describe the new emerging wireless networks that use the CR technology to exploit the spectrum opportunities. However, we prefer to use the term OSNs that exactly describes what this network means.

There are two types of users in OSNs: Primary Users (PUs) owning licenses to use exclusively assigned spectrum bands, and Secondary Users (SUs) having no spectrum licenses but seeking for any spectrum opportunities. The SUs can make use of the unused spectrum portions of the PUs if they do not make any harmful interference to the PUs. Therefore, the SUs should be able to carry out two key functions: spectrum opportunity identification and spectrum access [2].

Although the basic idea of OSNs seems simple, the implementation of it is challenging. The co-existence with the primary networks, which may comprise of different types of PUs, and the spread of the spectrum opportunities over wide spectrum bands and their consequent challenges make the research in this area very challenging [3]. Fortunately, with the advanced technologies in the new evolution of Cognitive Radios (CRs), implementation of OSNs can be envisioned. Cognitive Radios are promising technologies that can be used by SUs to perform two key functions: detecting the spectrum opportunities by spectrum sensing and exploiting these opportunities by spectrum accessing [4], [5]. These two functions are related and one cannot work properly without the other. This leads to the concept of cross-layer design in wireless networks. Since distributed networks may be the practical architecture that attracts the future applications of spectrum secondary usage, we will focus on distributed OSNs throughout this paper.

Researchers in OSNs try to tackle some new challenges not found in the traditional wireless networks. Since most of these challenges are related to the design of the Medium Access Control (MAC), several protocols have been proposed. Most of these protocols are discussed in a recent survey [6]. Indeed, the MAC protocols for OSNs can be considered in general as multichannel MAC protocols with special requirements. Reference [7] provides comprehensive comparison between these multichannel MAC protocols, while [8] compares between the opportunistic multichannel MAC protocols.

Some researchers have proposed using Markov decision

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process to develop an analytical framework for OSNs. In [9], each SU pair decides, without cooperation with other SUs, when to sense and when to access the spectrum based on the Partial Observable Markov Decision Process (POMDP) framework where optimal and suboptimal decision rules are discussed. In [10], a separation principle that optimizes the spectrum sensing at the physical layer and then optimizes the spectrum access at the MAC layer is used to reduce the computational complexity of the POMDP approach. However, the computational complexity of this approach may still not be suitable for this kind of networks.

Other researchers have proposed frameworks based on statistical information about the existence of PUs. The authors of [11] have proposed statistical MAC (SCA-MAC) protocols, while the proposed MAC in [12] is called opportunistic cognitive MAC (OC-MAC), which is almost the same concept of that in [11] except it uses a different handshake mechanism. Both of these two works use statistical sensing about the PUs from the last time slot, so if the status of the PUs in the current time slot significantly changes for any reason, the decision taken by the secondary receiver may not be the best any more, and possibly the secondary transmission may increase the interference to the PUs to an unacceptable level.

The slotted time MAC structure approach has been proposed by some researchers. In [13], an opportunistic MAC protocol based on this approach for the data and control channels has been proposed. This protocol requires each SU to be equipped with two radios: a traditional radio devoted for the control channel and a Software Defined Radio (SDR) to sense and transmit/receive data. Therefore, the hardware cost is a main issue in this study. Moreover, when the number of the SUs is small, the average throughput of the secondary network is consequently low. In [14], a distributed multichannel MAC protocol for CRNs (MMAC-CR) is proposed based on a slotted time structure also. It is almost similar to that of IEEE 802.11 PSM, and the sensing scheme is similar to that proposed for IEEE 802.22, i.e., on two phases: fast sensing and fine sensing. Although, the used sensing scheme may increase the accuracy of PUs detection, it is at the cost of reducing the remaining time for data exchanging; moreover, the evaluation of this protocol is mainly done by simulation, so analytical analysis is necessarily required.

The hardware constraints are the main concern in [15]. Each SU node is assumed to be equipped with a single half-duplex CR. This proposed hardware constrained MAC (HC-MAC) deals well with the sensing and transmission constraints using optimal stopping time rule; however, the simultaneous transmission from faraway secondary nodes may lead to inaccurate detection of the PUs; moreover, the spectrum utilization is not optimized since there may be some available channels not exploited by any secondary users.

The sensing time is a key parameter in the spectrum sensing in OSNs; therefore, it should be optimized to obtain a reasonable sensing result that maintains acceptable interference to the primary network while maximizing the spectrum utilization. In [16]-[22], the sensing time is optimized based on some proposed models and scenarios.

Although several MAC protocols have been proposed to tackle some of the new challenges in the distributed OSNs, designing practical and efficient such protocols is still in its infancy, so more research efforts are needed to realize the concept of this emerging wireless networks. Cooperation between the SUs can compensate for the need of complex hardware. Cooperation here implies that the SUs cooperate with each other to identify the spectrum opportunities and also to exploit these opportunities. To the best of our knowledge, there is no such study that provides this twofold cooperation in distributed OSNs considering the hardware limitations and costs in addition to the requirements of both the primary and secondary users. In this paper, we develop a MAC framework that can handle this cooperation to achieve the ultimate goals of the OSNs without need for complex hardware. In order to control the spectrum sensing and accessing efficiently, we propose a new dynamic ID numbering approach that helps out to order the SUs in a distributed manner. Furthermore, we investigate a computationally simple but efficient sensing algorithm that relies on an innovative sensing policy called Allocated-group Sensing Policy (ASP) in order to assist the SUs to optimally identify the spectrum opportunities online.

The remainder of this paper is organized as follows. Section II provides the system model. The proposed MAC framework is presented in Section III. In Section IV, the Allocated-group Sensing Policy is investigated and evaluated. Using this sensing policy, the sensing time duration and hence the sensing algorithm are analyzed and evaluated in Section V. Finally, Section VI concludes this paper.

II. System Model

In OSNs, as mentioned before, there are two types of networks: primary and secondary. The primary networks consist of PUs that have licenses to exclusively use one or more spectrum bands; however, they do not use the spectrum all the time and all the locations, so some channels in these bands are spatiotemporal underutilized. In order to efficiently utilize the spectrum, the spectrum regulator coordinates with the primary network holders to open up these bands to be utilized by a secondary network that consists of SUs seeking for spectrum opportunities. Moreover, the PUs have the priority to use the spectrum, and can reclaim the channel(s) at any time without notifying the SUs.

A. Primary Network Model

Consider primary networks consisting of N non-overlapped channels numbered from 1 to N based on its sequence in the spectrum. Each channel of the N licensed channels can be modeled at any time slot as ON/OFF source, i.e., either occupied by a PU or idle. Therefore, the states of each channel can be modeled as two states Markov chain, and the i-th channel utilization at any time slot can be written as:

$$\delta_i = \frac{\beta_i}{\alpha_i + \beta_i}; \quad i = 1, 2, ..., N, \tag{1}$$

where α_i is the probability that the channel i transits from state ON to state OFF, and β_i is the probability that it transits from state OFF to state ON.

B. Secondary Network Model

The secondary network consists of M total number of SUs seeking for spectrum opportunities over the N licensed channels. Any secondary node is equipped with a single CR transceiver that has the ability to sense at most L channels in sequence and access at most K channels simultaneously based on its hardware and technology constraints, where $1 \leq L, K \leq N$. The errors that may occur during the spectrum sensing at the physical layer will be considered.

In order to exchange their control messages, the SUs use a local Common Control Channel (CCC) dedicated to them. The CCC can be either a channel in unlicensed bands or a channel licensed to the SUs especially for the purpose of spectrum sharing in OSNs. The SUs that are in the range of each other form a single-hop ad hoc network covering a relatively small area; however, the SUs may cover larger area in a multi-hop network scenario. In this paper, we consider the single-hop case. Assuming the communication range of the legacy PUs is larger than that of the SUs, each single-hop SUs group can be considered to be under the same coverage of the PUs set.

III. The MAC Framework

We propose a cooperative MAC framework based on the slotted time MAC structure shown in Fig.1. All the licensed channels and the control channel are slotted into time slots each with T time duration. Moreover, the control channel is further divided into four phases. The first phase is called First Registration and Sensing Phase (1RSP), the second phase is the Reporting Phase (RP) that is divided into N mini-slots corresponding to the N licensed channels, the third phase is the Second Registration and Competing Phase (2RCP), and the fourth phase is the Leaving Phase (LP). The data will be exchanged on the identified available channels during the 2RCP and LP phases together, so this duration is called Data Period (DP). The purposes of these phases are discussed in Section III-A. The primary signals are assumed to be constant during each time slot, i.e., each channel is assumed to be either occupied by a PU or idle. Moreover, the duration of the time slot must be chosen to be large enough for the SUs to exchange their control and data packets; however, it should not exceed a threshold that maintains the potential interference to be tolerable to the PUs (see Section V).

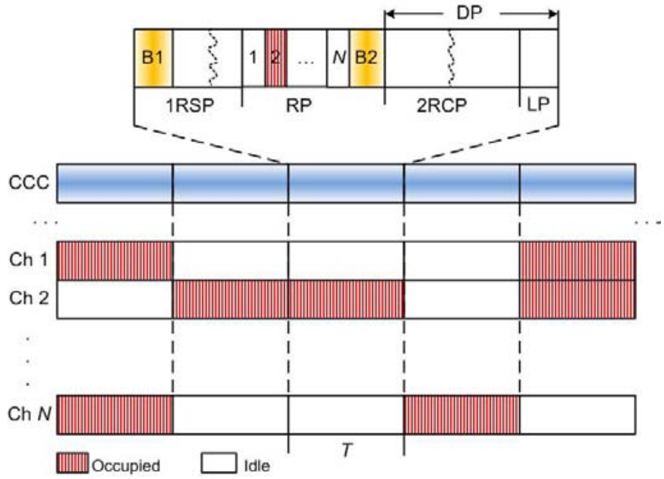

Fig. 1. The MAC framework.

A. MAC Protocol Overview

Based on the phases illustrated in Fig.1, the proposed MAC protocol is described in the following.

1) First Registration and Sensing Phase(1RSP):

- At the beginning of each time slot, the first winner from the last 2RCP phase sends beacon B1 for two reasons. The first reason is to synchronize the network. Second, this beacon contains important information broadcasted to the other SUs. This information includes the new total number of the SUs in the network, M, the number of the winning users in the last 2RCP phase, M_w, and the number of the leaving users in the LP phase, M_l, in addition to the old dynamic ID numbers of the winning and leaving users.
- All other users use this information to calculate the new number of the users involved in the sensing process, i.e., $M_s = M - M_w$, and to update their dynamic ID number as will be discussed in the dynamic ID updating algorithms in Section III-B.
- Spectrum Sensing: the sensing users sense the N channels based on a sensing algorithm, which will be discussed in Sections V.
- First Registration: any new user having packets to send must exchange Request-to-Register (RTR) and RTR-Acknowledgment (RTR-ACK) with the first winner and get its dynamic ID number based on a distributed algorithm that will be discussed in Section III-B.

2) Reporting Phase (RP):

- Each user involved in the sensing process sends tones at the mini-slots only if it detects primary signals on the corresponding sensed channels to inform the winning users about the existence of PUs on these channels.
- All the winning users monitor the CCC at this phase and get full picture about the spectrum opportunities.
- At the end of this phase, the first winner sends another updating beacon, i.e., B2. This beacon has

twofold. The first is to tighten the network synchronization, and the second is to update the value of M.

- The other users use beacon B2 to update their information.

3) Data Period (DP):

- Based on the number of the identified available channels, N_a, each winning user calculates how many channels can be accessed as follows. If $M_w \geq N_a$, then only a number of assigned winning users, M_{aw}, which are the first N_a of the winning users, are eligible to access the spectrum. Each of them will access one channel based on its order and the corresponding available channel order. The remaining winning users should join the other competing users in the next 2RCP phase. If $M_w < N_a$, then each winning user can access at least $n_a = \lfloor N_a/M_w \rfloor$ channels, where $\lfloor x \rfloor$ means the real number x is rounded down to the nearest integer number; however, when N_a/M_w is not an integer number, the remaining $N_a - n_a$ channels should be divided equally between the first winning users based on their order and the corresponding order of the available channels.
- The eligible winning users access the assigned available channels using the Orthogonal Frequency Division Multiplexing Access (OFDMA) technique and exchange their data and acknowledgments on those channels.

4) Second Registration and Competing Phase (2RCP):

- All the remaining users, i.e., $M - M_{aw}$, compete using a fair access mechanism, such as RTS/CTS, and record their winning orders, i.e., the first, second, and so on.
- Any intended receiving user that is not registered yet in the network will get its dynamic ID number from the access mechanism based on its winning sequence and includes it in the replying message. The other winning and competing users update the M value.

5) Leaving Phase (LP):

- Users that want to leave the network send short messages called Request-to-Leave (RTL) containing their dynamic ID numbers in this phase. They may leave either to save their power when they do not have packets to send or to join another network.
- The new first winning user records the M_l and their dynamic ID numbers to broadcast them in the next beacon B1.

B. Dynamic ID Numbering

The SUs can cooperate efficiently to sense and access the spectrum if each has a unique ID number that may change dynamically each time slot. As mentioned before, the first winning user broadcasts B1 that includes the new numbers M, M_w, and M_l in addition to the old ID numbers of the winning pairs and the leaving users where these ID numbers are ordered from low to high; moreover, it sends B2 to update the value of M. In the following, all distributed algorithms used in obtaining or updating the dynamic ID numbers of the SUs in the network are provided.

1) The new winning users update their dynamic ID numbers based on their winning order using Algorithm 1 as follows:
   Algorithm 1
   i-th winning user$\leftarrow$ ID # $(M - i + 1)$,
   where $1 \leq i \leq M_w$.

2) The sensing users having old dynamic ID numbers less than or equal to the number of the new sensing users, i.e., M_s , do nothing, while the sensing users having old ID numbers greater than the new number of M_s must update their ID numbers using Algorithm 2 as follows:
   Algorithm 2
   For each sensing user, if its old ID $>$ new M_s, then,
   Last old ID $\leftarrow$ 1st ID on B1,
   i-th last old ID $\leftarrow$$i$-th ID on B1,
   where i=1, 2,... .

   Using steps 1 and 2, we have M_s sensing users with new ID numbers ordered from 1 to M_s and M_w winning users with new ID numbers ordered from $M_s + 1$ to M.

3) During the 1RSP phase, each new user exchanges registering packets with the first winner and gets its ID number based on its appearance using Algorithm 3 as follows:
   Algorithm 3
   i-th new user$\leftarrow$ ID # $(M + i)$,
   where i= 1, 2, ...

4) During the 2RCP phase, the receiving user that is not already registered in the network gets its dynamic ID number from the access mechanism's packets based on their sequence.

C. General Notes

1) Since the first winning user has the key function of broadcasting B1 and B2 in this protocol, there should be a backup user to do this function in case the first winner fails to do it for any reason. The other winning users can do the same job, so they monitor the first winner, and if it fails, the second winner will replace it and if not the third and so on. The failure user will realize this and should become the last winner.
2) In case there are only two users in the network wanting to communicate with each other, the one that wants to transmit sends B1, and the receiver senses the channels while the transmitter registers any new user, then the receiver reports its observation on the RP phase and the transmitter figures

out which channels are available to be used in the DP duration. If there are new users registered at the 1RSP phase, the network will become with many users and everything works as discussed previously, and if not, the procedure of two users will be repeated.

3) In order to establish a secondary network, any SU want to communicate with other SUs scans the intended CCC. If it does not find control packets on this CCC, then it will realize that it may be the first user that should establish the network and send beacon B1. If there is a collision with other secondary user trying to establish the network too, both of them will realize that the network is still empty of users, so they have to try to send B1 again using random back off time.

IV. Sensing Policy

A spectrum sensing policy is required to manage the detecting of the spectrum opportunities. This policy should assist to identify which and how many channels are available to be used by the SUs. Therefore, when the percentage of the sensed channels out of the N channels increases, the throughput of the secondary network is expected to increase based on the activity of the PUs.

The channel is said to be available at a specific time when it is not used by any PU at that time; however, the channel utilization given by (1) is unknown to the SUs. Let N_a be the random number of the available channels at time slot t. Knowing that the channels that can be exploited are just that sensed by the SUs, the average number of the available and sensed channels at time slot t can be calculated as:

$$\overline{N_a} = \sum_{n=0}^{NP_{sens}} n\Pr\{N_a = n, \text{sensed}\}, \tag{2}$$

where NP_{sens} is the number of the sensed channels out of the N channels. The activities of the PUs on each channel, δ_i, can be estimated by collecting statistical information during the previous time slots and then using a technique such as Bayesian learning [21]. However, in order to simplify the analysis without loss of generality, let $\delta_i = \delta$ for all i, then $\Pr\{N_a\text{,sensed}\}$ is binomial and (2) can be rewritten as:

$$\begin{aligned}\overline{N_a} &= \sum_{n=0}^{NP_{sens}} n \binom{NP_{sens}}{n} (1-\delta)^n \delta^{(NP_{sens}-n)} \\ &= (1-\delta)NP_{sens}.\end{aligned} \tag{3}$$

In other words, more spectrum opportunities can be exploited if a proper sensing policy is investigated to sense as many as possible channels.

The sensing process is considered to be ideal if the all N licensed channels can be sensed. Therefore, $P_{sens} = 1$ in ideal sensing case. Based on the system model, each SU can sense only L out of the N channels, so the P_{sens} highly depends on M_s and L, during the 1RSP phase. In the following, three sensing policies namely Random Sensing Policy (RSP), Distinct-group Sensing Policy (DSP), and Allocated-group Sensing Policy (ASP) are proposed and discussed. Eventually, the best of them compared to the ideal sensing case will be chosen as the sensing policy that can be integrated in the proposed MAC framework.

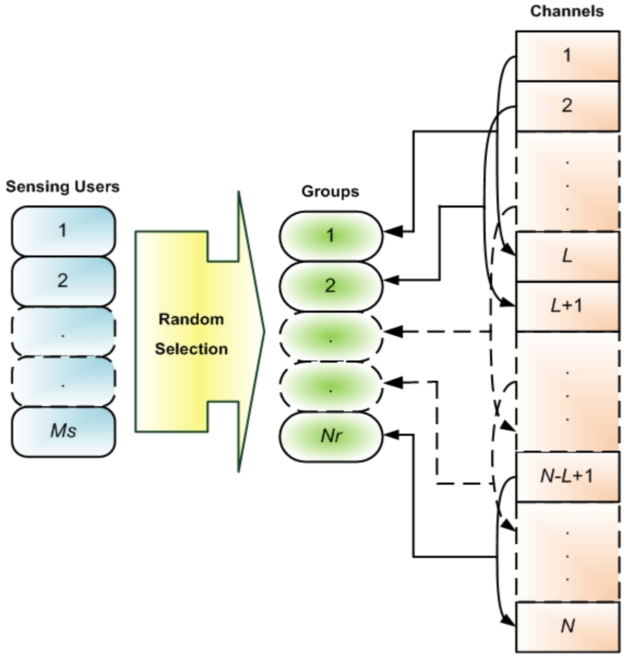

Fig. 2. Channel group selection in the RSP policy.

A. Random Sensing Policy

In the RSP policy, each sensing user chooses independently and uniformly L consecutive channels out of the N channels as shown in Fig. 2. Therefore, there are a number of possible channel groups given by:

$$N_r = N - L + 1. \tag{4}$$

Similar to [13], the probability mass function (pmf) of the sensed channels can be modeled as $(N_r + 1)$-state Markov chain. However, each SU is assumed to be able to sense only one channel in [13], while each user can sense L channels in sequence in this paper. The Markov chain can be written mathematically as:

$$q_{ij} = \begin{cases} i/N_r; & j = i, \\ 1 - i/N_r; & j = i+1, \\ 0; & \text{o.w.} \end{cases} \tag{5}$$

and the probability transition matrix of this chain can be given by:

$$Q = \{q_{ij}\}; \qquad 0 \le i, j \le N_r. \tag{6}$$

The probability of C channels are sensed by M_s sensing users can be evaluated by calculating the M_s-step transition probability from state 0 to state c as follows [13]:

$$\Pr\{C = c\} = Q_{(0,c)}^{M_s}, \tag{7}$$

where the right hand side of (7) means the element in row 0 column c of the M_s-step transition matrix. Therefore, the probability of the sensed channels can be given as:

$$P_{sens} = \frac{1}{N_r}\sum_{c=0}^{N_r} cQ_{(0,c)}^{M_s}. \tag{8}$$

B. Distinct-group Sensing Policy

For the DSP policy, the N channels are divided into distinct non-overlapped channel groups given by:

$$N_d = \left\lceil \frac{N}{L} \right\rceil, \tag{9}$$

where $\lceil x \rceil$ means the real number x is rounded up to the nearest integer number. Each sensing user chooses independently and uniformly one of the groups and starts to sense L channels beginning by the first channel of the chosen group as shown in Fig. 3. When N/L is not an integer number, the last group will contain some channels overlapped with the previous group. Similar to what have been done in the RSP policy, (N_d+1)-state Markov chain is used to find the pmf of the sensed channels. Finally, the probability of the sensed channels in this policy can be given as:

$$P_{sens} = \frac{1}{N_d}\sum_{c=0}^{N_d} cQ_{(0,c)}^{M_s}. \tag{10}$$

C. Allocated-group Sensing Policy

The randomness in both RSP and DSP policies is expected to decrease the average number of the sensed channels and consequently to decrease the average aggregate throughput of the secondary network. The main purpose of ASP policy is to ensure that each sensing user will sense different channel group from any other group sensed by any other sensing user when the number of the sensing users is less than or equal to the number of the channel groups. Using the same channel grouping of DSP policy shown in Fig. 3, each sensing user chooses a group deterministically instead of random selection as follows. After updating the dynamic ID numbers of all the SUs and before starting the sensing process at the 1RSP phase, each sensing user calculates how many channel groups there are based on (9) and chooses a specific group using Algorithm 4 as follows:

Algorithm 4
Calculate $num = $ mod(user-dynamic-ID, N_d)
If $num = 0$, choose channel group # N_d.
Otherwise, choose channel group # num.

Therefore, the percentage of the sensed channels in this policy can be given as:

$$P_{sens} = \begin{cases} \frac{LM_s}{N}; & M_s < N_d, \\ 1; & M_s \geq N_d. \end{cases} \tag{11}$$

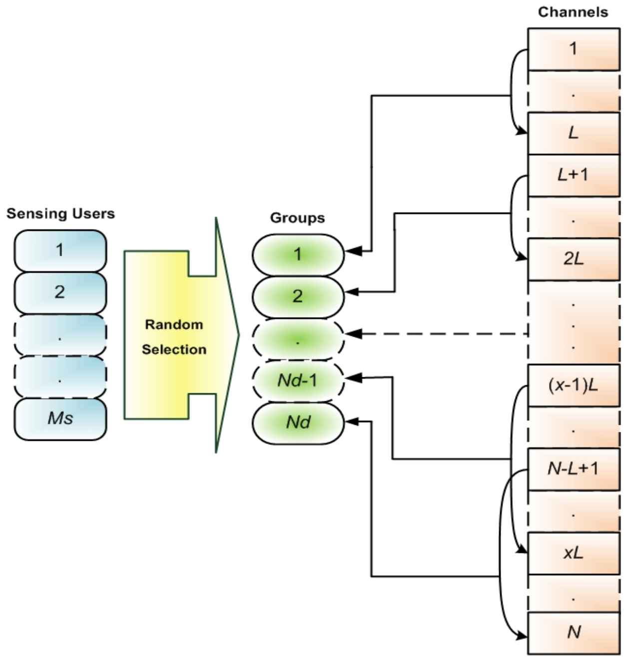

Fig. 3. Channel group selection in the DSP policy.

D. Performance Evaluation

The performance of the proposed sensing policies discussed above will be evaluated in this subsection. The performance here means the percentage of the sensed channels out of the N licensed channels, i.e., P_{sens}. Since the channel group in RSP and DSP policies are chosen randomly, we use simulation in order to validate the analytical results.

Fig. 4 shows the performance comparison of the three proposed sensing policies with respect to the number of the sensing users. It can be seen that the ASP policy, which is a deterministic sensing method, outperforms the other two random policies, where it needs only $M_s = N/L$ sensing users to achieve the ideal sensing case. However, due to the randomness of the other sensing policies, more sensing users are required to achieve the ideal sensing case, e.g., around 40 sensing users are required for the DSP policy while more and more sensing users are required for the RSP policy. Moreover, the DSP policy is better than that of the RSP policy since the number of the channel groups in the DSP policy is less than that of the RSP policy. It is obvious that the simulation and analytical results are almost identical for both DSP and RSP policies, which verifies the used analytical expressions.

It is desirable also to examine the performance of these sensing policies with respect to the number of the sensed channels per user. As shown in Fig. 5, the performance of the ASP policy increases sharply with increasing L until saturates at the ideal sensing case once the number of the sensed channels per user becomes $L = \text{ceil}(N/M_s)$. However, using this number of sensing users, the performance of the RSP policy reaches the ideal sensing case only when each sensing user can sense all

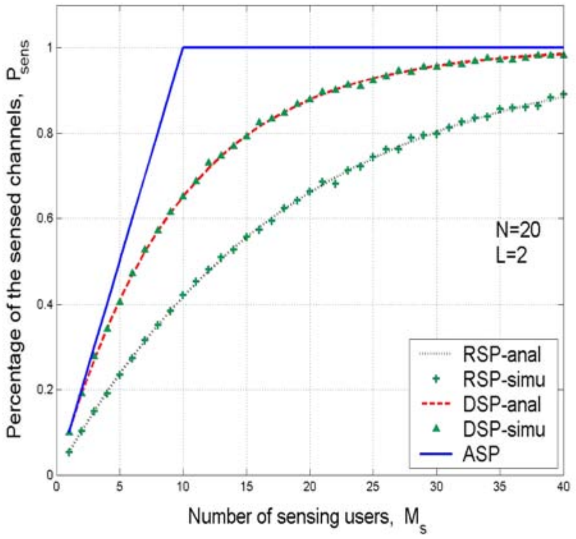

Fig. 4. Performance comparison between the proposed sensing policies, N=20 and L=2.

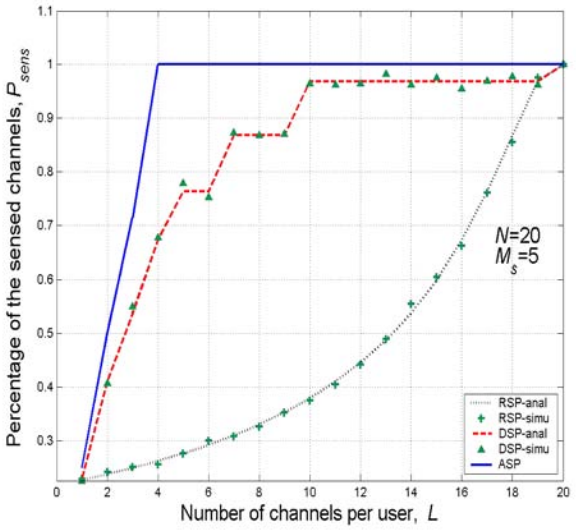

Fig. 5. Performance comparison between the proposed sensing policies, N=20 and $M_s = 5$.

the licensed channels. Moreover, the performance of the DSP policy increases in steps based on the number of the channel groups and the overlapped channels between the last two channel groups if N/L is not an integer number. The simulation results in this figure are also consistent with the analytical results.

From these two figures, the ASP is able to sense higher number of the intended licensed channels, i.e., more spectrum opportunities can be identified even with lower number of sensing users. Therefore, the ASP policy can be integrated into the proposed MAC framework in order to manage the SUs involving in the sensing process to identify as many as possible spectrum opportunities.

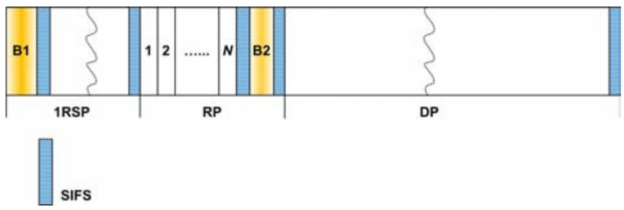

Fig. 6. The MAC frame time.

V. SPECTRUM SENSING ALGORITHM

The required duration for the spectrum sensing is related to two key issues in OSNs: the spectrum utilization and the interference to the PUs. One of the principles of OSNs is to maximize the spectrum usage by utilizing efficiently the available unused channels, so SUs are required to detect the spectrum opportunities as fast as possible in order to exploit these opportunities as long as possible for transmitting the secondary traffic. However, the SUs must maintain its potential interference to the PUs under a predetermined level acceptable by the PUs; therefore, the SUs must sense the spectrum for enough time to meet this interference constraint. These two requirements necessitate designing the MAC frame time shown in Fig. 6 in an optimal way.

A. Spectrum Utilization

The spectrum utilization can be defined as the percentage of time that the sensed channels are utilized; therefore, the required spectrum utilization is related to the sensing policy and the frame time of the proposed MAC protocol as follows:

$$\eta = \frac{T - T_c - \tau}{T} P_{sens}, \qquad (12)$$

where T is the overall time slot duration, and τ is the sensing duration during the sensing phase. In addition, T_c is the time duration for the control messages, which can be given by:

$$T_c = T_{B1} + T_{B2} + NT_{ms} + 5\text{SIFS}, \qquad (13)$$

where T_{B1} and T_{B2} are the time duration for beacon packets B1 and B2 respectively and T_{ms} is the time duration of each mini-slot corresponding to the N licensed channels. Moreover, a Short Inter Frame Space (SIFS) time is used in order to give time for the propagation delay and for tuning the transceiver to the next phase.

B. Interference to the PUs

The potential harmful interference to the PUs may happen when the SUs transmit for longer time than the tolerant interference duration acceptable by the PUs. Moreover, the potential interference may happen due to sensing errors made by the SUs. When the SUs identify some licensed channels as idle and send packets on them while they are occupied, there will be collisions with the primary traffic. The acceptable sensing error level of the SUs can be interpreted in terms of the required detection level of the PUs.

In the sensing at the physical layer, there are two related hypothetic parameters: the probability of detection, P_d, and the probability of false alarm, P_f. The probability of detection is a measure of the ability of the SUs to detect the presence of the primary signals, and it is desirable to be maximized in order to protect the PUs from the interference of secondary signals. However, the probability of false alarm is the probability of announcing a primary signal is present while it is not, and it is required to be minimized in order to increase the spectrum opportunities. Using a simple energy detector, these two probabilities can be related for each licensed channel as follows [17]:

$$P_f^{(i)} = Q\left(\sqrt{2\gamma+1}Q^{-1}\left(P_d^{(i)}\right) + \sqrt{t_s^{(i)}B}\gamma\right), \quad (14)$$

where γ is the SNR detection sensitivity of the detector, B is the bandwidth of the sensed channel, t_s is the required sensing time for channel i, and $Q(.)$ is the Q-function, which is given by $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-t^2/2)dt$.

C. Average Aggregate Throughput

In order to obtain higher throughput for the secondary network, it is important to design the parameters of the sensing duration in an optimal way. Since the data packets are sent during the Data Period, DP, the average number of the available sensed channels given by (3) can be exploited during this time only. Suppose that the SUs divide the intended spectrum bands into N channels with equal bandwidth, B, so without considering the sensing error, the average aggregate throughput of the secondary network can be given as:

$$\overline{\Phi} = \frac{T - T_c - \tau}{T}(1-\delta)NBP_{sens}. \quad (15)$$

Let us define the normalized average aggregate throughput of the secondary network as:

$$\overline{\Theta} = \frac{\overline{\Phi}}{(1-\delta)NB} = \frac{T - T_c - \tau}{T}P_{sens}. \quad (16)$$

Now, considering the sensing error and using the ASP sensing policy, (16) becomes as:

$$\overline{\Theta} = \begin{cases} \frac{1}{N}\sum_{j=1}^{M_S}\sum_{i=1}^{L_j}\frac{T-T_c-\tau}{T}\left(1-P_{f_j}^{(i)}\right); & M_sL_j \le N, \\ \frac{1}{N}\sum_{i=1}^{N}\frac{T-T_c-\tau}{T}\left(1-Q_f^{(i)}\right); & M_sL_j > N. \end{cases} \quad (17)$$

where τ is the sensing duration, $P_{f_j}^{(i)}$ is the probability of false-alarm by user j for channel i, and $Q_f^{(i)}$ is the probability of false-alarm in the cooperative sensing of channel i, which is a kind of OR-rule decision cooperative sensing. These values can be given respectively as:

$$\tau = \max_j \sum_{i=1}^{L_j} t_{s_j}^{(i)}; \quad 1 \le j \le M_s, \quad (18)$$

$$P_{f_j}^{(i)} = Q\left(\sqrt{2\gamma_j+1}Q^{-1}\left(P_{d_j}^{(i)}\right) + \sqrt{t_{s_j}^{(i)}B}\gamma_j\right), \quad (19)$$

$$Q_f^{(i)} = 1 - \prod_{j=1}^{u_i}\left(1 - P_{f_j}^{(i)}\right), \quad (20)$$

where u_i in (20) means the number of the sensing users cooperate to sense channel i.

It is clear from (17) that maximizing the average throughput leads to maximum spectrum utilization, so one objective of the OSNs is met. The design of the spectrum sensing duration now becomes an optimization problem that can be defined as:

$$\begin{aligned} &\max_{\tau>0} \quad \overline{\Theta} \\ &\text{s.t.} \quad P_d^{(i)} \ge P_d^{th}, \\ &\qquad T \le T_{max}, \end{aligned} \quad (21)$$

where P_d^{th} is the probability of detection threshold and T_{max} is the maximum time slot duration. These two parameters should be chosen to maintain the interference to the primary network under a specific level. It is obvious that these two parameters depend on the traffic type of the primary network, and for each primary network, there may be different requirements of these parameters. However, determining the values of these two parameters is beyond this research work at this time, so we assume that they are known, e.g., given by the spectrum regulator or the primary networks' owners.

The solution of (21) can be simplified based on the proposed system model. All the SUs are assumed to be equipped with identical CRs that have the same SNR detection sensitivity, and assuming that they detect at the minimum SNR, so they have the same ability of spectrum sensing, i.e., $\gamma_j = \gamma$. Moreover, according to the proposed protocols each sensing user is required to sense the same number of channels, so (17) can be rewritten as:

$$\overline{\Theta} = \begin{cases} \frac{M_sL}{N}\frac{(T-T_c-Lt_s)}{T}\left(1-P_f\right); & M_sL \le N, \\ \frac{T-T_c-Lt_s}{T}\left(1-Q_f\right); & M_sL > N. \end{cases} \quad (22)$$

In the OR-rule cooperative sensing, the probability of false-alarm, Q_f, can be found as:

$$Q_f = 1 - (1-P_f)^{u_c}, \quad (23)$$

where P_f is the individual probability of false-alarm made by each cooperative sensing user and u_c is the number of the cooperative sensing users. However, according to the ASP sensing policy, some channels may be sensed by different numbers of sensing users, so we have to find these numbers first.

In the ASP sensing policy, the number of the cooperative sensing users, u_c, and the number of the channels sensed cooperatively, N_c, when the number of the sensing users is greater than the number of the channel group, i.e., $M_s > N_d$ where $N_d = \lceil N/L \rceil$, can be found as (24). Therefore, the average value of the probability of cooperative false-alarm given in (23) can be obtained as (25).

However, it is known that the cooperative sensing increases the probability of detection as well as the probability of false-alarm, but increasing the false-alarm

$$u_c = \begin{cases} u_{c1} = \lfloor M_s/N_d \rfloor, \\ u_{c2} = u_{c1} + 1, \\ u_{c3} = 2u_{c1}, \end{cases} ; N_c = \begin{cases} N_{c1} = N - N_{c2} - N_{c3}, \\ N_{c2} = \text{mod}(M_s, N_d)L, \\ N_{c3} = L - \text{mod}(N, L). \end{cases} \quad (24)$$

$$Q_f = 1 - \left(\frac{N_{c1}}{N}(1 - P_{f1})^{u_{c1}} + \frac{N_{c2}}{N}(1 - P_{f2})^{u_{c2}} + \frac{N_{c3}}{N}(1 - P_{f3})^{u_{c3}} \right). \quad (25)$$

is not desirable in OSNs. In order to balance between these two probabilities, each cooperative sensing user is required to recalculate its requisite individual probability of detection based on the number of cooperative sensing users. The probability of detection in OR-rule cooperative sensing is given by:

$$Q_d = 1 - (1 - P_d)^{u_c}. \quad (26)$$

Now, for a given value of Q_d, which maintains the potential interference of the SUs to the PUs under a specific level, the individual detection probability that each sensing user should meet can be found as:

$$P_d = 1 - (1 - Q_d)^{1/u_c}. \quad (27)$$

Therefore, the individual false alarm probabilities P_{f1}, P_{f2}, and P_{f3} in (25) can be obtained as (28). Finally, the normalized average throughput given by (22) can be rewritten as (29).

Thus, the optimization problem in (21) can be solved using (29) subject to $Q_d \geq P_d^{th}$ and $T \leq T_{max}$. By this optimization problem we want to find the optimal sensing duration, i.e., $\tau = Lt_s$, which depends on two values: the required sensing time for each channel and the number of the sensed channels that each user can sense. Our ultimate goal is to develop a sensing algorithm that can be executed online to find the optimal sensing duration. In the following we will discuss how to develop this algorithm.

D. Sensing Algorithm

The time required to sense each channel, t_s, is expected to be small for practical threshold values of the required probability of detection and the probability of false-alarm, say 0.95 and 0.01 respectively. That means, even if we want to find the optimal value of the sensing time, its acceptable range will be small and does not affect the sensing duration significantly. Therefore, the sensing duration mainly depends on the number of the sensed channels rather than the sensing time for each channel. The minimum required sensing time for any channel given the threshold values of the detection probability, P_d^{th}, and the probability of false-alarm, P_f^{th}, can be found from (14) as:

$$t_{s_{min}} = \left(\frac{\sqrt{2\gamma + 1}Q^{-1}(P_d^{th}) - Q^{-1}(P_f^{th})}{\gamma\sqrt{B}} \right)^2. \quad (30)$$

Using this value, the optimal number of the sensed channels can be found by maximizing the throughput given in (29). The first constraint mentioned in (21), i.e., $Q_d \geq P_d^{th}$, is implied in calculating the minimum required sensing time in (30). Therefore, the optimization problem becomes as:

$$\begin{aligned} L^* = \arg\max_{L} \quad & \overline{\Theta} \\ \text{s.t.} \quad & T \leq T_{max}, \\ & 1 \leq L \leq N, \\ & L \in I, \end{aligned} \quad (31)$$

where I means a set of positive integer numbers.

This optimization problem is Nonlinear Integer Programming (NIP). Since the value of the variable L is not binary, one approach to solve this problem is to relax the value of L to be a real number, then solve the problem as a standard Non-Linear Programming (NLP) problem, and finally round the output value of L up to the nearest integer number. However, solving an optimization problem online may not be possible in OSNs due to the time limitation.

Fortunately, much simpler and intuitive value of the optimal number of the sensed channels can be guessed. When there are M_s of identical users trying to sense N channels, the intuitive value of L is just $\lceil N/M_s \rceil$; however, when the number of the sensing users is small compared to the N channels, and each of them is allowed to sense a large number of channels, this may come at the cost of decreasing the spectrum utilization and consequently the secondary throughput, so the value of L should not exceed its maximum value that maximizes the throughput when $M_sL \leq N$, which can be found from the first part of (29) as:

$$\begin{aligned} \frac{\partial \overline{\Theta}}{\partial L} &= 0, \\ \Rightarrow L &= \frac{T - T_c}{2t_s}. \end{aligned} \quad (32)$$

Therefore, the optimal number of the sensed channels can be found as:

$$L^* = \min\left(\left\lceil \frac{N}{M_s} \right\rceil, \left\lceil \frac{T_{max} - T_c}{2t_s} \right\rceil \right). \quad (33)$$

Finally, in order to set up the time of the MAC frame, each SU calculates the optimal sensing duration, which is just the multiplication of the required minimum sensing time given by (30) and the optimal number of the sensed channels given by (33).

Thus, each SU should be preloaded by a sensing algorithm that determines how long to sense each channel, how many channels to sense, and which channels to sense based on the sensing policy. This

$$P_{fi} = Q\left(\sqrt{2\gamma+1}Q^{-1}(1-(1-Q_d)^{1/u_{ci}}) + \sqrt{t_sB}\gamma\right); \qquad i = 1, 2, 3. \tag{28}$$

$$\overline{\Theta} = \begin{cases} \frac{M_sL}{N}\frac{(T-T_c-Lt_s)}{T}\left(1 - Q\left(\sqrt{2\gamma+1}Q^{-1}(Q_d) + \sqrt{t_sB}\gamma\right)\right); & M_sL \leq N, \\ \frac{T-T_c-Lt_s}{T}\sum_{i=1}^{3}\frac{N_{ci}}{N}\left(1 - Q\left(\sqrt{2\gamma+1}Q^{-1}(1-(1-Q_d)^{1/U_{ci}}) + \sqrt{t_sB}\gamma\right)\right)^{u_{ci}}; & M_sL > N. \end{cases} \tag{29}$$

algorithm, which is computationally simple and can be implemented online, is summarized in the following.

Sensing Algorithm

For each sensing user, after receiving the beacon B1 on the CCC channel, do the following:

1) Extract the content information,
2) Update the dynamic ID using Algorithm 2,
3) Calculate how many sensing users using: $M_s = M - M_w$,
4) Calculate how long to sense each channel using (30),
5) Calculate how many channels to sense using (33),
6) Calculate how many channel groups using (9),
7) Determine which channel group to sense using Algorithm 4, and
8) Start to sense.

E. Numerical Results

In this subsection, some numerical results are presented to illustrate the findings of this section. Similar to [17], the parameters B, T_{max}, and γ are chosen to be 6MHz, 100ms, and -15dB respectively. Moreover, we choose $T_{B1} = T_{B2} = 100\mu$s, $T_{ms} = 10\mu$s, and SIFS=15μs. The probability of detection and the probability of false-alarm are chosen to be 0.95 and 0.01, respectively, unless any of them is stated with different value elsewhere.

Fig. 7 illustrates the minimum sensing time required to identify any spectrum opportunity on a sensed channel for given values of the probability of detection and the probability of false-alarm. It is clear that the required sensing time slightly increases with increasing the probability of detection. This means, when the PUs need higher protection from the potential interference of the SUs, the SUs are required to sense each channel for longer time. On the other hand, when the secondary network needs smaller probability of false-alarm, the SUs are required to spend more time to sense each channel. For example, in practical situations, the primary network may need the probability of detection to be 0.95 while the secondary network may require the false-alarm to be 0.01, so each secondary user should sense each channel for 2.7ms assuming the channels are identical.

We would like to see the behavior of the secondary throughput with respect to the number of the sensed channels. The normalized average throughput is plotted versus the number of the sensed channels for different numbers of sensing users in Fig. 8. Obviously, for each number of the sensing users, there is an optimal number of the channels that should be sensed by each sensing user to maximize the secondary throughput. This optimal value is consistent with the closed form in (33). In general, the throughput increases with increasing L until all the N channels are sensed, i.e., when $M_sL = N$, where the optimal number of L appears, then the throughput decrease beyond the optimal L. This behavior can be explained as follows. Before the optimal value of L, there

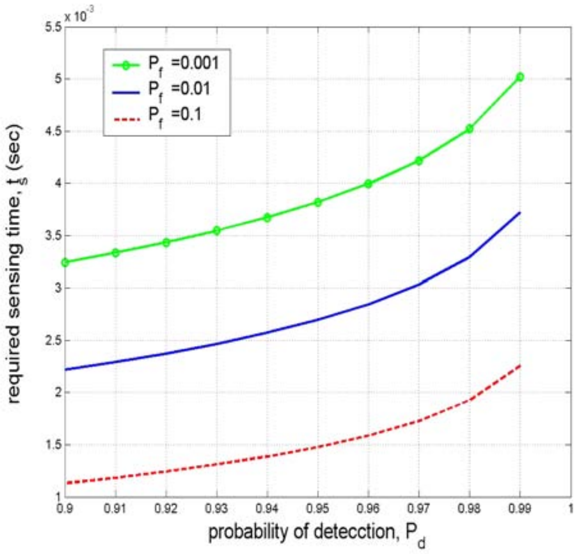

Fig. 7. The required sensing time with respect to the probabilities of detection and false-alarm.

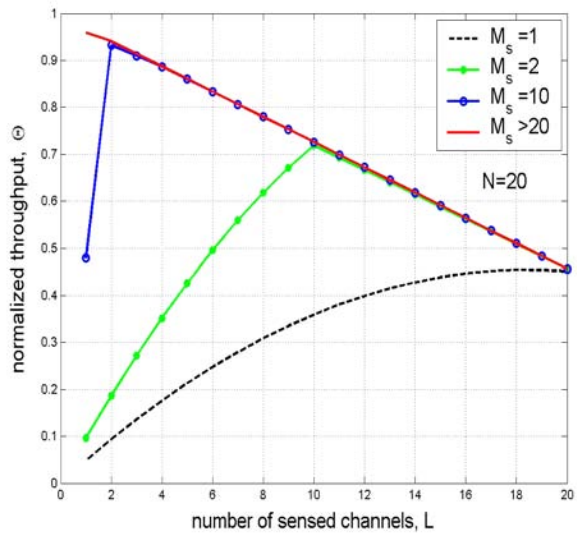

Fig. 8. The secondary normalized throughput with respect to the number of the sensed channels.

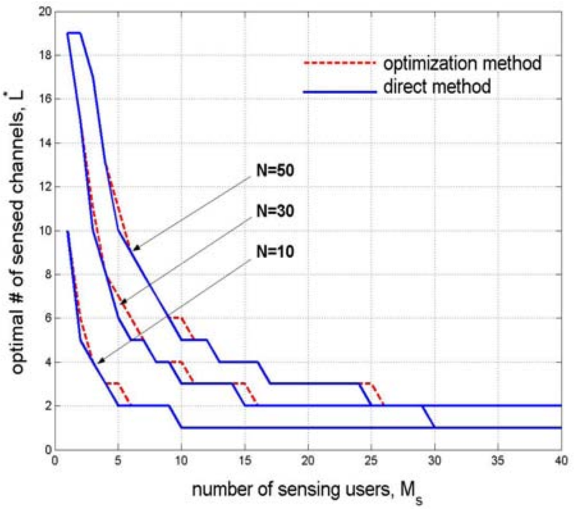

Fig. 9. The optimal number of sensed channels using two methods.

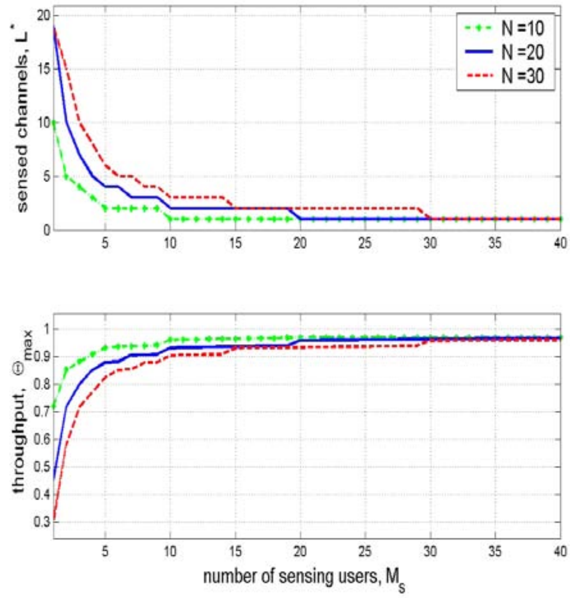

Fig. 10. Optimal number of the sensed channels and the corresponding throughput.

are some channels are not sensed, so this will lower the average throughput; however, after the optimal L, there are some channels over-sensed that comes at the cost of increasing the sensing duration, so the remaining time that is supposed to be credit for data will be decreased. The throughput improves with increasing the number of the sensing users until this number is equal to the number of the licensed channels and then saturates.

In order to verify the closed form of obtaining the optimal number of the sensed channels, Fig. 9 compares the optimal number of the sensed channels obtained from the solution to the optimization problem defined in (31) and the direct closed form in (33) for different numbers of sensing users. There are small differences at some points between the two methods due to the approximation used in solving the optimization problem when relaxing the L to be real number and then round it up to the nearest integer number; however, we can conclude that the two methods are equivalent.

Fig. 10 illustrates the maximum normalized throughput and the optimal number of the sensed channels per user for different numbers of the licensed channels. Some intuitive observations can be drawn from this figure. First, more sensing users are required to improve the average throughput when the number of the licensed channels are high, which is intuitive since more licensed channels means the spectrum opportunities are expected to be high, so more users are required to identify them. Second, when the number of the sensing users is relatively low, each one of them is required to sense more channels to maximize the throughput; however, with increasing the number of the sensing users, the optimal number of the sensed channels per user decreases until reaches one channel when $M_s \geq N$ and the throughput saturates. Therefore, in the situations when the power is concern, the ASP policy can include a rule that allows just N users to sense the spectrum and the others do nothing or even turn to sleep mode to save their power.

In the MAC framework, it is important to determine the optimal spectrum sensing duration. In Fig. 11, the optimal sensing duration is plotted with respect to the number of the sensing users for different values of the probability of detection threshold. As expected, the optimal sensing duration decreases with increasing the number of the sensing users when the other parameters are fixed. In fact, decreasing the sensing duration is desirable; however, this decreasing almost saturates when $M_s \geq N$ as discussed before. Another observation can be drawn from this figure. The required sensing duration increases when the required probability of detection threshold increases, which is intuitive since more primary network protection requires more sensing time to achieve this protection level.

A higher value of the maximum slot time, i.e., T_{max}, is desirable by the SUs, but the opposite is true for the PUs. In fact, the exact threshold of the time slot is governed by the primary network requirements; however, we want to study its influence on the proposed MAC frame time. Fig. 12 illustrates this influence. The optimal sensing duration is the same for all the values of T_{max} except when there is only one sensing user, which can be explained easily by referring to (33). On the other hand, the throughput is affected by the value of T_{max}. When T_{max} is small and the number of the sensing users is also relatively small compared to the N channels, the throughput becomes low; however, the difference between the throughput curves becomes smaller until almost finishes with increasing the number of the sensing users. This is because larger part of the slot time is used to sense more channels when the number of the sensing users is small, while when each user senses smaller number of channels, the throughput improves.

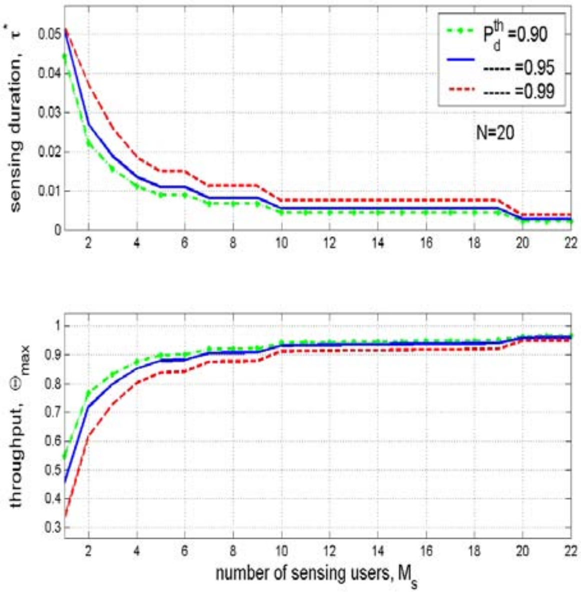

Fig. 11. Optimal sensing duration for different levels of required probability of detection and the corresponding throughput.

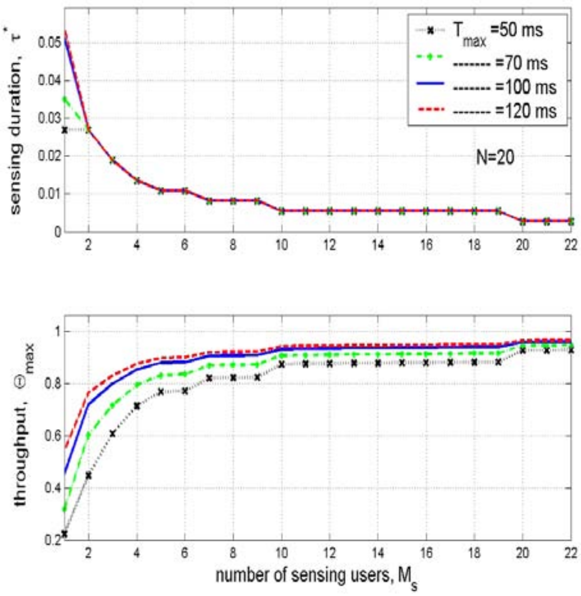

Fig. 12. Optimal sensing duration for different levels of the maximum slot time and the corresponding throughput.

VI. Conclusion And Future Work

In this paper, in order to compensate for the need of complex hardware, we have proposed a novel cooperative MAC framework for distributed OSNs considering the requirements of both the primary and secondary users. Moreover, we have investigated a simple computational but efficient spectrum sensing algorithm that relies on an innovative spectrum sensing policy. This algorithm assists each SU to identify online which channels, how many channels, and for how long to sense. We have found that using the proposed framework with this sensing algorithm, the spectrum opportunities can be identified efficiently even with only a small number of the SUs each equipped with a CR transceiver. Consequently the secondary throughput and the spectrum utilization can be maximized while constraining the interference to the PUs.

The proposed MAC framework supports simultaneous multiple access of SUs in order to decrease the traffic delay of the secondary network. An optimal access algorithm that considers the limitations of the access mechanism and balances between the number of the sensing and access users is of our interest in the future research work in addition to handling the multi-hop secondary network scenario.

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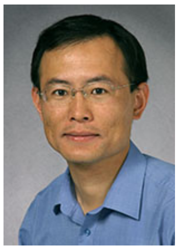

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