Adaptive Admission-Control and Channel-Allocation Policy in Cooperative Ad Hoc Opportunistic Spectrum Networks

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***Abstract*—In this paper, we propose an admission-control scheme and channel-allocation policy for ad hoc opportunistic spectrum networks (OSNs) based on user dynamic IDs. By dividing the secondary users (SUs) into sensing and accessing groups, they can cooperate to exploit as many unused channels as possible. However, the number of sensing users and the number of accessing users are balanced to efficiently identify and then utilize the available channels. We then study the secondary network behavior to investigate the parameters that can be used to control the number of admitted users. The secondary network controller in each time slot adjusts the controlling parameters to admit only the number of users that meet the quality-of-service (QoS) requirements. Moreover, the admitted SUs use their dynamic IDs and the order of the available channels to determine which channels can be allocated to each of them. Extensive numerical and simulation results are provided to demonstrate the effectiveness of the proposed admission-control and channel-allocation policy.**

***Index Terms*—Channel-allocation policy, discontiguous orthogonal frequency-division multiplexing access (D-OFDMA), opportunistic spectrum networks (OSNs), user admission control.**

I. Introduction

THE RAPID increase of applications of wireless networks has been witnessed in the last two decades; however, the natural resource of the frequency spectrum is running out due to the fixed spectrum-allocating regulations, which has led to the so-called spectrum scarcity [1]. Since the spectrum is the lifeblood of wireless communications, it should efficiently be used, or the emerging wireless applications would no longer be supported. In the literature, different technical terminologies have interchangeably been used to describe the new emerging wireless networks, which use the cognitive radio (CR) technology to exploit the spectrum opportunities, such as CR networks (CRNs), dynamic spectrum-access networks, and opportunistic spectrum-access networks (OSNs). We use the term OSNs in this paper.

The OSNs consist of two types of users: primary users (PUs) owning licenses to exclusively use 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 make no harmful interference to the PUs. Therefore, the SUs should be able to carry out two key functions: Identify the unused spectrum, and access it [2].

Although the basic idea of OSNs seems simple, the implementation of it is very difficult. The coexistence 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 very challenging [3]. Fortunately, with the advanced technologies in the new evolution of CRs, the implementation of OSNs can be envisioned. CRs are promising technologies that can be used by SUs to perform the spectrum sensing and then the spectrum access. These two functions are related, and one cannot properly work without the other [4], [5]. Since ad hoc networks may be the practical architecture that attracts future applications of spectrum secondary usage, we will focus on ad hoc OSNs throughout this paper.

In [6], we have developed a cooperative medium access control (MAC) framework for distributed OSNs, where a sensing algorithm has been investigated to assist each sensing user to determine which channels and how many channels to sense and for how long to sense each channel. In this paper, we will study how to control the number of SUs that can be supported by the secondary network to ensure quality-of-service (QoS) levels and how to allocate the identified available channels to them. Specifically, we focus on the following issues.

1) *The access mechanism*: The most suitable access technique for OSNs should be the discontiguous orthogonal frequency-division multiplexing access (D-OFDMA). This mechanism can assist in aggregating the throughput on disjoint channels; however, it has some limitations such as the spectrum fragments and the RF ability of the CR.
2) *Sufficient number of sensing users*: It is important to balance the number of sensing users and the number of users that can be admitted to access the identified available channels to maintain QoS levels for the SUs.
3) *Assigning a number of accessing users*: There will be a number of sensing users and a number of accessing users. Assigning a user as an access user requires a kind of coordination between the users.
4) *Spectrum-allocation policy*: How to allocate the identified available channels to the admitted users is an important issue to efficiently utilize the spectrum, i.e., each admitted user should know which and how many channels to access.

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The multiuser orthogonal frequency-division mutiplexing (OFDM) technique has widely appeared in the literature of CRNs as the spectrum-access mechanism with different resource-allocation schemes. In [7], a resource-allocation algorithm that ensures proportional rates to predefined target rates for SUs using multiuser OFDM was proposed for non-real-time services, while in [8], a spectrum-assignment algorithm was proposed to utilize the disjoint spectrum bands using D-OFDM. The hardware constraints were considered in designing the MAC framework in [6], [9]. In [10]–[12], joint admission and power-control schemes were proposed to meet certain QoS requirements considering the interference to the PUs in CRNs. Moreover, queuing approaches were used in [13] and [14] to study the SU throughput and delay and to develop admission-control and channel-allocation methods for CRNs. A call-admission control strategy integrated with a QoS-based spectrum handoff mechanism was proposed in [15] to improve the QoS and spectrum utilization in a centralized CRN, while user admission control with and without spectrum handover for the ongoing secondary transmissions was studied in [16]. Call-admission control with an opportunistic scheduling scheme was proposed in [17]. Moreover, class-based call-admission control schemes were proposed in [18] and [19] to improve the blocking probability and secondary throughput of specific CRNs. In [20], user admission and eviction control considering the user satisfaction was suggested to maximize the profit of a wireless service provider employing CRNs. Finally, a cross-layer optimization framework that integrates spectrum sensing and call-admission control was proposed in [21] for centralized CRNs to minimize the secondary dropping rate, taking into account the secondary blocking rate and the interference to the PUs.

In this paper, we propose to regulate the spectrum access of cooperative distributed OSNs based on the user dynamic IDs and the slotted-time MAC structure developed in [6]. With the help of the secondary network controller at each time slot, the admitted users use their dynamic IDs and the order of the identified available channels to determine which channels can be allocated to each of them. We model the dynamic behavior of the secondary network by a set of difference equations to investigate the system design parameters that can be used to control the number of admitted users. Using these controlling parameters, the secondary network controller at each time slot can admit only a number of users that maintain QoS levels required by the secondary network.

The remainder of this paper is organized as follows. Section II provides the system model. The dynamic behavior of the system are described in Section III. The channel-allocation policy and the admission control are presented in Section IV. In Section V, the average aggregate throughput and average delay of the SU are derived. Extensive numerical and simulation results with detailed discussions are provided in Section VI to evaluate the system performance. Finally, Section VII concludes this paper.

II. System Model

A. Primary and Secondary Networks

There are two types of networks in the system: primary and secondary networks, where the secondary network works with the concept of OSNs to avoid the potential harmful interference to the PUs. The primary networks consist of N nonoverlapped 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 an ON/OFF source, i.e., either occupied by a PU or idle. Therefore, the states of each channel can be modeled as a two-state Markov chain, and the ith channel utilization at any time slot can be written as

$$\delta_i = \frac{\beta_i}{\alpha_i + \beta_i}, \qquad i = 1, 2, \ldots, N \tag{1}$$

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.

The secondary network consists of a number of SUs seeking for spectrum opportunities over the N licensed channels in an ad hoc network. Any secondary node is equipped with a single CR transceiver that has the ability to sense at most L channels in sequence and simultaneously access at most K channels based on its hardware and technology constraints, where $1 \leq L$, $K \leq N$.

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 a larger area in a multihop network scenario. In this paper, we consider the single-hop case. Assuming that the communication range of the legacy PUs is larger than that of the SUs, each single-hop SU group can be considered to be under the same coverage as that of the PU set.

B. Overview of the MAC Protocol

The secondary network uses the cooperative MAC protocol developed in [6] to control the spectrum-sensing and spectrum-access functions of the OSNs. This MAC protocol basically uses a local common control (CC) channel that is divided into time slots, as shown in Fig. 1. The CC channel can be either a channel in unlicensed bands or a channel licensed to the SUs, particularly for the spectrum sharing purpose in OSNs. The CC channel and the N licensed channels are synchronously slotted by the CRs into time slots. 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. 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. Moreover, the CC channel is divided into three phases. The first phase is called the sensing-and-registration phase (SRP). In the SRP, a number of existing users sense the intended licensed channels using the sensing algorithm from [6]; in the meantime, the network controller, which is the first winner from the last reserving phase in each time slot, registers the new users that want to join this network by exchanging registration messages with them and assigns a dynamic ID number for each new user based on its registering sequence order. The second phase is the reporting phase (RP), where the sensing users report their observations by sending tones on minislots corresponding to the N channels indicating the occupied channels, while the winning users monitor this

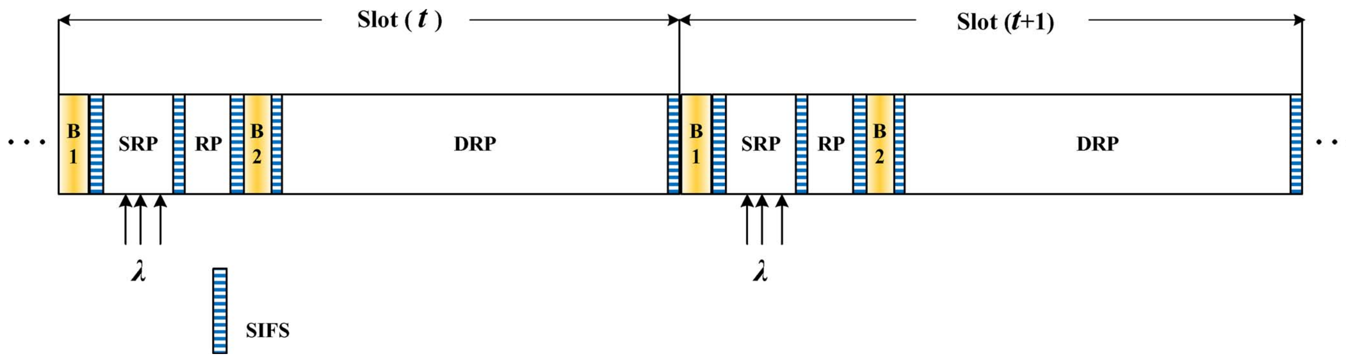

Fig. 1. Slotted-time structure of the CC Channel.

phase to get a full picture about the available channels. The third phase is the data and reserving phase (DRP). Based on how many available channels, some or all of the winning users access these channels based on a channel-allocation policy described later in this paper. The remaining users try to reserve the identified available channels at the next time slot. In the DRP, the data are sent through the identified available channels, while the reserving messages are exchanged through the CC channel. In addition to these three phases, there are two beacons, named B1 and B2, used by the network controller to broadcast any required information to the SUs.

The SUs are mainly divided into two groups: a number of sensing users M_s and a number of winning users M_w. The winning users are those that successfully reserve the next time slot to transmit their packets, while the remaining users are considered to be sensing users. Moreover, each user has its own unique dynamic ID number based on whether it is a sensing user or a winning user. These dynamic IDs are initially obtained during the registering process, where the IDs are assigned to the users based on their registering sequence, and then, the users update their IDs each time slot, maintaining their sequence order in the network using the broadcast information on beacon B1.

Each sensing user uses its ID to decide how to sense the spectrum based on a sensing policy called allocated-group sensing policy (ASP) described in detail in [6]. In ASP, each sensing user deterministically chooses a group of L channels and starts to sense each channel in sequence for t_s sensing time. In [6], the optimal number of channels that can be sensed and the required sensing time by each user are obtained considering the potential interference to the PUs and the spectrum utilization in addition to the hardware cost and limitation. It is found that the number of sensed channels per user can be given as

$$L = \min\left(\left\lceil \frac{N}{M_s} \right\rceil, \left\lceil \frac{T - T_c}{2t_s} \right\rceil\right) \tag{2}$$

where $\lceil x \rceil$ is the ceil operator that rounds up the real number x into the nearest integer number, N is the number of licensed channels, M_s is the number of sensing users, T is the slot time duration, and T_c is the time duration for the MAC control messages, which is fixed for all time slots and can be given as

$$T_c = T_{\mathrm{B1}} + T_{\mathrm{B2}} + NT_{\mathrm{ms}} + 5\mathrm{SIFS} \tag{3}$$

where T_{B1} and T_{B2} are the time duration for beacons B1 and B2, respectively, and T_{ms} is the time duration of each minislot corresponding to reporting each channel of the N licensed channels at the RP. Moreover, a short-interframe-space (SIFS) time is used to give time for the propagation delay and for tuning the transceiver to the next phase. The t_s in (2) is the time to sense each channel by sensing each user, which is given by

$$t_s = \left(\frac{\sqrt{2\gamma+1}Q^{-1}\left(P_d^{\mathrm{th}}\right) - Q^{-1}\left(P_f^{\mathrm{th}}\right)}{\gamma\sqrt{B}}\right)^2 \tag{4}$$

where B and γ are the bandwidth of the channel and the signal-to-noise ratio sensitivity of the detector, respectively. P_d^{th} and P_f^{th} are the thresholds of the probability of detection and the probability of false alarm required by the primary and secondary networks, respectively, and $Q(\cdot)$ is the Q-function, which is given by $Q(x) = (1/\sqrt{2\pi})\int_x^\infty \exp(-t^2/2)dt$.

The admitted users access the allocated channels using the D-OFDMA access mechanism, where the spread of the K channels that can be accessed by each user are assumed to be within the channel span ability of the user. Moreover, the new users join the network with arrival rate λ, and the secondary network is always saturated by SUs.

III. Dynamic Behavior of the System

In this section, we study the instantaneous behavior of the system, which is important to understand how the network resources are shared by the SUs in each time slot, and we study also the steady-state behavior of the secondary network, which is important to decide the system parameters in an efficient way to meet the QoS requirements of the SUs. Based on the MAC protocol, the SUs try to reserve the next time slot at the current time slot; moreover, the number of reserving users should be related to the number of sensing users in such a way to balance between spectrum sensing and spectrum access that together should maximize the spectrum utilization and maintain tolerable interference to the PUs. Therefore, the system behavior dynamically varies over a number of dependent consecutive time slots. Since there are many variables used in the analysis, the main variables are listed in Table I for convenience.

TABLE I
MAIN VARIABLES USED IN THE ANALYSIS

Variable	Description
N	Number of the licensed channels
L	Number of the sensed channels per user
N_a	Number of the available channels
N_{res}	Number of the reserving slots
n_a	Number of the allocated channels per user
λ	Arrival rate of the SUs
λ_{ad}	Admitted rate of the SUs
M_s	Number of the sensing users
M_r	Number of the remaining users at the DRP phase
M_w	Number of the winning users
M_{aw}	Number of the admitted winning users
$M_{w_{max}}$	Max. number of the winning users
M_{B1}	Number of the users at beacon B1
M_{B2}	Number of the users at beacon B2
M_{res}	Number of the reserving users
τ	Sensing duration
t_s	sensing time per channel
T	Duration of each time slot
T_c	Duration of the control messages
T_{B1}	Duration of beacon B1
T_{B2}	Duration of beacon B2
T_{ms}	Mini-slot duration of the RP phase
T_{DRP}	Duration of the DRP phase
T_{res}	Duration of the mini-slot reserving time
S	Average aggregate throughput
Θ	Normalized average aggregate throughput
D	User waiting delay
δ	Activity of the PUs on the licensed channels
p	Receiver responding probability to the reserving message
P_{aw}	Probability of a user being admitted

A. *Instantaneous System Behavior*

In beacon B1 at time slot t, the first winner from time slot $(t-1)$ broadcasts the new number of SUs in the network M_{B1}, which can mathematically be given as

$$M_{\text{B1}}^{(t)} = M_{\text{B2}}^{(t-1)} - M_{\text{aw}}^{(t-1)} \tag{5}$$

where $M_{\text{B2}}^{(t-1)}$ is the number of SUs in the network broadcast on beacon B2 at time slot $(t-1)$, and $M_{\text{aw}}^{(t-1)}$ is the number of admitted winning users at time slot $(t-1)$. Moreover, the first winner broadcasts the IDs of the $M_{\text{aw}}^{(t-1)}$ users and the number of winning users; therefore, the remaining users update their IDs based on whether they are sensing or winning users.

All the users calculate the number of sensing users to set up the time duration of the phases. The number of these sensing users can be found as

$$M_s^{(t)} = M_{\text{B1}}^{(t)} - M_w^{(t-1)} \tag{6}$$

where $M_w^{(t-1)}$ is the number of winning users at the DRP of time slot $(t-1)$. Therefore, the time duration of the SRP, which reflects the sensing duration, is calculated as

$$\begin{aligned}\tau^{(t)} &= L^{(t)} t_s \\ &= \min\left(\left\lceil \frac{N}{M_s^{(t)}} \right\rceil, \left\lceil \frac{T-T_c}{2t_s} \right\rceil\right) t_s.\end{aligned} \tag{7}$$

Since the time durations of the SRP and the DRP are inversely proportional, the duration of the DRP is given by

$$T_{\text{DRP}}^{(t)} = T - \tau^{(t)} - T_c. \tag{8}$$

The sensing users sense the intended N licensed channels based on the sensing algorithm developed in [6] and report their observations on the RP, while the winning users monitor the RP to get information about how many channels are available at the current time slot $N_a^{(t)}$ and their IDs in the spectrum chart. In other words, each winning user has a vector indicating the available channels as

$$\mathbf{c}^T = \{c_i\}, \qquad c_i \in \{0,1\}; \quad i = 1, 2, \ldots, N \tag{9}$$

where $c_i = 0$ means that the channel with an ID indicating c_i is not available, while it is available when $c_i = 1$. It is clear that

$$N_a^{(t)} = \sum_{i=1}^{N} c_i \tag{10}$$

which is a random number that depends on the activities of the PUs on the N channels given in (1).

The SUs that are registered in the network stay in the network until they transmit their packets. Since there may be new SUs joining the network, the number of SUs in the network is updated by the current first winner on beacon B2; therefore, the new number can be given as

$$M_{\text{B2}}^{(t)} = M_{\text{B1}}^{(t)} + \left\lfloor \lambda \tau^{(t)} \right\rfloor \tag{11}$$

where $\lfloor x \rfloor$ is the floor operator that rounds down the real number x into the nearest integer number, λ is the arrival rate of the users joining the network during the SRP, and $\tau^{(t)}$ is the duration of the SRP given in (7).

Some or all of the winning users are admitted to access the spectrum based on how many channels are identified as available ones by the sensing users in the current time slot. The number of winners that can be admitted is given as

$$\begin{aligned}M_{\text{aw}}^{(t)} &= \begin{cases} M_w^{(t-1)}, & M_w^{(t-1)} < N_a^{(t)} \\ N_a^{(t)}, & M_w^{(t-1)} \geq N_a^{(t)} \end{cases} \\ &= \begin{cases} M_{\text{B1}}^{(t)} - M_s^{(t)}, & M_{\text{B1}}^{(t)} - M_s^{(t)} < N_a^{(t)} \\ N_a^{(t)}, & M_{\text{B1}}^{(t)} - M_s^{(t)} \geq N_a^{(t)} \end{cases}\end{aligned} \tag{12}$$

where $M_w^{(t-1)}$ is the number of winning users at the DRP of time slot $(t-1)$, and $N_a^{(t)}$ is the number of identified available channels at time slot t. The number of remaining users is given by

$$M_r^{(t)} = M_{\text{B2}}^{(t)} - M_{\text{aw}}^{(t)}. \tag{13}$$

These remaining users should try to reserve the next time slot.

To support concurrent transmissions, a number of users should be allowed to reserve the next time slot. Any transmitting user registered in the network can reserve the next time slot for transmission if it successfully exchanges reserving messages with its intended receiver during the DRP. These messages can be seen as exchanging the *de facto* request-to-send and clear-to-send control packets. However, when the number of competing users is high, the probability of collision increases; therefore, the SUs use their ID sequence to enter the reserving process instead. Since each user in the network has a unique dynamic ID updated in each time slot and this ID reflects the sequence order of that user in the network, each user knows which user is the first, second, and so on, in the network that can enter the reserving process at the DRP; therefore, SUs reserve based on the first-in–first-out concept. The reserving user is considered as the winner when it successfully exchanges the reserving messages with its receiver. Let each reserving pair exchange these messages during a reserving time denoted as T_{res}; then, the number of reserving slots can be given by

$$N_{\mathrm{res}}^{(t)} = \left\lfloor \frac{T_{\mathrm{DRP}}^{(t)}}{T_{\mathrm{res}}} \right\rfloor = \left\lfloor \frac{T - \tau^{(t)} - T_c}{T_{\mathrm{res}}} \right\rfloor . \tag{14}$$

However, the number of winning users should carefully be chosen in such a way that they do not affect the sensing process, i.e., the number of winning users and the number of sensing users should be balanced to efficiently utilize the unused spectrum. All the N licensed channels can be identified when $M_s L \geq N$, where, from (2), L should not exceed $\lceil (T - T_c)/2t_s \rceil$; therefore, $M_s \geq \lceil 2t_s N/(T - T_c) \rceil$, and the minimum number of sensing users that can sense all the N licensed channels is given by

$$M_s = \left\lceil \frac{2t_s N}{T - T_c} \right\rceil \tag{15}$$

and the maximum number of winning users is given by

$$M_{w_{\max}}^{(t)} = M_r^{(t)} - \left\lceil \frac{2t_s N}{T - T_c} \right\rceil . \tag{16}$$

Since the winning users are deterministically scheduled to exchange their reserving messages on the CC channel based on their dynamic IDs, there are no collisions between the winning users during this process. Therefore, the successful exchange of the reservation messages mainly depends on the ability or even the willingness of the intended receiver to respond to the sender. The outputs of the reserving process are random, and they can be written in a vector as

$$\mathbf{w} = \{w_i\}, \qquad w_i \in \{0, 1\}; \quad i = 1, 2, \ldots, M_{w_{\max}}^{(t)} \tag{17}$$

where $w_i = 1$ indicates that a user has successfully exchanged the reserving messages with its intended receiver and that it is considered to be a winner. The first nonzero element of $\mathbf{w}$ indicates which user is the first and so on. The order of the winning users is important in allocating the identified available channels to them, as will be discussed in the next section. Obviously, the number of reserving users can be obtained as

$$M_{\mathrm{res}}^{(t)} = \sum_{i=1}^{N_{\mathrm{res}}^{(t)}} w_i . \tag{18}$$

Finally, the number of winning users for the next time slot can be found as

$$M_w^{(t)} = \begin{cases} M_{\mathrm{res}}^{(t)}, & M_{\mathrm{res}}^{(t)} < M_{w_{\max}}^{(t)} \\ M_{w_{\max}}^{(t)}, & M_{\mathrm{res}}^{(t)} \geq M_{w_{\max}}^{(t)} \end{cases} . \tag{19}$$

B. Steady-State System Behavior

It is desirable to find the closed-form solutions of the difference equations that describe the system at any time slot and help to study the steady state of the system. The two main quantities in the set of these equations are the dynamic number of users at beacon B1 given in (5) and the dynamic number of sensing users given in (6). Once the solutions of these two equations are found, any other quantity in the system can be found. Substituting (11) and (12) in (5), we get (20), shown at the bottom of the page, where $\tau^{(t-1)}$ and $N_a^{(t-1)}$ depend on the $M_s^{(t-1)}$ that can be found from (6) as

$$M_s^{(t-1)} = M_{\mathrm{B1}}^{(t-1)} - M_w^{(t-2)} \tag{21}$$

and $M_w^{(t-2)}$ can be found from (19).

However, finding the closed-form solutions of these equations is very difficult; moreover, the randomness of the number of available channels and the number of reserving users in each time slot adds another difficulty dimension; therefore, a numerical analysis will be used instead.

IV. Channel Allocation and Admission Control

Developing an allocation method for the identified available channels to the admitted users and controlling the number of admitted users are the main goals of this paper. In Sections IV-A and B, the proposed channel allocation and admission control are presented.

A. Channel-Allocation Policy

Since the identified available channels may be disjoint due to the spectrum fragmentation, the admitted winning users

$$M_{\mathrm{B1}}^{(t)} = \begin{cases} \left\lfloor \lambda \tau^{(t-1)} \right\rfloor + M_s^{(t-1)}, & M_{\mathrm{B1}}^{(t-1)} - M_s^{(t-1)} < N_a^{(t-1)} \\ M_{\mathrm{B1}}^{(t-1)} + \left\lfloor \lambda \tau^{(t-1)} \right\rfloor - N_a^{(t-1)}, & M_{\mathrm{B1}}^{(t-1)} - M_s^{(t-1)} \geq N_a^{(t-1)} \end{cases} \tag{20}$$

should use the D-OFDMA technique as the channel-access mechanism to overcome the spectrum fragmentation. Based on the identified available channels, each admitted user can access at least a number of channels given by

$$n_a^{(t)} = \left\lfloor \frac{N_a^{(t)}}{M_{\mathrm{aw}}^{(t)}} \right\rfloor. \tag{22}$$

To efficiently utilize the unused spectrum, all the identified available channels should be used; therefore, some of the first $M_{\mathrm{aw}}^{(t)}$ admitted users may access $(n_a^{(t)} + 1)$ channels if $N_a^{(t)}/M_{\mathrm{aw}}^{(t)}$ is not an integer number. User fairness can be maintained by allocating only $n_a^{(t)}$ channels to each admitted user; however, this will affect the utilization efficiency of the spectrum, i.e., there is a tradeoff between spectrum utilization and user fairness. The identified available channels are allocated to the admitted users based on the users' IDs and the order of the $n_a^{(t)}$ channels in the spectrum. Substituting (12) in (22), we obtain

$$n_a^{(t)} = \begin{cases} \left\lfloor \frac{N_a^{(t)}}{M_{\mathrm{B1}}^{(t)} - M_s^{(t)}} \right\rfloor, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} < N_a^{(t)} \\ 1, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} \geq N_a^{(t)}. \end{cases} \tag{23}$$

As mentioned in the system model, the spread of $n_a^{(t)}$ is assumed to be within the spectrum span ability of the user; therefore, each admitted user can access its corresponding allocated channels.

B. Admission Control

From the channel-allocation policy, the SUs share the identified available channels based on their IDs and the order of the identified available channels. To maintain certain QoS (i.e., average throughput and delay) levels in the secondary network, the number of users that can be admitted to access the identified available channels should be controlled. In the system model, there are many parameters that affect the number of admitted users; however, not all these parameters can flexibly be controlled. The two most important flexible parameters that can be adjusted are the minislot reserving time T_{res} and the admitted user rate λ_{ad}.

Based on the average number of unused licensed channels and the required QoS level, the network controller, which is the first winner at each time slot, determines the acceptable number of arrivals that can be registered in the network at the RSP. This number is given by $\lambda_{\mathrm{ad}}\tau^{(t)}$. Since $\tau^{(t)}$ varies from time slot to time slot, depending on the number of sensing users in each time slot, as it appears from (7), the network controller should adjust λ_{ad} to maintain the required QoS level; therefore, λ_{ad} can be used as an admission-control parameter. It can be adjusted in each time slot by registering only the intended acceptable number of users, i.e., responding to the request-to-register messages from the acceptable number of new users and assigning dynamic IDs to them. In other words, the network controller sharps the user arrival rate by admitting only a portion of the arrivals. Moreover, the first winner determines the minislot reserving time that meets the required QoS level and broadcasts it at beacon B2. Based on their IDs' order, the reserving users exchange the reserving messages with the intended receivers during this minislot reserving time.

Let the required QoS level in the secondary network be denoted as a utility function given by $U(\lambda_{\mathrm{ad}}, T_{\mathrm{res}})$. The optimal admission parameters can be found by solving the following optimization problem:

$$\begin{aligned} \max_{\lambda_{\mathrm{ad}}, T_{\mathrm{res}}} \quad & U(\lambda_{\mathrm{ad}}, T_{\mathrm{res}}) \\ \text{s.t.} \quad & 0 < T_{\mathrm{res}} < T_{\mathrm{DRP}}^{(t)} \\ & \lambda_{\mathrm{ad}} > 0 \end{aligned} \tag{24}$$

where maximizing the utility function implies maximizing the average aggregate throughput, minimizing the average delay, minimizing the blocking probability of the rejected SUs, or minimizing the dropping rate of handover users. In this paper, we are interested in studying the effects of these controlling parameters on the average aggregate throughput and waiting delay of the SUs in the network rather than finding their optimal values, which requires defining a utility function representing the required QoS of the secondary traffic.

V. Average Throughput and Delay of the Secondary User

This section presents the analytical analysis of the average aggregate throughput and user waiting delay in the secondary network. Considering the proposed channel-allocation policy, the effects of the admitted control parameters, as well as other system parameters, on the network performance can be assessed.

A. Average Aggregate Throughput

Considering the interference to the PUs, the spectrum sensing in OSNs is related to the probability of detection required by the primary network as well as the probability of false alarm required by the secondary network. The SU average throughput is affected by the probability of false alarm by a factor $(1 - P_f^{\mathrm{th}})$, where P_f^{th} is the threshold of the probability of false alarm, which should be very small (e.g., 0.01) to efficiently utilize the identified available channels. To simplify the derivation without loss of generality, we neglect this factor. Each admitted user can access either $n_a^{(t)}$ or $n_a^{(t)} + 1$, as mentioned in Section IV; therefore, the average aggregate throughput (in channels per user) can simply be found from the expectation of the $n_a^{(t)}$ without the floor operator as

$$\begin{aligned} \overline{S}^{(t)} &= E\left[n_a^{(t)}\right] \\ &= \begin{cases} \frac{E\left[N_a^{(t)}\right]}{M_{\mathrm{B1}}^{(t)} - M_s^{(t)}}, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} < E\left[N_a^{(t)}\right] \\ 1, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} \geq E\left[N_a^{(t)}\right] \end{cases}. \end{aligned} \tag{25}$$

The number of identified available channels $N_a^{(t)}$ depends on the activities of the PUs on each channel, which is given by δ_i in (1). To simplify the analysis without loss of generality, let $\delta_i = \delta$ for all i; then, the number of available and sensed channels can be modeled by binomial distribution. The average of the identified available channels using the ASP developed in [6] can be given as

$$E\left[N_a^{(t)}\right] = \begin{cases} (1-\delta)L^{(t)}M_s^{(t)}, & L^{(t)}M_s^{(t)} < N \\ (1-\delta)N, & L^{(t)}M_s^{(t)} \geq N. \end{cases} \quad (26)$$

Let $\overline{N}_a^{(t)} = E[N_a^{(t)}]$; then, the average aggregate throughput of the SU (in channels per user) can be given as

$$\overline{S}^{(t)} = \begin{cases} \frac{\overline{N}_a^{(t)}}{M_{\mathrm{B1}}^{(t)} - M_s^{(t)}}, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} < \overline{N}_a^{(t)} \\ 1, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} \geq \overline{N}_a^{(t)} \end{cases} \quad (27)$$

and the steady-state average aggregate throughput of each SU can be found from

$$\overline{S} = \lim_{t\to\infty} \overline{S}^{(t)}. \quad (28)$$

It is desirable to find the normalized average aggregate throughput of the secondary network, which reflects the percentage of the identified available channels out of the licensed channels and the portion of time of using these channels. In other words, it indicates the actual usage of the licensed channels by the SUs. The normalized average aggregate throughput can be found by

$$\overline{\Theta}^{(t)} = M_{\mathrm{aw}}^{(t)} \frac{\overline{S}^{(t)}}{\overline{N}_a^{(t)}} \frac{\left(T - \tau^{(t)} - T_c\right)}{T}. \quad (29)$$

By substituting the values of $M_{\mathrm{aw}}^{(t)}$, $\overline{S}(t)$, and $\overline{N}_a^{(t)}$, (29) can be rewritten as

$$\overline{\Theta}^{(t)} = \begin{cases} \frac{L^{(t)}M_s^{(t)}}{N} \frac{\left(T-\tau^{(t)}-T_c\right)}{T}, & L^{(t)}M_s^{(t)} < N \\ \frac{T-\tau^{(t)}-T_c}{T}, & L^{(t)}M_s^{(t)} \geq N \end{cases} \quad (30)$$

and the steady-state normalized average aggregate throughput of the secondary network can be obtained as

$$\overline{\Theta} = \lim_{t\to\infty} \overline{\Theta}^{(t)}. \quad (31)$$

B. Average User Waiting Delay

The average SU waiting delay can be defined as the average time spent by an SU registered in the network to be admitted to transmit its packets on the allocated available channels. Based on the system model, the secondary network always has SUs that want to transmit their packets; therefore, the delay evaluation depends on the saturated network analysis.

The $M_w^{(t)}$ winning users have to wait $T_{\mathrm{DRP}}^{(t)} + T_c + \tau^{(t+1)}$ time duration to know how many of them are allowed to access the identified available channels at time slot $(t+1)$, while the remaining users have to try again to be winners in the coming time slots. Therefore, from Fig. 1, the time a user has to wait to get a chance to transmit its packets can be given as

$$D^{(t)} = 3\mathrm{SIFS} + T_{\mathrm{RP}} + T_{\mathrm{B2}} + \frac{1}{P_{\mathrm{aw}}^{(t)}}\left(T_{\mathrm{DRP}}^{(t)} + T_c + \tau^{(t+1)}\right) \quad (32)$$

where $T_{\mathrm{RP}} = NT_{\mathrm{ms}}$ is the time duration of the RP, $T_{\mathrm{DRP}}^{(t)} = T - \tau^{(t)} - T_c$ is the time duration of the DRP at time slot t, and $P_{\mathrm{aw}}^{(t)}$ is the probability of being an admitted winner, which can be found as

$$P_{\mathrm{aw}}^{(t)} = \frac{M_{\mathrm{aw}}^{(t+1)}}{M_r^{(t)}} \quad (33)$$

and therefore, (32) can be rewritten as

$$D^{(t)} = 3\mathrm{SIFS} + NT_{\mathrm{ms}} + T_{\mathrm{B2}} + \frac{M_r^{(t)}}{M_{\mathrm{aw}}^{(t+1)}}\left(T - \tau^t + \tau^{(t+1)}\right) \quad (34)$$

where $M_r^{(t)}$ can be given from (11) and (13) as

$$\begin{aligned} M_r^{(t)} &= M_{\mathrm{B2}}^{(t)} - M_{\mathrm{aw}}^{(t)} \\ &= M_{\mathrm{B1}}^{(t)} + \lambda_{\mathrm{ad}}\tau^{(t)} - M_{\mathrm{aw}}^{(t)} \\ &= \begin{cases} \lambda_{\mathrm{ad}}\tau^{(t)} + M_s^{(t)}, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} < N_a^{(t)} \\ M_{\mathrm{B1}}^{(t)} + \lambda_{\mathrm{ad}}\tau^{(t)} - N_a^{(t)}, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} \geq N_a^{(t)} \end{cases} \end{aligned} \quad (35)$$

where the floor operator used in (11) is removed here since we are calculating the average value. From (12), $M_{\mathrm{aw}}^{(t+1)}$ can be given as

$$M_{\mathrm{aw}}^{(t+1)} = \begin{cases} M_w^{(t)}, & M_w^{(t)} < N_a^{(t+1)} \\ N_a^{(t+1)}, & M_w^{(t)} \geq N_a^{(t+1)} \end{cases}. \quad (36)$$

Therefore, the average user delay can be found as

$$\begin{aligned} \overline{D}^{(t)} &= 3\mathrm{SIFS} + NT_{\mathrm{ms}} + T_{\mathrm{B2}} \\ &\quad + \frac{E\left[M_r^{(t)}\right]}{E\left[M_{\mathrm{aw}}^{(t+1)}\right]}\left(T - \tau^{(t)} + E\left[\tau^{(t+1)}\right]\right) \end{aligned} \quad (37)$$

where $E[M_r^{(t)}]$ can be found from (35) as

$$E\left[M_r^{(t)}\right] = \begin{cases} \lambda_{\mathrm{ad}}\tau^{(t)} + M_s^{(t)}, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} < \overline{N}_a^{(t)} \\ M_{\mathrm{B1}}^{(t)} + \lambda_{\mathrm{ad}}\tau^{(t)} - \overline{N}_a^{(t)}, & M_{\mathrm{B1}}^{(t)} - M_s^{(t)} \geq \overline{N}_a^{(t)} \end{cases} \quad (38)$$

and $E[M_{\mathrm{aw}}^{(t+1)}]$ can be found from (36) as

$$E\left[M_{\mathrm{aw}}^{(t+1)}\right] = \begin{cases} E\left[M_w^{(t)}\right], & E\left[M_w^{(t)}\right] < E\left[N_a^{(t+1)}\right] \\ E\left[N_a^{(t+1)}\right], & E\left[M_w^{(t)}\right] \geq E\left[N_a^{(t+1)}\right] \end{cases} \quad (39)$$

where $E[M_w^{(t)}]$ can be found from (19) as

$$E\left[M_w^{(t)}\right] = \begin{cases} E\left[M_{\mathrm{res}}^{(t)}\right], & E\left[M_{\mathrm{res}}^{(t)}\right] < E\left[M_{w_{\max}}^{(t)}\right] \\ E\left[M_{w_{\max}}^{(t)}\right], & E\left[M_{\mathrm{res}}^{(t)}\right] \geq E\left[M_{w_{\max}}^{(t)}\right] \end{cases}. \quad (40)$$

As mentioned in Section III, the reserving is a random process. Let receiver i respond to the reserving message sent by transmitter i with certain probability p_i. To simplify the analysis without loss of generality, assume that $p_i = p$ for all i; then, the reserving process can be modeled as a binomial distribution. From (18), $E[M_{\text{res}}^{(t)}] = pN_{\text{res}}^{(t)}$, and from (16), $E[M_{w_{\max}}^{(t)}]$ can be found as

$$E\left[M_{w_{\max}}^{(t)}\right] = E\left[M_r^{(t)}\right] - \frac{2t_s N}{T - T_c} \tag{41}$$

where $E[M_r^{(t)}]$ is given by (38). By denoting $E[M_{w_{\max}}^{(t)}]$ as $\overline{M}_{w_{\max}}^{(t)}$, (40) can be rewritten as

$$E\left[M_w^{(t)}\right] = \begin{cases} pN_{\text{res}}^{(t)}, & pN_{\text{res}}^{(t)} < \overline{M}_{w_{\max}}^{(t)} \\ \overline{M}_{w_{\max}}^{(t)}, & pN_{\text{res}}^{(t)} \geq \overline{M}_{w_{\max}}^{(t)} \end{cases}. \tag{42}$$

Similar to finding $E[N_a^{(t)}]$ in (26), $E[N_a^{(t+1)}]$ in (39) can be found, which depends on the $M_s^{(t+1)}$ given from (6) as

$$\begin{aligned} M_s^{(t+1)} &= M_{\text{B1}}^{(t+1)} - M_w^{(t)} \\ &= M_{\text{B2}}^{(t)} - M_{\text{aw}}^{(t)} - M_w^{(t)} \\ &= M_{\text{B1}}^{(t)} + \lambda_{\text{ad}}\tau^{(t)} - M_{\text{aw}}^{(t)} - M_w^{(t)} \end{aligned} \tag{43}$$

$$E\left[M_s^{(t+1)}\right] = M_{\text{B1}}^{(t)} + \lambda_{\text{ad}}\tau^{(t)} - E\left[M_{\text{aw}}^{(t)}\right] - E\left[M_w^{(t)}\right] \tag{44}$$

where $E[M_w^{(t)}]$ is given in (42), and $E[M_{\text{aw}}^{(t)}]$ can be given from (12) as

$$E\left[M_{\text{aw}}^{(t)}\right] = \begin{cases} M_{\text{B1}}^{(t)} - M_s^{(t)}, & M_{\text{B1}}^{(t)} - M_s^{(t)} < \overline{N}_a^{(t)} \\ \overline{N}_a^{(t)}, & M_{\text{B1}}^{(t)} - M_s^{(t)} \geq \overline{N}_a^{(t)} \end{cases}. \tag{45}$$

Finally, $E[\tau^{(t+1)}]$ can be found from (7) but with time slot $(t+1)$ instead of t, i.e., it depends on $E[M_s^{(t+1)}]$, which is given by (44). By substituting $E[M_r^{(t)}]$, $E[M_{\text{aw}}^{(t)}]$, and $E[\tau^{(t+1)}]$ into (37), the average user waiting delay can be found. Last, the steady-state average user waiting delay in the secondary network until it is admitted to transmit can be found from

$$\overline{D} = \lim_{t\to\infty} \overline{D}^{(t)}. \tag{46}$$

VI. Performance Evaluation

In this section, we present the numerical and simulation results of the proposed admission control and channel-allocation policy. The numerical parameters used in the performance evaluation are listed in Table II. The evaluation is performed on two levels: on the time slot level that describes the interaction activities of the users in one time slot and on the steady-state level of the secondary network that describes the capability of the secondary network.

A. One Time Slot Level

For each time slot, a number of sensing users should identify the available licensed channels; therefore, this number is expected to affect the whole performance of the system. In the following three figures, we will show the relations between the number of sensing users and the different important quantities in the secondary network.

TABLE II
Numerical Parameters for Performance Evaluation

Parameter	Value	Description
B	6 MHz	Bandwidth of each licensed channel
T	50 ms	Duration of each time slot
P_d^{th}	0.95	Probability of detection threshold
P_f^{th}	0.01	Probability of false-alarm threshold
γ	-15 dB	SNR detection sensitivity of the SU's detector
δ	0.3	The activity of the PUs
N	30	The number of the licensed channels
T_{B1}	100 μs	Duration of beacon B1
T_{B2}	100 μs	Duration of beacon B2
T_{ms}	10 μs	Mini-slot duration of the RP phase
SIFS	15 μs	Short inter-frame space duration

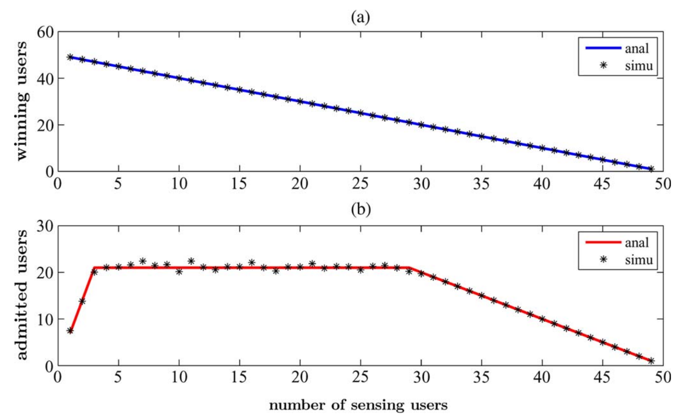

Fig. 2. Number of (a) winning users M_w and (b) admitted users M_{aw} with respect to the number of sensing users M_s in a time slot when $M_{\text{B1}} = 50$ (users), $\lambda_{\text{ad}} = 1$ (user/ms), and $T_{\text{res}} = 2$ (ms).

Fig. 2 shows the relation between the number of winning and admitted users with respect to the number of sensing users. It can be seen that the sensing and winning users are inversely related. This is because, for each time slot, the total number of SUs is divided into sensing and winning users; therefore, increasing one type will linearly decrease the other. On the other hand, the number of admitted users is related to the number of identified available channels. When the number of sensing users is too small, i.e. $M_s \leq 3$ users, the number of identified channels is small; therefore, the number of admitted users is small too, and it increases until it equals the average number of identified channels, where each admitted user will access only one channel. When the number of sensing users is greater than the number of licensed channels, i.e. $M_s \geq N$, the number of remaining users is less than N channels and therefore, the number of admitted users decreases. The simulation results are consistent with the analytical results.

The analytical and simulation results of Fig. 3 illustrate that when there is a sufficient number of sensing users, they can identify the number of average available licensed channels. However, when the number of sensing users is relatively small compared with the number of N channels, each sensing user is required to sense more channels to identify all these channels;

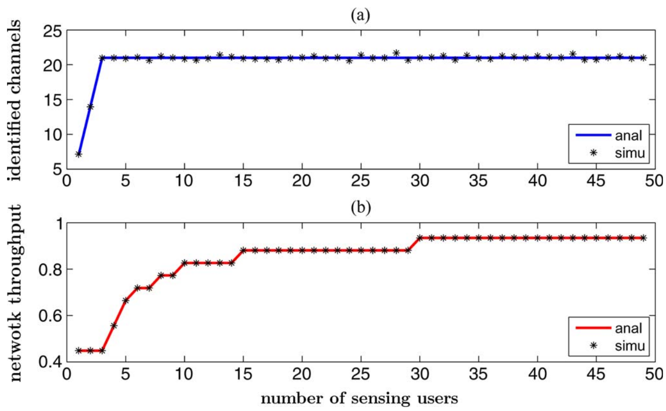

Fig. 3. Relation between the number of sensing users M_s and (a) the number of identified licensed channels N_a and (b) the network normalized average aggregate throughput $\overline{\Theta}$ in a time slot when $M_{\mathrm{B1}} = 50$ (users), $\lambda_{\mathrm{ad}} = 1$ (user/ms), and $T_{\mathrm{res}} = 2$ (ms).

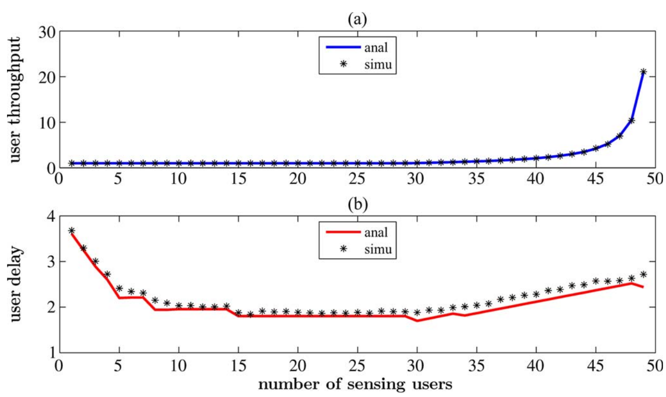

Fig. 4. SU's (a) average aggregate throughput, $\overline{S}$ (in channels per user) and (b) average waiting delay $\overline{D}$ (in time slots) with respect to the number of sensing users M_s at a time slot when $M_{\mathrm{B1}} = 50$ (users), $\lambda_{\mathrm{ad}} = 1$ (user/ms), and $T_{\mathrm{res}} = 2$ (ms).

consequently, the sensing duration increases, which is at the cost of the remaining time that should be used for data transmission by the admitted users at the DRP. This is what makes the network throughput increase in steps until it saturates when the number of sensing users is equal to the number of licensed channels, where each sensing user senses only one channel. It can be seen that the SUs can utilize up to 0.95 of the available spectrum, while the remaining 0.05 is the cost of the signaling overheads and the sensing time, which reflects the effectiveness of the used MAC protocol.

Fig. 4 shows the average aggregate throughput of the SU and its average waiting delay in the network with respect to the number of sensing users. The admitted users decreases with an increasing number of sensing users when $M_s \geq N$, as can be seen from Fig. 2(b); therefore, each admitted user has the chance to obtain more allocated channels; consequently, its average aggregate throughput increases. However, the cost of allocating more channels to fewer users increases the average waiting delay of the user in the network. Therefore, there is a QoS tradeoff between the average aggregate throughput and the average delay of the SU in the network. It can be seen that the minimum waiting delay in the network is when the number of sensing users is equal to the number of licensed channels,

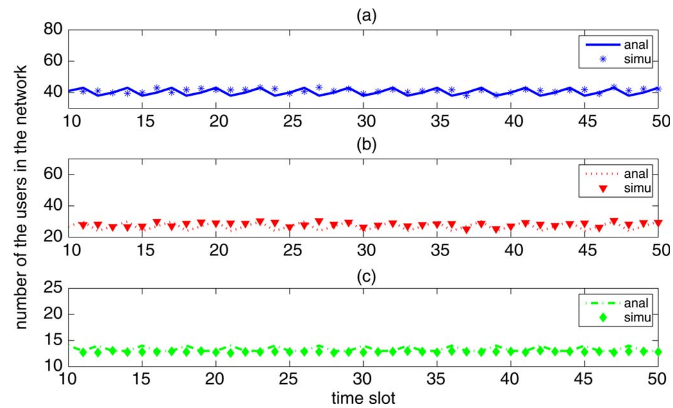

Fig. 5. Number of (a) users at beacon B1 M_{B1}, (b) sensing users M_s, and (c) admitted winning users M_{aw} in the secondary network for a number of time slots when $T_{\mathrm{res}} = 3$ (ms) and $\lambda_{\mathrm{ad}} = 3$ (user/ms).

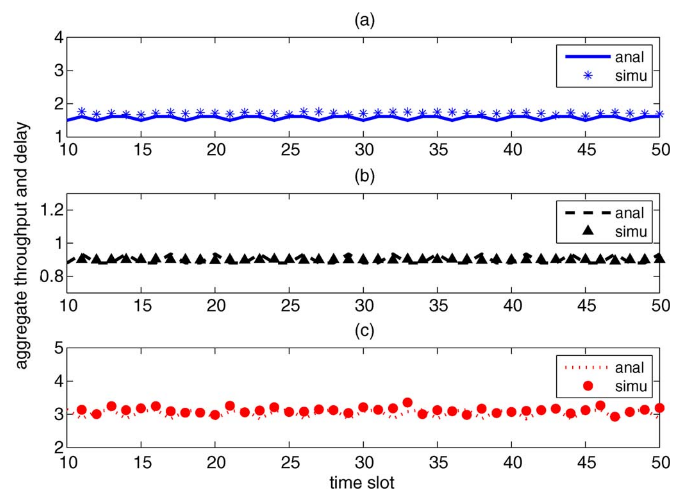

Fig. 6. Average (a) user aggregate throughput $\overline{S}$ (in channels per user), (b) network normalized aggregate throughput $\overline{\Theta}$, and (c) user delay $\overline{D}$ (in time slots) for a number of time slots when $T_{\mathrm{res}} = 3$ (ms) and $\lambda_{\mathrm{ad}} = 3$ (user/ms).

which is always the case since each sensing user senses only one channel, i.e., the sensing duration is minimum, and the number of access users is maximum; therefore, the users get the chance to access the available channels faster; consequently, the user delay is the minimum.

B. Steady-State Level

In the long run of the network, the network performance quantities are in the steady state; therefore, the network capability in terms of the number of admitted users, the average aggregate throughput, and the average delay can be studied. Fig. 5 shows the number of users in the network based on their functions, while Fig. 6 shows the user average aggregate throughput, the secondary network average aggregate throughput, and the average waiting delay in the steady state. From these two figures, it can be seen that the aforementioned quantities converge to specific values based on the system parameters, regardless of the initial start of the network. The ripples on the curves indicate the relations between the system parameters that reflect the mathematical coefficients of the random difference

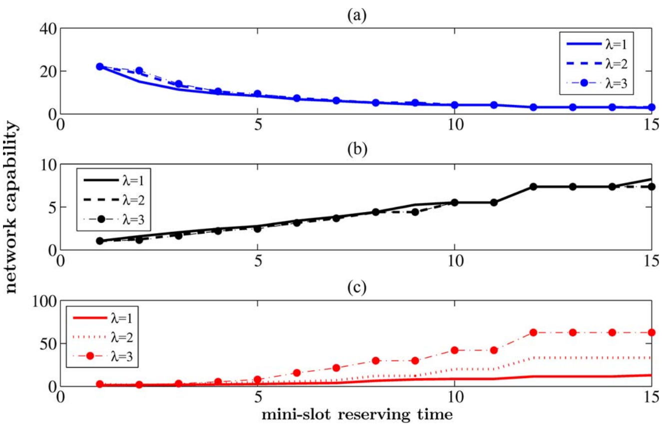

Fig. 7. Effects of the minislot reserving time T_{res} (in milliseconds) on the network capability. (a) Average number of admitted users $\overline{M}_{\mathrm{aw}}$. (b) User average aggregate throughput $\overline{S}$ (in channels per user). (c) User average delay $\overline{D}$ (in time slots).

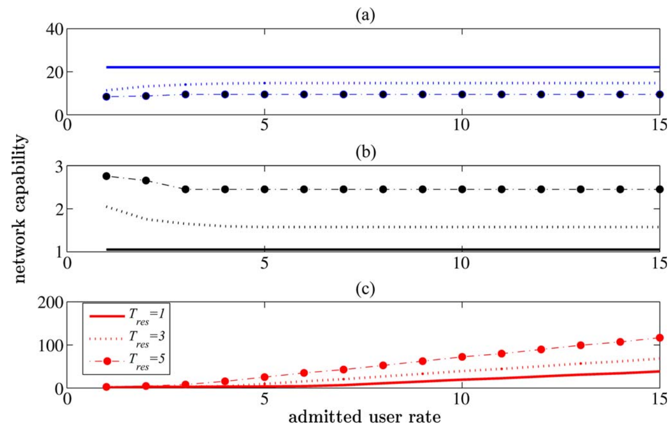

Fig. 8. Effects of the admitted user rate λ_{ad} (in users per milliseconds) on the network capability. (a) Average number of admitted users $\overline{M}_{\mathrm{aw}}$. (b) User average aggregate throughput $\overline{S}$ (in channels per user). (c) User average delay $\overline{D}$ (in time slots).

equations discussed in Section III. Since the simulation results of Figs. 5 and 6 verify the analytical results in the steady-state case, we will consider only the analytical results in the following figures.

One of the main design parameters in the system is the minislot reserving time at the DRP T_{res}. Based on the minislot reserving time duration, the number of users that can win to reserve the next time slot can be controlled. Fig. 7 shows the effects of choosing this parameter on the secondary network capability. When this duration increases, the number of winning users can be decreased; consequently, the expected number of admitted users at the next time slot decreases. When the number of admitted users decreases, the admitted users get a higher chance to access more identified channels; therefore, their average aggregate throughput increases; however, the average delay also increases because the number of users accumulates in the network due to decreasing the number of admitted users. In this figure, the effect of increasing the admitted user rate is shown. Increasing the admitting rate will increase the waiting delay in the network when the other parameters are fixed, but it will almost not affect the number of admitted users or the average aggregate throughput.

The second important design parameter is the admitted user rate λ_{ad}. This parameter can be controlled by the first winner that broadcasts on beacon B1 and registers the new users, as discussed in Section IV-B. To meet certain QoS levels in the secondary network, the first winner will admit just a number of new users. Fig. 8 illustrates the effects of the admitted user rate on the network capability. In general, admitting more users will increase the average delay in the network. It can be seen from the figure that increasing the minislot reserving time duration affects the network capability as well.

Fig. 9 illustrates the effects of the receiver responding probability p at the reserving process on the network capability. This parameter cannot be controlled as a system design parameter; however, its influences on the network capability should be considered while designing the other parameters. When this probability increases, the successful exchange of the reserving messages increases. Since more winning users can be assigned,

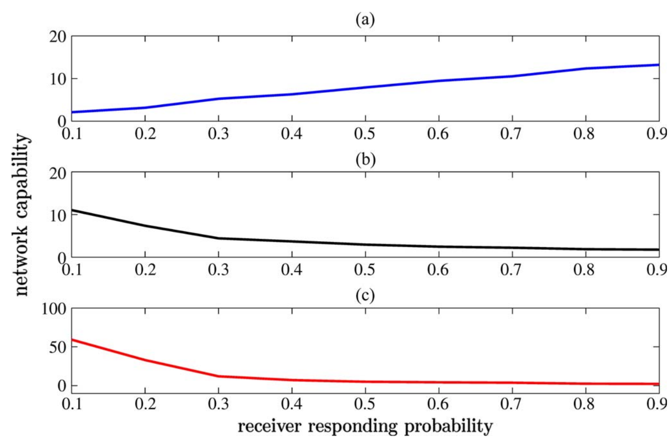

Fig. 9. Effects of the receiver responding probability p on the network capability when $T_{\mathrm{res}} = 3$ (ms) and $\lambda_{\mathrm{ad}} = 2$ (user/ms). (a) Average number of admitted users $\overline{M}_{\mathrm{aw}}$. (b) User average aggregate throughput $\overline{S}$ (in channels per user). (c) User average delay $\overline{D}$ (in time slots).

more admitted users can be accepted on the next time slot; however, this will not only decrease the user average aggregate throughput but also decrease the delay. Based on the information of the probability of receiver response, which can be learned over the time, the minislot reserving time should be chosen properly.

Choosing the time slot duration T is related to the tolerable interference to the PUs, i.e., for different PUs, there may be different interference requirements. Increasing this time duration is expected to increase the secondary network throughput; however, this will increase the interference to the PUs. Therefore, its effects on the secondary network capability should be studied. Fig. 10 shows these effects, which are almost similar to what was shown in Fig. 9 but with different values; however, when the number of admitted winning users saturates, the average user delay starts to slightly increase with increasing the time slot duration because, in this case, the users are required to wait longer until they probably get the chance to access the available channels in the coming time slots; moreover, for the given set of parameters, there are some ripples on the average delay curve due to the calculation averaging.

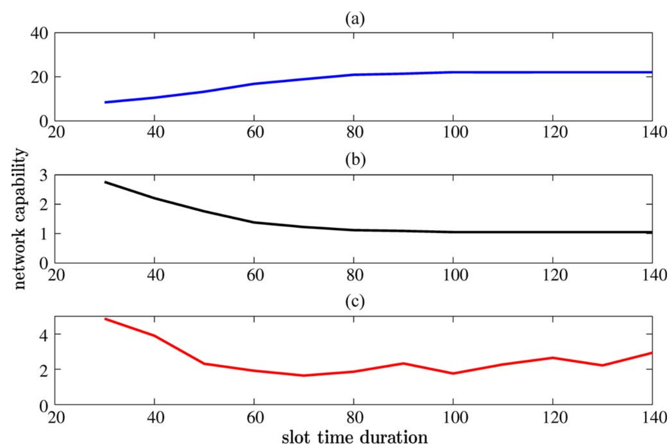

Fig. 10. Effects of the slot time duration T (in milliseconds) on the network capability when $T_{\mathrm{res}} = 3$ (ms) and $\lambda_{\mathrm{ad}} = 2$ (user/ms). (a) Average number of admitted users $\overline{M}_{\mathrm{aw}}$. (b) User average aggregate throughput $\overline{S}$ (in channels per user). (c) User average delay $\overline{D}$ (in time slots).

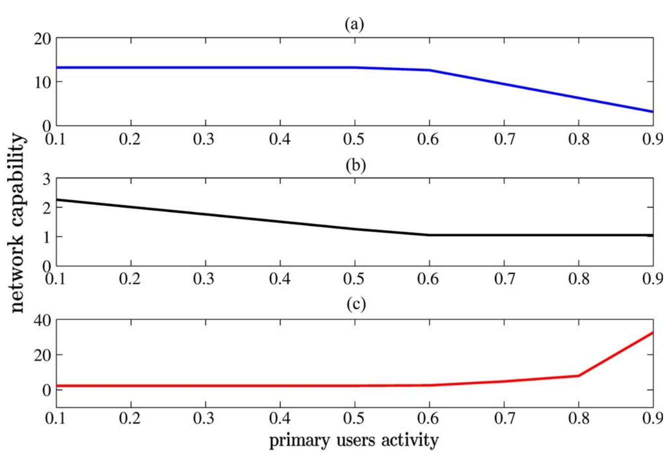

Fig. 11. Effects of the primary user activity δ on the network capability when $T_{\mathrm{res}} = 3$ (ms) and $\lambda_{\mathrm{ad}} = 2$ (user/ms). (a) Average number of admitted users $\overline{M}_{\mathrm{aw}}$. (b) User average aggregate throughput $\overline{S}$ (in channels per user). (c) User average delay $\overline{D}$ (in time slots).

The availability of licensed channels is dependent on the activity of the PUs on those channels, which cannot be controlled but should be considered. Fig. 11 illustrates the effects of the activity of the PUs δ on the secondary network capability. The average number of identified channels is $(1 - \delta)N$; however, the maximum number of admitted users is 13 based on the given values of T_{res} and λ_{ad}; therefore, only 13 of the identified channels can be exploited. When δ increases above 0.5, the number of admitted users linearly decreases since the average number of identified channels linearly decreases. Moreover, the average aggregate throughput linearly decreases with a decrease in the average number of identified channels, while the average delay is constant until each admitted user accesses only one channel, where the delay increases with decreasing the average number of available channels.

VII. Conclusion and Future Work

In this paper, we have developed an admission-control scheme and a channel-allocation policy for cooperative ad hoc OSNs based on user dynamic IDs. With the help of the secondary network controller in each time slot, the admitted SUs use their dynamic IDs and the order of the identified available channels to determine which available channels can be allocated to each of them. Moreover, we have investigated the adjusting parameters that can be used to control the number of admitted users by studying the dynamic system behavior using a set of difference equations. We have found that the two flexible parameters that can be used to control the capability of the secondary network to support concurrent transmissions are the minislot reserving time and the admitted user rate. The network controller in each time slot uses these controlling parameters to admit only a number of SUs that meet the QoS requirements of the secondary network.

The proposed admission control and channel-allocation policy can be applied for real and nonreal time secondary traffic. Defining QoS utility functions and then finding the optimal admission-control parameters for each type of secondary traffic will be investigated in our future work.

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