QoS Provisioning for Heterogeneous Services in Cooperative Cognitive Radio Networks

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***Abstract*—In this paper, we propose a spectrum allocation framework that jointly considers the Quality-of-Service (QoS) provisioning for heterogeneous secondary Real-Time (RT) and Non-Real Time (NRT) users, the spectrum sensing, spectrum access decision, channel allocation, and call admission control in distributed cooperative Cognitive Radio Networks (CRNs). Giving priority to the RT users with QoS requirements in terms of the dropping and blocking probabilities, a number of the identified available channels are allocated to the optimum number of the RT users that can be admitted into the network, while the remaining identified available channels are allocated adaptively to the optimum number of the NRT users considering the spectrum sensing and utilization indispensability. Extensive analytical and simulation results are provided to demonstrate the effectiveness of the proposed QoS-based spectrum resource allocation framework.**

***Index Terms*—Cognitive Radio Networks, Heterogeneous Secondary Users, QoS Provisioning, Spectrum Resource Allocation.**

I. Introduction

WITH THE fixed spectrum allocation policy that has been used since the beginning of the spectrum regulation to assign different spectrum bands to different wireless applications, it has been observed that most of the allocated spectrum bands are underutilized. Therefore, if these bands can be opportunistically used by new emerging wireless networks, the spectrum scarcity can be resolved [1]. Cognitive Radios (CRs) are promising technology that can identify and then exploit the spectrum opportunities. In Cognitive Radio Networks (CRNs), the spectrum can be utilized by two kinds of users: Primary Users (PUs) and Secondary Users (SUs). The PUs are those users having exclusive licenses to use certain spectrum bands for specific wireless applications, so their Quality-of-Service (QoS) should be guaranteed with certain thresholds, i.e., the PUs may allow for some unharmful degradations in their QoS levels. On the other hand, the SUs are equipped with CRs and can exploit any under utilized band; moreover, they should depend on themselves to identify the spectrum opportunities without collaboration from the PUs [2]. The CRNs can be centralized or ad hoc networks. Due to the ease of deployment, the ad hoc CRNs are expected to attract more future applications of the secondary spectrum usage. In distributed ad hoc CRNs, there is no central user or node that controls the network, so each SU should depend on itself to decide how to sense and which available spectrum to access. Moreover, cooperation between the SUs can facilitate the spectrum identification and exploitation.

The concept of the CRNs leads to support the increasing demands of advanced wireless applications and to efficiently utilize the precious radio resource. However, there are many challenges that must be tackled in order to realize this concept. In addition to identify and exploit the spectrum opportunities, providing QoS for the SUs is very critical in CRNs. The availability fluctuation of the licensed channels poses serious difficulties in providing acceptable QoS for the SUs. When the channel availability varies depending on the PUs activities on the licensed channels, the secondary traffic flows should be regulated accordingly to guarantee the QoS requirements of the SUs. Therefore, unlike the traditional QoS provisioning that mainly depends on the traffic statistics, providing QoS for the SUs should be realized through the spectrum sensing, spectrum access decision and allocation, and the admission control across the involved network layers. In CRNs, when a PU appears on a channel used by a SU, the SU must vacate that channel and try to find another available channel to complete its ongoing transmission, which is known as spectrum handover [1]; however, there is a possibility of dropping the call due to unavailable channel. Moreover, the probability of blocking the incoming calls increases when the activities of the PUs are high on the licensed channels. Therefore, the dropping and blocking probabilities are related to the aggregate throughput and service waiting time of the SUs. Furthermore, the underutilized spectrum should be used efficiently by the SUs.

Several QoS provisioning approaches have been proposed for CRNs, which can be classified in general into four categories. The first category investigates the Medium Access Control (MAC) protocol and opportunistic scheduling design, which can provide QoS for the SUs in different secondary network models [3]-[8]. The second category focuses on power allocation schemes that are aware of the QoS for different scenarios of CRNs [9]-[11]. The third category develops different call admission control and channel allocation schemes to guarantee certain QoS requirements of the SUs [12]-[20]. Different from call admission control of the traditional wireless networks such as cellular networks, which has been extensively studied in the literature [21], call admission control for CRNs must be spectrum aware, i.e., to admit a new SU into the network, there should be spectrum available and identified through spectrum sensing to guarantee the required QoS in terms of the blocking and dropping probabilities. Finally, the

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fourth category studies the QoS provisioning considering the services and applications carried out by CRNs [22]-[28].

In this paper, we jointly consider the QoS provisioning of heterogeneous secondary Real Time (RT) and Non-Real Time (NRT) users, the spectrum sensing, spectrum access decision, channel allocation and call admission control in distributed cooperative CRNs. Based on the statistical information of the available channels that can be learned over the time by the CRs, we allocate a number of the available channels that are identified by spectrum sensing to the optimum number of the RT users maintaining their dropping and blocking probability QoS levels. These users are allowed to access the available channels in consecutive time slots until they successfully transmit their packets. The remaining available channels in each time slot are allocated adaptively to the optimum number of the NRT users with variable data rate to efficiently utilize the unused spectrum. We provide detailed analytical and simulation results to evaluate the proposed QoS provisioning framework.

The remainder of this paper is organized as follows. Section II presents the system model. Detailed analysis of the QoS-based spectrum allocation for the RT and NRT users is given in Section III. Numerical and simulation results are provided in Section IV. The paper is concluded in Section V.

II. System Model

A. Network Model

The CRN consists of a number of SUs cooperating to identify and exploit the unused spectrum portions by intended legacy primary networks that may comprise of different PUs. The proposed CRN is a distributed network, i.e., there is no central node that can manage the network; therefore, each SU must depend on itself to decide how to sense and access the unused spectrum with coordination with the other SUs. The SUs are deployed in a region, where they are within the communication range of each other, and the coverage area of the PUs is larger than that of the SUs. Each SU is equipped with a single CR transceiver. This transceiver can sense at most L channels in sequence and access a number of channels simultaneously if these channels are within its spectrum span ability using the Discontiguous Orthogonal Frequency Division Multiplexing Access (D-OFDMA) technique. The intended licensed spectrum to the PUs consists of N non-overlapped channels, where each licensed channel is given an ID based on its sequence in the spectrum. At any time, each licensed channel is either occupied by a PU or idle, so the status of the i-th channel at any time can be modeled as a two-state Markov chain as shown in Fig. 1, and the primary occupancy of the channel 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 occupied state to idle state, and β_i is the probability that it transits from idle state to occupied state.

Distinguishing a channel as an occupied one or not by a PU at any time slot is determined by spectrum sensing. Since the total number of the available channels at any time slot depends on the overall activity of the PUs on the N channels regardless of the details of the occupancy of each channel, it is sufficient to know the average overall activity of the PUs to estimate the total number of the available channels. Therefore, without loss of generality, we assume that $\delta_i = \delta, \forall i$, where δ is the average overall activity of the PUs. The distribution of the number of the available channels can be estimated by the CRs based on historical statistical measurements about the intended licensed channels. With this statistical distribution, the QoS requirements of the SUs can be studied.

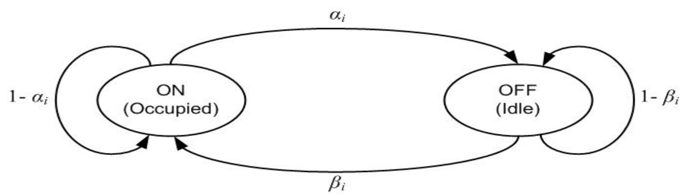

Fig. 1. Model of the licensed channels.

B. MAC Framework

The SUs use the cognitive MAC framework in [5] to manage their spectrum sensing and access. Fig. 2 illustrates one time slot of the MAC structure on the Common Control (CC) channel. There are three phases: Sensing and Registering Phase (SRP), Reporting Phase (RP), and Data and Reserving Phase (DRP) in addition to two beacons B1 and B2. Since the CRN is a distributed one, at each time slot, any winning user at the DRP phase from the last time slot can work as a network coordinator, so as a rule the first winner coordinates the network, and if it fails, the second winner should coordinate and so on. The network coordinator helps to register the new arriving users by assigning them unique dynamic IDs and broadcast information about how many users are in the network and how many users have left at beacons B1 and B2. The dynamic ID of each user reflects its sequence in the network among the registered SUs. Moreover, the SUs update their dynamic IDs once they get the information on beacon B1. The SUs use their dynamic IDs to cooperate with each other to sense the N licensed channels and to access the identified available channels. The MAC protocol is briefly described as follows:

1) at beacon B1, there are M_w winning users from the last reserving phase and M_s sensing users. The sensing users sense the licensed channels at the SRP based on a sensing policy (will be discussed briefly in the next subsection) and report their observations on the RP, while the winning users monitor the RP to get full spectrum picture, i.e., which channels are available and which are not;
2) at the end of the SRP, there are M_n new users successively registered in the network with the help of the network coordinator;
3) at beacon B2, there are M_{aw} access winning users, where $0 \leq M_{aw} \leq M_w$ based on the number of the identified available channels, N_a, the number of the allocated channels per admitted user, and the number of the sensing users in the next time slot, i.e., there is

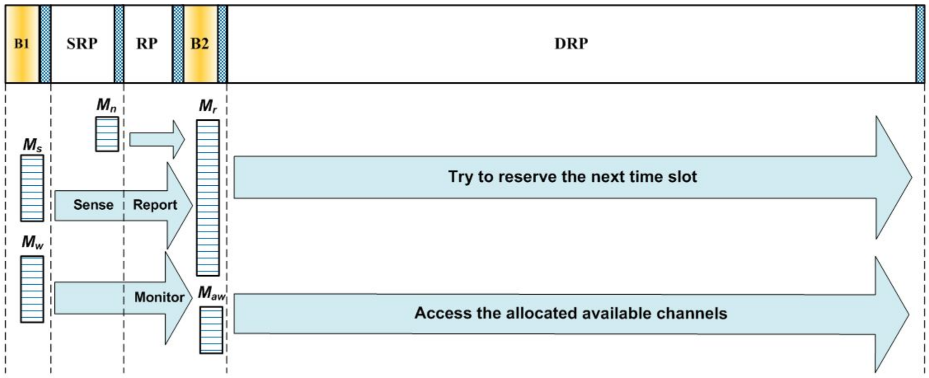

Fig. 2. Structure of one time slot of the MAC framework.

balance between the number of the access users and the number of the sensing users. The remaining users, M_r, are the summation of the new users, sensing users, and the winning users that cannot access the available channels; and

4) at the DRP, the admitting winning users access the available channels based on an allocation policy, while the remaining users try to reserve the potential available channels at the next time slot.

C. Spectrum Sensing Policy

In order to exploit as many channels as possible, the SUs cooperate to identify the unused licensed channels using a deterministic sensing policy called Allocated-group Sensing Policy (ASP) [5]. Each sensing user determines and then senses a group of L channels in sequence based on its dynamic ID and the IDs of the channels, where each channel requires t_s sensing time. Then, it reports its observations about the available channels on the RP. Considering the potential interference to the PUs and also the spectrum utilization, the optimum number of the sensed channels per user is given as [5]

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

where $\lceil x \rceil$ is the nearest integer number greater than or equal to x, M_s is the number of the sensing users, N is the number of the licensed channels, T is the time slot duration, and T_c is the time duration for the MAC control messages given as

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

where T_{B1} and T_{B2} are the time duration for beacons B1 and B2, respectively, NT_{ms} is the time duration of reporting the N licensed channels at the RP, and T_{SIFS} is the Short Inter Frame Space (SIFS) time for the propagation delay and for tuning the transceiver to the next phase. Moreover, the required time to sense each channel is given as [5]

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

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-t^2/2)dt$, P_d and P_f are the probability of detection and false-alarm thresholds, respectively, required by the PUs and SUs, B is the bandwidth of the licensed channel, and γ is the signal-to-noise ratio sensitivity of the detector. Based on the number of the sensing users, the intended N licensed channels can be partially (when $LM_s < N$) or fully (when $LM_s \geq N$) identified; moreover, when M_s is small comparing to N, each sensing user is required to sense more channels, which is at the cost of increasing the sensing duration. This explains the importance of balancing between the number of the sensing users that identify the available channels and the number of the access users that can exploit these available channels.

D. QoS Provisioning

The proposed CRN can support secondary RT and NRT users concurrently. The RT user (e.g., VOIP) requires constant data rate and acceptable average packet delay; moreover, it is annoying to drop an RT user once it is established, so the RT user dropping probability should not exceed a certain threshold; furthermore, blocking the RT user from accessing the network is not desired, so the blocking probability should also be within an acceptable threshold. For the NRT user (e.g., Data transferring), the most important QoS requirement in the context of CRNs is the throughput. Considering both RT and NRT users, the spectrum utilization is an ultimate goal in employing the CRN. Fig. 3 shows the proposed QoS provisioning model. Since the RT users are delay sensitive, they are given priority to access the available channels once they are admitted in the network using spectrum handover. Spectrum handover in this context implies that whenever an RT user is allowed to access an allocated channel at the current time slot, this user will be allowed to access an allocated available channel, if any, in the coming consecutive time slots until it completes its ongoing transmission. The remaining available channels in each time slot are utilized by NRT users.

E. Channel Allocation and Call Admission Control

Since there are two user classes in the network, the dynamic IDs of the SUs reflect their sequences in their classes. Using these dynamic IDs, each user in the network can decide distributively which channels to access as follows. For the RT users, an RT admitted user will access an available channel from the total identified available channels based on the ID sequence of the RT admitted user in its class and the ID

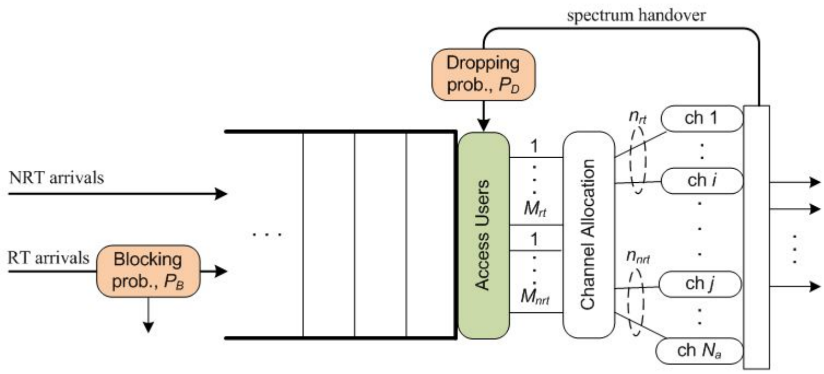

Fig. 3. The RT and NRT QoS provisioning model.

sequences of the available channels, e.g., the first RT admitted user will access the first available channel and so on. The remaining available channels, if any, will be utilized by the NRT users similarly, i.e., each NRT access user will access one or more available channels based on its ID sequence in its class and the ID sequences of the remaining available channels. Moreover, based on the distribution of the number of the available channels, the network coordinator in each time slot admits only the number of the RT users that guarantees their QoS requirements. Furthermore, to support as many as possible NRT users, the adaptive optimum number of them are allowed to access the remaining available channels considering the balance between the number of the sensing users and the number of the access users. The NRT users may access more than one available channel to efficiently utilize the unused spectrum.

III. Analysis of the QoS-Based Spectrum Allocation

In this section, we develop analytical models for the QoS provisioning of the RT and NRT users. By using the proposed spectrum resource allocation framework, we can find the optimal numbers of the RT and NRT users that can be admitted to access the available channels.

A. The RT User

It is expected that dropping the ongoing RT user is more annoying than blocking the user from the beginning. Therefore, the user dropping probability should not exceed a certain threshold to guarantee the users' satisfactions. The dropping probability in this context can be defined as the probability of having an unavailable channel for the ongoing user due to the occurrence of a PU on the licensed channel. Suppose that there are N_{rt} channels carrying ongoing RT users, where each user requires one channel from the available N_a channels. The dropping probability of the ongoing RT user can be defined as

$$P_D = \Pr(N_a \leq N_{rt} - 1). \tag{5}$$

The distribution of the number of the available channels can be learned by the CRs over the time based on historical statistical information about the activity of the PUs. Although any statistical distribution can be used, binomial distribution is the most appropriate one; therefore, without loss of generality, let the N_a available channels follow binomial distribution with parameters N and $(1-\delta)$, where the first is the number of the licensed channels and the second is the availability of the channels, then (5) can be rewritten as

$$P_D = F\left(N_{rt} - 1; N, 1-\delta\right), \tag{6}$$

where δ is given by (1) and $F(k;n,p)$ is the cumulative distribution function (cdf) of the binomial distribution, which can be given in terms of regularized incomplete beta function as

$$\begin{aligned} F(k;n,p) &= \sum_{i=0}^{k} \binom{n}{i} p^i (1-p)^{(n-i)} \\ &= (n-k) \binom{n}{k} B(1-p; n-k, k+1) \\ &= I_{1-p}\left(n-k, k+1\right), \end{aligned} \tag{7}$$

where $B(x;a,b) = \int_0^x t^{a-1}(1-t)^{b-1}dt$ is the incomplete beta function. From (6), the number of the channels that maintain the dropping probability of the RT user within a certain threshold can be found as

$$N_{rt} = 1 + F^{-1}\left(P_D; N, 1-\delta\right), \tag{8}$$

where $F^{-1}(p_k;n,p)$ is the inverse cdf of the binomial distribution that returns the smallest integer k evaluated at the cdf value of p_k.

The RT user dropping probability should be very small. However, when the number of the licensed channels is relatively small (say $N < 5$) and the activity of the PUs is high (say $\delta > 0.5$), the RT user blocking probability due to the channel unavailability (i.e., because of active PUs) may increase up to 100%, i.e., there will be no any RT user allowed to access the available channels. Therefore, there should be balance between these two contrary requirements. The blocking probability due to the channel unavailability can be found as

$$\begin{aligned} P_{B_{un}} &= \Pr(A_{rt} > N_{rt}) \\ &= 1 - \Pr(A_{rt} \leq N_{rt}), \end{aligned} \tag{9}$$

where A_{rt} is the number of the RT users arriving in each time slot, which can be naturally assumed to be a Poisson process, so (9) can be rewritten as

$$\begin{aligned} P_{B_{un}} &= 1 - \sum_{j=0}^{N_{rt}} \frac{A_{rt}^j}{j!} \exp(-A_{rt}) \\ &= 1 - \frac{\Gamma(N_{rt}+1, A_{rt})}{N_{rt}!}, \end{aligned} \tag{10}$$

where $\Gamma(s,x) = \int_x^\infty t^{s-1}e^{-t}dt$ is the upper incomplete gamma function.

In addition to the user blocking probability due to the channel unavailability, the RT user will be blocked also when the N_{rt} channels are busy carrying N_{rt} ongoing RT users (i.e., because of other SUs). For practical acceptable dropping probability, e.g., around 0.01, the probability of having a number of available channels less than N_{rt} is very small comparing to the probability of having at least N_{rt} channels, so it can be neglected; therefore, the blocking probability due to busy channels carrying other RT users can be modeled as an M/G/N_{rt}/N_{rt} queuing system. In [29], it is proven that the blocking probability of this system can be given by the Erlang B Formula as

$$P_{B_{bs}} = \frac{(A_{rt}E[X])^{N_{rt}}/N_{rt}!}{\sum_{j=0}^{N_{rt}}(A_{rt}E[X])^j/j!}, \tag{11}$$

where $E[X]$ is the expected service time of the RT user. In order to find the average service time of the RT user, it is necessary to know how the RT packets are sent. These packets are actually sent during the DRP; however, the winning users cannot start sending until they get information about the available channels during the SRP and RP as discussed in the MAC protocol, so the packets require one time slot to be successively transmitted. From Fig. 2, the duration of the DRP is given as $T_{DRP} = T - Tc - T_{SRP}$, where T_{SRP} is the duration of the SRP that depends on the sensing policy and can be given as

$$T_{SRP} = \begin{cases} \min\left(\left\lceil \frac{N}{M_s} \right\rceil, \left\lceil \frac{T-T_c}{2t_s} \right\rceil\right) t_s, & LM_s < N \\ \left\lceil \frac{N}{M_s} \right\rceil t_s, & LM_s \geq N. \end{cases} \tag{12}$$

Since T_{SRP} may vary from time slot to time slot depending on the number of the sensing users, T_{DRP} varies accordingly. To efficiently utilize the T_{DRP}, the packet size varies, which can be determined in the transportation layer [30]. However, this is out of the scope of this paper. Let the arrival RT users have i.i.d. numbers of packets to transmit with an arbitrary distribution that has an average of l packets, and each packet is sent on an available channel at each time slot, so the traffic utilization (in Erlang) is just $\rho = E[X]A_{rt} = lTA_{rt}$, and (11) can be rewritten as

$$P_{B_{bs}} = \frac{\rho^{N_{rt}}/N_{rt}!}{\sum_{j=0}^{N_{rt}} \rho^j/j!}. \tag{13}$$

Using the relation $\sum_{j=0}^{s-1} \frac{x^j}{j!} = \frac{\Gamma(s,x)\exp(x)}{(s-1)!}$, (13) can be rewritten in terms of Gamma function as

$$P_{B_{bs}} = \frac{\rho^{N_{rt}}\exp(-\rho)}{\Gamma(N_{rt}+1,\rho)}. \tag{14}$$

Therefore, the overall blocking probability of the arrival RT users can be given as

$$\begin{aligned} P_B &= 1 - (1-P_{B_{un}})(1-P_{B_{bs}}) \\ &= 1 - \frac{\Gamma(N_{rt}+1, A_{rt})}{N_{rt}!}\left(1 - \frac{(lTA_{rt})^{N_{rt}}\exp(-lTA_{rt})}{\Gamma(N_{rt}+1, lTA_{rt})}\right). \end{aligned} \tag{15}$$

Since the actual serving rate of the RT users is $A_{rt}(1-P_B)$, the average number of the RT users in the CRN can be found from Little's formula as

$$\begin{aligned} \overline{M}_{rt} &= lTA_{rt}(1-P_B) \\ &= \frac{lTA_{rt}\Gamma(N_{rt}+1, A_{rt})}{N_{rt}!} \\ &\quad \cdot \left(1 - \frac{(lTA_{rt})^{N_{rt}}\exp(-lTA_{rt})}{\Gamma(N_{rt}+1, lTA_{rt})}\right). \end{aligned} \tag{16}$$

In order to maximize the average number of the RT users, the network coordinator in each time slot decides how many RT users can be admitted to guarantee the dropping and blocking probabilities of the RT users to be within certain values. Therefore, we define the following optimization problem

$$\begin{aligned} A_{rt}^* = \arg\max_{A_{rt}} \quad & \overline{M}_{rt} \\ \text{s.t.} \quad & P_B \leq P_B^{th} \\ & P_D \leq P_D^{th} \\ & A_{rt} \in \mathbf{I}^+, \end{aligned} \tag{17}$$

where $\mathbf{I}^+$ means the set of positive integer numbers. It is obvious that the optimization problem is nonlinear integer programming. In fact, since the CRN is a distributed ad hoc network, it is desirable to find a simple computational yet accurate expression for the spectrum access decision rather than using an optimization algorithm that requires more time to get results. Fortunately, for practical values of the used quantities in (17), the solution is always the one that satisfies the first constraint, as will be seen in Figs. 6–9. Therefore, A_{rt}^* can be found by first finding the zeros of the first constraint and then choosing the one that is in the appropriate range, i.e., $0 \leq A_{rt} \leq N_{rt}$. Furthermore, the overall blocking probability is due to that when the available channels are busy carrying other RT users (see Fig. 5), so the blocking probability can be approximated as $P_B \approx P_{B_{bs}}$. Therefore, it can be inferred that the number of the admitted RT users is mainly affected by the probability of having the available channels busy carrying other RT users. From (14), the first constraint of (17) can be approximated as

$$\frac{(lTA_{rt})^{N_{rt}}\exp(-lTA_{rt})}{\Gamma(N_{rt}+1, lTA_{rt})} \leq P_B^{th}. \tag{18}$$

Define the following polynomial

$$f(A_{rt}) = (lTA_{rt})^{N_{rt}}\exp(-lTA_{rt}) - P_B^{th}\Gamma(N_{rt}+1, lTA_{rt}), \tag{19}$$

then the solution of (17) can be approximated as $A_{rt}^* \approx Z_1(f(A_{rt}))$, where the operator $Z_1(\cdot)$ means the first zero of the given polynomial. Since the actual number of the RT arrivals may be less than A_{rt}^*, the number of the RT users that can be admitted by the network coordinator is given by

$$A_{rt}^{ad} = \min(A_{rt}, A_{rt}^*). \tag{20}$$

Finally, the average number of the RT users in the system can be approximated as

$$\overline{M}_{rt} \approx lTA_{rt}^{ad}\left(1 - \frac{(lTA_{rt}^{ad})^{N_{rt}}\exp(-lTA_{rt}^{ad})}{\Gamma(N_{rt}+1, lTA_{rt}^{ad})}\right). \quad (21)$$

B. The NRT User

In order to efficiently utilize the unused spectrum, all the remaining available channels should be used by the NRT users. In this subsection, we will determine the optimal number of the NRT users that can access the spectrum simultaneously at each time slot and study how to allocate the remaining available channels to them considering the spectrum sensing and utilization indispensability.

Based on the spectrum sensing policy discussed in Section II.C and the MAC time structure shown in Fig. 2, the normalized identified unused spectrum that can be exploited by the SUs can be given as

$$U = \begin{cases} \frac{(T-T_c-T_{SRP})}{T}\frac{LM_s}{N}(1-P_f), & LM_s < N \\ \frac{(T-T_c-T_{SRP})}{T}(1-Q_f), & LM_s \geq N, \end{cases} \quad (22)$$

where P_f is the probability of false alarm of each sensing user, and Q_f is the probability of false alarm of cooperative sensing users since in case of $LM_s \geq N$ each channel may be sensed by more than one sensing user. In [5], it has been shown that the probability of false alarm increases in the case of OR-rule cooperative sensing, so the sensing users can adjust their detection capabilities to maintain the probability of the false alarm of the cooperative sensing to be equal to that of the single sensing case, i.e., $Q_f = P_f$.

The available channels that are not used by the RT users should be utilized by the NRT users. Since the goal is to support as many NRT users as possible to access the available channels simultaneously, we initially assume that each NRT user can access one available channel. Therefore, considering the number of the RT and NRT access users, the normalized aggregate throughput of the CRN is given as

$$\Theta = \begin{cases} \frac{(T-T_c-T_{SRP})}{T}\frac{LM_s}{N}\frac{(M_{rt}+M_{nrt})}{N_a}(1-P_f), & LM_s < N \\ \frac{(T-T_c-T_{SRP})}{T}\frac{(M_{rt}+M_{nrt})}{N_a}(1-P_f), & LM_s \geq N, \end{cases} \quad (23)$$

where M_{rt} is the number of the RT users that access some of the available channels and M_{nrt} is the number of the NRT users that can access the remaining available channels. The number of the sensing users can be found as follows

$$M_S = M_{B2} - M_n - M_{rt} - M_{nrt}, \quad (24)$$

where M_{B2} is the total number of the SUs in the network at beacon B2, and M_n is the average number of the new users registered in the network with the help of the network coordinator at each time slot. By substituting (12) in (23) and considering (24), the normalized aggregate throughput can be rewritten as shown in (25).

The optimal number of the NRT users that can access the remaining available channels concurrently in each time slot can be found by maximizing (25) with respect to M_{nrt} using any appropriate optimization technique. However, the computational time is a key issue for this kind of network. Therefore, we are trying to find a closed form expression for the optimal value of M_{nrt} rather than using an optimization algorithm. Using the closed form, the SUs can decide almost immediately how many NRT users can access the available channels. By choosing the design parameters carefully, we can maintain $\frac{N}{M_S} < \frac{T-T_c}{2t_s}$, e.g., the duration of the time slot[1] can be chosen as $T > \frac{2Nt_s}{M_s} + T_c$, so the number of the sensed channels always greater than or equal to the N channels, i.e., $LM_s \geq N$, and (25) can be reduced to be (26). For all the feasible values of M_{nrt} and the other parameters, (26) is always increasing or concave function, so the optimal value of M_{nrt} in each time slot can be found using $\frac{\partial\Theta}{\partial M_{nrt}} = 0$ to get (27), where $[x]$ means rounding the real number x to the nearest integer number.

With the adaptive optimal number of the NRT access users, the unused spectrum may not be efficiently utilized since there may be some available channels not occupied due to the balance between the number of the sensing users and the number of the access users. To efficiently utilize the spectrum, the NRT access users are allowed to access more than one channel using the D-OFDMA access technique if there are still available channels in each time slot. In this way, it can be guaranteed that all the available channels are utilized, i.e.,

$$M_{rt} + n_{nrt}M_{nrt}^* = N_a, \quad (28)$$

where n_{nrt} is the number of the available channels that each NRT access user can occupy in each time slot. Substituting (27) and arranging (28), n_{nrt} can be given as (29).

Suppose the NRT users have homogeneous demands. The n_{nrt} will be allocated equally to the NRT access users if it is an integer number; however, if n_{nrt} is not an integer number, there may be a considerable number of available channels not allocated to access users, i.e., the available spectrum may not be utilized efficiently. Therefore, three possible channel allocating scenarios are proposed as follows:

1) allocating $\lfloor n_{nrt} \rfloor + 1$ to some of the first NRT access users and $\lfloor n_{nrt} \rfloor$ to the others based on the first-come first-service rule;
2) allocating $\lfloor n_{nrt} \rfloor$ to all the NRT users, and allocating the remaining unallocated channels as extra channels to the network coordinator. This can be seen as a reward for the network coordinator since it wastes some of its own resources to manage the CRN at the current time slot; and
3) allocating just $\lfloor n_{nrt} \rfloor$ channels to all the NRT access users if the user fairness is more important than the spectrum utilization efficiency.

In fact, choosing one of these three allocating scenarios should depend on the QoS satisfaction of the NRT users since different CRN operators may have different satisfaction metrics. Allocating the available channels to NRT users with heterogeneous demands is out of the scope of this paper.

Since the N_a available channels follow binomial distribution, their average can be given as

$$N_a = \begin{cases} (1-\delta)LM_s, & LM_s < N \\ (1-\delta)N, & LM_s \geq N. \end{cases} \quad (30)$$

[1] In the IEEE 802.22 standard, the MAC time slot is 160 ms [31].

$$\Theta = \begin{cases} \frac{(1-P_f)LM_s}{TNN_a}\left(T - T_c - \min(\left\lceil \frac{N}{M_s}\right\rceil, \left\lceil \frac{T-T_c}{2t_s}\right\rceil)t_s\right)(M_{rt}+M_{nrt}), & LM_s < N \\ \frac{(1-P_f)}{TN_a}\left(T - T_c - \left\lceil \frac{N}{M_s}\right\rceil t_s\right)(M_{rt}+M_{nrt}), & LM_s \geq N \end{cases} \tag{25}$$

$$\Theta = \frac{(1-P_f)}{TN_a}\left(T - T_c - \left\lceil \frac{N}{M_{B2} - M_n - M_{rt} - M_{nrt}}\right\rceil t_s\right)(M_{rt}+M_{nrt}) \tag{26}$$

$$M^*_{nrt} = \min\left(\left[M_{B2} - M_n - M_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}\right], N_a - M_{rt}\right) \tag{27}$$

$$n_{nrt} = \frac{N_a - M_{rt}}{\min\left(\left[M_{B2} - M_n - M_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}\right], N_a - M_{rt}\right)} \tag{29}$$

$$\overline{M}^*_{nrt} = \min\left(M_{B2} - M_n - \overline{M}_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}, (1-\delta)N - \overline{M}_{rt}\right) \tag{31}$$

$$\overline{n}_{nrt} = \frac{(1-\delta)N - \overline{M}_{rt}}{\min\left(M_{B2} - M_n - \overline{M}_{rt} - \sqrt{\frac{(M_{B2}-M_n)Nt_s}{T-T_c}}, (1-\delta)N - \overline{M}_{rt}\right)} \tag{32}$$

$$\overline{\Theta} = \frac{(1-P_f)}{(1-\delta)NT}\left(T - T_c - \frac{Nt_s}{M_{B2} - M_n - \overline{M}_{rt} - \overline{M}^*_{nrt}}\right)(\overline{M}_{rt} + \overline{n}_{nrt}\overline{M}^*_{nrt}) \tag{33}$$

The average of the adaptive optimal number of the NRT access users and their average number of allocated channels can be given by (31) and (32), respectively, where $\overline{M}_{rt}$ is given in (21). Finally, the average normalized aggregate throughput can be given as (33).

IV. Numerical and Simulation Results

In this section, we first show how the average number of the identified available channels is used to allocate the channels for both RT and NRT users, and validate the relation between the admitted and access RT users with simulation results. We then illustrate the accuracy of the approximation of the blocking probability used to find the average number of the RT users in the network. Finally, we evaluate the average aggregate throughput, average number of RT and NRT users in the network, and the number of the allocated channels to the NRT users. All the parameters used for the evaluation are summarized in Table I.

TABLE I
THE PARAMETERS USED IN THE EVALUATION.

Parameter	Value	Description
P_d	0.95	Probability of detection threshold
P_f	0.01	Probability of false-alarm threshold
B	6 MHz	Bandwidth of each licensed channel
T	100 ms	Duration of each time slot
γ	-15 dB	SNR detection sensitivity of the SU's detector
N	20	The number of the licensed channels
δ	0.3	The activity of the PUs
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
T_{SIFS}	15 μs	Short inter-frame space duration
P_D	0.01	Dropping probability threshold
P_B	0.1	Blocking probability threshold
l	20	Average number of the packets of the RT user

Fig. 4 shows the fluctuation in the number of the available channels for different time slots using the distribution in (6). Based on the distribution of the number of the available channels and the acceptable level of the dropping probability threshold, there are N_{rt} identified available channels can support RT users, and the remaining identified available channels can be used by NRT users in each time slot. It is clear that at most of the time, the number of the channels that can support the RT users are available; however, at time slots 30 and 50 some users are dropped, respectively. Moreover, at time slot 96, there is no any available channel left for the NRT users. Distinguishing which channels are available at each time slot is determined by spectrum sensing.

In Fig. 5, the average number of the RT users that can be supported by the network and their blocking probability are illustrated with respect to the number of the RT admitted users. With the increase number of the RT admitted users, their blocking probability increases gradually until all of them are blocked. The blocking probability due to other RT access users, i.e., $P_{B_{bs}}$, increases faster than the blocking probability due to the PUs, i.e., $P_{B_{un}}$, until the number of the admitted RT users is above the average number of the available channels,

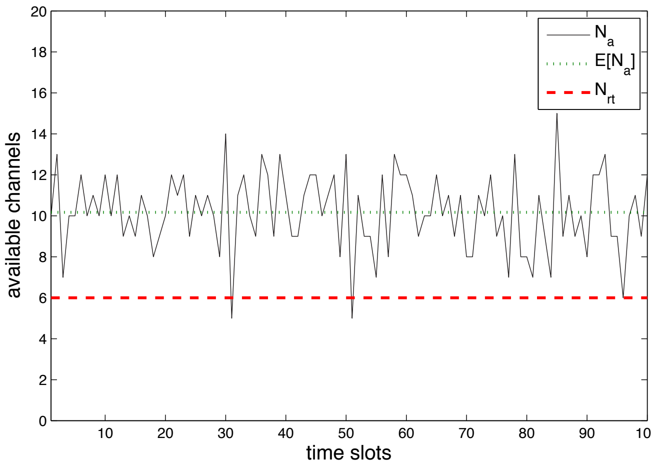

Fig. 4. Simulation of the available channels, N_a, their mean, $E[N_a]$, and the number of the channels that can support RT users, N_{rt}; for $N = 20$ channels, $\delta = 0.5$, and $P_D = 0.01$.

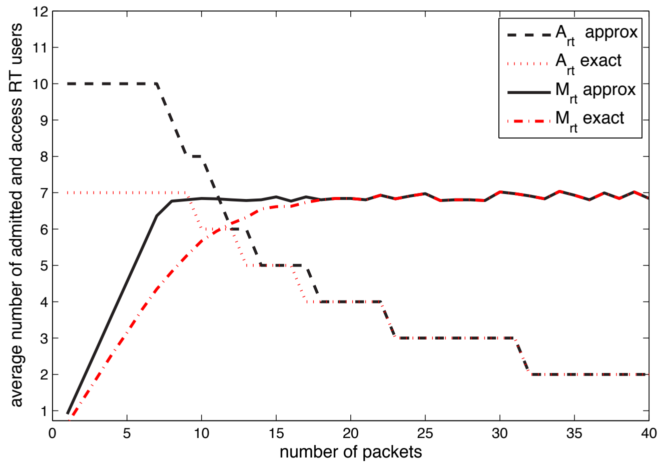

Fig. 6. Approximated and exact number of admitted RT users, A_{rt}, and access RT users, $\overline{M}_{rt}$, for different number of packets, l, when $N = 20$ channels, $\delta = 0.3$, $P_D = 0.01$, and $P_B = 0.1$.

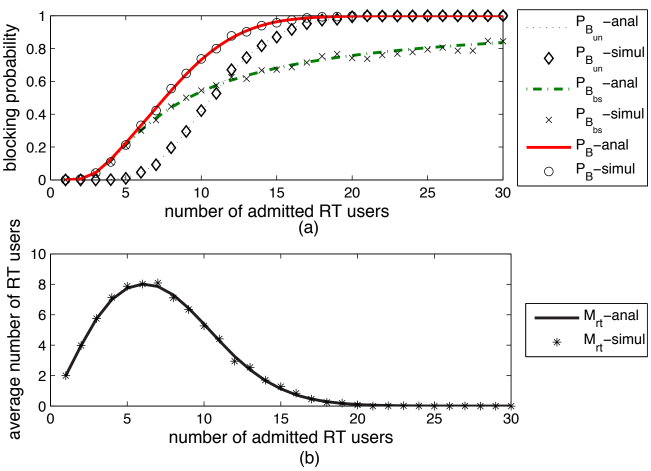

Fig. 5. Relation between the number of the admitted RT users, A_{rt}, and (a) blocking probabilities, $P_B, P_{B_{un}}, P_{B_{bs}}$ and (b) average number of the RT users in the network, $\overline{M}_{rt}$; for $N = 20$ channels, $\delta = 0.3$, $P_D = 0.01$, and $l = 20$ packets.

where $P_{B_{un}}$ becomes faster since there are no any more available channels. Moreover, for the desired level of the blocking probability (e.g., < 0.15), the blocking is due to serving other RT users. This explains why the overall blocking probability is approximated as $P_B \approx P_{B_{bs}}$ in the analysis, which is true for all practical values of the used parameters as can be calculated using (11) and (14) for $P_{B_{un}}$ and $P_{B_{bs}}$, respectively. Furthermore, there is an optimum number of the admitted RT users that maximizes the average number of the served RT users considering the required blocking probability threshold, which necessitates integrating the QoS provisioning with the call admission control. Finally, the good match of the numerical and simulation results validates our analysis.

For given dropping and blocking probability thresholds, the optimal number of the admitted and average number of the access RT users are shown in Fig. 6 for different average number of packets that the RT user has. When the RT user has fewer numbers of packets to transmit, more RT users can be admitted in the network; however, when the RT user has many number of packets to transmit, the number of the RT admitted users decreases because each RT user needs more time to transmit its packets, while the average number of the RT access users in the network increases with the increase of the number of the packets until it saturates at the number that guarantees the required dropping and blocking probability thresholds. Actually, this figure demonstrates the interaction between the numbers of the admitted and access RT users, so for the acceptable QoS levels, admission control has to be applied. Moreover, it can be seen that the approximation of the blocking probability, i.e., $P_B \approx P_{B_{bs}}$, which is used in the analysis is very accurate and even exact for the practical case when the RT user has large number of packets to transmit.

Fig. 7 illustrates the optimal numbers of the admitted and access RT users for different threshold values of the blocking probability. As expected, more RT users can be admitted and hence more RT users can access the available channels if the blocking threshold is acceptably increased. It is shown also that the approximation of $P_B \approx P_{B_{bs}}$ is precise and even exact when $P_B < 0.15$, which reflects the practical acceptable blocking level. The same behavior can be seen in Fig. 8 for the dropping probability threshold. Since the number of the available channels that support the RT users increases with increasing the dropping probability threshold, the average number of the access RT users increases in steps. Moreover, the exact and approximated values of the number of the admitted and access RT users are the same, which validates the used blocking probability approximation.

The availability of the channels is dependent on the activity of the PUs. Fig. 9 shows the effects of this dependency on the number of the admitted and access RT users. When the PUs increase their activities in using the licensed channels, the blocking probability of the RT users increases until all of them are blocked. The blocking probability approximation is validated also here since the exact and approximated values of the number of the admitted and access RT users are identical.

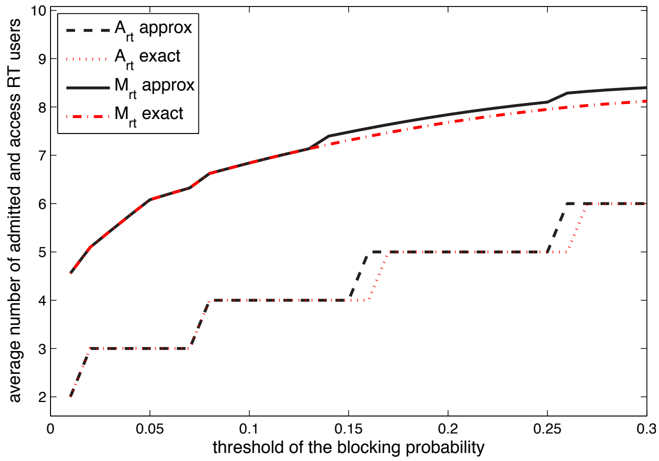

Fig. 7. Approximated and exact number of admitted RT users, A_{rt}, and access RT users, $\overline{M}_{rt}$, for different threshold values of the blocking probability, P_B; for $N = 20$ channels, $\delta = 0.3$, $P_D = 0.01$, and $l = 20$ packets.

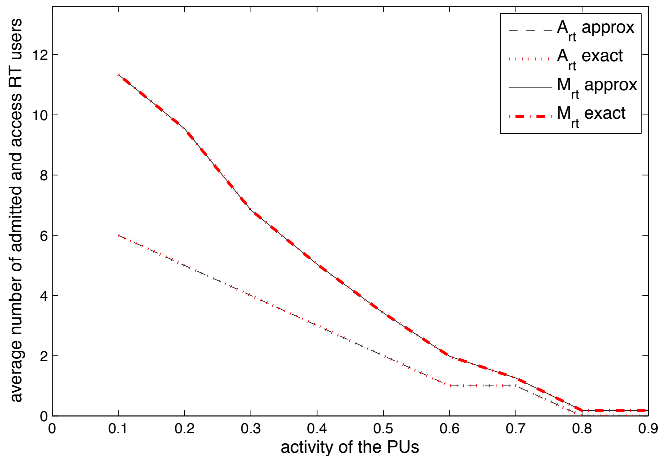

Fig. 9. Approximated and exact number of admitted RT users, A_{rt}, and access RT users, $\overline{M}_{rt}$, for different values of the activity of the PUs, δ; for $N = 20$ channels, $P_D = 0.01$, $P_B = 0.1$, and $l = 20$ packets.

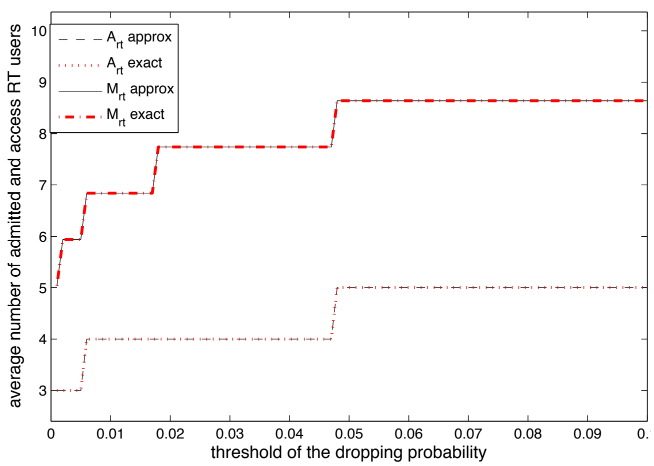

Fig. 8. Approximated and exact number of admitted RT users, A_{rt}, and access RT users, $\overline{M}_{rt}$, for different threshold values of the dropping probability, P_D; for $N = 20$ channels, $\delta = 0.3$, $P_B = 0.1$, and $l = 20$ packets.

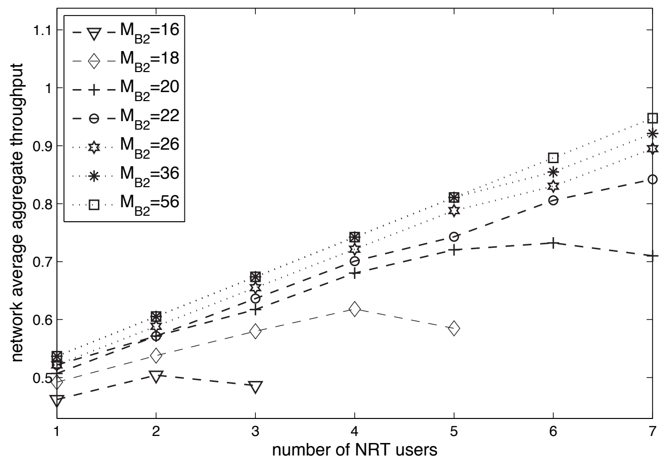

Fig. 10. The network aggregate throughput, Θ, with respect to the number of the NRT access users, M_{nrt}, for different numbers of the users in the network, M_{B2}; for $N = 20$ channels, $\delta = 0.3$, $P_D = 0.01$, $P_B = 0.1$, and $l = 20$ packets.

Fig. 10 shows the relation between the number of the NRT access users and the aggregate throughput for different total numbers of the SUs in the network, i.e., M_{B2}. For given dropping and blocking probability thresholds, the optimal number of the RT access users are admitted to utilize their allocated channels considering their acceptable QoS levels, and the remaining available channels are used by some NRT access users. When the total number of the users in the network is relatively small, only a few number of the NRT users can access the remaining available channels, and there is always an optimum number of them maximizing the aggregate throughput. However, even at the optimal number of the NRT access users, the aggregate throughput is relatively low. This is because there is balance between the number of the sensing users and the number of the access users in the MAC framework, i.e., balancing between identifying the available channels and exploiting these channels. On the other hand, when the total number of the users is high, the aggregate throughput always increases with the increase of the number of the NRT access users since there are enough number of sensing users that can identify all the available channels. The aggregate throughput can be efficiently utilized by allowing each NRT access users to access more than one available channel as will be discussed in the following.

Fig. 11 illustrates the average number of the RT access users, NRT access users, allocated channels to each NRT access user, and the average aggregate throughput of the network with respect to the total number of the SUs in the network. Since the RT users have priority to access the available channels, a number of the RT users, which guarantees the acceptable dropping and blocking probability, access the available channels regardless of the total number

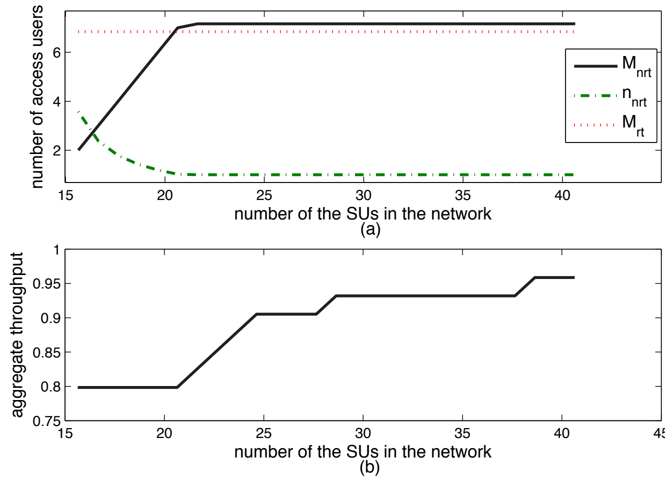

Fig. 11. Relation between the number of the SUs in the network, M_{B2}, and: (a) the average number of the RT access users, $\overline{M}_{rt}$, NRT access users, $\overline{M}_{nrt}$, and NRT allocated channels, $\overline{n}_{nrt}$, and (b) the network average aggregate throughput, $\overline{\Theta}$; for $N = 20$ channels, $\delta = 0.3$, $P_D = 0.01$, $P_B = 0.1$, and $l = 20$ packets.

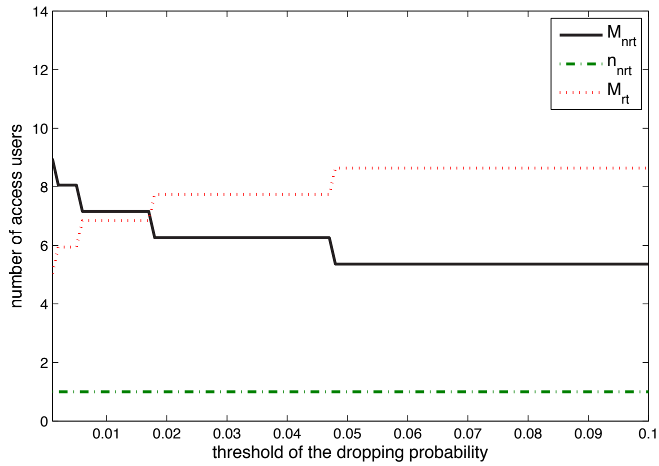

Fig. 12. Average number of the RT access users, $\overline{M}_{rt}$, NRT access users, $\overline{M}_{nrt}$, and NRT allocated channels, $\overline{n}_{nrt}$, for different threshold values of the dropping probability, P_D; for $N = 20$ channels, $\delta = 0.3$, $P_B = 0.1$, and $l = 20$ packets.

of the users in the network, while a few NRT users can access the remaining available channels when the total number of the users in the network is small, as shown in Fig. 10; however, to utilize the remaining available channels, more than one channel are allocated to each NRT access user where the average number of the allocated channels decreases until it reaches only one channel per each NRT access user with increasing the total number of the users in the network. Moreover, the average aggregate throughput of the network increases with the increase of the total number of the users in the network since there are enough number of sensing and access users.

Fig. 12 and Fig. 13 show that the average number of the RT access users increases if the dropping and blocking probability thresholds are acceptably increased; however this is at the cost of reducing the average number of the NRT access users. If the average number of the NRT and RT access users are required to be equal, there are specific values of the dropping and blocking probability thresholds that can be chosen, e.g., for the given set of parameters, the dropping and blocking probability thresholds are around 0.018 and 0.12, respectively.

Finally, Fig. 14 shows how the activity of the PUs affects the average numbers of the RT and NRT access users. Both of them decrease with the increase of the activity of the PUs; however, the average number of the RT access users decreases faster since the RT users require strict dropping and blocking QoS levels that are highly dependent on the number of the available channels, while the NRT users only send their packets whenever there are available channels.

V. Conclusion

In this paper, we have proposed and analyzed a QoS-based spectrum allocation framework that supports heterogeneous secondary RT and NRT users in distributed cooperative CRNs. This framework jointly considers the QoS provisioning, the spectrum sensing, spectrum access decision, channel allocation, and call admission control. Based on the statistical

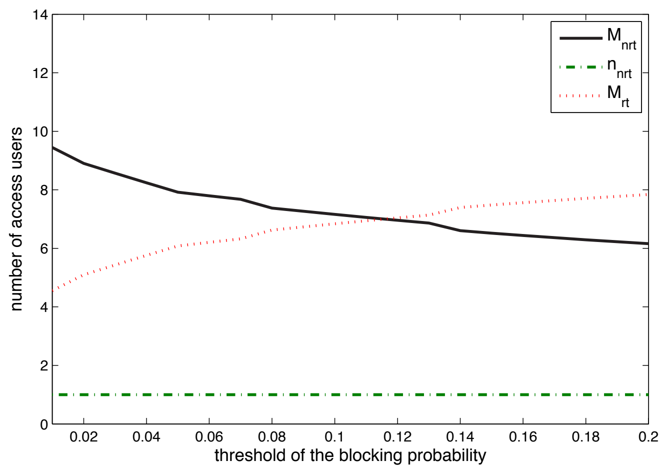

Fig. 13. Average number of the RT access users, $\overline{M}_{rt}$, NRT access users, $\overline{M}_{nrt}$, and NRT allocated channels, $\overline{n}_{nrt}$, for different threshold values of the blocking probability, P_B; for $N = 20$ channels, $\delta = 0.3$, $P_D = 0.01$, and $l = 20$ packets.

information of the available licensed channels that can be learned over the time, a number of the available channels identified after spectrum sensing are allocated to the optimum number of RT users considering their dropping and blocking probability requirements. The remaining available channels can be allocated adaptively to the optimum number of NRT users considering the spectrum sensing and utilization essentiality. Depending on the rigorousness of the PUs, with the proposed QoS-based spectrum resource allocation framework, the distributed cooperative CRNs can efficiently utilize the unused spectrum and guarantee the QoS requirements of both the RT and NRT users served concurrently in the network. Resource management and QoS provisioning for SUs in multi-hop CRNs are of our interest in the future research work.

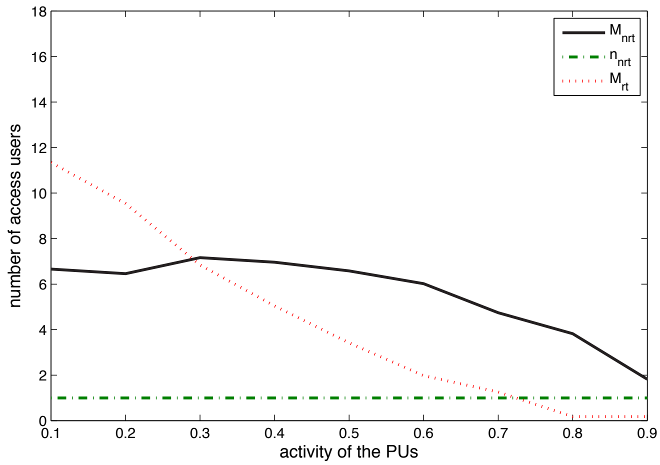

Fig. 14. Average number of the RT access users, $\overline{M}_{rt}$, NRT access users, $\overline{M}_{nrt}$, and NRT allocated channels, $\overline{n}_{nrt}$, for different values of the activity of the PUs, δ; for $N = 20$ channels, $P_D = 0.01$, $P_B = 0.1$, and $l = 20$ packets.

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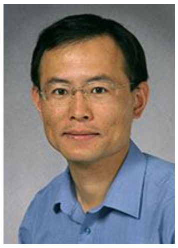

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