Optimal SMDP-Based Connection Admission Control Mechanism in Cognitive Radio Sensor Networks

Elahe Hosseini and Reza Berangi

Traffic management is a highly beneficial mechanism for satisfying quality-of-service requirements and overcoming the resource scarcity problems in networks. This paper introduces an optimal connection admission control mechanism to decrease the packet loss ratio and end-to-end delay in cognitive radio sensor networks (CRSNs). This mechanism admits data flows based on the value of information sent by the sensor nodes, the network state, and the estimated required resources of the data flows. The number of required channels of each data flow is estimated using a proposed formula that is inspired by a graph coloring approach. The proposed admission control mechanism is formulated as a semi-Markov decision process and a linear programming problem is derived to obtain the optimal admission control policy for obtaining the maximum reward. Simulation results demonstrate that the proposed mechanism outperforms a recently proposed admission control mechanism in CRSNs.

Keywords: Cognitive radio sensor networks, Admission control, Quality of service, Semi Markov decision process, Quality of service.

I. Introduction

Dynamic spectrum access (DSA) is one of the main solutions for efficiently using the spectrum in wireless networks. Cognitive radio (CR) is a valuable technology for providing DSA to solve the spectrum scarcity problem. Primary users (PUs) are licensed users who have a higher priority to use channels than CR-equipped users. CR-equipped users can use the spectrum bands in the absence of PUs according to basic CR operations: spectrum sensing, spectrum decision, and spectrum handoff [1]. A CR user senses the channels periodically (spectrum sensing), if a PU enters its licensed channel, the CR user leaves the channel immediately to minimize the interference on the transmission of PUs (spectrum handoff) and decides to select another free channel (spectrum decision) [1].

There are some applications such as industrial control and surveillance in wireless sensor networks (WSNs) that have some specific features such as delay sensitivity and burst traffic. With regard to these features and the requirements of WSNs, these networks can employ the benefits of CR technology to satisfy these requirements and overcome the spectrum scarcity problem. WSNs with CR-equipped nodes are called CR sensor networks (CRSNs) [2]. Because of the burst nature of sensor network traffic and the high dynamicity of cognitive channels, it is necessary to manage the traffic of CRSNs.

Admission control is a crucial mechanism for providing QoS when there are many users simultaneously requesting access to a network with the limited resources. Connection admission control (CAC) can be considered as a proactive congestion control [3], [4] that estimates the network resources and then determines which data flows to transmit.

There are some studies on CAC in CR networks. The authors of [5] considered a joint admission control and channel allocation method using a Markov decision process to support

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the delay-sensitive communications of CR users. In [6], three admission control schemes were proposed that use a discrete-time Markov chain to minimize the forced termination probability of CR users. A joint admission control, eviction control, and bandwidth management framework was proposed in [7] using a semi Markov decision process. In [8], a CAC framework was proposed based on channel reservation for CR users and the buffer size of the handoff operation to analyze the dropping and blocking probabilities. The authors of [9] considered a joint admission control, scheduling, and spectrum handoff to improve the performance of multimedia transmissions using a Markov model.

These studies proposed some admission control schemes along with cognitive channel allocation, scheduling, spectrum handoff, or bandwidth management methods that are related to admission control in the lower layers of the network. However, the CAC mechanisms in the higher layer focus on the data flows and prefer to send fewer valuable data flows reliably rather than several data flows incompletely. This feature of CAC improves the event reliability in CRSNs.

In [10], a CAC mechanism was proposed based on the average capacity of CR channels and a defined event reliability metric. This mechanism estimates the network resources on average and does not make decisions based on the network state at each decision instance. To the best of our knowledge, there is no study on CAC in CRSNs based on the instantaneous network state.

In this study, a CAC mechanism for CRSNs is proposed based on the weight of data flows, the required resources of each data flow, and the network state at each decision instance. The network state is composed of the number of active PUs, the ID, and the number of CR sensors that are sending data toward the sink node during the decision instances. This mechanism is formulated as a semi-Markov decision process (SMDP) in order to reach an optimal decision-making framework for each network state over the network lifetime. In the proposed mechanism, the number of required channels for each data flow is estimated by a graph coloring approach at each decision instance. Using this resource estimation, the network state and the optimal decision at each state are determined. The aim of this admission control is to send the maximum number of valuable data flows by considering the available network resources at each decision instance. In contrast, when the PU activity is high and the network resources are limited, sending a few valuable data flows is desirable to send more valuable information of an event toward the sink. The optimal decision policy of the proposed SMDP model is obtained by solving a linear programming problem. In summary, the main contributions of this paper are:

- the proposal of a CAC mechanism in CRSNs based on SMDP modeling.
- resource estimation of data flows by a graph coloring approach.

The simulation results indicate the superiority of the proposed CAC mechanism over the proposed admission control in [10] in terms of packet loss probability, end-to-end delay, and jitter. The rest of this paper is organized as follows. Section II states the system model. The problem definition, formulation, and solution are explained in Section III. Simulation results are presented in Section IV, and finally, the paper concludes with some remarks in Section V.

II. System Model

This paper considers a CRSN with three types of nodes, CR sensor nodes, CR relay nodes, and a sink node, which are placed within a certain finite area to provide multiple views. The number of CR sensor users, CR relay nodes, and PUs are denoted by N_S, N_R, and N_{PU}, respectively. With regard to an event that has occurred in the event area, some sensors request to send a data flow toward the sink. According to the physical conditions of the event and sensor nodes such as sensors' location, the distance of the sensors from the event, and their angle of view of the sensing area, the induced data flows of different sensor nodes have different importance. Therefore, different weights are calculated for the data flows requesting transmission in the proposed weighting scheme in [10]. It is assumed that these sensors generate data flows with Poisson traffic [9]. The sink node has the knowledge about sensor nodes to decide on the admission of data flows.

The source sensor nodes are the CR users that have requested to send their data flow to sink. Therefore, in the rest of paper, we use the terms admission to CR user, admission to source sensor nodes, and admission to data flows interchangeably.

A CR node has two main modes: sensing mode and operating mode. First, a CR node senses the licensed spectrum to decide whether it is idle or occupied by a PU. Sensing time and sensing frequency are denoted by t_s and f_s, respectively [11]. After sensing, the CR node enters operating mode and sends data in a licensed spectrum channel if it is free of PUs. The PUs' activity is modelled as exponentially distributed interarrivals; thus, their arrival to their related channels is independent. The traffic of a PU can be modelled as a two-state arrival-departure process with arrival rate r_a and departure rate r_d. A PU has two states: ON and OFF [12]. The ON state represents the period during which the PU operates on a channel and a CR node cannot use it. The OFF state represents the period during which the PU does not operate on a channel and CR nodes can hence use it. There are *CH* cognitive channels with the same bandwidth. For each channel, there is a

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PU ($N_{\mathrm{PU}} = CH$) and all the CR channels have similar PU activity. In each channel, a PU operates based on its arrival rate r_{a} and departure rate r_{d}. When a PU starts to operate on its licensed channel, the operations of each active CR node on the licensed channel in the CRSN are stopped. In other words, the activity of all CR nodes in the CRSN is affected by the PUs' activity.

III. Problem Definition and Formulation

In a CRSN, several sensors are deployed in the event area to provide multiple observations of an event. When an event occurs, depending on the event place and sensing radius, some of the sensor nodes send data flows toward the sink node. Because of the constraints of the cognitive channels, sending all flows is not reasonable. Furthermore, it is necessary to inform the sink node of some information about the event. Therefore, a CAC is needed to ensure the QoS of the CRSN.

The SMDP is a powerful tool for analyzing stochastic decision control processes satisfying Markov features with random decision epochs. The SMDP has many potential applications in telecommunications, reliability control, and maintenance [13].

In an SMDP, there is a finite state set and a finite action set for each state. At each decision epoch, the system is in one of the states. The system state evolves in different decision epochs according to a transition probability matrix that depends on the current system state and selected action from the action set. According to the selected action in each state transition, a cost/reward is obtained. The aim is to optimize the long-term average cost/reward [13]. A block diagram of the SMDP is depicted in Fig. 1.

With regard to the SMDP properties, the considered problem, and network assumptions, the appropriate theory to model the decision-making process for this admission control is SMDP. It is necessary to identify the SMDP components related to this problem, and they are introduced in the next sections.

1. State Space

The system state represents some network information at the beginning of each decision epoch. Define row vector $\mathbf{n}(t) = [n_1(t), n_2(t), \ldots , n_N(t)]$, where $n_i(t) \in \{0, 1\}$ denotes the admission condition of the induced data flow from sensor i in the event area at decision epoch t. Here, $n_i(t) = 1$ indicates that sensor node i has been admitted for sending and is sending data flow toward the sink node. In addition, $n_i(t) = 0$ indicates that sensor node i has not been admitted for sending data. Define $q(t)$ to be the number of active PUs in the network at decision epoch t. The network state is given by $s(t) = (n(t), q(t))$ at decision epoch t and $s = (n, q)$ in the steady state. The average number of required channels for each network state is considered as function $\gamma(n)$. Thus, the number of channels used by the admitted flows plus active PUs should be less than CH. Therefore, state space S can be defined as follows.

$$S = \{ s = [\mathbf{n}, q] : n_i \in \{0,1\}, 0 \le q \le CH, \gamma(\mathbf{n}) + q \le CH \}. \quad (1)$$

Function $\gamma(\mathbf{n})$ is described in the next section.

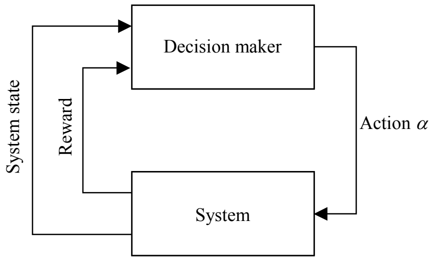

Fig. 1. Block diagram of SMDP.

2. Average Number of Required Channels

The main responsibility of admission control is to estimate the network resources and make decisions based on the needs of users and available network resources. The number of CR free channels is one of the main network resources in CRSNs that should be estimated to decide the admission of data flows.

To send sensors' data toward the sink node, some CR channels are required. The number of these required channels depends on the system state, routing protocol, and network topology (number of contending nodes). The system state represents which sensors are sending their information toward the sink node. We consider the steady-state behavior of the routing protocol. In this way, a node selects one of the next hop nodes with a specific probability that does not change rapidly over time [14].

Therefore, for each sensor node, there are several possible routes toward the sink node. To decide the optimal admission of data flows in the network, the optimal number of required channels should be estimated that minimizes the data packet collision. Assume there are K_i ($0 \le i \le N_S$) possible routes between sensor node i and the sink node. Sensor i uses its possible route d with probability $P_{i,d}$. Therefore, there are $\prod_{i=1}^{N_S} (K_i)^{n_i}$ possible combinations of routes for the data flows of the admitted sensor nodes at each network state. Each possible combination of routes of the network state forms a network subgraph. At each considered network subgraph, the nodes have a different number of contending nodes for the transmission of data packets to the sink node. To decrease the data packet collision, the optimal number of channels required at each possible combination of routes can be determined according to the maximum number of contending nodes of the current subgraph nodes. The problem of finding the optimal required number of channels at each possible combination of routes can be modeled by graph coloring approach. According to vertex coloring, different colors are assigned to each two adjacent vertices of a graph [15]. Each color label is equivalent to a CR free channel. The minimum number of required colors at each possible combination of routes can be considered to be the minimum number of required channels.

Assume the minimum number of required channels at each possible route configuration is denoted as $\Omega(i_1n_1, i_2n_2, \ldots, i_{N_S}n_{N_S})$, where $i_1, i_2, \ldots, i_{N_S}$ are the selected route indexes of sensor 1, sensor 2, … , sensor N_S, respectively, and $n_i \in \{0,1\}$, $i = 1, 2, \ldots, N_S$ is the admission state of sensor i described above. The value of the product i_bn_b is zero when sensor b is not admitted and is i_b when sensor b is admitted. The notation I_b denotes product i_bn_b.

According to these definitions, the optimal average number of channels required at each state ($\gamma(\mathbf{n})$) can be calculated as follows.

$$\gamma(\mathbf{n}) = \sum_{i_1=1}^{K_1}\sum_{i_2=1}^{K_2}\cdots\sum_{i_{N_S}}^{K_{N_S}}\left\{\left(P_{1,i_1}\right)^{n_1}\left(P_{2,i_2}\right)^{n_2}\cdots\left(P_{N_S,i_{N_S}}\right)^{n_{N_S}}\times\Omega(I_1, I_2, \cdots, I_{N_S})\right\}. \tag{2}$$

The value of $\Omega(I_1, I_2, \ldots, I_{N_S})$ is calculated by the minimum number of colors required for the network graph when sensors 1, 2, … , N_S send data packets in routes $i_1, i_2, \ldots, i_{N_S}$ toward the sink. Therefore, $\gamma()$ is the function of the network state.

3. Action Space

At each decision epoch, an action a is selected as the result of the admission control decision for the next epoch. Action a at decision epoch t can be defined as $a(t) = [a_1(t), a_2(t), \ldots, a_N(t)]$. Here, $a_i(t) = 1$ indicates sensor i is admitted for sending data flow at decision epoch t and $a_i(t) = 0$ represents a rejection decision about this flow. Hence, action space A can be defined as

$$A = \left\{a{:}a_i \in \{0,1\}, 0 \le i \le N_S, \sum_{i=1}^{N_S} a_i \le 1\right\}. \tag{3}$$

Here, $a = [0, 0, \ldots, 0]$ means that no data flow is admitted. At each decision epoch, the admission control mechanism determines the admission of the sensors' send request and at most admits one of the requesting sensors' data flows. Action set A_s is defined for the state s as follows:

$$A_s = \{a \in A : s = [\mathbf{n}, q], [\mathbf{n} + a, q] \in S\}, \tag{4}$$

where A_s is a subset of A and A_s contains all valid actions at state s. In other words, by taking action a at state $s(\mathbf{n} + a)$, the new state ($[\mathbf{n} + a, q]$) must be a member of state set, that is, $[\mathbf{n} + a, q] \in S$.

4. State Transition

Assuming states $s = [n_s, q_s]$ and $x = [n_x, q_x]$, transition probability $P_{sx}(a)$ is the probability of transition from state S to state x by selecting action a. There are several types of events in this admission control mechanism: (i) PU arrival on a channel that is free of CR users, (ii) PU arrival on a channel that is using by a CR user who leaves the channel, (iii) PU departure from a channel, and (iv) CR user arrival. When a PU departs from a related channel, there is at least one CR user request in the queue that can use this free channel. The event rates of the mentioned events are $\sum_{i=1}^{N_S} r_\mathrm{a}\delta(CH - \gamma(n_x) - q_x)$, $\sum_{i=1}^{N_S} r_\mathrm{a}\left(1 - \delta(CH - \gamma(n_x) - q_x)\right)$, $\sum_{i=1}^{N_S} q_s r_\mathrm{d}$, and $\sum_{i=1}^{N_S} a_i r_\mathrm{d}$ $\left(1 - \delta(CH - \gamma(n_x) - q_x)\right)$, respectively, where function $\delta(i)$ is defined as follows.

$$\delta(i) = \begin{cases} 1 & i \ge 0, \\ 0 & i < 0. \end{cases} \tag{5}$$

These events are an independent Poisson processes, thus the sum of these events also follows a Poisson process [16]. The total event rate of this system is the sum of the event rates of events (i), (ii), (iii), and (iv). Therefore, the inter-event time of this model is the inverse of the total event rate. This inter-event time can be defined as the expected sojourn time of the SMDP. The sojourn time is the average time after action a is selected in current state s until the next decision epoch $\tau_s(a)$.

$$\tau_s(a) = \left\{\sum_{i=1}^{N_S} r_\mathrm{a} + \sum_{i=1}^{N_S} q r_\mathrm{d} + \sum_{i=1}^{N_S} a_i r_\mathrm{d}\right\}^{-1}. \tag{6}$$

The transition probabilities can be derived using the decomposition property of the Poisson process. The transition probabilities between the states of this system are determined as

$$P_{sx}(a) = \begin{cases} r_\mathrm{a}\delta(CH - \gamma(n_x) - q_x)\tau_s(a), & x = s + PU, \\ q_s r_\mathrm{d}\tau_s(a), & x = s - PU, \\ r_\mathrm{a}\left(1 - \delta(CH - \gamma(n_x) - q_x)\right)\tau_s(a), & x = s + PU - \psi(CR), \\ a\, r_\mathrm{d}\delta(CH - \gamma(n_x) - q_x)\tau_s(a), & x = s + CR, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Here, $s + PU$ and $s - PU$ are the arrival and departure of a PU, respectively, which are equivalent to $s + [0, 1]$ and $s - [0, 1]$, respectively. In addition, $s + CR$ and $s - CR$ are equivalent to $s + [1, 0]$ and $s - [1, 0]$, respectively, and $\psi(CR)$ represents the most worthless CR user who is transmitting data packets toward the sink node. The worth of CR users is determined based on their weight. According to this admission control mechanism, when a PU starts using its related channel while there is no free channel for CR users, the most worthless CR user leaves using CR channel and stops sending data.

5. Policy and Reward Function

A policy π is a function that maps a state space to an acceptable action space. For each state $s \in S$, an action is chosen according to policy π. Here, Π is the acceptable policy space. Reward function $R(s, a)$ is the average reward obtained in a network in current state s after action a is selected until the next decision epoch. The reward function is the reward earned by the weight of the newly admitted sensor node to send data flow at each decision epoch. This function is defined as the sum of the weights of admitted flows for sending to the sink node, which can be defined as

$$R(s,a)=\sum_{i=1}^{N_S} a_i \omega_i . \tag{8}$$

The average reward is considered as a performance measure. Inspired by [17], the average reward function for $\forall \pi \in \Pi$ is defined as

$$J_\pi(s_0)=\lim_{T\to\infty}\frac{1}{T}E\left\{\int_0^T R(s(t),a(t))\,\mathrm{d}t\right\}, \tag{9}$$

where the s_0 is the initial SMDP state and $E\{\cdot\}$ is the expectation function. The purpose is to find the optimal policy $\pi^* \in \Pi$ that maximizes the average reward for all initial states. In contrast, the aim is to find the best policy that maximizes the average value of the sent information via the admitted sensors.

6. Linear Programming Solution for SMDP

Optimal policy π^* can be obtained by solving a constrained linear programming optimization problem. This linear programming problem can be formulated as follows [13]:

$$\max_{m_{sa}\ge 0, s\in S, a\in A_s} \sum_{s\in S}\sum_{a\in A_s}\sum_{i=0}^{N_S} w_i a_i \tau_i(a) m_{sa}$$

subject to

$$\sum_{a\in A_s} m_{sa} - \sum_{a\in A_s}\sum_{i=0}^{N_S} P_{sx}(a) m_{sa} = 0, \quad x \in S, \tag{10}$$

$$\sum_{a\in A_s}\sum_{i=0}^{N_S} \tau_i(a) m_{sa} = 1,$$

where the m_{sa} is the decision variable for $\forall s \in S$, $\forall a \in A_s$. The term $\tau_s(a)m_{sa}$ is equivalent to the steady state probability of being in state s and the selection of action a. The objective is the maximization of the reward function, which is the maximization of the average value of admitted flows. The first and second constraints are balance and normalization equations, respectively. Optimal solution m^*_{sa} is obtained through this linear programming. Optimal policy π^* is given by [13]

$$\pi^*_{sa}=\frac{m_{sd}}{\sum_{a\in A_s} m_{sa}}, \forall s \in S, \forall a \in A_s . \tag{11}$$

IV. Experimental Results

In this section, the performance of the proposed mechanism is evaluated through CogNS, which is a simulation framework based on NS-2 [17] for CR networks [18]. A CRSN is placed in a 50 m × 50 m field. Six PUs and frequency channels were used. It is assumed each PU individually has the license to use the related frequency channel. The values of N_S, N_R, and N_{CR} were set to 8, 3, and 7, respectively. The sensing time and operating time are considered as 0.01 and 0.6 s, respectively. The default values of the PUs' arrival and departure rates are considered to be one; these two rates were changed for different experiments. The packet size was 100 bytes, and the simulation time was 200 s. Each experiment was run five times and the results are averaged.

The proposed admission control mechanism was evaluated by several experimental results for different PU activity settings. PU activity (r_d, r_a) is determined by the length of ON and OFF periods of PU transmissions. When the PU arrival rate r_a is greater than the PU departure rate r_d, this state is considered to be a "high PU activity" state. Furthermore, when the PU arrival rate is smaller than the PU departure rate, this state is considered to be a "low PU activity" state. In addition, when the PU arrival

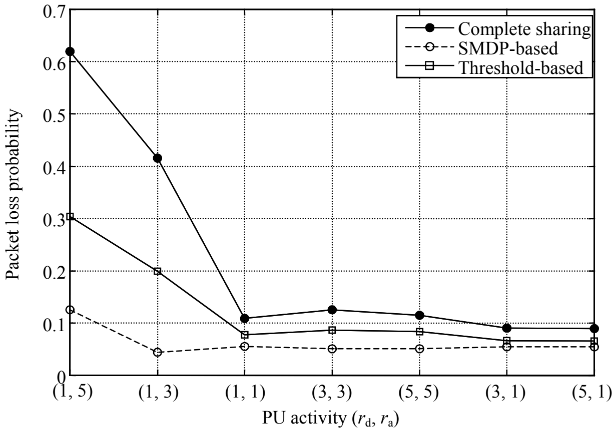

Fig. 2. Average packet loss probability for different PU activities in a network with complete sharing, and networks with SMDP-based and threshold-based admission control mechanisms.

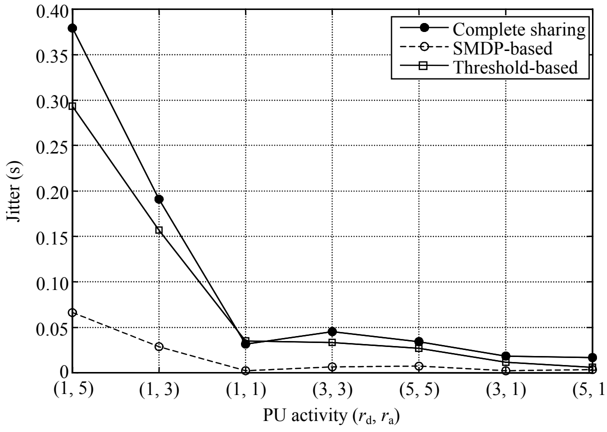

Fig. 3. Average jitter for different PU activities in a network with complete sharing and networks with SMDP-based and threshold-based admission control mechanisms.

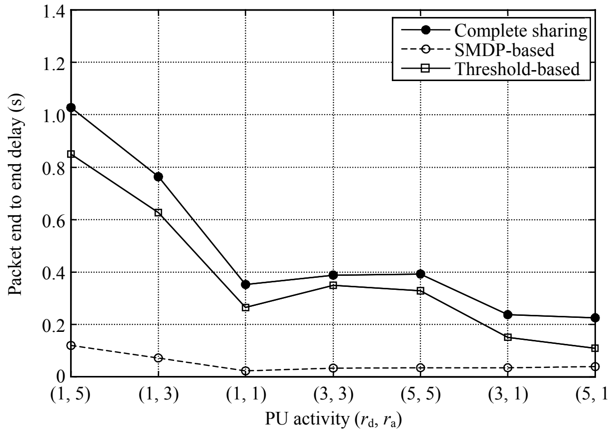

Fig. 4. Average packet end-to-end delay for different PU activities in a network with complete sharing and networks with SMDP-based and threshold-based admission control mechanisms.

rate is equal to the PU departure rate, this state is considered to be a "medium PU activity" state [10]. According to these definitions, the PU activities (3, 1) and (5, 1) belong to the low PU activity state, the PU activities (1, 1), (3, 3), and (5, 5) belong to the medium PU activity state, and the PU activities (1, 2), (1, 3), (1, 4), (1, 5), and (1, 6) belong to the high PU activity state.

Here, the performance of the proposed SMDP-based mechanism is evaluated and compared with the threshold-based mechanism proposed in [10] and a network without any admission control (referred to as a complete sharing network). Figures 2 to 5 illustrate the effect of the proposed admission control mechanism on the QoS metrics packet loss probability, jitter of packets, end-to-end delay, and average reward per second, respectively. These figures compare each metric for three scenarios, that is, complete sharing, a network with an SMDP-based admission control mechanism, and a network with Threshold-based admission control mechanism for different PU activities.

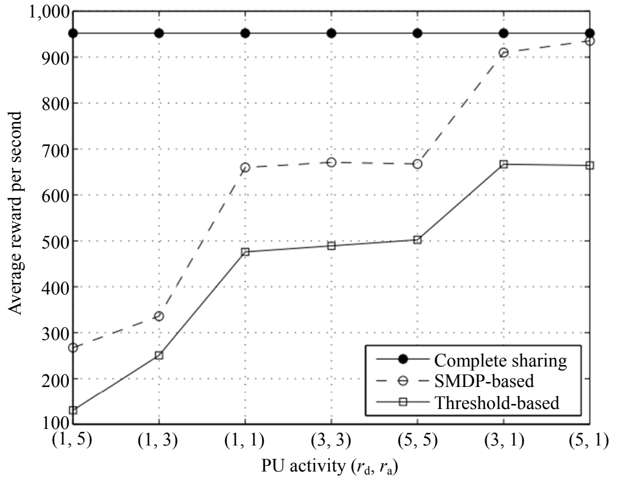

Fig. 5. Average reward per second for different PU activities in the network with complete sharing and networks with SMDP-based and threshold-based admission control mechanisms.

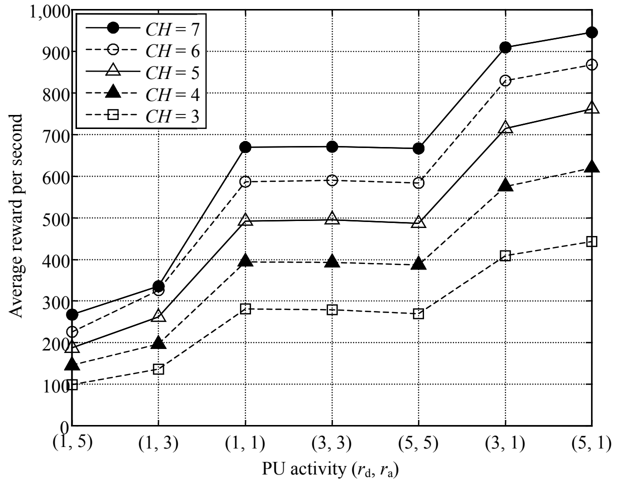

Fig. 6. Average reward per second for different channel numbers and different PU activities.

This proposed admission control estimates the average channels required by the flows. Using this estimation, the network admits more valuable flows to send data toward the sink over the network lifetime. According to Fig. 2, the packet loss ratio of the network is reduced by the proposed SMDP-based admission control, especially during high PU activities, that is, (1, 3) and (1, 5).

In the literature, the jitter metric is defined as the variance of packet end-to-end delay. Sending data flows according to the decisions of the proposed admission control reduces the average jitter of data packets, as depicted in Fig. 3. Furthermore, this mechanism reduces the packet end-to-end delay, as illustrated in Fig. 4.

The average gained reward per second for three considered

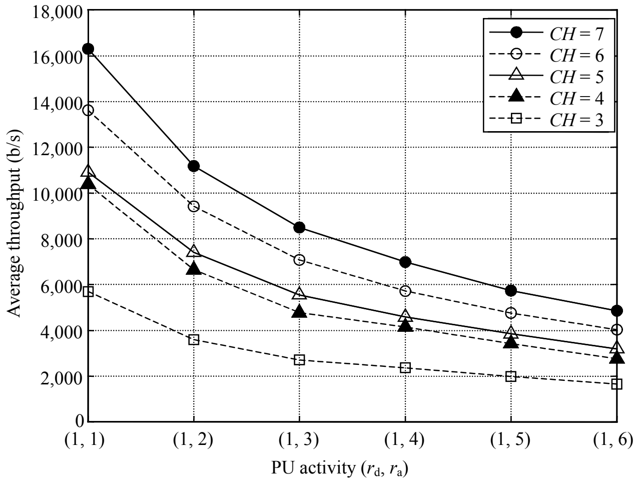

Fig. 7. Average throughput for different channel numbers and different PU activities.

scenarios is illustrated in Fig. 5, where most reward is obtained in the complete sharing scenario because it sends all data flows toward the sink. Moreover, the reward of the SMDP-based mechanism is greater than the threshold-based mechanism because of its more accurate decision making.

As depicted in these figures, the SMDP-based admission control performs better than the threshold-based admission control and the complete sharing with respect to packet loss probability, packet jitter, end-to-end delay, and average reward per second.

Figure 6 represents the average reward earned by the optimal policy in different states of the network. This figure illustrates the average reward per second in networks with different channel numbers for different PU activities. The channel number was varied from 3 to 7. The existence of more channels in the network allows more data flows to be admitted and more reward to be earned. In low PU activities, the network earns the highest reward and in the high PU activities, the network earns lowest reward because of the existence of more PUs. The highest reward is earned for PU activity (5, 1) and seven channels.

Figure 7 depicts the throughput of the networks with different channel numbers for different PU activities. The channel numbers were varied from 3 to 7. As illustrated in this figure, network throughput decreases when the PU entrance rate increases or the number of channels decreases. The highest throughput was obtained for PU activity (1, 1) and seven channels.

V. Conclusions

In this paper, we proposed an optimal CAC mechanism to support the QoS of CR users in CRSNs. The proposed mechanism was modeled as an SMDP and the optimal policy was obtained by solving the SMDP related linear programming problem. This proposed mechanism decreases the jitter, end-to-end delay, and packet loss ratio of the packets in the network. The performance of the CAC was evaluated by an NS-2 based simulation. The simulation results indicate that the proposed mechanism outperforms the previous proposed admission control mechanism in CRSNs. Given the requirements of CRSNs, the end-to-end delay and power constraints could be added to this SMDP model as future work.

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