Admission Control in Cognitive Radio Networks with Finite Queue and User Impatience

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***Abstract*—For session-level quality-of-service (QoS) provisioning in cognitive radio networks (CRNs), it is essential to adopt an effective admission control scheme with appropriate parameters. In this paper, a framework for admission control and session-level performance analysis is proposed by taking into account several factors such as channel reservation for handoff secondary users (SUs), buffers for handoff SUs and newly arriving SUs, limited buffer size, and queued SUs' leaving due to impatience. The whole system is modeled by a multi-dimensional continuous-time Markov chain, where important session-level QoS performance metrics, i.e., dropping probability and blocking probability are derived.**

***Index Terms*—Cognitive radio network, admission control, finite queueing, secondary user impatience, channel reservation.**

I. INTRODUCTION

In a spectrum overlay cognitive radio network (CRN), secondary users (SUs) must leave the channels upon the reappearance of primary users (PUs) and handoff to other vacant channels to protect the PUs' transmissions. Therefore, handoff is an intrinsic operation of SUs. To guarantee session-level quality-of-service (QoS), several admission control policies have been proposed [1-5]. In [1], [2], channel reservation has been employed to reserve a number of channels only for handoff SUs. On the other hand, in [3], [4], [5], waiting buffer is used to hold either handoff SUs or new SUs when there is insufficient radio resources.

In this paper, we propose a general framework to analyze the session-level QoS performance in CRNs. The framework includes factors such as finite-size buffer for handoff SUs/new SUs to reduce dropping/blocking probability, and departure of queued SUs due to impatience. Unlike existing works, we consider buffers for both new SUs and handoff SUs, and departure of queued SUs due to user impatience. In particular, the system (including PU system and SU system) is modeled by a multi-dimensional continuous-time Markov chain (CTMC). Compared with the existing models, several new states and new trigger conditions of state transition are introduced in the proposed model, i.e., the new states resulted from handoff SU buffer and new SU buffer, the new states resulted from different admission policies of PUs and the two kinds of SUs, and the new trigger conditions of state transition brought in by impatient SUs. To reflect the properties of the framework, several interactions are considered when calculating the transition rates of the CTMC, i.e., the impact of the handoff SU queue on the new SU queue, the influence of finite buffer size on the state transition rates, and the queue length change due to SUs' impatience. Based on the proposed framework, the session-level QoS metrics such as dropping probability and blocking probability are derived. Numerical results are compared with simulation results to validate the accuracy of our proposed model and analytical results. As a result, this analytical results can be used as a guideline to design system parameters in CRN like number of reserved channels and buffer sizes for a given QoS constraint.

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II. SYSTEM MODEL

Consider a PU network overlayed an infrastructure-based CRN. There are a total of N channels, which are shared by PUs and SUs in a spectrum overlay manner. Each channel can accommodate one PU or SU, and T channels are reserved for the handoff SUs, where $0 \leq T \leq N$.

Each PU or SU requires only one channel for transmission. In addition, a PU can be admitted if the N channels are not all occupied by other PUs (i.e., there is vacant channel or the channel occupied by SU). The SU can only use the channel currently not occupied by PUs, and must leave the channel immediately upon PUs' reappearing on the channel. The SU who vacates the channel for PU is called handoff SU. It should find another vacant channel and complete handoff as soon as possible to avoid the interruption of its on-going call. It is admitted if there is any vacant channel. In case of no vacant channel, it is queued in a handoff SU buffer with size Q_{h}. If the buffer is full, it will be dropped. A new SU is admitted if the number of vacant channels is larger than T, otherwise it will be queued in a new SU buffer with size Q_{n}. If there is no room in the buffer, it will be blocked. Therefore, PUs have the highest priority and new SUs have the lowest priority.

Furthermore, we assume that the arrival processes of the PUs and SUs are both Poisson processes with arrival rates λ_{p} and λ_{s}, respectively. Their service times are exponentially distributed with rates μ_{p} and μ_{s}, respectively. Thus, the load intensities of the PUs and SUs are $\rho_{\mathrm{p}} = \lambda_{\mathrm{p}}/\mu_{\mathrm{p}}$ and $\rho_{\mathrm{s}} = \lambda_{\mathrm{s}}/\mu_{\mathrm{s}}$, respectively. The patience time of the queued handoff (new) SU is assumed to be exponentially distributed with mean $1/\mu_{\rm h}$ $(1/\mu_{\rm n})$.

III. PERFORMANCE ANALYSIS

A. CTMC Model

The system is modeled using a multi-dimensional CTMC. The states are described by four variables $(n_{\rm p}, n_{\rm s}, q_{\rm h}, q_{\rm n})$, where $n_{\rm p}$, $n_{\rm s}$, $q_{\rm h}$, and $q_{\rm n}$ denote the numbers of in-service PUs, in-service SUs, queued handoff SUs, and queued new SUs, respectively. Hence, the state space includes three parts, which corresponds to the following three cases.

Case I: The number of vacant channels is larger than the predefined number of reserved channels T, so neither handoff SUs nor new SUs will be queued in their corresponding buffers. The corresponding state space is

$$\Gamma_1 = \{n_{\rm p}, n_{\rm s}, q_{\rm h}, q_{\rm n} | n_{\rm p} + n_{\rm s} < N - T, q_{\rm h} = 0, q_{\rm n} = 0\}. \quad (1)$$

Case II: There are vacant channels but the number is no larger than T. In this case, no handoff SUs will be queued, but there may be new SUs queued in the new SU buffer. The corresponding state space is

$$\begin{aligned}\Gamma_2 = \{&n_{\rm p}, n_{\rm s}, q_{\rm h}, q_{\rm n} | 0 \le n_{\rm s} \le N - T, \\ &N - T \le n_{\rm p} + n_{\rm s} < N, q_{\rm h} = 0, 0 \le q_{\rm n} \le Q_{\rm n}\}.\end{aligned} \quad (2)$$

Case III: There is no vacant channel, thus both the handoff SUs and new SUs may be queued in their corresponding buffers. The corresponding state space is

$$\begin{aligned}\Gamma_3 = \{&n_{\rm p}, n_{\rm s}, q_{\rm h}, q_{\rm n} | 0 \le n_{\rm s} \le N - T, \\ &n_{\rm p} + n_{\rm s} = N, 0 \le q_{\rm h} \le Q_{\rm h}, 0 \le q_{\rm n} \le Q_{\rm n}\}.\end{aligned} \quad (3)$$

State transitions are triggered by the following events: PU arrival, in-service PU departure, SU arrival, in-service SU departure, queued handoff SU departure, queued new SU departure. In the following subsections, we will elaborate the state dynamics under the aforementioned three cases.

1) Case I: The number of vacant channels is larger than T, so the two buffers are always empty. Hence, the state transition rates are as those of the system without buffers [1], [2], i.e.,

$$\begin{cases} P_{(n_{\rm p},n_{\rm s},0,0),(n_{\rm p}+1,n_{\rm s},0,0)} = \lambda_{\rm p}, \\ P_{(n_{\rm p},n_{\rm s},0,0),(n_{\rm p},n_{\rm s}+1,0,0)} = \lambda_{\rm s}, \\ P_{(n_{\rm p},n_{\rm s},0,0),(n_{\rm p}-1,n_{\rm s},0,0)} = n_{\rm p} \cdot \mu_{\rm p}, \\ P_{(n_{\rm p},n_{\rm s},0,0),(n_{\rm p},n_{\rm s}-1,0,0)} = n_{\rm s} \cdot \mu_{\rm s}, \end{cases} \quad (4)$$

which correspond to PU arrival, SU arrival, in-service PU departure, and in-service SU departure, respectively. The state transition diagram for Case I is shown as Fig. 1.

2) Case II: The number of vacant channels is no larger than T, thus the new SUs will be queued in the new SU buffer if there is any room. Besides arrivals of PUs and SUs, and departures of in-service PUs and SUs, departures of queued new SUs can also trigger state transition.

Upon PU arrival, similar to Case I,

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p}+1,n_{\rm s},0,q_{\rm n})} = \lambda_{\rm p}. \quad (5)$$

Upon SU arrival, the new SU is queued in the new SU buffer if there is any room, otherwise it is blocked and no transition occurs, i.e.,

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p},n_{\rm s},0,q_{\rm n}+1)} = \lambda_{\rm s}, \quad \text{for } q_{\rm n} < Q_{\rm n}. \quad (6)$$

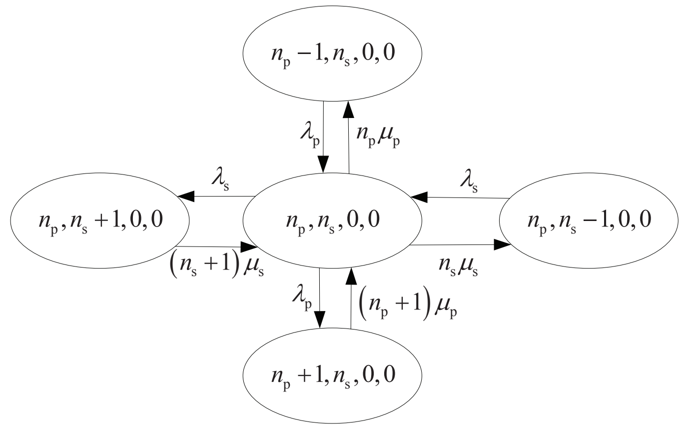


Fig. 1. State transition diagram for Case I.

Upon in-service PU leaving the network, a channel becomes vacant and the state transition may be as one of the following two situations.

- $n_{\rm p} + n_{\rm s} = N - T$ and $q_{\rm n} > 0$: After a PU departs, the number of vacant channels will be $T+1$, which is larger than T. Thus, the head-of-line SU in the new SU buffer can be assigned a channel and begin its transmission, i.e.,

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p}-1,n_{\rm s+1},0,q_{\rm n}-1)} = n_{\rm p} \cdot \mu_{\rm p}, \quad \text{for } n_{\rm p} + n_{\rm s} = N - T \text{ and } q_{\rm n} > 0. \quad (7)$$

- Otherwise: The number of vacant channels is still no larger than T after a PU leaves the network, or there is no queued new SU, i.e.,

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p}-1,n_{\rm s},0,q_{\rm n})} = n_{\rm p} \cdot \mu_{\rm p}, \quad \text{for } n_{\rm p} + n_{\rm s} > N - T \text{ or } q_{\rm n} = 0. \quad (8)$$

Similarly, upon in-service SU leaving the network, there are also two situations.

- $n_{\rm p}+n_{\rm s} = N-T$ and $q_{\rm n} > 0$: A channel becomes vacant which can be used by an SU in the new SU buffer, i.e.,

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p},n_{\rm s},0,q_{\rm n}-1)} = n_{\rm s} \cdot \mu_{\rm s}, \quad \text{for } n_{\rm p} + n_{\rm s} = N - T \text{ and } q_{\rm n} > 0. \quad (9)$$

- Otherwise: The queued new SU cannot leave the buffer in this situation since the number of vacant channels after the SU departure is still no larger than T or the new SU buffer is empty, i.e.,

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p},n_{\rm s}-1,0,q_{\rm n})} = n_{\rm s} \cdot \mu_{\rm s}, \quad \text{for } n_{\rm p} + n_{\rm s} > N - T \text{ or } q_{\rm n} = 0. \quad (10)$$

Upon one of the queued new SUs leaves the buffer due to impatience, the state will transit as follows:

$$P_{(n_{\rm p},n_{\rm s},0,q_{\rm n}),(n_{\rm p},n_{\rm s},0,q_{\rm n}-1)} = q_{\rm n} \cdot \mu_{\rm n}. \quad (11)$$

The state transition diagram for Case II with $q_{\rm n} < Q_{\rm n}$ is shown in Fig. 2, where the indicator variables θ_1 and θ_2 are

$$\theta_1 = \begin{cases} 1, & \text{for } n_{\rm p} + n_{\rm s} = N - T, \\ 0, & \text{for } n_{\rm p} + n_{\rm s} > N - T. \end{cases} \quad (12)$$

$$\theta_2 = \begin{cases} 1, & \text{for } q_{\rm n} > 0, \\ 0, & \text{for } q_{\rm n} = 0. \end{cases} \quad (13)$$

The transition diagram for Case II with $q_{\rm n} = Q_{\rm n}$ can be derived from Fig. 2 by deleting the states with the variable $q_{\rm n} + 1$.

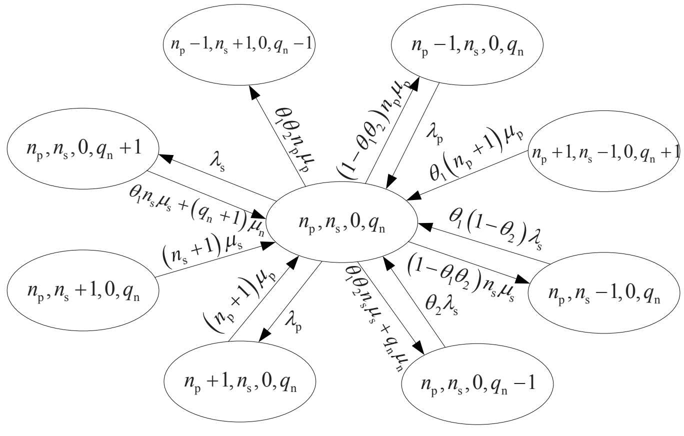


Fig. 2. State transition diagram for Case II ($q_{\mathrm{n}} < Q_{\mathrm{n}}$).

3) Case III: The number of vacant channels is zero, thus all the handoff SUs and new SUs will be queued in their buffers. Arrivals of PUs and SUs, departures of in-service PUs and SUs, and departures of queued handoff and new SUs can trigger state transition.

Upon PU arrival, if the number of in-service SUs is zero, the PU will be blocked and no state transition will occur. If the number of in-service SUs is larger than zero, one of these SUs must vacate its channel and join the handoff SU buffer if the buffer is not full as follows:

$$\begin{cases} P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}}+1,n_{\mathrm{s}}-1,q_{\mathrm{h}}+1,q_{\mathrm{n}})} = \lambda_{\mathrm{p}}, & \text{for } q_{\mathrm{h}} < Q_{\mathrm{h}}, \\ P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}}+1,n_{\mathrm{s}}-1,q_{\mathrm{h}},q_{\mathrm{n}})} = \lambda_{\mathrm{p}}, & \text{for } q_{\mathrm{h}} = Q_{\mathrm{h}}. \end{cases} \tag{14}$$

Upon SU arrival, the new SU will be queued in the new SU buffer if there is any room, otherwise the SU will be blocked and no state transition will occur as follows:

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}+1)} = \lambda_{\mathrm{s}}, \quad \text{for } q_{\mathrm{n}} < Q_{\mathrm{n}}. \tag{15}$$

Upon in-service PU departure, a channel becomes vacant then the state may transit as one of the following situations

- $q_{\mathrm{h}} > 0$: The head-of-line queued handoff SU will be admitted and assigned a channel, i.e.,

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}}-1,n_{\mathrm{s}}+1,q_{\mathrm{h}}-1,q_{\mathrm{n}})} = n_{\mathrm{p}} \cdot \mu_{\mathrm{p}}, \quad \text{for } q_{\mathrm{h}} > 0. \tag{16}$$

- Otherwise: The handoff SU buffer is empty, thus,

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}}-1,n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}})} = n_{\mathrm{p}} \cdot \mu_{\mathrm{p}}, \quad \text{for } q_{\mathrm{h}} = 0. \tag{17}$$

Upon in-service SU departure, two situations may happen.

- $q_{\mathrm{h}} > 0$: The head-of-line SU in the handoff SU buffer will leave the buffer and become an in-service SU, i.e.,

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}}-1,q_{\mathrm{n}})} = n_{\mathrm{s}} \cdot \mu_{\mathrm{s}}, \quad \text{for } q_{\mathrm{h}} > 0. \tag{18}$$

- Otherwise: The handoff SU buffer is empty, thus,

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}},n_{\mathrm{s}}-1,q_{\mathrm{h}},q_{\mathrm{n}})} = n_{\mathrm{s}} \cdot \mu_{\mathrm{s}}, \quad \text{for } q_{\mathrm{h}} = 0. \tag{19}$$

Upon one of the queued new SUs leaves the buffer because of impatience,

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}-1)} = q_{\mathrm{n}} \cdot \mu_{\mathrm{n}}. \tag{20}$$

Similarly, upon an impatient queued handoff SUs leaves,

$$P_{(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}},q_{\mathrm{n}}),(n_{\mathrm{p}},n_{\mathrm{s}},q_{\mathrm{h}}-1,q_{\mathrm{n}})} = q_{\mathrm{h}} \cdot \mu_{\mathrm{h}}. \tag{21}$$

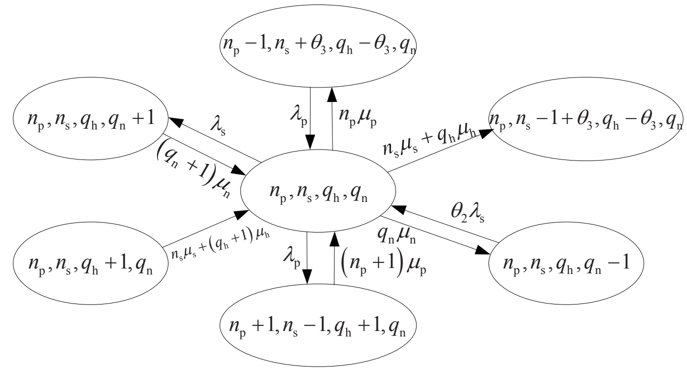


Fig. 3. State transition diagram for Case III ($q_{\mathrm{n}} < Q_{\mathrm{n}}$ and $q_{\mathrm{h}} < Q_{\mathrm{h}}$).

The state transition diagram for Case III with $q_{\mathrm{n}} < Q_{\mathrm{n}}$ and $q_{\mathrm{h}} < Q_{\mathrm{h}}$ is shown in Fig. 3, where the indicator variable θ_2 is defined by Eq. (13), and θ_3 is defined as

$$\theta_3 = \begin{cases} 1, & \text{for } q_{\mathrm{h}} > 0, \\ 0, & \text{for } q_{\mathrm{h}} = 0. \end{cases} \tag{22}$$

The transition diagram for Case III with $q_{\mathrm{n}} = Q_{\mathrm{n}}$ can be derived from Fig. 3 by deleting the state with the variable $q_{\mathrm{n}} + 1$. For Case III with $q_{\mathrm{h}} = Q_{\mathrm{h}}$, the transition diagram can be derived from Fig. 3 by deleting the state $(n_{\mathrm{p}}, n_{\mathrm{s}}, q_{\mathrm{h}} + 1, q_{\mathrm{n}})$, replacing the state $(n_{\mathrm{p}} + 1, n_{\mathrm{s}} - 1, q_{\mathrm{h}} + 1, q_{\mathrm{n}})$ by $(n_{\mathrm{p}} + 1, n_{\mathrm{s}} - 1, q_{\mathrm{h}}, q_{\mathrm{n}})$, and deleting the directed line from $(n_{\mathrm{p}} + 1, n_{\mathrm{s}} - 1, q_{\mathrm{h}}, q_{\mathrm{n}})$ to $(n_{\mathrm{p}}, n_{\mathrm{s}}, q_{\mathrm{h}}, q_{\mathrm{n}})$.

According to the analysis above, the transition rates between every two states of the multi-dimensional CTMC model can be derived, and the transition rate matrix can be formed. Hence, the stationary state probability vector $\mathbf{\Pi}$, which is constituted by the stationary state probabilities $\pi(n_{\mathrm{p}}, n_{\mathrm{s}}, q_{\mathrm{h}}, q_{\mathrm{n}})$, can be derived through a simple Gauss-Seidel method [3], [6].

B. QoS Metrics

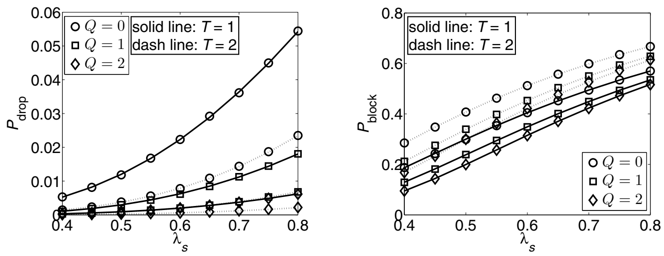
With the stationary state probability vector $\mathbf{\Pi}$, session-level QoS metrics such as the blocking probability and the dropping probability can be derived.

1) Blocking Probability: The blocking probability is defined as the ratio of the total SU blocking rate and the total SU arrival rate, thus, it is given by

$$P_{\text{block}} = \left[\sum_{\{q_{\mathrm{n}}=Q_{\mathrm{n}}\}} \lambda_{\mathrm{s}} \cdot \pi(n_{\mathrm{p}}, n_{\mathrm{s}}, q_{\mathrm{h}}, q_{\mathrm{n}}) + \sum_{\{q_{\mathrm{n}} \le Q_{\mathrm{n}}\}} q_{\mathrm{n}} \cdot \mu_{\mathrm{n}} \cdot \pi(n_{\mathrm{p}}, n_{\mathrm{s}}, q_{\mathrm{h}}, q_{\mathrm{n}}) \right] \Big/ \lambda_{\mathrm{s}}, \tag{23}$$

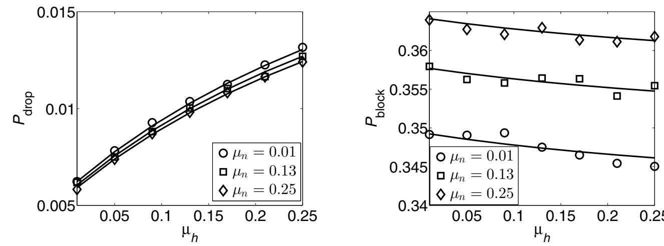
where, the numerator, which is the total SU blocking rate, contains two parts since an SU is blocked when the number of vacant channels is no larger than T and the new SU buffer is full, or the queued new SUs leave the buffer due to the impatience.

2) Dropping Probability: Similarly, the dropping probability is defined as the ratio of the total SU dropping rate and the total arrival rate of the successfully accessed SUs, and is



(a) Dropping probability. (b) Blocking probability.

Fig. 4. Performance metrics with different Q and T.



(a) Dropping probability. (b) Blocking probability.

Fig. 5. Performance metrics with different $\mu_{\rm h}$ and $\mu_{\rm n}$.

given by

$$P_{\rm drop} = \left[\sum_{\{q_{\rm h}=Q_{\rm h}\}} \lambda_{\rm p} \cdot \pi\left(n_{\rm p}, n_{\rm s}, q_{\rm h}, q_{\rm n}\right) + \sum_{\{q_{\rm h}\le Q_{\rm h}\}} q_{\rm h} \cdot \mu_{\rm h} \cdot \pi\left(n_{\rm p}, n_{\rm s}, q_{\rm h}, q_{\rm n}\right)\right] \Big/ \lambda_{\rm success}, \quad (24)$$

where $\lambda_{\rm success} = \lambda_{\rm s} \cdot (1 - P_{\rm block})$ is the total arrival rate of the successfully accessed SUs. The numerator of Eq. (24) responds to the two cases where dropping happens: the handoff SUs buffer is full or the queued handoff SUs leaves due to impatience.

With this analysis, optimization problems can be formulated to find the optimal parameters (such as the optimal buffer sizes and the optimal number of reserved channels) to meet given session-level QoS requirements under certain system settings (i.e., arrival rates and service rates of PUs and SUs, and impatience degree of new SUs and handoff SUs).

IV. Simulation and Numerical results

In this section, simulation and numerical results are presented to verify our model and analysis in Section III. The simulation results are obtained through averaging 10 runs, each contains 10^6 state-transition events. The total number of the channels N is set to be 8. The arrival rates of the PUs and SUs follow $\lambda_{\rm p}/\lambda_{\rm s} = 0.2$. The service rates of the PUs and SUs are $\mu_{\rm p} = 0.05$ and $\mu_{\rm s} = 0.1$, respectively. The leaving rates of impatient SUs in handoff SU buffer and new SU buffer are $\mu_{\rm h} = 0.01$ and $\mu_{\rm n} = 0.005$, respectively. For the sake of space limit, the handoff SU buffer and new SU buffer are set to have the same size Q.

Fig. 4 shows the performance with different Q ($Q = 0$ shows the case where no buffer is considered) and T, where the leaving rates of impatient SUs in handoff SU buffer and new SU buffer are set to be $\mu_{\rm h} = 0.01$ and $\mu_{\rm n} = 0.005$, respectively. The marks are simulated results and lines are numerical ones. First, the numerical results are consistent with the simulated ones, which verifies the accuracy of our analysis. Second, from the solid lines in all the subfigures, it is found that with the help of buffers, both blocking probability and dropping probability becomes smaller. The dash lines show the same phenomenon. Third, for the lines with the same mark (and colour) in Fig. 4(a) and Fig. 4(b), it is obvious that reserving more channels for the handoff SUs leads to a lower dropping probability at the cost of blocking probability, which is consistent with the conclusions in [1], [2].

Fig. 5 gives the impacts of $\mu_{\rm h}$ and $\mu_{\rm n}$ on the performance metrics, where $T = 1$ and $Q = 1$. It can be seen from Fig. 5 that departure due to impatience of the queued handoff SUs has two opposite effects on the system: direct contribution to dropping probability because it is one of the causes of dropping, and indirect impact on blocking probability since it alleviates the system load intensity. That is, lager $\mu_{\rm h}$ leads to higher $P_{\rm drop}$ and lower $P_{\rm block}$. Similarly, the departure due to impatience of the queued new SUs has direct contribution to blocking probability because it is a cause of blocking, and indirect impact on dropping probability since it alleviates the system load intensity. Therefore, lager $\mu_{\rm n}$ results in higher $P_{\rm block}$ and lower $P_{\rm drop}$.

V. Conclusions

A general framework is proposed for analyzing the performance of admission control in CRNs with finite queuing, impatient SUs, and channel reservation. With this framework, system parameters can be chosen optimally for a given session-level QoS requirement. Moreover, this framework can be easily applied to analyze systems without handoff and/or new SU buffer(s) ($Q_{\rm h} = 0$ and/or $Q_{\rm n} = 0$), impatient SUs ($\mu_{\rm h} = 0$ and/or $\mu_{\rm n} = 0$), and/or channel reservation ($T = 0$). For future work, one can extend the proposed framework to include the priority of SU traffic and the effect of spectrum sensing errors.

References

[1] X. Zhu, L. Shen, and T.-S. Yum, "Analysis of cognitive radio spectrum access with optimal channel reservation," *IEEE Commun. Lett.*, vol. 11, no. 4, pp. 304–306, Apr. 2007.

[2] W. Ahmed, J. Gao, H. Suraweera, and M. Faulkner, "Comments on 'Analysis of cognitive radio spectrum access with optimal channel reservation'," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4488–4491, Sep. 2009.

[3] Y. Zhang, "Dynamic spectrum access in cognitive radio wireless networks," in *Proc. 2008 IEEE Inter. Conf. Commun.*, pp. 4927–4932.

[4] S. Tang and B. Mark, "Analysis of opportunistic spectrum sharing with Markovian arrivals and phase-type service," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 3142–3150, June 2009.

[5] V. Tumuluru, P. Wang, D. Niyato, and W. Song, "Performance analysis of cognitive radio spectrum access with prioritized traffic," *IEEE Trans. Veh. Technol.*, vol. 61, no. 4, pp. 1895–1906, Apr. 2012.

[6] S. Ross, *Introduction to Probability Models*, 10th edition. Elsevier, 2011.