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ORIGINAL RESEARCH

Queueing based spectrum management in cognitive radio networks with retrial and heterogeneous service classes

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Abstract
Cognitive radio is an emerging technology, aimed at efficient use of the scarce radio spectrum. In cognitive radio networks (CRNs), spectrum licensed to the primary users (PUs) is shared by the secondary users (SUs) which affects the performance of the network. This paper proposes a novel spectrum management scheme for CRNs, where heterogeneous secondary real-time and non-real time users compete for the available channels with primary users and utilize two types of buffers under the probability retrial policy. To enhance the quality of service (QoS) for the secondary users (SUs), spectrum handoff and call buffering strategies with retrial policy are employed jointly so that SUs that would otherwise be blocked or forcibly dropped could be queued and possibly served later. The whole system is modeled using a multi-dimensional continuous-time Markov chain (CTMC) and accordingly, the QoS performance metrics are derived. Numerical results are presented which illustrate that the provision of queues under the proposed retrial policy increases overall network resource utilization and throughput while decreasing blocking and dropping probabilities.

Keywords Cognitive radio network · Markov chain · Retrial · Priority queue · Spectrum handoff · Heterogeneous traffic

1 Introduction

Radio spectrum is the most valuable resource to implement wireless communications. With the rapid development of new applications in wireless communications, the traditional static spectrum allocation scheme reveals its inherent limitation. As part of the fifth generation (5G) paradigm, cognitive radio (CR) technology is identified as a promising solution to alleviate the problem of spectrum scarcity and improve the spectral efficiency through dynamic spectrum allocation strategy (Krishna 2017; Liang 2019; Huang et al. 2019; Khan and Al Islam 2019).

Spectrum resources in cognitive radio networks (CRNs) are shared by typically two types of users: Primary users (PUs) and secondary users (SUs). PUs are licensed users and they are authorized to use the designated channels whenever as needed. In contrast, SUs are unlicensed users and they are only allowed to access channels opportunistically without interfering PUs. In this way, the spectrum utilization can be significantly improved. However, many challenges remain to successfully implement CRNs. One of the most challenging problems is how to provide efficient spectrum management in a mobile CRN environment in order to ensure that SUs get benefit from the spectrum without interfering with PUs (Zhao et al. 2018).

In a CRN, SUs' access and use of the spectrum are dependent on and limited by PUs' activity. It follows that a SU cannot be guaranteed instant access to the network, thus, to reflect the realistic scenario of the delayed access network (queueing delay), effective queueing disciplines in CRNs have gained importance (Paluncic et al. 2018). Although there is vast research on the analysis of priority queues with a single channel facility, efforts on the characterization of multichannel queues are not as extensive or productive due to their complications. This is essentially unfortunate since the modeling of many telecommunications problems can be suitably placed in the framework of a multi-server system, such as multichannel CRNs (Zhao and Yue 2015; Tadayon 2016; El-Toukhey et al. 2016). Moreover, in CRNs, the PUs have absolute priority over SUs and hence may interrupt

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the transmission of SUs. In practice, interrupted users may retry again for transmission. From this point of view, the consideration of the retrial phenomenon is very important while designing these CR systems.

In addition, the evolving 5G networks are envisioned to provide services that have different Quality of Service (QoS) and Quality of Experience (QoE) (Falcão et al. 2018). As observed, most works on performance analysis of dynamic channel access in CRNs have simply ignored or partially explored the consideration of heterogeneous users. However, for the practical and realistic CRN, it is imperative to analyze and investigate the heterogeneous SUs consideration because of its significance.

To circumvent such limitations, this paper proposes a novel and comprehensive queue based spectrum management scheme supporting heterogeneous users. Since spectrum handoff offers an opportunity to SUs for continuing their communication, it is of critical significance to determine the action of PUs (Nandakumar et al. 2019). The proposed scheme aims to enhance the performance of CRNs by providing SUs with the ability of dynamically seeking and exploiting opportunities without interfering with PUs. For the performance evaluation of the proposed scheme, five dimensional continuous-time Markov chain (CTMC) model is developed which considers all spectrum access factors that have not been fully accounted in previous studies. Based on this, different performance metrics including blocking probability, dropping probability, throughput and overall spectrum utilization of the system are derived. The main contributions of this work are highlighted as follows.

1. To obtain more realistic results of performance evaluation, the performance of heterogeneous SU traffic i.e. real-time traffic (RSU) and non-real time traffic (NRSU) is investigated in a multichannel CRN environment.
2. To reduce the blocking probability and the forced dropping probability, a queue-based solution is developed for the preemptive priority model. While real-time applications such as voice over Internet protocol (VoIP) and video conference can't tolerate delay, non-real time applications such as file transfer and email can tolerate acceptable delay. Incorporated with the spectrum handoff, we deploy two finite size buffers that are dedicated for allocation to the newly arriving NRSUs and the interrupted NRSUs performing handoff respectively.
3. Consequently, if the interrupted NRSU is queued, then its dropping probability decreases but at the same time risks a longer queueing delay. Also, it has been noted earlier that for RSUs being delay sensitive, it is better not to serve the interrupted RSUs (Balapuwaduge et al. 2014). Motivated by these observations, third, we employ probability retry policy for interrupted NRSUs, which is referred to as a compromise between two extremes (Zhao et al. 2014), i) scenario where the return of interrupted NRSUs is definite for later transmission i.e. with probability 1, a larger delay for NRSUs is expected, ii) forced termination of interrupted NRSUs' connection results in a higher termination rate. In view of this, considering the trade-off between delay and dropping rate, with probability (p)-retry policy, an interrupted NRSU returns to the buffer with retrial probability p ($0 < p < 1$).

The remainder of the paper is organized as follows. The related work is presented in Section 2. The system model under study is described in Section 3. Section 4 describes the proposed analytical framework. The performance metrics are listed in Section 5. In Sections 6 and 7, we provide some useful insights by means of the numerical results and conclusions.

2 Related work

In the literature, various studies have been conducted on spectrum management in CRNs from different perspectives. Wang et al. (2011) and Lee and Yeo (2015) presented the analysis of channel availability by employing spectrum handoff. The results by Lee and Yeo (2015) depict that execution of scheme with spectrum handoff results in higher channel availability than not executing spectrum handoff. However, the blocking probability and the forced dropping probability of SUs grows rapidly with the increment in arrival rates of PU and SU. Thus, how to diminish probabilities of blocking and forced dropping for SUs despite higher user arrival rates brings up an interesting question.

To address this issue, recently, Hoque et al. (2019) evaluated the performance of CRN using a preemptive queueing network model for different spectrum handoff schemes. Kalil et al. (2017) and Aggarwal et al. (2019) proposed the spectrum access strategies with buffering for new as well as interrupted SUs. However, in spite of considering the queueing model, Aggarwal et al. (2019) did not analyze the SU performance in terms of performance metrics such as throughput, blocking and dropping probability which is of paramount importance.

Some authors assumed the forced termination of interrupted SUs' connection which results in the higher termination rate of the SUs (Chu et al. 2014; Suliman and Lehtomäki 2015). On the other hand, some authors considered that instead of direct leaving, an interrupted SU is suspended to wait for future transmission in a buffer (Zhao et al. 2013). However, this kind of definite suspension for retrial transmission (i.e. with probability 1), may cause a greater delay for the SU. It follows that the delay of SUs can be reduced to some extent by considering the suspension to wait in buffer with some retrial probability (Zhao et al. 2014), which motivates our work. Note additionally that all the aforementioned work is limited to the homogeneity of SUs.

Abhaya et al. (2013) evaluated a deadline based scheduling system by considering multiple streams of requests. Whereas, the evaluation is limited to a single channel facility. In order to increase the spectrum handoff utilization for SUs, Bayrakdar and Calhan (2017) proposed a priority based queueing model for CRNs. Saad et al. (2018) focused on the spectrum access queuing based scheme for prioritized multi-channel CRNs. However, the works therein considered the non-preemptive priorities and the derived QoS metrics are distinct from the metrics defined in this paper. The main limitation of the available literature is that all the realistic elements and key factors are not modeled in a single work, which may affect the accuracy of the results.

This work is motivated by the aforementioned interesting studies and a need to have a rigorous mathematical framework that considers all the key features for spectrum access. As shown in Table 1, different from those existing works, the scheme proposed in this paper is designed by jointly considering five main features, i.e., multi-channel CRNs, hybrid SU traffic, queueing scheme, spectrum handoff, and retrial phenomenon. In brief, this paper encompasses a wide range of important features, allowing the analysis of their joint effects in more complex scenarios.

3 Network scenario and assumptions

We consider a scenario where RSUs and NRSUs compete for the available channels with PUs which has higher priority over SUs. The licensed radio spectrum is divided into C frequency channels, and a PU or SU utilizes only one channel for its transmission. Each NRSU is equipped with two finite size buffers i.e. handoff buffer and new buffer to hold NRSUs' handoffs and new NRSUs' arrivals with sizes Q_h and Q_n, respectively. A new SU is admissible if only there is an idle channel available or else, in case of an RSU, it gets blocked, while in the case of an NRSU, it gets queued in the new buffer. However, if there is not enough waiting space in the new buffer, then this newly arriving NRSU also gets blocked. At the arrival instant of PU, the SU has to vacate the channel and leave it to PU. To avoid interruption of its on-going transmission, the preempted SU is allowed to access another idle channel so as to complete its handoff. In case of no idle channel found, the interrupted NRSU either gets queued in the handoff buffer for later transmission with retrial probability p or with probability $(1-p)$, it gives up its transmission and leaves the system. Again, in case the handoff buffer is full, it gets dropped. In contrast, the interrupted RSU is blocked when no idle channel exists for handoff. Meantime, the channels which become idle are allocated to the awaiting NRSUs queued in the buffers. The probability of selection of an NRSU from the new buffer is α $(0 < \alpha < 1)$, then the probability of its selection from the handoff buffer is $(1-\alpha)$, in a way giving higher priority to the users in the handoff buffer $(\alpha < 0.5)$. We also assume that the arrivals of PU, RSU, and NRSU follow Poisson processes with rates λ_1, λ_2 and λ_3, respectively. And their service times follow an exponential distribution with parameters μ_1, μ_2 and μ_3, respectively. In line with the aforementioned assumptions, we depict the proposed spectrum access strategy in Fig. 1 and the nomenclature is given in Table 2.

4 Markov chain modeling

We develop an analytical model utilizing a five-dimensional CTMC with discrete states for the proposed spectrum management scheme. Let $\boldsymbol{x} = (i, n, s, t, q)$ represents a state of the CTMC model where i, n, s, t, and q denotes the numbers of in-service PUs, in-service RSUs, in-service NRSUs, NRSUs queued in new buffer, and NRSUs queued in handoff buffer, respectively. The state space for the model is given by

$$S = \{(i,n,s,t,q) | 0 \leqslant i \leqslant C, 0 \leqslant n \leqslant C-i,\\ 0 \leqslant s \leqslant C-i-n, 0 \leqslant t \leqslant Q_n, 0 \leqslant q \leqslant Q_h\}.$$

The system dynamics is classified into three cases: PUs, RSUs and NRSUs events which refer to their arrivals and departures. We describe the system dynamics in the

Table 1 Comparison of various analytical models for CRNs, where the signs "✓" and "×" indicate that the analytical model "does" and "does not" consider the corresponding feature, respectively

Reference	Multi-channel Facility	Hybrid SU Traffic	Buffer Support	Spectrum Handoff	Retrial Phenomenon
Zhao et al. (2014)	×	×	✓	×	✓
Suliman and Lehtomäki (2015)	✓	×	×	✓	×
Bayrakdar and Calhan (2017)	×	✓	×	✓	×
Aggarwal et al. (2019)	×	×	✓	✓	×
Proposed model	✓	✓	✓	✓	✓

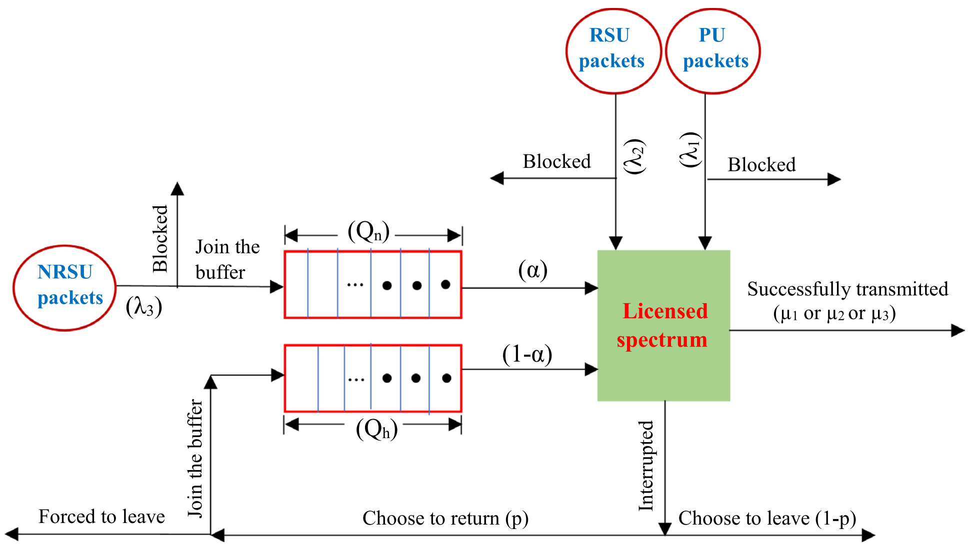

Fig. 1 Illustration of the proposed queueing based spectrum access strategy with p-Retry policy

Table 2 Nomenclature

Symbol	Description
C	Total number of channels in a cell.
Q_n	Buffer capacity for non-real time secondary users' new calls.
Q_h	Buffer capacity for non-real time secondary users' handoff calls.
λ_1	Arrival rate for primary users.
λ_2	Arrival rate for real time secondary users.
λ_3	Arrival rate for non-real time secondary users.
$1/\mu_1$	Average service time for primary users.
$1/\mu_2$	Average service time for real time secondary users.
$1/\mu_3$	Average service time for non-real time secondary users.
p	Retrial probability for non-real time secondary users' handoff calls.
α	Probability of selection of a non-real time secondary user from the new buffer.

following subsections to obtain the balance equations. For use in the sequel, we define an indicator variable, θ as

$$\theta = \begin{cases} 0; & \text{if } t = 0 \\ 1; & \text{if } q = 0 \\ \alpha; & \text{if } t > 0 \text{ and } q > 0. \end{cases}$$

A. PU events

When a PU appears at the system, then it either selects a free channel with probability $\gamma^1_{(i,n,s)} = \frac{C-(i+n+s)}{C-i}$ or preempts one of the ongoing RSU with probability $\gamma^2_{(i,n,s)} = \frac{n}{C-i}$ or preempts one the ongoing NRSU with probability $\gamma^3_{(i,n,s)} = \frac{s}{C-i}$. Fig. 2 shows the state transition diagram of PU events wherein the state (i, n, s, t, q) transits to one of the following states:

- State $(i+1, n, s, t, q)$ with rate $\lambda_1\gamma^1_{(i,n,s)}\theta_1$ when the PU occupies a free channel, where $\theta_1 = 1$ if $0 \leqslant i+n+s < C, t = 0, q = 0$ and 0 otherwise, OR with rate $\lambda_1\gamma^2_{(i,n,s)}\theta_2$ when the PU preempts an RSU and the preempted RSU performs handoff to a vacant channel, where $\theta_2 = 1$ if $0 < i+n+s < C, n > 0, t = 0, q = 0$ and 0 otherwise, OR with rate $\lambda_1\gamma^3_{(i,n,s)}\theta_3$ when the PU preempts an NRSU and the preempted NRSU performs handoff to a vacant channel, where $\theta_3 = 1$ if $0 < i+n+s < C, s > 0, t = 0, q = 0$ and 0 otherwise.

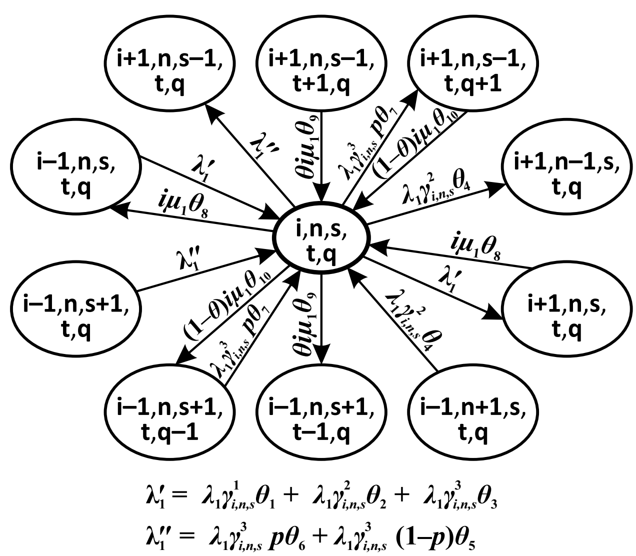

Fig. 2 State transition diagram for PU events

- State $(i+1, n-1, s, t, q)$ with rate $\lambda_1 \gamma^2_{(i,n,s)} \theta_4$ when the PU preempts an RSU and the preempted RSU is dropped, where $\theta_4 = 1$ if $i+n+s = C, n > 0, 0 \leqslant t \leqslant Q_n, 0 \leqslant q \leqslant Q_h$ and 0 otherwise.
- State $(i+1, n, s-1, t, q)$ with rate $\lambda_1 \gamma^3_{(i,n,s)} (1-p) \theta_5$ when the PU preempts an NRSU, the preempted NRSU gives up its transmission and gets dropped, where $\theta_5 = 1$ if $i+n+s = C, s > 0, 0 \leqslant t \leqslant Q_n, 0 \leqslant q \leqslant Q_h$ and 0 otherwise, OR with rate $\lambda_1 \gamma^3_{(i,n,s)} p \theta_6$ when the PU preempts an NRSU, the preempted NRSU chooses to join the buffer and gets dropped, where $\theta_6 = 1$ if $i+n+s = C, s > 0, 0 \leqslant t \leqslant Q_n, q = Q_h$ and 0 otherwise.
- State $(i+1, n, s-1, t, q+1)$ with rate $\lambda_1 \gamma^3_{(i,n,s)} p \theta_7$ when the PU preempts an NRSU and the preempted NRSU gets queued in the handoff buffer, where $\theta_7 = 1$ if $i+n+s = C, s > 0, 0 \leqslant t \leqslant Q_n, 0 \leqslant q < Q_h$ and 0 otherwise.
- State $(i-1, n, s, t, q)$ with rate $i\mu_1 \theta_8$ when the PU completes its service and both the buffers are empty, where $\theta_8 = 1$ if $0 < i+n+s \leqslant C, i > 0, t = 0, q = 0$ and 0 otherwise.
- State $(i-1, n, s+1, t-1, q)$ with rate $\theta i \mu_1 \theta_9$ when the PU completes its service and the NRSU at the head of the new buffer occupies the idle channel, where $\theta_9 = 1$ if $i+n+s = C, i > 0, 0 < t \leqslant Q_n, 0 \leqslant q \leqslant Q_h$ and 0 otherwise.
- State $(i-1, n, s+1, t, q-1)$ with rate $(1-\theta) i \mu_1 \theta_{10}$ when the PU completes its service and the NRSU at the head of the handoff buffer occupies the idle channel, where $\theta_{10} = 1$ if $i+n+s = C, i > 0, 0 \leqslant t \leqslant Q_n, 0 < q \leqslant Q_h$ and 0 otherwise.

B. RSU events

Analogous to the PU events, when RSU appears, it either occupies an idle channel (if any) or gets blocked. Fig. 3 shows the state transition diagram of RSU events wherein the state (*i*, *n*, *s*, *t*, *q*) transits to one of the following states:

- State $(i, n+1, s, t, q)$ with rate $\lambda_2 \beta_1$ when an arriving RSU occupies a vacant channel, where $\beta_1 = 1$ if $i+n+s < C, t = 0, q = 0$ and 0 otherwise.
- State $(i, n-1, s, t, q)$ with rate $n\mu_2 \beta_2$ when an RSU completes its service and both the buffers are empty, where $\beta_2 = 1$ if $i+n+s \leqslant C, n > 0, t = 0, q = 0$ and 0 otherwise.
- State $(i, n-1, s+1, t-1, q)$ with rate $\theta n \mu_2 \beta_3$ when an RSU completes its service and the NRSU at the head of the new buffer enters the service, where $\beta_3 = 1$ if $i+n+s = C, n > 0, 0 < t \leqslant Q_n, 0 \leqslant q \leqslant Q_h$ and 0 otherwise.

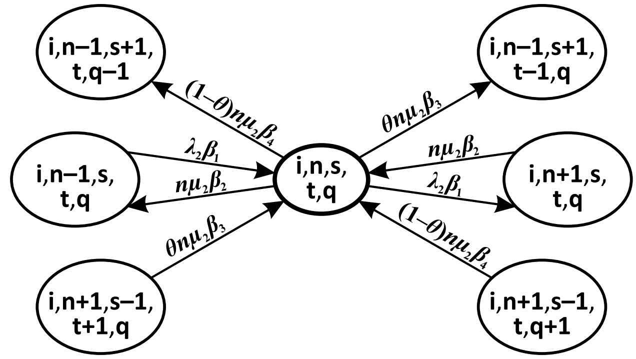

Fig. 3 State transition diagram for RSU events

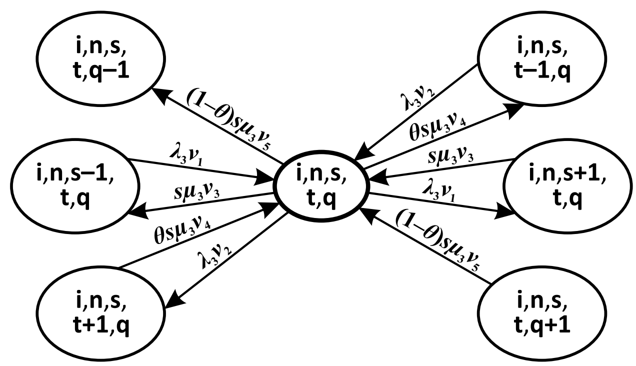

Fig. 4 State transition diagram for NRSU events

- State $(i, n-1, s+1, t, q-1)$ with rate $(1-\theta) n \mu_2 \beta_4$ when an RSU completes its service and the NRSU at the head of the handoff buffer enters the service, where $\beta_4 = 1$ if $i+n+s = C, n > 0, 0 \leqslant t \leqslant Q_n, 0 < q \leqslant Q_h$ and 0 otherwise.

C. NRSU events

An NRSU event refers to NRSU arrival or departure. When an NRSU appears then it either occupy an idle channel (if any) or gets queued in the new buffer if it has a waiting space. Otherwise, gets blocked. Fig. 4 shows the state transition diagram of NRSU events wherein the state (*i*, *n*, *s*, *t*, *q*) transits to one of the following states:

- State $(i, n, s+1, t, q)$ with rate $\lambda_3 \nu_1$ when an arriving NRSU occupies a vacant channel, where $\nu_1 = 1$ if $i+n+s < C, t = 0, q = 0$ and 0 otherwise.
- State $(i, n, s, t+1, q)$ with rate $\lambda_3 \nu_2$ when there is no idle channel and the newly arriving NRSU

gets queued in the new buffer, where $v_2 = 1$ if $i+n+s = C, 0 \leqslant t < Q_n, 0 \leqslant q \leqslant Q_h$ and 0 otherwise.

- State $(i, n, s-1, t, q)$ with rate $s\mu_3 v_3$ when an NRSU completes its service and both the buffers are empty, where $v_3 = 1$ if $i+n+s \leqslant C, s > 0, t = 0, q = 0$ and 0 otherwise.
- State $(i, n, s, t-1, q)$ with rate $\theta s\mu_3 v_4$ when an NRSU completes its service and the NRSU at the head of the new buffer enters for service, where $v_4 = 1$ if $i+n+s = C, s > 0, 0 < t \leqslant Q_n, 0 \leqslant q \leqslant Q_h$ and 0 otherwise.
- State $(i, n, s, t, q-1)$ with rate $(1-\theta)s\mu_3 v_5$ when an NRSU completes its service and the NRSU at the head of the handoff buffer enters for service, where $v_5 = 1$ if $i+n+s = C, s > 0, 0 \leqslant t \leqslant Q_n, 0 < q \leqslant Q_h$ and 0 otherwise.

D. Balance equations

Based on the aforementioned analysis, we can obtain the transition rates between any two states of the considered five-dimensional CTMC, and thereby can formulate the state transition rate matrix, Q. Let $\pi_{\boldsymbol{x}}$ denote the steady state probability of being in state $\boldsymbol{x}$. Accordingly, the steady state probability vector Π, which is constituted by the stationary probabilities, $\pi_{(i,n,s,t,q)}$ can be determined using the balance equations and the normalizing equation, given by

$$\Pi Q = 0, \quad \sum_{(i,n,s,t,q)\in S} \pi_{(i,n,s,t,q)} = 1. \tag{1}$$

Accordingly, in order to evaluate the performance of CRN, we derive different performance metrics that are relevant to analyze the communication QoS.

5 Performance metrics

The validity of any CTMC model can be best deciphered in terms of its performance metrics.

First, the *NRSU forced dropping probability*, P_{fd} which occurs when an interrupted NRSU upon preemption by a PU ends searching without finding a new idle channel to handoff. In addition, the interrupted NRSU chooses to return to the handoff buffer for later retrial but finds the buffer full, then the NRSU has to drop its communication before its service is finished. Note that the forced dropping probability of NRSUs can be expressed as the ratio of mean forced dropping rate of NRSUs to the mean admitted NRSU rate. Correspondingly, P_{fd} is given by

$$P_{fd} = \frac{\lambda_1 p \sum_{i=0}^{C} \sum_{n=0}^{C-i} \sum_{t=0}^{Q_n} \pi_{(i,n,C-i-n,t,Q_h)}}{\lambda_3(1-P_{bnr})}, \tag{2}$$

where P_{bnr} is the blocking probability of NRSUs given by

$$P_{bnr} = \sum_{i=0}^{C} \sum_{n=0}^{C-i} \sum_{q=0}^{Q_h} \pi_{(i,n,C-i-n,Q_n,q)}. \tag{3}$$

Second, the *NRSU self dropping probability*, P_{sd}, which on the other hand occurs when an interrupted NRSU finds all channels occupied and chooses to give up its transmission by leaving the system voluntarily. Thus, P_{sd} is given as follows

$$P_{sd} = \frac{\lambda_1 (1-p) \sum_{i=0}^{C} \sum_{n=0}^{C-i} \sum_{t=0}^{Q_n} \sum_{q=0}^{Q_h} \pi_{(i,n,C-i-n,t,q)}}{\lambda_3(1-P_{bnr})}. \tag{4}$$

Third, the *NRSU throughput*, T can be defined as the product of the number of successful NRSU connections per unit time and the service time per completed connection (Kalil et al. 2013). Therefore,

$$T = \lambda_3(1-P_{bnr})(1-P_{fd})^2(1-P_{sd})^2\mu_3^{-1}. \tag{5}$$

Fourth, an RSU gets blocked if on its arrival, all channels are occupied. Thus, the *RSU blocking probability*, P_{br} can be expressed as

$$P_{br} = \sum_{i=0}^{C} \sum_{n=0}^{C-i} \sum_{t=0}^{Q_n} \sum_{q=0}^{Q_h} \pi_{(i,n,C-i-n,t,q)}. \tag{6}$$

Fifth, we calculate the *channel utilization*, U as the average number of channels utilized over the total number of available channels. That is,

$$U = \frac{1}{C} \sum_{i=0}^{C} \sum_{n=0}^{C-i} \sum_{s=0}^{C-i-n} \sum_{t=0}^{Q_n} \sum_{q=0}^{Q_h} (i+n+s)\pi_{(i,n,s,t,q)}. \tag{7}$$

6 Numerical results and discussion

This section presents numerical results to illustrate the effectiveness of the proposed scheme. The operating parameters are configured as follows: $C = 6, \alpha = 0.3, p = 0.7, \lambda_1 =$ varies, $\lambda_2 = 10, \lambda_3 = 15, \mu_1 = 2, \mu_2 = 4, \mu_3 = 4, Q_n = 4$ and $Q_h = 2$, unless otherwise stated. In view of the fact that handoff user services demand higher priority over new user services, the probability of selection of a user from the new buffer for channel access, $\alpha = 0.3$ is taken for our numerical experiment, which is a reasonable configuration (Balapuwaduge et al. 2014).

In Fig. 5, the NRSU forced dropping probability versus PU arrival rate is presented for different values of buffer sizes. As expected, the dropping probability increases with an increase in the PU arrival rate and the effect is more noticeable for lower values of λ_1. However, the dropping probability is significantly reduced using our queueing based strategy compared to the one operating without any buffer. The reason is that the would be dropped NRSUs are not rejected but instead queued in the buffer to provide channel access when available. Moreover, a larger buffer size allows accomodating more users' requests, leading to further decrease in forced dropping probability, notably for reasonable higher values of λ_1.

The NRSU blocking probability as a function of PU arrival rate, λ_1 is illustrated in Fig. 6. We notice that when the system is operated without queues, it shows higher probability values compared to those with queues. However, an interesting behavior is observed with respect to an increase in the buffer sizes and the values of λ_1. The result reveals that the increase in the size of handoff buffer has more significant impact than that of the new buffer and results in the increment of NRSUs' blocking probability. This is due to the priority privilege given to the users in the handoff buffer over those in the new buffer for channel access. In accordance, the comparison of the proposed model (i.e., with finite queues) and the model without any queue (Suliman and Lehtomäki 2015) in Figs. 5 and 6 indicate that the system performance gets significantly affected by the support of queues.

Further, Figs. 7 and 8 depict the NRSU throughput and channel utilization as a function of PU arrival rate. These results confirm improved performance in contrast with the strategy without any retrial transmission. Since employing the retry policy allows the would be dropped NRSUs to join the handoff buffer. Therefore, with higher retrial probability the number of NRSUs returning to the buffer increases which, in turn, results in more NRSUs to be transmitted and thus results in higher throughput. Besides, accordingly the time period for which channels remain in the idle state also gets reduce and thereby improves the spectrum utilization significantly.

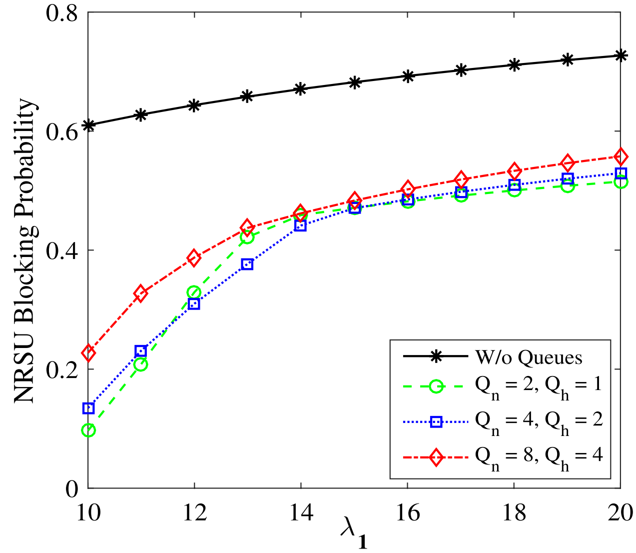

Fig. 6 NRSU blocking probability as a function of λ_1

The self dropping probability of NRSU for different retrial probabilities is plotted in Fig. 9 as λ_1 varies. We observe that with higher active PUs, it is less likely for an interrupted NRSU to handoff to an idle channel, resulting in a higher self dropping probability. As shown in the figure, the self dropping probability of NRSU decreases using the proposed spectrum access strategy with *p*-retry policy in contrast with the strategy without any retrial transmission. When using the retry policy, the interrupted users due to

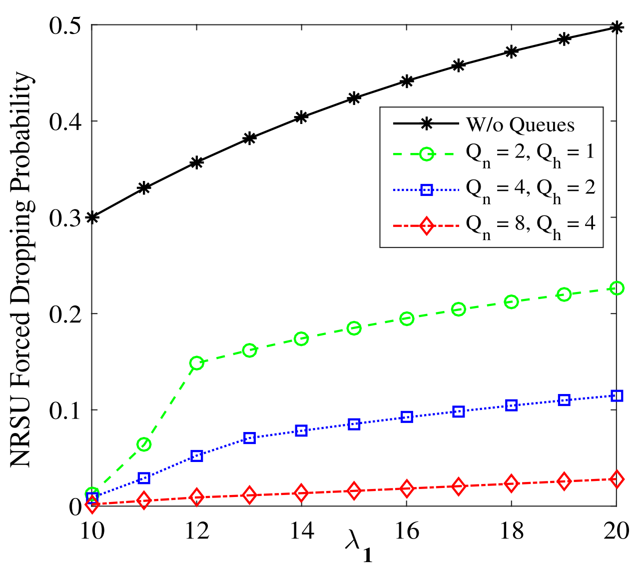

Fig. 5 NRSU forced dropping probability as a function of λ_1

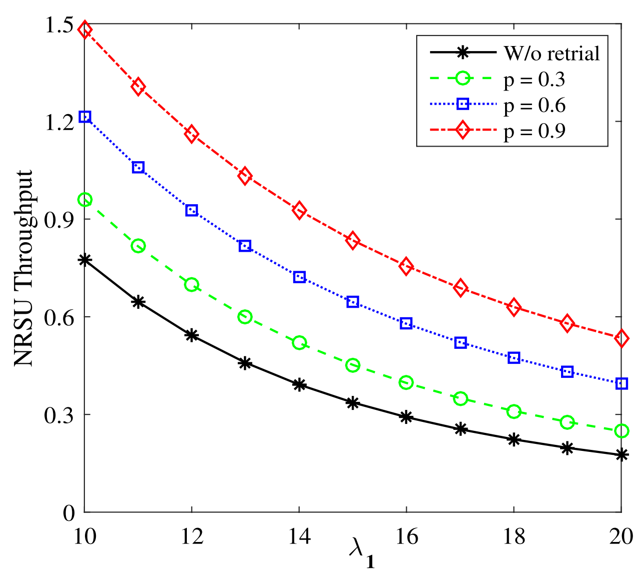

Fig. 7 NRSU throughput as a function of λ_1

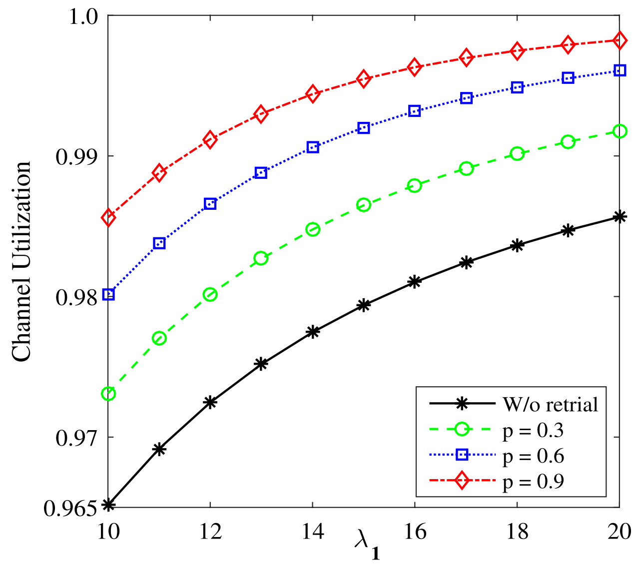

Fig. 8 Spectrum utilization as a function of λ_1

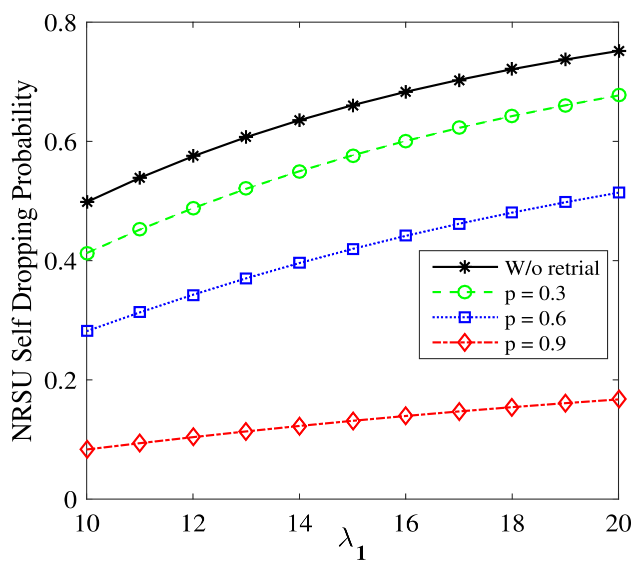

Fig. 9 NRSU self dropping probability as a function of λ_1

insufficient channels instead of being dropped are allowed to queue into the buffer for later retrial transmission. This results in lower self dropping probability. Moreover, the larger the retrial probability is, the lesser the number of interrupted NRSUs getting dropped will be, so the self dropping probability of NRSU gets significantly reduced further. Based on the results in Figs. 7, 8 and 9, which depict the comparison of the proposed model (i.e., with retrial phenomenon) to the models without retrial phenomenon (Tang et al. 2016), we can conclude that the achievable throughput, utilization and dropping probability are substantially affected by the provision of a retrial.

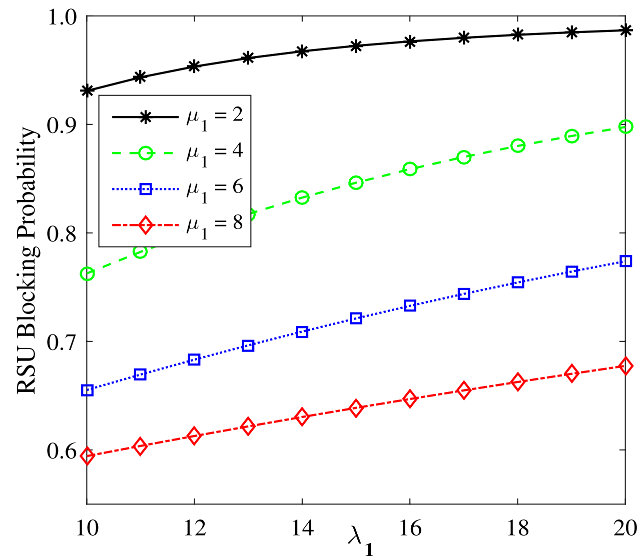

Fig. 10 RSU blocking as a function of λ_1

Finally, Fig. 10 exhibits the variation of RSU blocking probability with PU arrival rate and different service rates. Intuitively, an increase in the PU arrival rate increases the RSU blocking probability. On the contrary, with a higher PU service rate, the probability of the system being in a busy state decreases, resulting in lower RSU blocking probability. Consequently, in brief, these results enable a trade-off that can be tuned according to the QoS requirements of the secondary traffic.

7 Conclusion

This paper proposed a queueing based spectrum management strategy for multi-channel CRNs supporting heterogeneous traffic. A joint design of the retrial phenomenon, buffering and switching handoff scheme is explored. In subsequence, an analytical framework utilizing a five-dimensional CTMC is developed to analyze the proposed strategy under realistic network operating conditions. We then evaluated the performance of the system in terms of different performance metrics. Numerical results are presented to highlight the analysis. With numerical results, we have illustrated that the integration of queues with retry policy in the proposed strategy outperforms the existing ones without any retrial transmission or a queue. In accordance, analytical results under the proposed strategy show significant improvements in terms of the throughput, spectrum utilization, forced dropping and blocking probabilities. In view of this, the results of the proposed strategy provide new insight into the operation of CRNs and can be utilized to develop practical and more accurate performance evaluation models for CRNs.

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Declarations

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Availability of data and material Not applicable

Code availability Not applicable

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