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A Buffering and Switching Scheme for Admission Control in Cognitive Radio Networks

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***Abstract*—Cognitive radio users (i.e. Secondary users) experience a lot of performance degradation due to the continuous appearance of the primary users in the cognitive radio networks. To minimize the effect of this phenomenon, we propose a buffering and switching scheme for admission control to enhance the performance of the secondary users. In the proposed scheme, the secondary users are competing for the available channels (i.e licensed and unlicensed) with two different kind of users and utilizing different kinds of buffers to reduce the blocking probability for newly arriving users and dropping probability for ongoing connection. The system is modeled using a multi-dimensional continuous-time Markov chain, where the performance metrics are obtained. The numerical results are verified using a discrete event simulations.**

***Index Terms*—Cognitive Radio Networks, Markov Chain, Spectrum Handoff.**

I. INTRODUCTION

Cognitive radio networks (CRN) are designed to operate under the mixed spectrum environment that consists of both licensed channels (LCs) and unlicensed channels (UCs) [1]. In CRN, the primary users (PUs) activities affect negatively the performance of the cognitive users or secondary users (SUs). The SU should vacate the channel immediately in case of the sudden appearance of a PU. The SU can use one of the following three coping techniques: (i) Channel switching, where an SU connection preempted by a PU switch to a free or reserved channel and otherwise the SU is dropped [2][3]; (ii) Buffering, where a handoff buffer is used from the moment of preemption by PUs until PU releases the channel [4]; and (iii) Buffering and channel switching, where SU connections preempted by PU first look for free channels, and when no free channels are found then the connections are buffered until PU leaves the channel.

All the aforementioned techniques utilize a number of LCs to evaluate the performance of SUs where the existence of the UCs and Classical Users (CUs) was neglected. In [5][6], the blocking probability and dropping probability of SUs are decreased using a mixed spectrum environment that consists of both LCs and UCs. In this paper, we propose two finite size buffers (waiting room) to hold the newly arriving SUs and the SUs performing spectrum handoffs in case of PU appearance. In addition, the SUs can perform a channel switching technique in a mixed spectrum environment as presented in [5][6]. Thus, the novelty of our technique is the utilization of buffering and channel switching technique in a mixed spectrum and users environment. To investigate the dynamics of the new technique, the system is modeled by multi-dimensional continuous-time Markov chain (CTMC) where different kinds of users competes for the available channels. These users can be categorized as follows: (i) PUs which are the owners of LCs, (ii) SUs which are cognitive radio users able to opportunistically accessing the available spectrum (i.e. LCs or UCs) and (iii) CUs which are users equipped with the conventional standards e.g. IEEE 802.11 and operate only in the UCs.

From the developed mathematical model, some performance metrics such as SU dropping probability, blocking probability and completion rate are obtained. The numerical results are verified using simulations. The remainder of the paper is organized as the following. In section II, the model assumption is given. Section III describes the proposed scheme. Furthermore, an extensive analytic model based on CTMC is developed in section IV. The numerical results and simulation are discussed in section V. Finally, the paper is concluded in section VI.

II. MODEL ASSUMPTIONS AND NOTATIONS

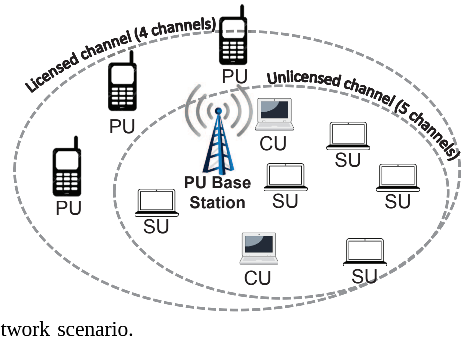

Fig. 1. Network scenario.

There are C_1 LCs and C_2 UCs, where the total number of channels C is given as $C = C_1 + C_2$. In addition, there are three types of users competing for the available LCs and UCs called PUs, SUs and CUs. The LCs are shared between PUs and SUs with higher priority is allocated to PUs. The UCs are shared between SUs and CUs without any priority. Each PU, SU or CU requires only one channel for transmission. We consider two finite size buffers to hold SUs handoffs and new SUs arrivals when there is no available LCs or UCs with sizes H and N respectively. Figure 1 shows a network scenario for three kinds of users: (i) Three PUs utilize four LCs, (ii) Five

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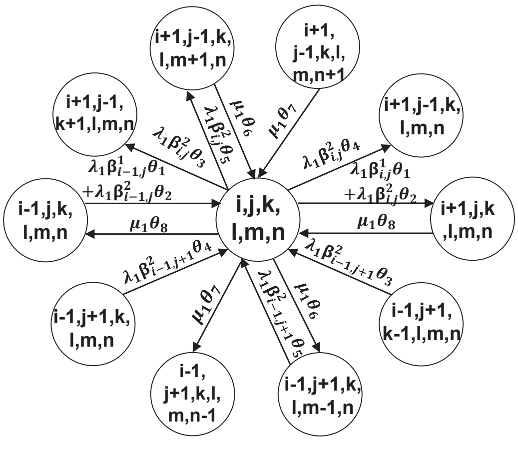

Fig. 2. Transition diagram for PU events in the system.

SUs compete to access four LCs and five UCs, and (iii) Two CUs utilize five UCs.

A PU can start its service if there is at least an idle LC or a LC occupied by SU. In the proposed scheme, we assume that the newly arriving SUs use the following procedure: The SU access firstly one of the LCs. If all LCs are occupied, the SU utilizes one of the UCs. If there are no idle channels from LCs and UCs, the newly arriving SUs is queued in a new SU buffer with size N. Otherwise, the SU gets blocked. In case of PU appearance, the SU should vacate the channel. In such a case, the SU is called handoff SU. For avoiding the interruption of its session, the SU performs a fast spectrum handoff (i.e. switching) to an idle UCs firstly. Secondly, if there are no idle UCs, a free LCs (if any) is used to perform the spectrum handoffs. Finally, the handoff SUs will be queued in a handoff buffer with size H. Otherwise, the SU gets dropped. Upon the CU arrival, it firstly access one of the UCs. If all UCs are occupied, it will be rejected.

The arrivals of PUs, SUs and CUs are assumed to be Poisson processes with arrival rates λ_1, λ_2 and λ_3, respectively. The service times of PU, SU and CU are exponential with rates μ_1, μ_2 and μ_3, respectively. The simplified exponential assumption has been widely used [4] and gives useful mean value information for the output measures.

III. SYSTEM OCCUPANCY

According to the previously mentioned assumptions, we may identify six variables of system occupancy i, j, k, l, m, and n which refer to the numbers of ongoing PUs, ongoing SUs which occupy LCs, ongoing SUs which occupy UCs, ongoing CUs which occupy the UCs, SUs in the handoff buffer and SUs queued in the new buffer, respectively. Thus, the process of spectrum access to LCs and UCs is modeled as a 6-dimensional Markov chain (i, j, k, l, m, n) with state space S given as :

$$\begin{aligned} S \;=\; & \{(i, j, k, l, m, n)\,|0 \le i \le C_1, 0 \le j \le C_1 - i, 0 \le k \le, C_2 \\ & , 0 \le l \le C_2 - k, 0 \le m \le H, 0 \le n \le N\} \end{aligned}$$

The system dynamics can be divided to three cases: PUs, SUs and CUs events (i.e. arrival and departure). To drive the global balance equation, we describe the system dynamics under the aforementioned assumptions during the following subsections.

A. PU Events

If a PU arrives at the system, then it may select an idle LC with probability $\beta^1_{i,j} = \frac{C_1 - i - j}{C_1 - i}$ or preempts one of the ongoing SU with probability $\beta^2_{i,j} = \frac{j}{C_1 - i}$. As shown in Figure 2, the state (i, j, k, l, m, n) transits to one of the following states:

- State $(i + 1, j, k, l, m, n)$ with rate $\lambda_1\beta^1_{i,j}\theta_1$ if the PU occupies an idle LC, where $\theta_1 = 1$ if $0 \le i + j < C_1$, $0 \le k + l \le C_2$, $m = 0$, $n = 0$ and 0 otherwise, OR with rate $\lambda_1\beta^2_{i,j}\theta_2$ if the PU preempts an ongoing SU and the preempted SU performs handoff to an idle LC, where $\theta_2 = 1$ if $0 < i + j < C_1$, $k + l = C_2$, $m = 0$, $n = 0$, $j > 0$ and 0 otherwise.
- State $(i + 1, j - 1, k + 1, l, m, n)$ with rate $\lambda_1\beta^2_{i,j}\theta_3$ if the PU preempts one of j ongoing SUs and the later performs handoff to an idle UC, where $\theta_3 = 1$ if $0 < i + j < C_1$, $0 \le k + l < C_2$, $m = 0$, $n = 0$, $j > 0$ and 0 otherwise.
- State $(i + 1, j - 1, k, l, m, n)$ with rate $\lambda_1\beta^2_{i,j}\theta_4$ if the PU preempts one of j ongoing SUs and the preempted SU is dropped, where $\theta_4 = 1$ if $i + j = C_1$, $k + l = C_2$, $m = H$, $0 \le n \le N$, $j > 0$ and 0 otherwise.
- State $(i + 1, j - 1, k, l, m + 1, n)$ with rate $\lambda_1\beta^2_{i,j}\theta_5$ if the PU preempts one of j SUs and the preempted SU is queued within the handoff buffer, where the $\theta_5 = 1$ if $i + j = C_1$, $k + l = C_2$, $0 \le m < H$, $0 \le n \le N$, $j > 0$ and 0 otherwise.
- State $(i - 1, j + 1, k, l, m - 1, n)$ with rate $\mu_1\theta_6$ if the PU completes its transmission and the head of line of the handoff buffer occupies a free LC, where the $\theta_6 = 1$ if $i + j = C_1$, $k + l = C_2$, $0 < m \le H$, $0 \le n \le N$ and 0 otherwise.
- State $(i - 1, j + 1, k, l, m, n - 1)$ with rate $\mu_1\theta_7$ if a PU departs and the head of line SU of the new buffer occupies the free LC, where $\theta_7 = 1$ if $i + j = C_1$, $k + l = C_2$, $m = 0$, $0 < n \le N$ and 0 otherwise.
- State $(i - 1, j, k, l, m, n)$ with rate $\mu_1\theta_8$ if a PU departs given that $H = 0$ and $N = 0$, where $\theta_8 = 1$ if $0 < i + j \le C_1$, $i > 0$, $0 \le k + l \le C_2$, $m = 0$, $n = 0$ and 0 otherwise.

Based on the PUs activities, the total flows out of state (i, j, k, l, m, n) are given as

$$\begin{aligned} PU_{out} \;=\; & \left(\lambda_1\beta^2_{i,j}\sum\nolimits_{u=2}^{5}\theta_u + \mu_1\sum\nolimits_{u=6}^{8}\theta_u + \lambda_1\beta^1_{i,j}\theta_1\right) \\ & \times p_{i,j,k,l,m,n} \end{aligned} \tag{1}$$

where $p_{i,j,k,l,m,n}$ denoting the steady state probability distribution of state $(i, j, k, l, m, n) \in S$. The total flows from other states into state (i, j, k, l, m, n) can be derived analogously to Eq. (1) as follows

$$\begin{aligned} PU_{in} = {} & \lambda_1\left(\beta^1_{i,j}\theta_1 + \beta^2_{i,j}\theta_2\right)p_{i-1,j,k,l,m,n} \\ & + \lambda_1\beta^2_{i,j}\theta_3 p_{i-1,j+1,k-1,l,m,n} + \lambda_1\beta^2_{i,j}\theta_4 p_{i-1,j+1,k,l,m,n} \\ & + \lambda_1\beta^2_{i,j}\theta_5 p_{i-1,j+1,k,l,m-1,n} + \mu_1\theta_6 p_{i+1,j,k,l,m+1,n} \\ & + \mu_1\theta_7 p_{i+1,j,k,l,m,n+1} + \mu_1\theta_8 p_{i+1,j,k,l,m,n} \end{aligned} \tag{2}$$

From (1) and (2), the local balance equation of the PUs activities can be obtained as $PU_{out} = PU_{in}$.

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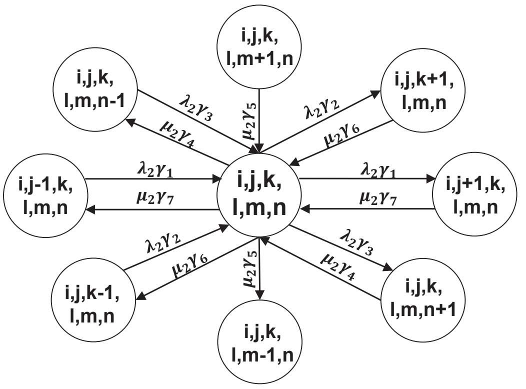

Fig. 3. Transition diagram for SU events in the system.

B. SU Events

In similar way to the PU events, upon SU arrival, it either occupy a free LC or UC (if any) or queued in the new SU buffer if it is empty. Otherwise, the arrived SU get blocked.

Referring to the transition diagram in Figure 3, the state (i, j, k, l, m, n). transits to one of the following states:

- State $(i, j+1, k, l, m, n)$ with rate $\lambda_2\gamma_1$ if an SU occupies an idle LC, where $\gamma_1 = 1$ if $i + j < C_1$, $k + l \leq C_2$, $m = 0$, $n = 0$ and 0 otherwise.
- State $(i, j, k+1, l, m, n)$ with rate $\lambda_2\gamma_2$ if an SU occupies an idle UC, where $\gamma_2 = 1$ if $i + j = C_1$, $k + l < C_2$, $m = 0$, $n = 0$ and 0 otherwise.
- State $(i, j, k, l, m, n+1)$ with rate $\lambda_2\gamma_3$ if there is no space in both LCs and UCs and the newly SU arrival queued in the new SU buffer, where $\gamma_3 = 1$ if $i + j = C_1$, $k + l = C_2$, $0 \leq m \leq H$, $0 \leq n < N$ and 0 otherwise.
- State $(i, j, k, l, m, n-1)$ with rate $\mu_2\gamma_4$ if an SU completes it services and the SU at the new buffer head of line enters service, where $\gamma_4 = 1$ if $i + j = C_1$, $k + l = C_2$, $m = 0$, $0 < n \leq N$, $j > 0$ and 0 otherwise.
- State $(i, j, k, l, m-1, n)$ with rate $\mu_2\gamma_5$ if an SU completes it services and the SU at the handoff buffer head of line enters service, where $\gamma_5 = 1$ if $i + j = C_1$, $k + l = C_2$, $0 < m \leq H$, $0 \leq n \leq N$, $j > 0$ and 0 otherwise.
- State $(i, j, k-1, l, m, n)$ with rate $\mu_2\gamma_6$ if an SU which occupies a UC completes it services and both handoff and new buffers are empty, where $\gamma_6 = 1$ if $i + j \leq C_1, k + l \leq C_2, m = 0, n = 0,\ k > 0$ and 0 otherwise.
- State $(i, j-1, k, l, m, n)$ with rate $\mu_2\gamma_7$ if an SU which occupies a LC completes it services and both handoff and new buffers are empty, where $\gamma_7 = 1$ if $i + j \leq C_1, k + l \leq C_2, m = 0, n = 0,\ j > 0$ and 0 otherwise.

Based on the SUs activities, the total flows out of state (i, j, k, l, m, n) are given as

$$SU_{out} = \left(\lambda_2 \sum\nolimits_{u=1}^{3} \gamma_u + \mu_2 \sum\nolimits_{u=4}^{7} \gamma_u\right) p_{i,j,k,l,m,n} \tag{3}$$

The total flows from other states into state (i, j, k, l, m, n) can be derived analogously to Eq. (3) as follows

$$\begin{aligned} SU_{in} &= \lambda_2\gamma_1 p_{i,j-1,k,l,m,n} + \lambda_2\gamma_2 p_{i,j,k-1,l,m,n} \\ &+ \lambda_2\gamma_3 p_{i,j,k,l,m,n-1} + \mu_2\gamma_4 p_{i,j,k,l,m,n+1} \\ &+ \mu_2\gamma_5 p_{i,j,k,l,m+1,n} + \mu_2\gamma_6 p_{i,j,k+1,l,m,n} \\ &+ \gamma_7 p_{i,j+1,k,l,m,n} \end{aligned} \tag{4}$$

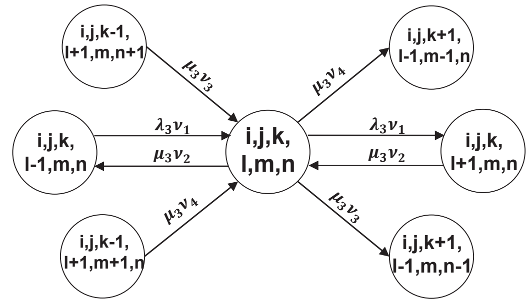

Fig. 4. Transition diagram for CU events in the system.

From (3) and (4), the local balance equation of the SUs activities can be obtained as $SU_{out} = SU_{in}$.

C. CU Events:

This includes CU arrival and departure. The activities of CUs in UCs affect the performance of SU. Upon CU arrival, it either occupy a free UC (if any) or rejected.

Referring to the transition diagram in Figure 4, the transition from state (i, j, k, l, m, n) to all other possible states due to the CU activity can be described as follows.

- State $(i, j, k, l+1, m, n)$: This event happens with rate $\lambda_3\upsilon_1$ if a CU occupies an idle UCs, where $\upsilon_1 = 1$ if $k + l < C_2, m = 0, n = 0$ and 0 otherwise.
- State $(i, j, k, l-1, m, n)$: This event happens with rate $\mu_3\upsilon_2$ if a CU departs without affecting the system, where $\upsilon_2 = 1$ if $k + l \leq C_2$, $m = 0, n = 0$ and 0 otherwise.
- State $(i, j, k+1, l-1, m, n-1)$: This event happens with rate $\mu_3\upsilon_3$ if a CU departs and the SU at the head of the line of the new SU buffer occupies a UC. The indicator variable $\upsilon_3 = 1$ if $k + l = C_2$, $m = 0$, $0 < n \leq N$ and 0 otherwise.
- State $(i, j, k+1, l-1, m-1, n)$: This event happens with rate $\mu_3\upsilon_4$ if a CU departs and head of the line SU in the handoff buffer occupies a UC. The indicator variable $\upsilon_4 = 1$ if $k + l = C_2$, $0 < m \leq H$, $0 \leq n \leq N$ and 0 otherwise.

Based on the CUs activities, the total flows out of state (i, j, k, l, m, n) are given as

$$CU_{out} = \left(\lambda_3\upsilon_1 + \mu_3 \sum\nolimits_{u=2}^{4} \upsilon_u\right) p_{i,j,k,l,m,n} \tag{5}$$

The total flows from other states into state (i, j, k, l, m, n) can be derived analogously to Eq. (5) as follows

$$\begin{aligned} CU_{in} &= \lambda_3\upsilon_1 p_{i,j,k,l-1,m,n} + \mu_3\upsilon_2 p_{i,j,k,l+1,m,n} \\ &+ \mu_3\upsilon_3 p_{i,j,k-1,l+1,m,n+1} + \mu_3\upsilon_4 p_{i,j,k-1,l+1,m+1,n} \end{aligned} \tag{6}$$

From (5) and (6), the local balance equation of the CUs activities can be obtained as $CU_{out} = CU_{in}$.

D. Global Balance Equation

The global balance equation of the system dynamics can be formulated using Figures 2-4 for $0 \leq i \leq C_1, 0 \leq j \leq C_1 - i, 0 \leq k \leq C_2, 0 \leq l \leq C_2 - k, 0 \leq n \leq H$, and $0 \leq m \leq M$ as follows.

$$PU_{out} + SU_{out} + CU_{out} = PU_{in} + SU_{in} + CU_{in} \tag{7}$$

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By substituting from equations (1)-(6) in (7), the global balance equation of system dynamics is obtained. Since it is a complicated to drive a closed form for $p_{i,j,k,l,m,n}$, we adopted an iterative algorithm to get $p_{i,j,k,l,m,n}$ as in [6].

IV. PERFORMANCE METRICS

First, an SU gets blocked if upon its arrival, all channels (i.e. LCs and UCs) are occupied and the buffer assigned for new SUs arrivals is full. In such a case, the SU blocking probability, P_b can be written as follows:

$$P_b = \sum_{i=0}^{C_1} \sum_{k=0}^{C_2} \sum_{m=0}^{H} p_{i,C_1-i,k,C_2-k,m,N}.$$

Second, an SU get dropped if it preempted by one of the PUs and all channels (i.e. LCs and UCs) are occupied. In addition, the handoff buffer is full. Therefore, the SU dropping probability P_d is calculated as follows:

$$P_d = \frac{\sum_{i=0}^{C_1-1} \sum_{k=0}^{C_2} \sum_{n=0}^{N} p_{i,C_1-i,k,C_2-k,H,n}}{\lambda_2(1-P_b)}$$

Third, SU completion rate, C_r can be defined as the number of successful SU connections per unit time. Thus, C_r can be written as follows: $C_r = (1-P_b)(1-P_d)\lambda_2$.

V. SIMULATION AND NUMERICAL RESULTS

For validating the proposed scheme, a discrete-event simulator has been conducted. The scenario that we tested is organized as shown in Figure 1. The following parameters are used in both the simulation and the numerical results: $\lambda_1 = varies$, $\lambda_2 = varies$, $\lambda_3 = 0.1$, $\mu_1 = 0.1$, $\mu_2 = 0.25$, $\mu_3 = 0.1$, $C_1 = 4$, $C_2 = 5$, $H = varies$ and $N = varies$.

Fig. 5-(a) shows SU blocking probability versus the PU traffic load with different new SU buffer sizes (i.e. N =0, 2 and 4) and $\lambda_1 = 0.3$. It is intuitive that by increasing the traffic load of PU, the blocking probability increases. However, the figure illustrates that with the help of the new buffer for the newly arriving SU, the blocking probability decreases compared to the one operating without buffer. Fig. 5-(b) plots the dropping probability of SUs against the PU traffic load for different handoff buffer sizes (i.e. H =0, 2 and 4). It is clear that, increasing the traffic load of PUs increases the dropping probability. With $H = 0$ (i.e., no handoff buffer), more packets get lost in the case of all LCs and UCs are busy and hence the dropping probability increases greatly. However, when there are available rooms in the handoff buffer (i.e., $H > 0$), the dropping probability of the ongoing connection of SU decreases since the interrupted connection will be buffered till a channel from LCs or UCs becomes free.

Finally, Fig. 6-(a) and (b) show the effect of PU traffic load on the SU completion rate under different handoff buffer sizes and new SU buffer sizes, respectively. From the figures, it can be seen that, as the PU traffic load increases, the SU completion rate decreases under different sizes of handoff buffer and new SU buffer. Also, when we increase the size of the handoff buffer and new SUs buffer, the SU completion rate improved greatly compared with those without buffers.

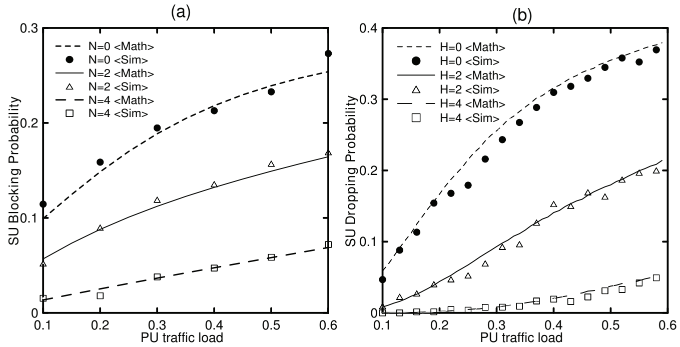

Fig. 5. (a) SU blocking probability with different new SU buffer sizes and (b) SU dropping probability with different handoff buffer sizes.

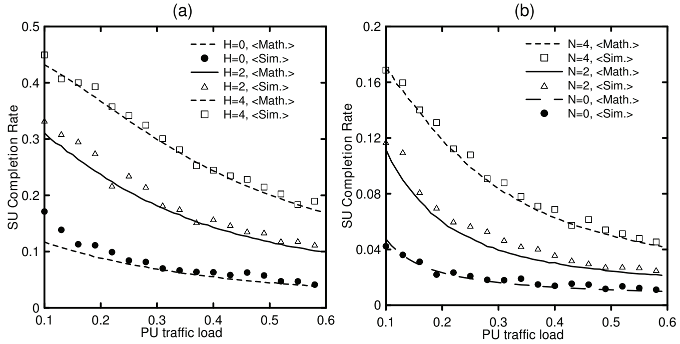

Fig. 6. (a) SU completion rate with different handoff buffer sizes and (b) SU completion rate with different new SU buffer sizes.

VI. CONCLUSIONS

In this letter, the performance of SUs using a buffering and switching scheme and operating in a mixed spectrum environment is investigated. Within this scheme, the system can be controlled by adopting different parameters for better performance for SUs. For example, the system can be evaluated without utilizing the buffers and with buffers. Different performance metrics are derived such as the blocking probability, dropping probability and SUs completion rate. The analytical results have been verified using a discrete event simulator. The results show that the performance of SUs can be enhanced greatly by using mixed strategy of buffering and switching compared to the one utilizing either buffering or switching.

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