Dynamic Spectrum Access in Cognitive Radio Wireless Networks

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***Abstract*— Cognitive radio wireless networks is an emerging communication paradigm to effectively address spectrum scarcity challenge. Spectrum sharing enables the secondary unlicensed system to dynamically access the licensed frequency bands in the primary system without any modification to the devices, terminals, services and networks in the primary system. In this paper, we propose and analyze new dynamic spectrum access schemes in the absence or presence of buffering mechanism for the cognitive Secondary Subscriber (SU). A Markov approach is developed to analyze the proposed spectrum sharing policies with generalized bandwidth size in both primary system and secondary system. Performance metrics for SU are developed with respect to blocking probability, interrupted probability, forced termination probability, non-completion probability and waiting time. Numerical examples are presented to explore the impact of key systems parameters like the traffic load on the performance metrics. Comparison results indicate that the buffer is able to significantly reduce the SU blocking probability and non-completion probability with very minor increased forced termination probability. The analytic model has been verified by extensive simulation.**

***Index Terms*— cognitive radio, dynamic spectrum access, spectrum sharing, channel assignment, spectrum handoff, blocking probability, interruption probability, forced termination probability**

I. INTRODUCTION

Cognitive radio, or Dynamic Spectrum Access (DSA), is an emerging communication paradigm to effectively address the spectrum insufficiency [1] [2]. Spectrum is a scarce and precious resource in wireless communication systems and networks. Cognitive radio refers to the potentiality that systems are aware of context and capable of reconfiguring themselves based on the surrounding environments and their own properties with respect to traffic load, congestion situation, network topology, and wireless channel propagation etc. This capability is particularly applicable to resolve heterogeneity, robustness, and openness, which are inherent challenges in the next-generation wireless communications systems. In the same frequency range, there are two coexisting systems: primary system and secondary system. Primary system refers to the licensed system with regulatory allocated spectrum. This system has the exclusive privilege to access the assigned spectrum range. Secondary system refers to the unlicensed cognitive system and can only opportunistically access the spectrum hole which is currently not used by the primary system. We call the subscriber in the primary system as Primary User (PU); and the subscriber in the secondary system as Secondary User (SU). Spectrum sharing strategy enables the secondary unlicensed system to dynamically access the licensed frequency bands in primary system without any modification to the devices, terminals, services, architectures and networks in the primary system [3]. In such case, the secondary system performs transparent for the primary system. Hence, on detecting the PU appearance in the particular frequency which is currently used by an SU, the SU has to vacate this frequency for the PU. At the same time, the SU will scan the frequency range and transfer its connection to another unused spectrum band, if available. This refers to spectrum handoff procedure.

Recently, there are few studies on the spectrum assignment [4]-[6]. In [4], a Markov Chain is presented to study controlled/uncontrolled channel assignment schemes in a spectrum sharing system. In [5], a model is developed to predict the behavior of open spectrum access in unlicensed bands. For the sake of analytical simplicity, the bandwidth in primary system and secondary system is respectively fixed as one and three. In [6], a channel reservation is reported for a spectrum sharing system. In the studies above, the forced termination probability and the non-completion probability during SU connection lifetime are not derived. In addition, an SU request will be directly blocked if there is no available resource. This may not be desirable.

In this paper, our contributions include three folds to advance the state-of-the-art in DSA networks. These aspects also indicate the major difference from the studies mentioned above. Firstly, we propose and analyze a new dynamic spectrum access scheme. To provide spectrum access priority, we consider the absence or presence of buffering mechanism for the cognitive SU, together with spectrum handoff capability. Spectrum handoff can be alternatively regarded as a priority policy for ongoing SU in service. Additionally, in stead of direct blocking SU requests, we introduce a finite queue to store the SU requests on their arrival when all bandwidth are occupied. When there is available spectrum later, the SU in the queue can use the freed bandwidth. It is noteworthy that performance of spectrum sharing with buffering mechanism is not theoretically investigated in the literature. Secondly, a Markov approach is developed to analyze the proposed spectrum sharing policy without/with buffering for the cognitive SU requests. The proposed model is general in terms of the size of bandwidth in the primary system and the secondary system. Performance metrics are developed with respect to SU blocking probability, SU interrupted probability, SU forced termination probability, SU non-completion probability and

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the ICC 2008 proceedings.

SU waiting time. Thirdly, numerical examples are presented to explore the interaction between key system parameters and performance metrics. It is found that the buffer is able to significantly reduce the SU blocking probability and non-completion probability with minor increased SU forced termination probability. The simulation result have been presented to validate the analysis.

To the best of our knowledge, there is no existing literature addressing the spectrum sharing in the presence of buffering for cognitive SU. Even for the spectrum sharing without buffer, there is no analysis validated by the simulation. The remainder of the paper is organized as follows. Section II presents the analytical model for the case in the absence of buffering for cognitive SU. Section III reports the analytic model for the case with buffer for cognitive SU. Section IV presents the analysis and simulation results. Section V concludes the work.

II. Spectrum Sharing without Buffering

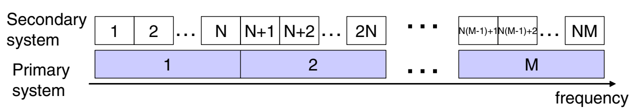

Fig. 1. System Model.

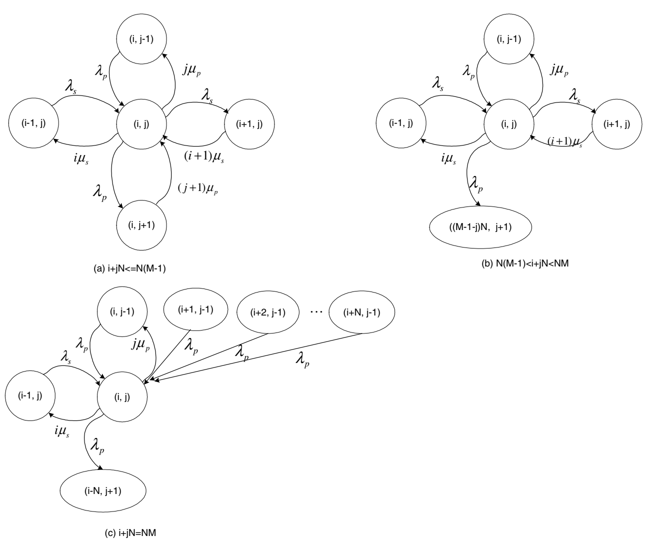

Fig. 2. System state transit for spectrum sharing without buffering.

Fig. 1 shows the spectrum sharing between the primary system and the secondary system. We define the term *band* as a bandwidth unit in the primary system; and the term *sub-band* as a bandwidth unit in the secondary system. Accordingly, a PU needs one band for service and an SU needs one sub-band for service. In the figure, M denotes the number of bands. Each band consists of N sub-bands. To avoid interference to PU, for a specific band used by a PU, the underlying N sub-bands are then unavailable for SU.

We assume that the PU and SU arrival processes follow Poisson process with the arrival rate λ_p and λ_s, respectively. The service times for PU and SU follow exponential distribution with mean $1/\mu_p$ and $1/\mu_s$, respectively. Let (i, j) represent the system state with i representing the number of sub-bands used by SU and j the number of bands used by PU. The state space Γ is given by

$$\Gamma = \{(i, j)|0 \le i \le NM; 0 \le j \le M; 0 \le i + jN \le NM\}$$

Let the indicator function $\mathbf{1}_{(i,j)}$ be equal to one if the state (i, j) is valid in the state space Γ, and zero otherwise. Let $\pi(i, j)$ be the steady state probability distribution for a valid state $(i, j) \in \Gamma$. Since a sub-band is unavailable if it is in the range of a busy band, for the state (i, j), the total number of busy sub-bands B_t is equal to the number of busy sub-bands for SU i plus N times the number of busy bands for PU, i.e. $B_t = i + jN$. The system dynamics are triggered by the following events: SU request arrival, SU service completion, PU request arrival and PU service completion. According to these events, the bandwidth access mechanism is defined as follows.

1) SU request arrival: For an SU request arrival, if there are free sub-bands, the SU is accepted and uses one unoccupied sub-band. If the total number of busy sub-bands B_t is equal to NM, the SU request is blocked.

2) SU service completion: When an SU completes its service, a sub-band is released.

3) PU request arrival: The bandwidth assignment for PU is transparent to the existence of SU. For a PU call connection arrival, if the number of PU in service is less than M, PU will use one band regardless whether there are SU in service over this band. If the total number of busy sub-bands B_t is no greater than $N(M-1)$, there is no terminated SU with spectrum handoff mechanism. However, in case the total number of busy sub-bands B_t is larger than $N(M-1)$, number of $B_t - N(M-1)$ SU in service is interrupted. The vacated sub-bands will be allocated to the PU request. In addition, in case the total number of busy sub-bands B_t is equal to NM and there are SU in service, N SU in service is interrupted. The vacated N sub-bands will constitute a single band and be allocated to the PU request. If the number of PU in service is M, the PU request is blocked.

4) PU service completion: When a PU completes its service, a band is released. This is equal to N sub-bands.

Fig. 2 shows the transit rate diagram. On the basis of the transit rate diagram, we develop the set of global balance equations. For the states satisfying $i + jN \le N(M-1)$ in Fig. 2(a),

$$\begin{aligned}(\lambda_s + i\mu_s + \lambda_p + j\mu_p)\pi(i, j) \\ = \lambda_s\pi(i-1, j) + (i+1)\mu_s\pi(i+1, j) \\ + \lambda_p\pi(i, j-1) + (j+1)\mu_p\pi(i, j+1) \qquad (1)\end{aligned}$$

For the states satisfying $N(M-1) < i + jN < NM$ in Fig. 2(b), the unique transition is due to a PU arrival and the interrupted SU.

$$
\begin{aligned}
&(\lambda_s + i\mu_s + \lambda_p \mathbf{1}_{((M-1-j)N,j+1)} + j\mu_p)\pi(i,j) \\
&= \lambda_s \pi(i-1,j) + (i+1)\mu_s \pi(i+1,j)\lambda_p \pi(i,j-1)
\end{aligned} \tag{2}
$$

For the states satisfying $i + jN = NM$ in Fig. 2(c), the unique transition is from a number of states $(m+r, j)$ $(m = 0, \cdots, N)$ directly into (i,j) due to a PU arrival.

$$
\begin{aligned}
&(i\mu_s + \lambda_p \mathbf{1}_{(i-N,j+1)} + j\mu_p)\pi(i,j) \\
&= \lambda_s \pi(i-1,j) + \lambda_p \sum_{m=0}^{N} \pi(i+m, j-1)
\end{aligned} \tag{3}
$$

In addition, the summation of all steady state probabilities satisfies the normalization constraint $\sum_{(i,j)\in\Gamma} \pi(i,j) = 1$. Combining the equations above, we can solve the set of the linear equations and consequently the steady state probability distribution. Therefore, the transit rate matrix, $\mathbf{Y}$, which governs the evolution of the multidimensional Markov chain, can be obtained. Let $\mathbf{\Pi}$ be the stationary state probability vector of the system and be in lexicographic order based on the state. Then, $\mathbf{\Pi}$ is the solution of linear equation $\mathbf{\Pi} = \mathbf{\Pi Y}$ and $\mathbf{\Pi e} = 1$ with $\mathbf{e}$ representing the column vector with all ones. The set of linear equations can be solved by using an iterative method SOR [7]. We present the SOR algorithm to calculate the steady state probability as follows:

1) Construct the matrix $\mathbf{Y}$;
2) Let the convergence criteria be ϵ, the relaxation factor be $\omega (1 \le \omega < 2)$;
3) Let initial state probability be $\mathbf{\Pi}^{(0)}$;
4) Repeat and calculate

$$
\mathbf{\Pi}^{(n)} = \omega \mathbf{\Pi}^{(n-1)} \mathbf{Y} + (1-\omega)\mathbf{\Pi}^{(n-1)} \tag{4}
$$

until the following inequality is held, or

$$
\sum_{y=1}^{\text{Total states in } \Gamma} \frac{\left| \mathbf{\Pi}_y^{(n)} - \mathbf{\Pi}_y^{(n-1)} \right|}{\left| \mathbf{\Pi}_y^{(n)} + \mathbf{\Pi}_y^{(n-1)} \right|} < \epsilon. \tag{5}
$$

5) Output the steady state probability $\mathbf{\Pi}$.

A. *Performance Metrics*

An SU is blocked when all bands and sub-bands are occupied. Hence, the SU blocking probability P_b is given by

$$
P_b = \sum_{\{(i,j)\in\Gamma | i+jN=NM\}} \pi(i,j) \tag{6}
$$

For an accepted SU, it may be interrupted during its service owing to a PU arrival. Let P_{Int} denote the probability that an SU is interrupted. We suppose the system state (i,j) upon the moment of a PU arrival. Two situations are considered to calculate P_{Int}. In case the number of total number of sub-bands $(i+jN)$ is greater than $N(M-1)$ and less than NM, the number of interrupted SU is equal to $i + jN - N(M-1)$. As a result, the SU interrupted probability in such situation P_{Int1} is given by

$$
P_{Int1} = \sum_{\{(i,j)\in\Gamma | N(M-1) < i+jN < NM\}} \frac{i + jN - N(M-1)}{i} \pi(i,j) \tag{7}
$$

In another case, when all bands and sub-bands are busy and there are SU in service, the number of interrupted SU is N. As a result, the SU interrupted probability in such situation P_{Int2} is given by

$$
P_{Int2} = \sum_{\{(i,j)\in\Gamma | i+jN=NM, i>0\}} \frac{N}{i} \pi(i,j) \tag{8}
$$

Combining the two situations above and under the condition that there are SU in service, we obtain the SU interrupted probability P_{Int} as follows

$$
P_{Int} = \frac{P_{Int1} + P_{Int2}}{\sum_{\{(i,j)\in\Gamma | i>0\}} \pi(i,j)} \tag{9}
$$

During an SU lifetime, a number of PU may arrive. For each PU arrival event, the SU may be interrupted with probability P_{Int}. Hence, during an SU lifetime, it may have a number of possibility to be interrupted. Let P_{ft} denote the SU forced termination probability, which is defined as the probability that an SU is forced to termination due to PU arrival. Let t_s denote the service time of an SU. Let $t_{p,1}$ denote the period from the SU service starting moment to the instant of the immediate next PU arrival. In addition, let $t_{p,r} (r = 2, 3, \cdots)$ denote the period between PU arrivals after the first PU arrival. Then, $t_{p,r}$ follows the exponential distribution with mean $1/\lambda_p$. The forced termination probability is given by

$$
P_{ft} = \sum_{r=1}^{\infty} Pr\left(t_s > \sum_{u=1}^{r} t_{p,u} \right) (1 - P_{Int})^{r-1} P_{Int} \tag{10}
$$

Denote $\xi_r = \sum_{u=1}^{r} t_{p,u}$. Then, ξ_r is an Erlang distributed random variable with parameter λ_p and r [8]. Its probability density function (pdf) $f_{\xi_r}(t)$ and the Laplace Transform of its pdf $f^*_{\xi_r}(s)$ are given by

$$
f_{\xi_r}(t) = \frac{\lambda_p (\lambda_p t)^{r-1}}{(r-1)!} e^{-\lambda_p t}; \quad f^*_{\xi_r}(s) = \left(\frac{\lambda_p}{s + \lambda_p} \right)^r
$$

In (10), we have

$$
\begin{aligned}
Pr\left(t_s > \sum_{u=1}^{r} t_{p,u} \right) &= \int_0^{\infty} f_{\xi_r}(t)[1 - F_{t_s}(t)]dt \\
&= \left(\frac{\lambda_p}{\mu_s + \lambda_p} \right)^r
\end{aligned}
$$

Substituting the result above into (10), we have

$$
\begin{aligned}
P_{ft} &= \sum_{r=1}^{\infty} \left(\frac{\lambda_p}{\mu_s + \lambda_p} \right)^r (1 - P_{Int})^{r-1} P_{Int} \\
&= \frac{\lambda_p P_{Int}}{\mu_s + \lambda_p P_{Int}}
\end{aligned} \tag{11}
$$

Another important performance metric is the probability that an SU request is not completed, i.e.SU non-completion probability P_{nc}. An SU is not completed when it is blocked upon the moment of its arrival or when it is forced to termination.

$$P_{nc} = P_b + (1 - P_b)P_{ft} \tag{12}$$

III. Spectrum Sharing with Buffering

A finite queue with length Q is introduced to save SU requests in case all sub-bands are occupied. Let (i, j, k) represent the system state with i representing the number of sub-bands used by SU, j the number of bands used by PU and k the number of SU requests saved in the queue. The state space Γ_B is given by

$$\begin{aligned}\Gamma_B = \{(i, j, k)|0 \le i \le NM; 0 \le j \le M;\\ 0 \le i + jN \le NM; 0 \le k \le Q\}\end{aligned} \tag{13}$$

Let $\mathbf{1}_{(i,j,k)}$ be equal to one if the state (i, j, k) is a valid state in the state space Γ_B, and zero otherwise. Let $\pi(i, j, k)$ be the steady state probability distribution for a valid state $(i, j, k) \in \Gamma_B$. The system dynamics are triggered by the following events: SU request arrival, SU service completion, PU request arrival and PU service completion. According to these events, the spectrum access mechanism is defined as follows.

1) SU request arrival: For an SU request arrival, if there are free sub-bands, the SU is accepted and uses one unoccupied sub-band. If the total number of busy sub-bands B_t is equal to NM and the queue is not full, the SU request is inserted into the tail of the queue. If the total number of busy sub-bands B_t is equal to NM and the queue is full, the SU request is blocked.

2) SU service completion: When an SU completes its service, a sub-band is released. If the queue is not empty, the top SU request will use this newly released sub-band.

3) PU request arrival: Similarly, the bandwidth assignment for PU is transparent to the existence of SU. For a PU call connection arrival, if the number of PU in service is less than M, PU will use one band regardless whether there are SU in service over this band. If the total number of busy sub-bands B_t is no greater than $N(M-1)$, there is no terminated SU with the help of spectrum handoff mechanism. However, in case the total number of busy sub-bands B_t is larger than $N(M - 1)$, number of $B_t - N(M - 1)$ SU in service is interrupted. The vacated sub-bands will be allocated to the PU request. In addition, in case the total number of busy sub-bands B_t is equal to NM and there are SU in service, N SU in service is interrupted. The vacated N sub-bands will constitute a single band and be allocated to the PU request. If the number of PU in service is M, the PU request is blocked.

4) PU service completion: When a PU completes its service, a band is released. This is equivalent with N sub-bands. If the queue is not empty with length k, $\min(k, N)$ SU requests will be deleted from the queue and occupy the newly released sub-bands. If the queue is empty, the released sub-bands N are kept free.

Fig. 3 shows the transit rate diagram. Comparing the transit rate diagram without buffering, this diagram indicates significantly different system dynamics due to the introduced queue, especially the state transit between non-neighboring states. For the states satisfying $i + jN \le N(M - 1), k = 0$,

$$\begin{aligned}&(\lambda_s + i\mu_s + \lambda_p + j\mu_p)\pi(i, j, 0)\\ &= \lambda_s\pi(i - 1, j, 0) + (i + 1)\mu_s\pi(i + 1, j, 0)\\ &\quad + \lambda_p\pi(i, j - 1, 0) + (j + 1)\mu_p\pi(i, j + 1, 0)\end{aligned} \tag{14}$$

For the states satisfying $N(M-1) < i+jN < NM; k = 0$,

$$\begin{aligned}&(\lambda_s + i\mu_s + \lambda_p\mathbf{1}_{((M-1-j)N,j+1,0)} + j\mu_p)\pi(i, j, 0)\\ &= \lambda_s\pi(i - 1, j, 0)\\ &\quad + (i + 1)\mu_s\pi(i + 1, j, 0)\lambda_p\pi(i, j - 1, 0)\\ &\quad + (j + 1)\mu_p \sum_{m=i-N}^{NM-(j+1)N} \pi(m, j + 1, i - m)\end{aligned} \tag{15}$$

For the states satisfying $i + jN = NM; k = 0$,

$$\begin{aligned}&(\lambda_s + i\mu_s + \lambda_p\mathbf{1}_{(i-N,j+1,0)} + j\mu_p)\pi(i, j, 0)\\ &= \lambda_s\pi(i - 1, j, 0) + (i + 1)\mu_s\pi(i + 1, j, 1)\\ &\quad + (j + 1)\mu_p\mathbf{1}_{(i-N,j+1,N)}\pi(i - N, j + 1, N)\\ &\quad + \lambda_p \sum_{m=0}^{N} \pi(i + m, j - 1, 0)\end{aligned} \tag{16}$$

For the states satisfying $i + jN = NM; 0 < k \le Q$,

$$\begin{aligned}&(\lambda_s + i\mu_s + \lambda_p\mathbf{1}_{(i-N,j+1,k)}\\ &+ j\mu_p\mathbf{1}_{(i+\min(k,N),j-1,k-\min(k,N))})\pi(i, j, k)\\ &= \lambda_s\pi(i, j, k - 1) + i\mu_s\pi(i, j, k + 1)\\ &\quad + (j + 1)\mu_p\mathbf{1}_{(i-N,j+1,k+N)}\pi(i - N, j + 1, k + N)\\ &\quad + \lambda_p\pi(i + N, j - 1, k)\end{aligned} \tag{17}$$

In addition, the summation of all steady state probabilities satisfies the normalization constraint $\sum_{(i,j,k)\in\Gamma_B} \pi(i, j, k) = 1$. Following the similar SOR algorith in the previous section, we can solve the set of the linear equations and consequently the steady state probability distribution.

A. Performance Metrics

An SU is blocked when all bands and sub-bands are occupied and the queue is full. Hence, the SU blocking probability P_b is given by

$$P_b = \sum_{\{(i,j,k)\in\Gamma_B|i+jN=NM,k=Q\}} \pi(i, j, k) \tag{18}$$

For an accepted SU in service, it may be interrupted due to a PU arrival. We suppose the system state (i, j, k) upon the moment of a PU arrival. Two situations are considered to calculate the interruption probability. In case the total number of sub-bands $(i+jN)$ is greater than $N(M-1)$ and less than NM, the number of interrupted SU is $[i + jN - N(M - 1)]$.

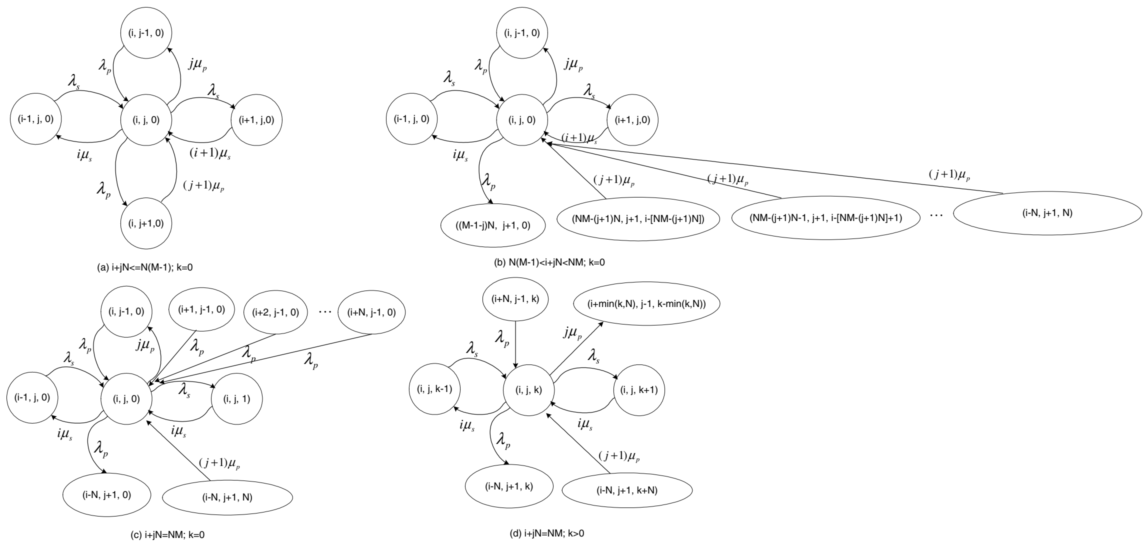

Fig. 3. System state transit for spectrum sharing with buffering.

As a results, the SU interrupted probability in such situation P_{Int1} is given by

$$P_{Int1} = \sum_{\{(i,j,k)\in\Gamma_B | N(M-1)<i+jN<NM\}} \frac{i+jN-N(M-1)}{i}\pi(i,j,k) \quad (19)$$

In another case, when all bands and sub-bands are busy and there are SU in service, the number of interrupted SU is N. As a result, the SU interrupted probability in such situation P_{Int2} is given by

$$P_{Int2} = \sum_{\{(i,j,k)\in\Gamma_B | i+jN=NM, i>0\}} \frac{N}{i}\pi(i,j,k) \quad (20)$$

Combining the two situations above and under the condition that there are SU in service, we obtain the SU interrupted probability P_{Int} as follows

$$P_{Int} = \frac{P_{Int1}+P_{Int2}}{\sum_{\{(i,j,k)\in\Gamma_B | i>0\}} \pi(i,j,k)} \quad (21)$$

Following the similar reasoning in the previous section, the SU forced termination probability P_{ft} and SU non-completion probability P_{nc} are given by

$$P_{ft} = \frac{\lambda_p P_{Int}}{\mu_s + \lambda_p P_{Int}} \quad (22)$$

$$P_{nc} = P_b + (1-P_b)P_{ft} \quad (23)$$

With the introduced queue for cognitive SU, the SU request may wait in the buffer before capturing a sub-band. The average queue length is given by

$$\overline{q} = \sum_{\{(i,j,k)\in\Gamma_B | i+jN=NM, 0<k\le Q\}} k\pi(i,j,k) \quad (24)$$

Let $P_{buffering}$ denote the probability that an SU will save in the buffer. This will take place when there is no free bands or sub-bands and the buffer is not full.

$$P_{buffering} = \sum_{\{(i,j,k)\in\Gamma_B | i+jN=NM, 0\le k<Q\}} \pi(i,j,k) \quad (25)$$

Consequently, for the buffering SU in the queue, the average waiting time W is given by

$$W = \frac{\overline{q}}{\lambda_s P_{buffering}} = \frac{\sum_{\{(i,j,k)\in\Gamma_B | i+jN=NM, 0<k\le Q\}} k\pi(i,j,k)}{\lambda_s \sum_{\{(i,j,k)\in\Gamma_B | i+jN=NM, 0\le k<Q\}} \pi(i,j,k)} \quad (26)$$

IV. Numerical Results

To validate the analytical model, a discrete-event simulation program in C++ is developed. Illustrative numerical examples are presented to demonstrate the interaction between the performance metrics and critical settings. If not specified, we choose the following default parameters: $M = 3$, $N = 6$, $\mu_s = 0.82$ and $\mu_p = 0.06$. Fig.4 shows the performance metrics in terms of SU request arrival rate λ_s with different queue length Q. In this example, $\lambda_p = 0.2\lambda_s$. In each figure, there are three curves. The solid line represents the result without buffer. The dashed line and dash-dot line represent the result with buffer length $Q = 2$ and $Q = 4$, respectively. The simulation results are presented (indicated by symbol) to validate the analytical model. It is clear that the simulation and analysis match with each other very well. It is observed that the blocking probability, forced termination and non-completion probability increases with higher SU arrival rate, which is intuitively understandable. The comparison indicates that the SU blocking probability P_b and the non-completion probability P_{nc} reduces significantly with minor increased forced termination probability P_{ft}. With longer queue, the

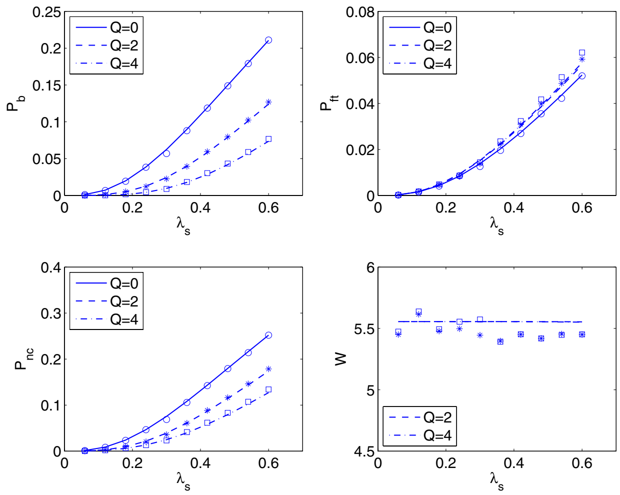

Fig. 4. Performance metrics in terms of SU arrival rate λ_s. The symbol '$\circ$' indicates the simulation result without buffering. The symbol '$*$' indicates the simulation result when $Q = 2$. The symbol '$\square$' indicates the simulation result when $Q = 4$.

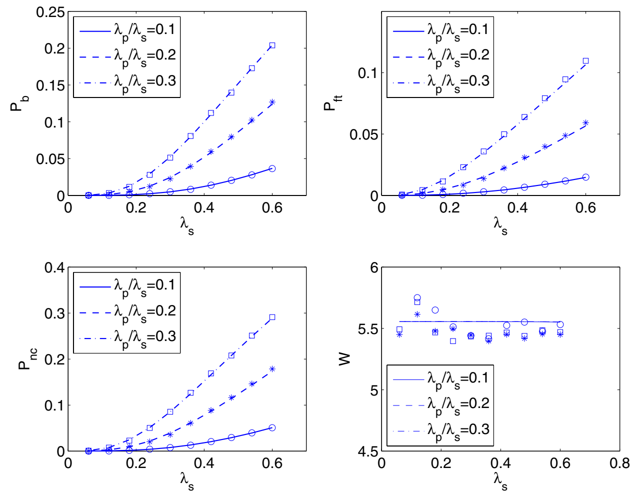

Fig. 5. Performance metrics in terms of SU arrival rate λ_s. The symbol '$\circ$' indicates the simulation result when $\lambda_p = 0.1\lambda_s$. The symbol '$*$' indicates the simulation result when $\lambda_p = 0.2\lambda_s$. The symbol '$\square$' indicates the simulation result when $\lambda_p = 0.3\lambda_s$.

SU blocking probability P_b and non-completion probability P_{nc} reduction becomes more significant. For the performance tradeoff on waiting time W, an advantage is that W almost keeps unchanged with increasing λ_s due to the finite size queue.

Fig. 5 shows the performance metrics in terms of SU request arrival rate λ_s with different PU arrival rate λ_p. In this instance, the queue length is fixed as $Q = 2$. Again, the analysis is consistent with the simulation. The blocking probability P_b increases with greater λ_p due to heavier traffic load to the primary system and consequently higher total traffic load over the limited bandwidth. The forced termination probability becomes larger with greater λ_p. With more PU arrivals, SU has the higher possibility to be interrupted and hence higher P_{ft}. The increased P_b and P_{ft} lead to more non-completed SU, i.e. higher P_{nc}.

V. Conclusions

New dynamic spectrum access schemes are proposed for cognitive radio wireless networks without and with buffering for the cognitive SU to avoid direct blocking. A Markov approach is developed to analyze the proposed spectrum sharing policies. Performance metrics for SU are developed with respect to blocking probability, interrupted probability, forced termination probability, non-completion probability and waiting time. The result indicate that the buffer is able to significantly reduce the SU blocking probability and non-completion probability with very minor increased forced termination probability. The analytic model has been verified by the simulation.

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