

Cognitive Radio Spectrum Access with Prioritized Secondary Users

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Abstract: Cognitive radio has been widely studied as one of the potential approaches for inefficient usage of frequency resources. In cognitive networks, secondary users not having a license for spectrum usage are allowed to opportunistically occupy an idle spectrum owned by a licensee named primary user. This paper considers multiple primary channels and three types of calls: primary calls, high priority secondary calls, and low priority secondary calls. The primary calls have the highest priority to use the channels and can reclaim any channel used by secondary ones. Therefore, the presence of secondary calls is entirely transparent to the primary ones. In this paper, a channel reservation scheme for high priority secondary calls is considered to reduce their blocking probability. Numerical results indicate that the channel reservation scheme can cause performance degradation such as significant increase of blocking probability and significant decrease of throughput for low priority secondary calls. To compensate the performance degradation due to channel reservation, we introduce a buffer for low priority secondary calls. Analytic model is suggested to characterize the effect of the channel reservation and the buffering on performance of secondary calls. Based on this model, we evaluate the blocking probability, the forced termination probability, and the throughput for both high and low priority secondary calls under various buffer sizes. Mathematical analysis shows that the buffering of low priority secondary calls can significantly decrease their blocking probability and increase their throughput.

Keywords: Cognitive Radio, Queueing System, Prioritized Secondary User

1 Introduction

Reports of spectrum efficiency reveal that a considerable region of the spectrum remains unused across both space and time [1]. As a solution for such inefficient spectrum usage, so-called cognitive radio (CR) has been intensively studied. Under this system, a secondary user (SU) that does not have a license to use the spectrum is allowed to opportunistically occupy an idle spectrum band owned by a licensee that is termed the primary user (PU) [2,3]. The transmissions of SU in CR networks can be effectively managed by dynamic spectrum access policy. Using the dynamic spectrum access policy, the SU calls are assigned

unused channels in the PU spectrum [4]. The opportunistic usage of spectrum may cause frequent spectrum handovers. In the event that a newly arriving PU accesses a channel, the transmission of a SU call on the channel, if any, is either reassigned to another unused licensed channel (i.e., handover occurs) or terminated (i.e., forced termination occurs). Thus, during spectrum access, the PU calls have a higher priority over the SU ones.

In most of CR literature, the total number of priority classes across all users in CR networks is assumed to be two; high priority class for PU calls and low priority class for SU calls. Lee [5]

developed an analytical model to evaluate performance of SU calls under non-saturation traffic conditions. Shin et al. [6] developed a preemptive priority queueing model to evaluate the system dwelling time of SU calls. Lee and Lee [7] developed a mathematical model to evaluate a CR network with single SU under non-saturation traffic conditions. Lee [8] proposed a simple approximate model for a CR network with multiple SUs. However, the above works did not consider prioritization among SU calls.

In this paper, we consider prioritization among SU calls while accessing licensed channels. The prioritization among SU calls can be determined based on their applications or prices paid for spectrum access [9]. For example, the SU calls with real-time traffic have higher priority than those with non real-time traffic. Only a few works [10,11,12] have taken prioritized SU calls into consideration. Wiggins et al. [10] and Gosh et al. [11] have not addressed the issue of spectrum handover under prioritized SU calls. Tumuluru et al. [12] developed two different dynamic spectrum access policies to handle the spectrum assignment and handover for SU calls with two priority classes. Developing analytical models for the two proposed policies, they investigated the case of channel reservation for high priority SU calls.

From our numerical results, we see that the channel reservation can degrade significantly the performance such as the blocking probability and the throughput of low priority SU calls. To compensate the performance degradation due to the channel reservation, we introduce a buffer for low priority SU calls. We develop an analytical model for CR network with channel reservation for high priority SU calls and a buffer for low priority SU calls. The performance of the CR network is evaluated in terms of the blocking probability, the forced termination probability, and the throughput for both high and low priority SUs.

2 Network Model

We assume that there are primary channels (indexed from 0 to $N-1$) available for transmissions by the primary and secondary users. The secondary user calls are classified into two priority classes. The high and low priority secondary user calls are denoted as SU1 and SU2 calls, respectively. We also assume that there is a buffer of size K for low priority SU2 calls, as shown in figure 1. The PU calls have the highest priority in accessing the channels.

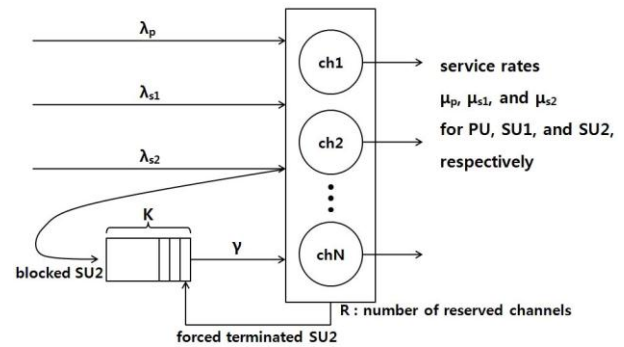


Figure 1: Illustration of the queueing model

Call arrivals of PU, SU1, and SU2 calls occur independently as Poisson processes with arrival rates λ_p , λ_{s1} , and λ_{s2} , respectively. An arriving high priority SU1 call is assigned one channel if there is at least one idle channel. Otherwise, if there are no idle channels, the SU1 call is blocked. However, a newly arriving SU2 call is assigned one channel only if the total number of idle channels is more than R , which is the number of channels reserved for high priority SU1 calls. Otherwise, if the total number of idle channels is less than or equal to R , the low priority SU2 call goes into the buffer and waits for retrial at the end of the buffer if the buffer is not full. If the buffer has already been full, the low priority SU2 call is blocked.

An arriving PU call is assigned one channel if there is at least one channel not occupied by other PU calls. The PU call can claim one of channels occupied by SU calls. When an arriving PU call claims a channel occupied by a SU call, the handoff mechanism is initiated. When a high priority SU1 call is interrupted, the interrupted SU1 call is assigned an idle channel, if any. If there are no idle channels, an ongoing SU2 call, if any, is terminated and the resulting idle channel is assigned to the interrupted SU1 call. If there are no idle channels and no ongoing SU2 calls, the interrupted SU1 call will be terminated. When a low priority SU2 call is interrupted, the interrupted SU2 call is assigned an idle channel, if any. If there are no idle channels, the interrupted SU2 call will be terminated. Every terminated SU2 call goes to the buffer and waits for retrial at the head of line of the buffer. In this case, if the buffer has already been full, a low priority SU2 call at the end of the buffer is pushed out by the terminated SU2 call. The low priority SU2 call at the head of line of the buffer will try to access an idle channel at exponential rate γ .

The service times independently follow exponential distributions with service rates μ_p ,

μ_{S1} , and μ_{S2} for primary user PU, high priority SU1, and low priority SU2 calls, respectively.

3 Performance Analysis

In this section, we develop an analytical model for CR network using continuous time Markov chain.

The state of the continuous time Markov chain is defined as (i, j, k, l) , where i , $0 \leq i \leq N$, represents the number of PU calls in transmission, j , $0 \leq j \leq N$, represents the number of high priority SU1 calls in transmission, k , $0 \leq k \leq N-R$, represents the number of low priority SU2 calls in transmission, and l , $0 \leq l \leq N$, represents the number of SU2 calls in the buffer. Since the total number of occupied channels in state (i, j, k, l) is calculated as $i + j + k$, the value $i + j + k$ should not exceed N for a valid state.

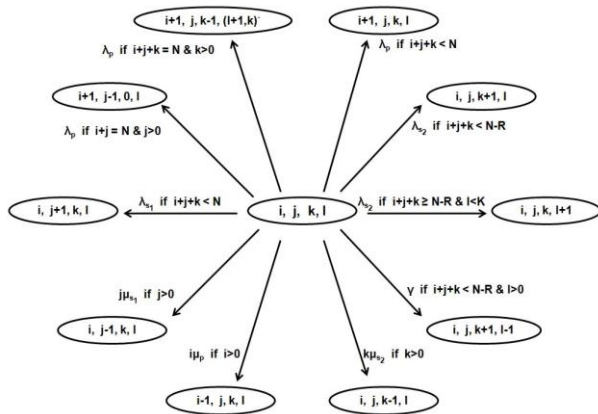


Figure 2: State transitions from state (i, j, k, l) with $0 \leq i + j + k \leq N$, $0 \leq k \leq N - R$, and $0 \leq l \leq K$.

The state transition diagram from state (i, j, k, l) is illustrated in figure 2, where $(a, b)^-$ denotes the minimum of a and b . State transitions from state (i, j, k, l) occur due to any one of the seven possible events, namely PU call arrival, SU1 call arrival, SU2 call arrival, PU call departure, SU1 call departure, SU2 call departure, and SU2 call retrial. Each state transition is represented by transition path, corresponding rate and possible condition.

Let $\{\pi(i, j, k, l)\}$ denote the steady state probability distribution of the continuous time Markov chain. The distribution $\{\pi(i, j, k, l)\}$ is easily obtained by finding the corresponding state transition rate matrix and applying the Gauss-Seidel method [13].

The performance measures for SU calls are expressed using the steady state probability distribution $\{\pi(i, j, k, l)\}$ of its continuous time Markov chain. We derive performance measures such as blocking probability, forced termination probability, and throughput for both high and low priority SU calls.

The blocking probability is defined as the probability that a SU call is not permitted to access channels and blocked. An arriving SU1 call is blocked if there are no idle channels. Thus, the blocking probability of high priority SU1 calls, denoted as P_{B1} , is expressed as in (3.1).

$$P_{B1} = \sum_{l=0}^K \sum_{k=0}^{N-R} \sum_{j=0}^{N-k} \pi(N-j-k, j, k, l) \quad (3.1)$$

An arriving SU2 call is blocked if the total number of idle channels is less than $N-R$ and the buffer is full. The low priority SU2 calls pushed out by PU calls or terminated SU2 calls are also considered to be blocked. The blocking probability of low priority SU2 calls, denoted as P_{B2} , is expressed as follows.

$$P_{B2} = \sum_{k=0}^{N-R} \sum_{j=0}^{N-k} \sum_{i=N-R-j-k}^{N-j-k} \pi(i, j, k, K) + \frac{\lambda_p}{\lambda_{s2}} \sum_{k=1}^{N-R} \sum_{j=0}^{N-k} \pi(N-j-k, j, k, K) \quad (3.2)$$

Note that the first term in (3.2) corresponds to the blocking of arriving SU2 calls, and the second term in (3.2) corresponds to the blocking of waiting SU2 calls pushed out by PU calls or terminated SU2 calls.

The forced termination probability is defined as the probability that an ongoing SU call is terminated by an incoming PU call. The forced termination probability for high priority SU1 calls, denoted as P_{F1} , is expressed as follows:

$$P_{F1} = \frac{\lambda_p \sum_{l=0}^K \sum_{j=1}^N \pi(N-j, j, 0, l)}{\lambda_{s1} (1 - P_{B1})} \quad (3.3)$$

To obtain the forced termination probability for low priority SU2 calls, we first calculate the channel access rate α (that is, the mean number of channel access per unit time) for low priority SU2 calls as follows:

$$\alpha = (\lambda_{s2} + \gamma) \sum_{l=0}^K \sum_{k=0}^{N-R-1} \sum_{j=0}^{N-R-k-1} \sum_{i=0}^{N-R-j-k-1} \pi(i, j, k, l) - \gamma \sum_{k=0}^{N-R-1} \sum_{j=0}^{N-R-k-1} \sum_{i=0}^{N-R-j-k-1} \pi(i, j, k, 0) \quad (3.4)$$

Thus, the forced termination probability for low priority SU2 calls, denoted as P_{F2} , is expressed as follows:

$$P_{F2} = \frac{\lambda_p}{\alpha} \sum_{l=0}^K \sum_{k=1}^{N-R} \sum_{j=0}^{N-k} \pi(N-j-k, j, k, l) \quad (3.5)$$

The throughput is defined as the mean number of successfully transmitted calls per unit time. Let ρ_{s1} and ρ_{s2} denote the throughput for high priority SU1 calls and low priority SU2 calls, respectively. The throughput ρ_{s1} for high priority SU1 calls is given by (3.6).

$$\rho_{s1} = \lambda_{s1} (1 - P_{B1}) (1 - P_{F1}) \quad (3.6)$$

And the throughput ρ_{s2} is given by (3.7).

$$\rho_{s2} = \lambda_{s2} (1 - P_{B2}) \quad (3.7)$$

4 Results and Discussion

In this section, numerical results are obtained for the blocking probability, the forced termination probability, and the throughput for both high and low priority SU calls. The parameters used in our experiment are as follows: the number of channels N is 5; the arrival rates λ_{s1} and λ_{s2} of SU1 and SU2 calls are set to 0.4; the service rates μ_p , μ_{s1} , and μ_{s2} of PU, SU1, and SU2 calls are 0.3, 0.8, and 0.8, respectively; the retrial rate γ of low priority SU2 call in the head of line of the buffer is 0.8; the number of reserved channels R is set to 0 and 2.

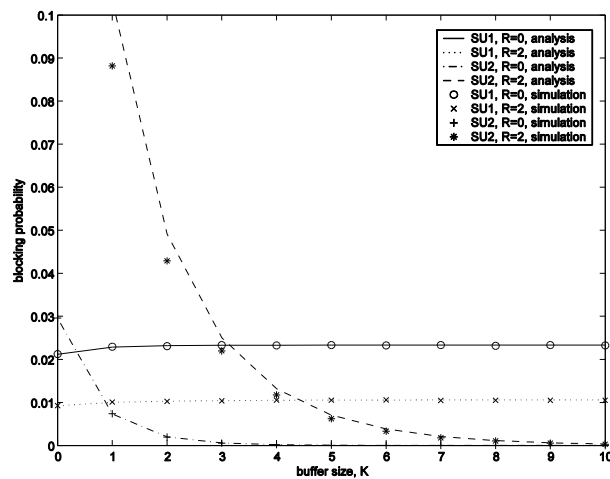


Figure 3: Blocking probabilities of SU1 and SU2 calls when $\lambda_p = 0.2$.

Figure 3 shows the blocking probabilities of high priority SU1 calls and low priority SU2 calls as functions of the buffer size K . The arrival rate λ_p of PU calls is set to 0.2 and the number of reserved channels R is set to 0 and 2 for this experiment. In case of no buffer (that is, $K=0$), it can be seen that the channel reservation scheme (in

case of $R=2$) decreases the blocking probability of high priority SU1 calls while it significantly increases that of low priority SU2 calls. Figure 3 also shows that with an increasing buffer size K , there is a noticeable decrease in the blocking probabilities of low priority SU2 calls for both $R=0$ and $R=2$, whereas there is almost no change in those of high priority SU1 calls. Note the excellent agreement between the analytical and simulation results in figure 3.

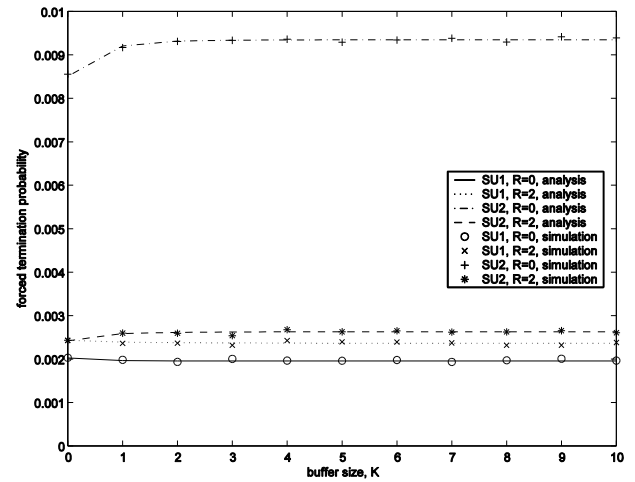


Figure 4: Forced termination probabilities of SU1 and SU2 calls when $\lambda_p = 0.2$.

Figure 4 shows the forced termination probabilities of high priority SU1 and low priority SU2 calls as functions of the buffer size K when the arrival rate of PU calls is $\lambda_p = 0.2$. It can be observed that the channel reservation scheme (in case of $R=2$) increases the forced termination probability of high priority SU1 calls while it decreases that of low priority SU2 calls. Figure 4 also shows that with an increasing buffer size K , there is very small change in all the forced termination probabilities of high priority SU1 calls and low priority SU2 calls.

Figure 5 shows the throughputs of high priority SU1 and low priority SU2 calls as functions of the buffer size K . The arrival rate λ_p is set to 0.2 and the number of reserved channels R is set to 0 and 2 for this experiment. In case of no buffer (that is, $K=0$), it can be seen that the channel reservation scheme (in case of $R=2$) increases a little the throughput of high priority SU1 calls while it significantly decreases the throughput of low priority SU2 calls. Figure 5 also shows that as the buffer size K increases, there is a noticeable increase in the throughput of low priority SU2 calls with channel reservation (in case of $R=2$), whereas

there is almost no change in the throughputs of low priority SU2 calls without channel reservation (in case of $R=0$), and there is also almost no change in the throughputs of high priority SU1 calls with/without channel reservation.

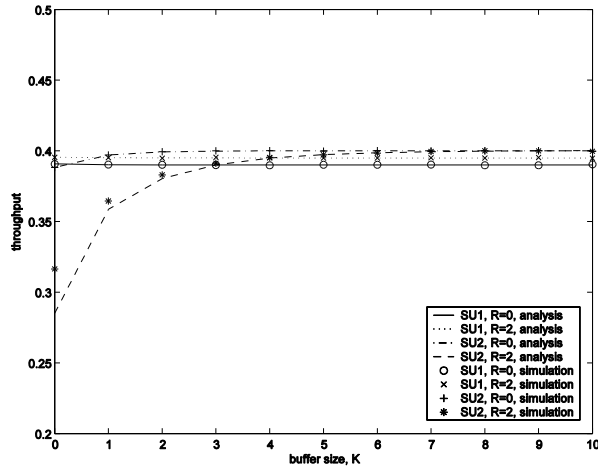


Figure 5: Throughputs of SU1 and SU2 calls when $\lambda_p = 0.2$.

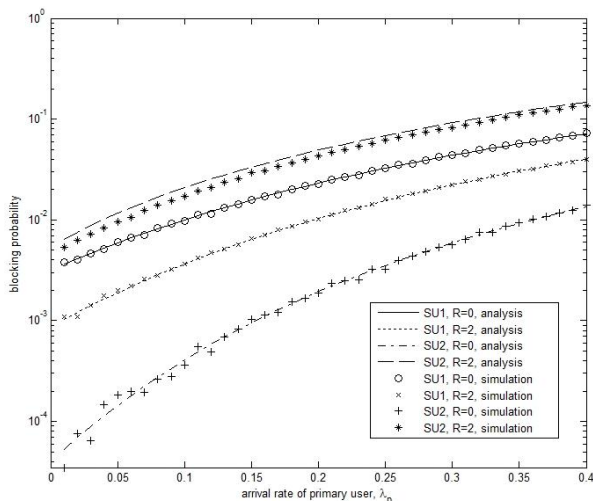


Figure 6: Throughputs Blocking probabilities of SU1 and SU2 calls when $K = 2$.

Figure 6 shows the blocking probabilities of high priority SU1 and low priority SU2 calls as functions of the arrival rate λ_p of PU calls. The buffer size K is set to 2 for this experiment. In case of no reserved channels (that is, $R=0$), the blocking probability of low priority SU2 calls is smaller than that of high priority SU1 calls due to the existence of the buffer for low priority SU2 calls. However, when the number of reserved channels R is 2, the blocking probability of high priority SU1 calls appears to be smaller than that of low priority SU2 calls.

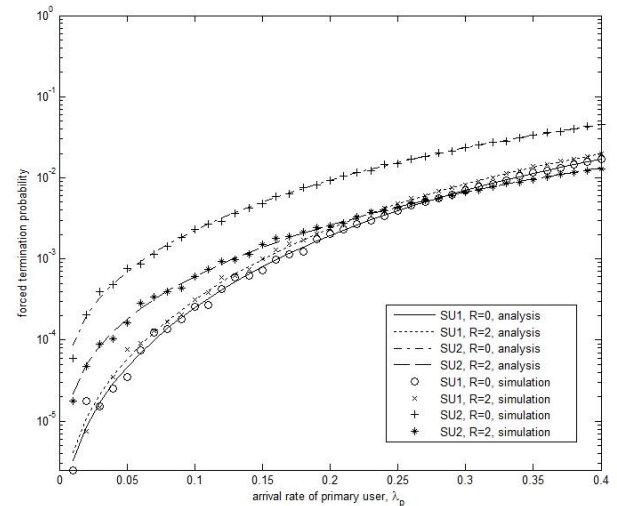


Figure 7: Forced termination probabilities of SU1 and SU2 calls when $K = 2$.

Figure 7 shows the forced termination probabilities of SU1 and SU2 calls as functions of the arrival rate λ_p of PU calls when the buffer size K is set to 2 for this experiment. It can be observed that the forced termination probabilities for all cases increase as λ_p increases. In case of no channel reservation scheme (that is, $R=0$), it can be seen that the forced termination probability of SU1 calls appear to be smaller than that of SU2 calls. When R is 2, for small λ_p the forced termination probability of high priority SU1 calls is also smaller than that of low priority SU2 calls. The difference between the forced termination probabilities of high priority SU1 and low priority SU2 calls decreases as the arrival rate λ_p of PU calls increases until the arrival rate is about 0.23. When the arrival rate λ_p of PU calls is larger than 0.23, the forced termination probability of high priority SU1 calls is larger than that of low priority SU2 calls because the high priority SU1 calls have more opportunities to access idle channels owing to the channel reservation scheme and so they have more possibility to be terminated by the arrivals of increasing PU calls.

Figure 8 shows the throughput of SU1 and SU2 calls as functions of the arrival rate λ_p of PU calls. The buffer size K is set to 2. It can be observed that the throughputs for all cases decrease slowly as λ_p increases. In case of no channel reservation scheme (that is, $R=0$), the throughput of low priority SU2 calls appear to be larger than that of high priority SU1 calls due to the existence of the buffer for low priority SU2 calls. However, when the number of reserved channels R is 2, the

throughput of high priority SU1 calls appears to be larger than that of low priority SU2 calls.

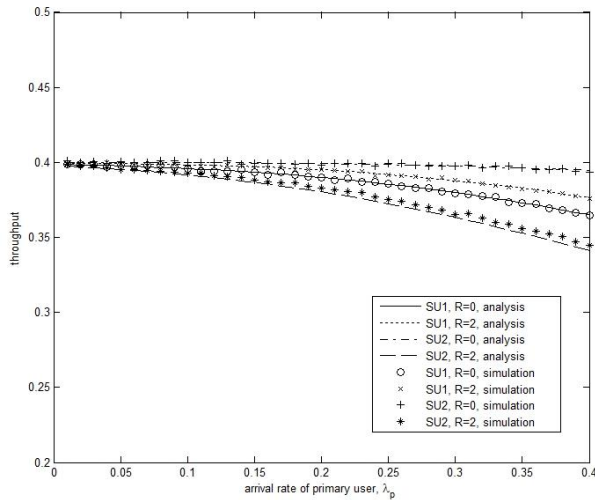


Figure 8: Throughputs of SU1 and SU2 calls when $K = 2$.

5 Conclusion

We investigated a dynamic spectrum access in cognitive radio networks, where secondary calls are prioritized into two priority classes, high priority secondary calls and low priority secondary calls. Channel reservation scheme for the high priority secondary calls was also investigated. Numerical results indicated that the channel reservation scheme can cause the performance degradation such as significant increase of blocking probability and significant decrease of throughput for low priority secondary calls. To compensate the performance degradation due to the channel reservation, we introduced a buffer for low priority secondary calls. Analytic model was suggested to characterize the effect of the channel reservation and the buffer on the performance of secondary calls. Based on this model, we evaluated the blocking probability, the forced termination probability, and the throughput for both high and low priority secondary calls under various buffer sizes. Numerical results showed that the buffer for low priority secondary calls can significantly decrease their blocking probability and increase their throughput.

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