Dynamic Spectrum Access Strategy for Multi-Channel Cognitive Radio Networks

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Abstract

In this paper, we present a dynamic spectrum access strategy to reduce the average overall system time of secondary users (SUs) in multi-channel cognitive radio networks. Before transmitting a packet, SU senses the spectrum environment. If there are free channels in the system, SU randomly selects one for transmitting. If all the channels are busy, we consider a probability-based spectrum selection scheme in which the access channel is chosen based on the predetermined probabilities for saving the sensing power and reducing the overall system time of SU. When the transmission of SU is preempted by the primary user (PU), SU will stay on the operating channel and retransmit the whole data after PU leaves the channel. SU may undergo multiple interruptions before finishing a successful transmission. The interruptions and retransmissions inevitably increase the overall system time of SU. We propose an analytical model by applying the preemptive repeat identical priority M/G/1 queueing theory. Based on the model, we obtain the overall system time expression of SU packets under different spectrum environment and find the optimal distribution vector for the probability-based spectrum access scheme to minimize the average overall system time for SU.

Keywords: *Cognitive radio, dynamic spectrum access, overall system time, queueing theory.*

1. Introduction

Cognitive radio technology has opened new doors to improve spectrum efficiency [1], [2]. The SU has the capability of sensing the spectrum and dynamically accessing the available spectrum opportunities [3]. However, the SU must suspend its transmission as soon as possible to avoid the interference to PU when a PU is detected on its occupied channel.

A SU packet may undergo multiple interruptions from the PU before finishing a successful transmission. Inevitably, the interruption procedure will cause a delay and increase the overall system time of a SU packet, which is defined as the duration from the instant of the packet arriving at system until the instant of finishing the whole transmission [4]. The overall system time is an important quality of service (QoS) metric for SU. Most of the published works on the delay performance analysis of SU consider that SU can resume the transmission from the interruption point [5-7]. In [5], the authors discussed the sensing-based and the probability-based spectrum access schemes of SU and applied the preemptive resume priority (PRP) M/G/1 queueing theory to evaluate the overall system time of the both schemes. However, in real wireless communication systems, preemption-resume strategy is not feasible, since each transmitted packet must carry signaling information such as the bits for cyclic redundancy check, MAC addresses *etc.*, [8]. Therefore, when the transmission of SU is interrupted by the PU, all the data transmitted until the interruption point is lost and the SU must retransmit the whole packet when the channel becomes idle again.

In this paper, we discuss the spectrum access strategy for SUs in multi-channel cognitive radio networks. Before transmitting packets in the system, SUs can learn the spectrum environment by sensing. The sensing results can only contain two cases: 1) there are available channels in the system 2) all the channels are occupied by the packets of PU or other SUs. For the first case, SU randomly selects one free channel and immediately starts transmitting packets without waiting. For the second case, SU can keep tracking until it finds an available channel [3], which may cause high energy consumption, or SU can randomly select one busy channel to wait [4], which may greatly increase the overall system time. Therefore, we propose the probability-based spectrum selection scheme in which the access channel is selected based on the predetermined probabilities. Furthermore, we investigate how to determine the optimal channel selection probability to minimize the average overall system time of SU with multiple interruptions and retransmissions under the second case. The major contributions include:

- We obtain explicit expressions for the expected overall system time of SU's packets by employing the preemptive repeat identical priority M/G/1 queueing theory.

- We discuss how to design the access strategies of SU packets when the entire channels are occupied.

The rest of this paper is organized as follows. In Section 2, we present the system model to characterize the probability-based spectrum access scheme. Next, we evaluate the overall system time of SU packets for two cases and obtain the optimal distribution vector for the probability-based spectrum selection scheme in Section 3. Then, numerical results are shown in Section 4. Finally, we give our concluding remarks in Section 5.

2. System Model and Problem Statement

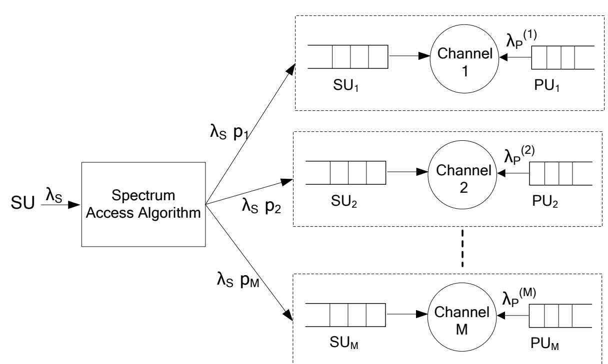

Figure 1. System Model of the Probability-based Channel Selection Scheme

We assume the system is composed of M channels which are licensed to M different PUs. Each packet of PU transmits on its dedicated licensed channel and all the packets of SUs can dynamically select their operating channels. If all of the M channels are busy, SU packets select their operating channel with suitable probability. Figure 1 illustrates the proposed system model of probability-based spectrum access scheme.

The distribution vector $\mathbf{p} = (p_1, p_2, \ldots, p_M)$ represents the results of spectrum selection, in which p_k denotes the probability of selecting channel k by SU packets. We assume that actions of PU and SU follow independent Poisson processes with generalized time distribution of transmission duration. $\lambda_p^{(k)}$ and λ_s represent the average arrival rates of PU packets on channel k and SU packets, respectively. Thus, the effective arrival rate of SU packets on channel k is $\lambda_s{}^{(k)} = \lambda_s p_k$. Because PU has higher priority to access the channel over SUs, we establish two virtual priority queues on each licensed channel as shown in Figure 1. When the transmission of SU is interrupted by PU, it will stay on the head of the low-priority queue and retransmit the whole packet after PU leaves. The packets with equal priority will act on the principle of FCFS (First Come First Served). Moreover, for simplification, we assume that SU can perfectly sense the existence of PU and can suspend its transmission as soon as the PU is detected.

In the probability-based spectrum selection scheme, the packets of SUs can access the low-priority queue of the selected channels as soon as they arrive based on the predetermined distribution vector $\mathbf{p}$. Therefore, the most important issue is to find the optimal distribution vector $\mathbf{p}$* to minimize the average overall system time of SU packets. Formally,

$$\mathbf{p}^* = \arg\min_{\forall p} E[S] = \arg\min_{\forall p} \sum_{k=1}^{M} p_k E[S_k]\,, \tag{1}$$

subject to

$$\sum_{k=1}^{M} p_k = 1, \quad and \quad 0 \le p_k < 1, \quad k = 1, 2, \ldots, M, \tag{2}$$

where $E[S_k]$ denotes the expected overall system time of SU packets on channel k and $E[S]$ denotes the average overall system time of SU packets over M channels. In Section 3, we show how to obtain the probability distribution.

3. Problem Formulation

3.1. Analysis of Overall System Time

In this paper, we consider PU and SU follow independent Poisson processes with generalized time distribution of transmission duration. Considering the interruption and retransmission of SU packet, we characterize the spectrum usage behavior between PU and SU applying preemptive repeat identical priority M/G/1 queueing model. First, we focus on the overall system time of SU packets on channel k. Let $X_p^{(k)}$ be the transmission duration of a PU packet on channel k; and $f_p^{(k)}$ is the probability density function of $X_p^{(k)}$. Furthermore, X_s represents the time that SU transmits a packet without interruptions and $f_s(x)$ represents the probability density function of X_s. Due to the homogeneity, we drop the subscript k in the following discussion without causing confusion.

The overall system time of SU for finishing a packet includes the waiting time in the queue (denoted by W) and the extended transmission time (denoted by T). We define the duration from the moment the data arrives in the system until the moment SU starts data transmission as the waiting time. And the extended transmission time is defined as the duration from the moment SU starts data transmission until the moment SU finishes the whole packet. Hence, we have

$$E[S] = E[W] + E[T]. \tag{3}$$

Suppose the N preemptions occur during the transmission because of the arrivals of packets of PU. The extended transmission time for a SU packet can be written as

$$T = X_s + \sum_{n=1}^{N} X_s(n) + \sum_{n=1}^{N} B_p(n). \tag{4}$$

Here, $B_p(n)$ is the busy period resulted from PU on channel k and $X_s(n)$ is the invalid transmission time because of the nth interruption. Given $Xs = x$, the distribution function (DF) of the number of interruptions is

$$\Pr[N = n \mid x] = (1 - e^{-\lambda_p x})^n e^{-\lambda_p x}, \quad n = 0, 1, 2 \ldots \tag{5}$$

Given that the transmission time x is preempted, the distribution of the invalid transmission time is given by

$$\Pr[X_s(n) \leqslant t \,|\, x \; is \; preempted] = \frac{1 - e^{-\lambda_p t}}{1 - e^{-\lambda_p x}}, \quad 0 \le t \le x. \tag{6}$$

Therefore, the Laplace-Stieltjes transform (LST) of the DF for $X_s(n)$ is given by

$$E[e^{-sX_s(n)} \,|\, x \, is \; preempted] = \int_0^x e^{-st} d\, \frac{1 - e^{-\lambda_p t}}{1 - e^{-\lambda_p x}} = \frac{\lambda_p}{s + \lambda_p} \frac{1 - e^{-(s+\lambda_p)x}}{1 - e^{-\lambda_p x}}. \tag{7}$$

That yields

$$E[e^{-sT} \,|\, N, x] = e^{-sx} \left[\frac{\lambda_p}{s + \lambda_p} \right]^N \left[\frac{1 - e^{-(s+\lambda_p)x}}{1 - e^{-\lambda_p x}} \right]^N \left[B_p^*(s) \right]^N, \tag{8}$$

where $B_p^*(s)$ is the LST of the DF for the busy period $B_p(n)$, which is independent of n. Then, we can get

$$E[e^{-sT} \,|\, x] = \sum_{n=0}^{\infty} E[e^{-sT} \,|\, N, x] \Pr[N = n \,|\, x] = \frac{e^{-(s+\lambda_p)x}}{1 - \frac{\lambda_p}{s + \lambda_p} B_p^*(s)[1 - e^{-(s+\lambda_p)x}]}. \tag{9}$$

By unconditioning on x, the LST $T^*(s)$ of the DF for the extended transmission time of SU can be written as

$$T^*(s) = E[e^{-sT}] = \int_0^{\infty} \frac{e^{-(s+\lambda_p)x} f_s(x)}{1 - \frac{\lambda_p}{s + \lambda_p} B_p^*(s)[1 - e^{-(s+\lambda_p)x}]} dx. \tag{10}$$

From (10), we can get

$$E[T] = (\frac{1}{\lambda_p} + E[B_p])(E[e^{\lambda_p X_s}] - 1), \tag{11}$$

and

$$E[T^2] = 2(\frac{1}{\lambda_p} + E[B_p])^2 E[(e^{\lambda_p X_s} - 1)^2] + (\frac{2}{\lambda_p^2} + \frac{2E[B_p]}{\lambda_p} + E[B_p^2])(E[e^{\lambda_p X_s}] - 1) - 2(\frac{1}{\lambda_p} + E[B_p])E[X_s e^{\lambda_p X_s}] \tag{12}$$

Referring to [9], one can obtain

$$E[B_p] = \frac{E[X_p]}{1 - \lambda_p E[X_p]}, \tag{13}$$

and

$$E[B_p^2] = \frac{E[X_p^2]}{(1 - \lambda_p E[X_p])^3}. \tag{14}$$

If the SU packet finds one idle channel when it arrives, it can begin transmitting data without waiting, therefore the overall system time equals the extended transmission time. However, the SU packet requires spending extra waiting time when all the channels are occupied. Then, we proceed to calculate the expected waiting time of SU packets. Let $P'(z)$ be the probability generating function (PGF) of the number of SU packets present in the system at the Markov points embedded at transmission completion time of a SU packet and at the ending time of busy periods of PU packets which arrive and find no SU packets in the system. Thus, we have

$$P'(z) = \sum_{k=0}^{\infty} \pi_k z^k, \quad k = 0,\ 1,\ \ldots \tag{15}$$

where π_k is the steady-state distribution for the number of SU packets. π_k can be expressed as follows

$$\begin{aligned}\pi_k &= \sum_{j=0}^{\infty} \pi_j p_{jk} \\ &= \sum_{j=0}^{\infty} \pi_j \int \frac{e^{-\lambda_s t}(\lambda_s t)^{k-j+1}}{(k-j+1)!} f_T(t)dt + \pi_0 \frac{\lambda_s}{\lambda_s + \lambda_p} \int \frac{e^{-\lambda_s t}(\lambda_s t)^k}{k!} f_T(t)dt + \pi_0 \frac{\lambda_p}{\lambda_s + \lambda_p} \int \frac{e^{-\lambda_p t}(\lambda_p t)^k}{k!} f_{B_p}(t)dt,\end{aligned} \tag{16}$$

where $f_T(t)$ represents the probability density function of T and $f_{B_p}(t)$ represents the probability density function of $B_p(n)$. Substituting (16) into (15), we can obtain

$$P'(z) = \left[\frac{P'(z) - P'(0)}{z} + \frac{\lambda_s}{\lambda_s + \lambda_p} P'(0)\right] T^*(\lambda_s - \lambda_s z) + \frac{\lambda_p}{\lambda_p + \lambda_s} P'(0) B_p^*(\lambda_s - \lambda_s z). \tag{17}$$

From the normalization condition $P'(1) = 1$, we can determine $P'(0)$ as

$$P'(0) = \frac{1 - \lambda_s E[T]}{1 - \frac{\lambda_p \lambda_s}{\lambda_p + \lambda_s}(E[T] - E[B_p])}. \tag{18}$$

Let $P(z)$ be the PGF of the number of SU packets in the system at the departure time of a SU packet. We can express $P(z)$ as

$$P(z)=\frac{\left[\frac{P'(z)-P'(0)}{z}+\frac{\lambda_s}{\lambda_s+\lambda_p}P'(0)\right]T^*(\lambda_s-\lambda_s z)}{1-\frac{\lambda_p}{\lambda_s+\lambda_p}P'(0)}. \quad (19)$$

Substituting (17) and (18) into (19), we get

$$P(z)=\frac{(1-\lambda_s E[T])[\lambda_s z-(\lambda_s+\lambda_p)+\lambda_p B_p^*(\lambda_s-\lambda_s z)]T^*(\lambda_s-\lambda_s z)}{\lambda_s(1+\lambda_p E[B_p])[z-T^*(\lambda_s-\lambda_s z)]}. \quad (20)$$

According to the PASTA property (Poisson arrivals see time averages), $P(z)$ is also the PGF of the number of SU packets at an arbitrary time.

If $W^*(s)$ denotes the LST of the DF for the waiting time of a SU packet in the queue, we have the relation

$$P(z)=W^*(\lambda_s-\lambda_s z)T^*(\lambda_s-\lambda_s z). \quad (21)$$

This yields

$$W^*(s)=\frac{(1-\lambda_s E[T])[s+\lambda_p-\lambda_p B_p^*(s)]}{(1+\lambda_p E[B_p])[s-\lambda_s+\lambda_s T^*(s)]}. \quad (22)$$

From (22) we have

$$E(W)=\frac{\lambda_s E[T^2]}{2(1-\lambda_s E[T])}+\frac{\lambda_p E[B_p^2]}{2(1+\lambda_p E[B_p])}. \quad (23)$$

Finally, by combining the corresponding equations (11)-(14) and (23), we can obtain the expected overall system time of SU for finishing a packet on one busy channel.

3.2. Optimization of Probability-based Access Strategy

According to the analysis in Section 2, we need to find the optimal distribution vector **p*** to minimize the average overall system time of SU packets. We get the average overall system time of probability-based access scheme $E[S]$ as

$$E[S]=\sum_{k=1}^{M}p_k E[S_k]=\sum_{k=1}^{M}p_k(E[T_k]+E[W_k])=\sum_{k=1}^{M}p_k(E[T_k]+\frac{\lambda_s p_k E[T_k^2]}{2(1-\lambda_s p_k E[T_k])}+\frac{\lambda_p^k E[(B_p^k)^2]}{2(1+\lambda_p^k E[B_p^k])}), \quad (24)$$

subject to

$$\sum_{k=1}^{M}p_k=1 \quad and \quad 0\le p_k<1 \ . \quad (25)$$

The average overall system time $E[S]$ is a convex function, therefore a global minimum exists for this function. We can use convex optimization theory to obtain the optimal distribution vector **p***[10].

4. Numerical Results

In the simulation, we assume the transmission duration of PU packets and SU packets

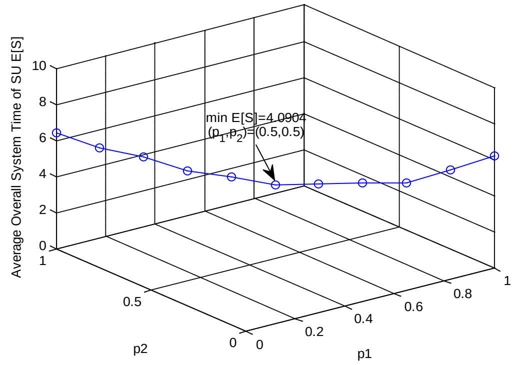

Figure 2. Average Overall System Time of SU Packets under Various Access Probability Vectors when PU Traffic Load is the Same

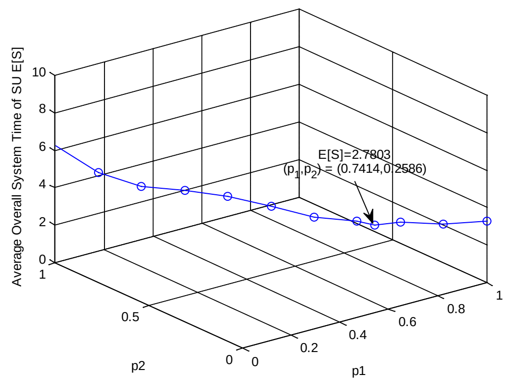

Figure 3. Average Overall System Time of SU Packets under Various Access Probability Vectors when PU Traffic Load is Different

without interruption follows the exponential distribution.

We consider a two-channel system in Figure 2 and Figure 3. They both show the effect of different channel access probabilities on the average overall system time of SU packets. In Figure 2, we assume that the two channels have the same PU traffic load and set the parameters as: for PU packets $(\lambda_p^1,\ \lambda_p^2)=(0.3, 0.3)$ and $(EX_p^1, EX_p^2)=(1,1)$; for SU packets, $\lambda_s = 0.2$ and $E[X_s]=1$.With the same PU traffic load, the optimal access strategy for SU packets is to select each channel with equal probability. In Figure 3, we consider the different PU traffic load on the two channels and set PU packets arrival rates as $(\lambda_p^1,\ \lambda_p^2)=(0.2, 0.3)$. One can find that there also exists an optimal access strategy (p_1, p_2) corresponding to the minimal average overall system time of SU.

In Figure 4 and Figure 5, we consider a four-channel system with following parameters: for PU packets, we set parameters $(EX_p^1, EX_p^2, EX_p^3, EX_p^4)=(0.8, 1, 1, 1.2)$ and $(\lambda_p^1, \lambda_p^2, \lambda_p^3, \lambda_p^4)=(0.2, 0.3, 0.4, 0.4)$; for SU packets, we assume the service rate of four channels are the same and equal $E[X_s]=0.8$.

Figure 4 shows the optimal distribution vector for the probability-based access strategy under various arrival rates of SU packets. As can be seen in Figure 4, the channel with lighter traffic load is selected by SU packets with larger probability. For example when $\lambda_s = 0.1$, all the SU packets choose channel 1 as their operating channel, because channel 1 has the lightest traffic load. As λ_s increases, the SU packets tend to select other channels for transmitting in order to balance the traffic load over all channels and reduce the overall system time. When $\lambda_s = 0.6$, the optimal distribution vector is (0.5774, 0.2704, 0.1042, 0.0480).

In Figure 5, we consider different access schemes when all the channels are occupied at the moment of a SU packet arriving at the system. We compare the average overall system time when the arrival rates of SU packets increase under the following two spectrum access schemes: 1) random access scheme; 2) probability-based access scheme. In both schemes, before transmitting the packet, SU senses the PU channels and randomly selects an idle channel to transmit if there is any. If not, SU packets randomly select one to wait in the first scheme. While in the second scheme, SU packets select access channels based on the probabilities which are calculated according to (1). We can find that the average system time both increases with the arrival rates of SU packets growing under two different access schemes owing to the occurrence of preemption by PU. However, our proposed probability-based access scheme has a shorter average system time with λ_s increasing. When $\lambda_s = 0.3$, the average system time of SU packets with the probability-based access scheme is about 6% less than that with the random access scheme. Such observations confirm the effectiveness of our spectrum access scheme.

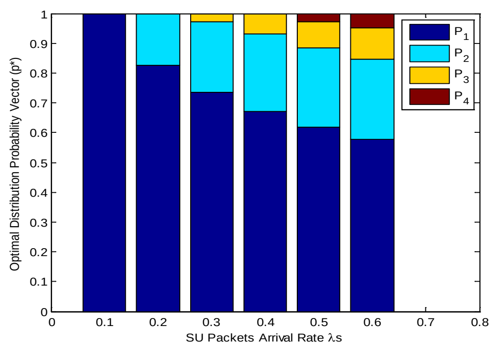

Figure 4. Optimal Distribution Probability Vector for the Access Strategy under Various Arrival Rates of SU Packets

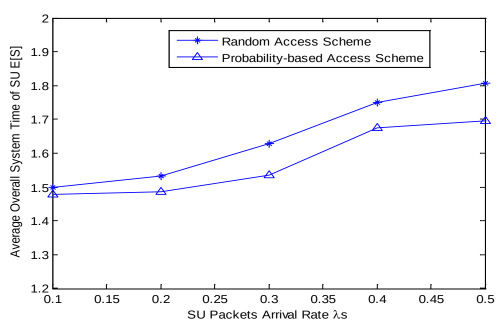

Figure 5. Comparison of the Average Overall System Time for Two Different Channel Access Schemes

4. Conclusion

In this paper, we study the spectrum access scheme of SU packets in cognitive radio networks. We propose an analytical model applying preemptive repeat identical priority M/G/1 queueing theory to evaluate the effect of transmission interruption and channel capacity on the average overall system time of SU packets. Based on the model, we obtain the expression of the average overall system time under different cases and discuss how to find the optimal access probability vector when the entire channels are occupied at the moment of SU packets arriving. Numerical results show the proposed spectrum access scheme can allocate spectrum resources to SUs reasonably and decrease the overall system time of SU packets.

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