Modeling and Analysis of Multi-User Spectrum Selection Schemes in Cognitive Radio Networks

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***Abstract*— In this paper, we study the spectrum selection problem in cognitive radio network with emphasis on resolving the channel contention and the spectrum sharing issues of multiple secondary users. For the traditional channel selection methods, the secondary users select their operating channels based on various criteria. However, these methods neglect the effect that multiple secondary users may content for the same channel if they have the same consensus on one particular good channel. Compared to the existing spectrum selection methods, we consider the sensing-based and the probability-based spectrum selection schemes which can prevent too many secondary users from contending the same channel. An analytical model integrated with the preemptive resume priority M/G/1 queuing network theory is developed to evaluate the overall transmission time of the both schemes. Based on this model, we discuss how to find the optimal selection probability for the probability-based scheme. Furthermore, we also analyze in which condition dependent of sensing time and traffic parameters that the sensing- or the probability-based scheme should be used. Based on the analytical results, we provide a principle to guide system operators which scheme should be used in CR networks. Then, we conclude that channel selection scheme should be adaptive to the variations of the traffic characteristics.** [1]

I. Introduction

Cognitive radio (CR) is an important technique to improve utilization efficiency of scarce spectrum [1]. A CR network consists of the primary and the secondary networks. The primary networks are defined as the systems with the licensed spectrum. It is increasingly evident from the recent measurement that the licensed spectrum is under-utilization. With the help of CR technique, the secondary networks are allowed to access the primary networks' unused licensed spectrum temporarily in order to increase spectrum utilization.

In CR networks, the spectrum selection functionality aims to help the secondary user distributively selects the best channel to transmit data. For the traditional channel selection methods, the secondary users select their operating channels based on various criteria, including the lightest traffic loads [2], the shortest expected waiting time [3], the largest idle probability [4], the longest expected remaining idle period [5], and the maximal expected throughput [6]. In these methods, all secondary users may select the same channel if they have the same consensus on one particular good channel, thereby causing the channel contention and congestion problem. In this paper, we investigate the spectrum selection issue with an emphasis on resolving the effects of channel contention and spectrum sharing between multiple secondary users.

A better spectrum selection scheme should simultaneously take the traffic statistics of both the primary users and the secondary users into account to distribute all secondary users to different channels. In this paper, two types of multi-user spectrum selection schemes are considered: (1) the instantaneously sensing-based spectrum selection scheme; and (2) the probability-based spectrum selection scheme.

- For the instantaneously sensing-based spectrum selection method, the secondary user selects its operating channel according to the *instantaneous* or *short-term* outcomes from spectrum sensing.
- For the probability-based spectrum selection method, the operating channel is selected based on the predetermined probability which are determined according to the *long-term* observation outcomes.

Note that the sensing outcomes in the both methods are affected by the traffic statistics of both the primary users and the secondary users.

Compared to the instantaneously sensing-based spectrum selection scheme, the probability-based spectrum selection scheme can result in shorter overall transmission time for the secondary users because it does not require to scan the huge spectrum to search the best operating channel [6]. Furthermore, because the probability-based spectrum selection scheme takes the *long-term* observation outcomes into account, it can select the channel which is interrupted by the primary users with lower probability to transmit data. Hence, this scheme can reduce total service time. Nevertheless, the probability-based spectrum selection scheme needs to prevent the secondary users from selecting a busy channel with high probability. Hence, one challenge for the probability-based spectrum selection scheme is to determine the optimal channel selection probability to minimize the overall transmission time.

In this paper, the overall transmission time for each connection is defined as the duration from the instant of data arriving at system until the instant of finishing the whole transmission. For each secondary connection, it cannot be transmitted until the selected channel becomes idle. Thus, the overall transmission time of the secondary connection consists of (1) waiting time, and (2) total service time. The

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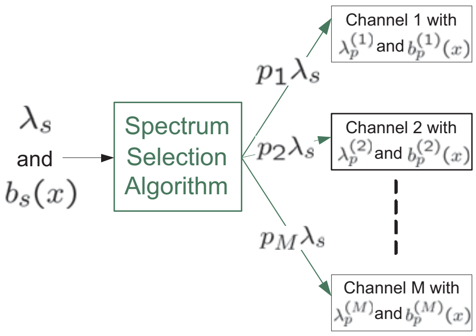

Fig. 1. An analytical model for spectrum selection mechanism.

overall transmission time of each secondary user depends on which channel is selected to transmit data. How to model the overall transmission time with multiple secondary users is challenging since the interaction between multiple secondary users must be taken into account. To the best of our knowledge, the analytical model for characterizing the overall transmission time with multiple secondary users has not been seen in the literature yet.

In this paper, we investigate how to model and evaluate the overall transmission time for the sensing-based and the probability-based spectrum selection schemes in CR networks. The major contributions of this paper are two folds:

- We discuss how to find the optimal selection probability for the probability-based spectrum selection method.
- Analyze in which condition dependent of sensing time and traffic parameters that the sensing- or the probability-based spectrum selection scheme should be used.

The rest of this paper is organized as follows. In Section II, we present the analytical model to characterize the spectrum selection mechanisms with multiple secondary users. Next, we show how to evaluate the overall transmission time of the secondary users based on this model in Section III. Then, numerical results are shown in Section IV. Finally, we give our concluding remarks in Section V.

II. Analytical Model for Spectrum Selection Mechanism

In this section, we present the analytical model to evaluate the overall transmission time of the secondary users for the sensing-based and the probability-based spectrum selection schemes. Fig. 1 illustrates the proposed analytical model. In this model, we assume that the arrival processes of the primary and the secondary users are Poisson. Let $\lambda_p^{(k)}$ and λ_s be the average arrival rates of the primary connections on channel k and the secondary connections, respectively. Furthermore, $X_p^{(k)}$ and X_s represent the transmission duration of the primary connections on channel k and the secondary connections, respectively; and $b_p^{(k)}(x)$ and $b_s(x)$ are the probability density functions (pdfs) of $X_p^{(k)}$ and X_s, respectively. Note that we assume the system parameters $\lambda_p^{(k)}$, λ_s, $b_p^{(k)}(x)$, and $b_s(x)$ are given in advance. They can be estimated by the existing models [7].

As shown in Fig. 1, the secondary user can select one of M independent channels to be its operating channel when it arrives at a CR system. The spectrum selection algorithm can be either the instantaneously sensing-based or the probability-based method. Based on the spectrum selection algorithm, each secondary user can dynamically and distributively select its operating channel. The distribution vector (denoted by $\mathbf{p} = (p_1, p_2, \cdots, p_M)$) is used to describe the results of spectrum selection. Specifically, the probability that the secondary users select channel k to be their operating channel is denoted by p_k. For different spectrum selection algorithms, we use different methods to evaluate this distribution vector. In the following, we show how to characterize the distribution vector $\mathbf{p}$ for the two considered channel selection schemes.

A. Distribution Vector for the Instantaneously Sensing-based Channel Selection

Firstly, for the instantaneously sensing-based spectrum selection scheme, each secondary user searches the idle channel from all candidate channels through spectrum sensing. If more than one idle channel is found, the secondary user uniformly selects one channel to be its operating channel from all idle channels. Furthermore, if all channels are busy, spectrum sensing shall be performed once again in the next sensing slot. Let $\Omega = \{1, 2, \ldots, M\}$ and $\rho^{(k)}$ be the busy probability of channel k. Then, the secondary user selects channel k to be its operating channel with probability:

$$p_k = (1-\rho^{(k)}) \sum_{S \subseteq \Omega/\{k\}} \left[\frac{1}{1+|S|} \prod_{i \in S} (1-\rho^{(i)}) \prod_{j \notin S} \rho^{(j)} \right] + \prod_{i \in \Omega} \rho^{(i)} p_k \ , \quad (1)$$

where the first term is the probability that channel k is selected to be the operating channel. When channel k and other $|S|$ channels are idle, channel k is selected to be the operating channel with probability $\frac{1}{1+|S|}$. Note that a secondary user must perform spectrum sensing again if all channels are busy at the current sensing slot. Thus, the second term is the probability that all channels are busy and channel k is selected to be the operating channel in the next sensing slot.

B. Distribution Vector for the Probability-based Channel Selection

Next, for the probability-based spectrum selection method, each secondary user selects its operating channel according to a predetermined distribution vector. In this case, an **Overall Transmission Time Minimization Problem** can be formulated as follows. Let $\mathbf{E}[T_p]$ be the average overall transmission time of the secondary users for the probability-based spectrum selection scheme. Given the set of candidate channels Ω, ***find the optimal distribution vector (denoted by $\mathbf{p}^*$) to minimize the average overall transmission time.*** Formally,

$$\mathbf{p}^* = \arg\min_{\forall \mathbf{p}} \mathbf{E}[T_p(\mathbf{p})] \ , \quad (2)$$

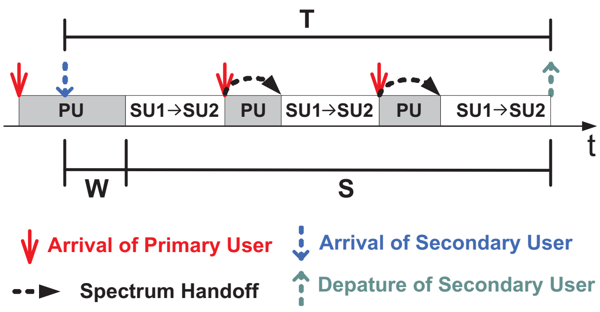

Fig. 2. The overall transmission time of the secondary users.

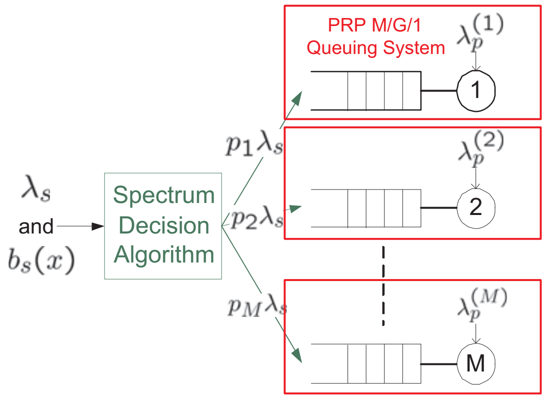

Fig. 3. The analytical model for spectrum selection where the channel usage behavior can be modeled by the PRP M/G/1 queueing network.

subject to:

$$\sum_{k\in\Omega} p_k = \sum_{k=1}^{M} p_k = 1 \ , \tag{3}$$

and

$$0 \le p_k \le 1 \quad \forall\ k \ . \tag{4}$$

Because $\rho^{(k)}$ is composed of the busy probability resulted from the primary users (denoted by $\rho_p^{(k)}$) and the busy probability resulted from the secondary users (denoted by $\rho_s^{(k)}$). Hence, this optimization problem also has the following constraint:

$$\begin{aligned} \rho^{(k)} &= \rho_p^{(k)} + \rho_s^{(k)} \\ &= \lambda_p^{(k)} \mathbf{E}[X_p^{(k)}] + p_k \lambda_s \mathbf{E}[X_s] \\ &\le 1, \quad \forall\ k \in \Omega \ , \end{aligned} \tag{5}$$

where $\mathbf{E}[X_p^{(k)}]$ and $\mathbf{E}[X_s]$ are the average connection length of the primary users on channel k and the secondary users, respectively. Note that determining the distribution vector should take the traffic statistics of each channel into account. In Section III, we show how to evaluate the distribution vector for two considered channel selection schemes.

III. Analysis of Overall Transmission Time

The overall transmission time (denoted by T) is an important performance measure for ensuring quality of service (QoS) of the secondary users, which consists of the waiting time (denoted by W) and the total service time (denoted by S) as shown in Fig. 2. Here, the waiting time is defined as the duration from the instant of data arriving at system until the instant of starting transmitting data. The total service time is defined as the duration from the instant of starting transmitting data until the instant of finishing the whole transmission. Within the transmission period of a secondary connection, it is likely to have multiple spectrum handoffs due to the interruption from the primary users. The spectrum handoff procedure helps the secondary users vacate the occupied channel and then resume the unfinished transmission when this channel becomes idle. Clearly, multiple spectrum handoffs will increase the total service time and degrade QoS for the latency-sensitive traffic of the secondary users [8].

To evaluate the overall transmission time of the secondary users with multiple handoffs, the proposed channel selection model is integrated with the preemptive resume priority (PRP) M/G/1 queuing network as shown in Fig 3. Based on the PRP M/G/1 queueing network model, we can characterize the spectrum usage behavior between the primary and the secondary users [9]. Some important properties for the PRP M/G/1 queueing network model are listed below:

- The primary users have the preemptive priority to interrupt the transmission of the connections of the secondary users.
- The interrupted connection of the secondary user can resume the unfinished transmission when channel becomes idle, instead of retransmitting the whole data.

Based on the analytical results, we can decide in which condition dependent of sensing time and traffic parameters that the sensing- or probability-based spectrum selection scheme should be used. Hence, the optimal overall transmission time (denoted by T^*) can be expressed as follows:

$$T^* = \min\left(T_s, T_p\right) \ , \tag{6}$$

where T_s and T_p are the overall transmission time of the secondary users for the sensing- and the probability-based spectrum selection methods, respectively.

A. Total Service Time of the Secondary Users

Firstly, we discuss how to derive the total service time of the secondary users. Let $\mathbf{E}[N^{(k)}]$ and $Y_p^{(k)}$ be the average number of interruptions for the secondary users of channel k and the average busy period resulted from the primary users of channel k, respectively. When a secondary user is interrupted by the primary users, it cannot transmit data on the current channel until all primary users in the present queue have been served. In this case, the secondary users of channel k must wait the duration of $Y_p^{(k)}$ on average after interruption event occurs. Thus, the total service time of the secondary users on channel k (denoted by $S^{(k)}$) can be expressed as follows:

$$S^{(k)} = \mathbf{E}[X_s] + \mathbf{E}[N^{(k)}] Y_p^{(k)} \ . \tag{7}$$

Then, the average total service time can be expressed as follows:

$$\mathbf{E}[S] = \sum_{k=1}^{M} p_k S^{(k)} \ . \tag{8}$$

Referring to [10], one can obtain $\mathbf{E}[N^{(k)}] = \lambda_p^{(k)}\mathbf{E}[X_s]$ and $Y_p^{(k)} = \frac{\mathbf{E}[X_p^{(k)}]}{1-\lambda_p^{(k)}\mathbf{E}[X_p^{(k)}]}$.

B. The Overall Transmission Time for the Instantaneously Sensing-based Spectrum Selection Method

Denote W_s as the average waiting time of the secondary users with the instantaneously sensing-based spectrum selection method. According to the definition of the overall transmission time, we can have

$$\mathbf{E}[T_s] = W_s + \mathbf{E}[S] \ . \qquad (9)$$

For the sensing-based spectrum selection scheme, the waiting time is the duration of finding at least one idle channel through spectrum sensing. Assume the channel busy probabilities at different time slots are independent, the pdf of this waiting time follows the geometric distribution. Hence, we have

$$W_s = \tau \sum_{i=1}^{\infty} i\rho^{i-1}(1-\rho) \ , \qquad (10)$$

where τ is the spectrum sensing time and ρ is the probability that all M channels are simultaneously busy, i. e.,

$$\rho \equiv \prod_{k=1}^{M} \rho^{(k)} \ . \qquad (11)$$

Finally, substituting (8) and (10) into (9), we can obtain the closed-form expression of the average overall transmission time for the sensing-based spectrum selection scheme.

C. The Overall Transmission Time with Probability-based Spectrum Selection Method

Let $\mathbf{E}[T_p^{(k)}]$ and $W_p^{(k)}$ be the average overall transmission time and the average waiting time of the secondary users of channel k for the probability-based spectrum selection scheme, respectively. According to the definition of the overall transmission time, we have

$$T_p^{(k)} = W_p^{(k)} + S^{(k)} \ . \qquad (12)$$

For the probability-based spectrum selection scheme, the waiting time is the duration spent in the waiting queue by a secondary user. Applying the PRP M/G/1 queueing theory [11], one can obtain that

$$W_p^{(k)} = \frac{\mathbf{E}[R^{(k)}]}{(1-\rho_p^{(k)})(1-\rho_p^{(k)}-\rho_s^{(k)})} \ , \qquad (13)$$

where $\mathbf{E}[R^{(k)}]$ is the average residual service time resulted from both the primary and the secondary users. Referring to [11], we have

$$\mathbf{E}[R^{(k)}] = \frac{1}{2}\lambda_p \mathbf{E}[(X_p^{(k)})^2] + \frac{1}{2}p_k\lambda_s \mathbf{E}[{X_s}^2] \ . \qquad (14)$$

Next, referring to (12), the average overall transmission time over all channels can be expressed as follows:

$$\begin{aligned} \mathbf{E}[T_p] &= \sum_{k=1}^{M} p_k T_p^{(k)} \\ &= \sum_{k=1}^{M} p_k W_p^{(k)} + \sum_{k=1}^{M} p_k S^{(k)} \ . \end{aligned} \qquad (15)$$

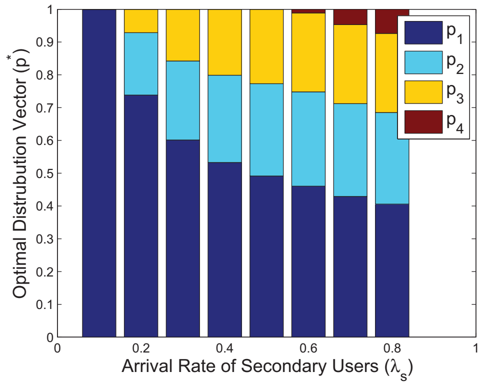

Fig. 4. The optimal distribution vector for the probability-based spectrum selection scheme over various arrival rates of the secondary users where $\mathbf{E}[X_s] = 0.8$.

Finally, substituting (7) and (13) into (15), we can obtain the relationship between the average overall transmission time and the distribution vector $\mathbf{p}$ for the probability-based spectrum selection scheme. Then, the optimal distribution vector $\mathbf{p}^*$ can be found by solving (2).

IV. Numerical Results

In our simulation, we assume that the transmission duration of the primary and the secondary connections follows the exponential distribution and the connections which have the same priority access channel with the first-come-first-served (FCFS) scheduling discipline.

Figure 4 shows the effect of various arrival rates of the secondary users (λ_s) on the optimal distribution vector for the probability-based spectrum selection scheme. We consider a four-channel system with the following system parameters: $(\lambda_p^{(1)}, \lambda_p^{(2)}, \lambda_p^{(4)}, \lambda_p^{(4)}) = (0.3, 0.3, 0.4, 0.4)$ and $(\mathbf{E}[X_p^{(1)}], \mathbf{E}[X_p^{(2)}], \mathbf{E}[X_p^{(3)}], \mathbf{E}[X_p^{(4)}]) = (1, 1.2, 1, 1.2)$. As shown in this figure, the distributed vector is plotted in each bar, and the summation of all probabilities in each bar is 1. With a smaller λ_s such as 0.1, all the secondary users prefer selecting channel 1 to be their operating channel because channel 1 has the lightest traffic loads. Furthermore, as λ_s increases, some secondary users tend to select other channels in order to balance the total traffic loads over all channels. For example, when $\lambda_s = 0.8$, the optimal distribution vector is $(0.4057, 0.2792, 0.2415, 0.0736)$. Inevitably, channel 1 is still selected to be the operating channel with the largest probability.

In Fig. 5, we consider the following parameters: $(\lambda_p^{(1)}, \lambda_p^{(2)}, \lambda_p^{(4)}, \lambda_p^{(4)}) = (0.1, 0.2, 0.4, 0.8)$ and $(\mathbf{E}[X_p^{(1)}], \mathbf{E}[X_p^{(2)}], \mathbf{E}[X_p^{(3)}], \mathbf{E}[X_p^{(4)}]) = (2, 1, 0.5, 0.125)$. Based on this setup, the busy probability (or utilization) of each channel is 0.2 when $\lambda_s = 0$. As λ_s increases, the channel utilization also increases. Because selecting channel 4 can result in shorter waiting time, the most of the secondary users prefer selecting channel 4 to be their operating channel even though all channels have the same busy probability resulted from the primary users. Hence, channel 4 has the highest channel utilization when $\lambda_s > 0$.

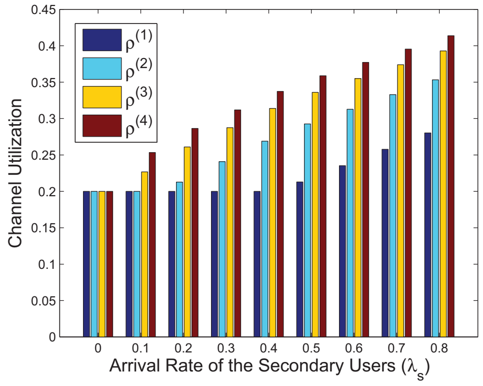

Fig. 5. The channel utilization over various arrival rates of the secondary users where $\mathbf{E}[X_s] = 0.8$.

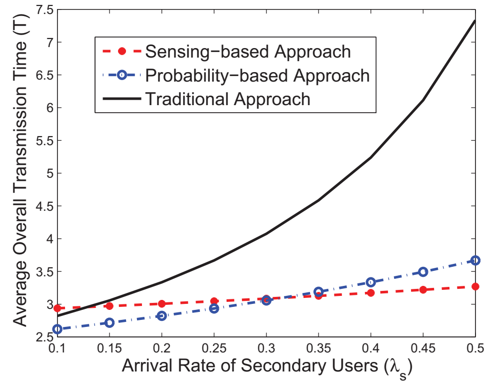

Fig. 6. Comparison of the overall transmission time for three different channel selection schemes where $\tau = 1.3$ and $\mathbf{E}[X_s] = 0.8$.

Figure 6 shows the effect of λ_s on the average overall transmission time for three different spectrum selection schemes: 1) instantaneously sensing-based method; 2) probability-based method; and 3) traditional method. In the first and the second spectrum selection schemes, the overall transmission time are calculated according to (9) and (15), respectively. For the traditional method, all secondary users select the same channel to be their operating channels. Here, we consider the following traffic parameters: $M = 2$, $\lambda_p^{(k)} = 0.4$ and $X_p^{(k)} = 1$ for each k. Furthermore, we assume that the spectrum sensing time τ is 1.3. One can find that both the multi-user spectrum selection schemes can significantly reduce the average overall transmission time compared to the traditional method, especially for a larger λ_s. In addition, we have the following observations. With a lower value of λ_s, the average overall transmission time of the probability-based scheme is shorter than that of the sensing-based scheme because the probability-based scheme can select the channels which has lowest interrupted probability. By contrast, when λ_s is large, the sensing-based scheme has a shorter overall transmission time because the sensing-based scheme can significantly reduce waiting time through spectrum sensing. Based on (6), the secondary users can intelligently adopt the best spectrum selection scheme to minimize the average overall transmission time.

V. Conclusions

In this paper, we study the spectrum selection problem in CR networks with emphasis on resolving the channel contention and the spectrum sharing issues of multiple secondary users. Specifically, an analytical model integrated with the PRP M/G/1 queuing network theory is developed to evaluate the overall transmission time for the sensing-based and the probability-based spectrum selection schemes. Based on this model, we discuss how to find the optimal selection probability for the probability-based spectrum selection method. Furthermore, we also analyze in which condition dependent of sensing time and traffic parameters that the sensing- or the probability-based spectrum selection scheme should be used. Numerical results demonstrate that a tradeoff of overall transmission time exists between the sensing-based and the probability-based schemes. Specifically, the probability-based spectrum selection scheme can reduce the overall transmission time compared to the sensing based spectrum selection when the traffic loads of the secondary users is light, whereas the sensing-based spectrum selection performs better in the condition of heavy traffic loads. Based on these observations, we provide a principle to guide system operators which scheme should be used in CR networks. Then, we conclude that channel selection scheme should be adaptive to the variations of the traffic characteristics.

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