PERFORMANCE GAINS FOR SPECTRUM UTILIZATION IN COGNITIVE RADIO NETWORKS WITH SPECTRUM HANDOFF

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ABSTRACT

Cognitive radio (CR) can improve spectrum utilization by allowing the secondary users to temporarily access the primary users' unutilized licensed spectrum. In order to guarantee quality of service (QoS) of the secondary users, spectrum handoff mechanism must be implemented in CR networks. Spectrum handoff procedures aim to help the secondary users vacate the spectrum and search the target channels to resume the unfinished transmission when the primary user appears at the occupied licensed band. In such a system, the most basic issue is how much CR technique can improve spectrum utilization. In order to quantify this gain, we propose a preemptive resume priority (PRP) M/G/1 queueing network model to characterize the spectrum usage behavior with multiple spectrum handoffs between the primary and the secondary users. Based on this model, we show how to evaluate spectrum utilization factor under different traffic loads. From the numerical results, we find that the utilization improvement on the channel with lower arrival rate of the primary connections is larger than the channel with higher arrival rate of the primary connections.[1]

I INTRODUCTION

Cognitive radio (CR) is an important technique to improve the 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 [5].

In CR networks, spectrum handoff is an important functionality to guarantee quality of service (QoS) of the secondary users [1]. When the high-priority primary users appear at its licensed band occupied by the secondary users, spectrum handoff procedures are initiated to help the low-priority secondary users vacate the occupied licensed spectrum and find suitable target channel to resume the unfinished transmission. In general, according to the decision timing for selecting the target channels, spectrum handoff mechanisms can be categorized into [7]: (1) proactive-decision spectrum handoff: make the target channels for spectrum handoff ready *before* data transmission according to the long-term observation outcomes [4], and (2) reactive-decision spectrum handoff: determine the target channel according to the results from *on-demand* wideband sensing. In this paper, we consider the reactive-decision spectrum handoff. The proactive-decision spectrum handoff has been discussed in [4].

The most basic issue is how much to gain for spectrum utilization from CR technique. In this paper, we propose a preemptive resume priority (PRP) M/G/1 queueing network model to characterize the spectrum usage behavior with multiple spectrum handoffs between the primary and the secondary users. Based on this model, we show how to evaluate spectrum utilization factor under different traffic loads in CR networks. Hence, the gain of spectrum utilization resulted from CR networks with spectrum handoff can be quantified.

The rest of this paper is organized as follows. In Section II, we introduce the system model and the spectrum handoff protocol which are considered in this paper. Next, we propose a PRP M/G/1 queueing network to model CR networks with multiple handoffs in Section III. Then, Section IV shows how to evaluate spectrum utilization factor based on the proposed queueing model. Finally, the numerical results and the concluding remarks are given in Sections V and VI, respectively.

II SYSTEM MODEL

II.A System Model

Consider a CR network where the primary and the secondary networks are simultaneously operating on M independent channels. In order to detect and protect the primary users, the secondary users must perform spectrum sensing periodically. Here, we assume that the secondary network is a slotted system and each secondary user partitions its data connection into many slot-sized frames before transmission. Then, the secondary users can alternatively enter the sensing phase and the transmission phase [8, 3]. The basic slot structure of the secondary networks is shown in Fig. 1. At the sensing phase, the secondary user senses the current operating channel to detect the appearance of the primary users. If this channel is idle, the secondary user can transmit data at the transmission phase. Otherwise, the secondary user performs spectrum handoff procedures to select the target channel and then resumes the transmission on the selected target channel. This kind of listen-before-talk strategy has been implemented in the clear channel assessment (CCA) of the IEEE 802.11 standard.

In this paper, the spectrum handoff protocol proposed in [7]

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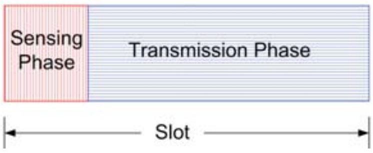

Figure 1: The slot structure of the secondary networks.

is considered. This protocol assumes the secondary user must stay on the current operating channel if all channels are busy when interruption event occurs. Multiple handoffs occur when a secondary connection is interrupted many times during its transmission duration. It will increase total service time and cause serious QoS issue for the secondary users. Basically, when spectrum handoff procedure is initiated, the secondary users must spend τ on wideband sensing and t_n on informing the corresponding receiver of the selected target channel at the control channel, respectively. If the target channel is the current operating channel, the secondary users will stay on the current channel. Hence, the total processing time for executing spectrum handoff procedure is $\delta \equiv \tau + t_n$. On the other hand, if the secondary user changes to another channel, the total processing time is $\delta' \equiv \tau + t_n + t_s$ where t_s is the channel switching time.

II.B An Illustrative Example for proactive-decision Spectrum Handoffs

Figure 2 shows an example where multiple spectrum handoffs occur during the whole secondary connection. The total service time (denoted by S) for the connection of a secondary user with multiple handoffs is defined as the duration from the instant of starting transmitting data until finishing the whole transmission. Handoff delay (denoted by D_i) is defined as the duration from the instant of stopping transmission until the instant of resuming the unfinished transmission. In this figure, HPC and LPC stands for the high-priority connections and the low-priority connections resulted from the primary user and the secondary users, respectively. Assume that the default channels of the secondary users SU1 and SU2 are channel Ch1 and their data connection is partitioned into total 29 small-sized frames. The multiple handoffs process is described as follows.

1. Firstly, SU1 transmits its data to the corresponding receiver SU2 on channel Ch1.
2. Next, at the first interruption, SU1 perform wideband sensing to find idle channel. In this case, SU1 changes to the idle channel Ch2 from channel Ch1. The handoff delay is δ'.
3. At the second interruption, SU1 stays on the current channel Ch2 because all channel are busy. SU1 can access the channel only after the high-priority primary connections of Ch2 finish their transmissions. In this case, handoff delay is the sum of δ and the busy period resulted from the primary connections of Ch2 (denoted by $Y_p^{(2)}$).
4. At the third interruption, SU1 finds both Ch1 and Ch3 are idle. Then, it uniformly picks one channel to be the target channel. In this example, SU1 selects channel Ch3 to be its target channel and thus handoff delay is δ_c.
5. Finally, the transmission of SU1 is finished on Ch3.

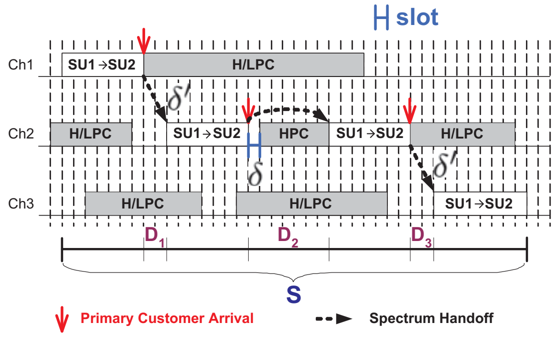

Figure 2: An example of transmission process for the secondary connection with three interruptions. The whole data connection is partitioned into four partitions due to multiple handoffs.

III PRP M/G/1 queueing Network

In this section, a PRP M/G/1 queueing network model is proposed to characterize the spectrum usage behavior with multiple spectrum handoffs between the primary and the secondary users. With this model, the channel utilization of CR networks can be analyzed. Hence, we can quantify the channel utilization improvement resulted from CR technique. Some important properties for PRP M/G/1 queueing network model are listed below:

- Primary connections have the preemptive priority to interrupt the transmission of secondary connections.
- The interrupted secondary connection is designed to resume the unfinished transmission, instead of retransmitting the whole data connection.
- The interrupted secondary connection's target channel can be different from its current operating channel, which is a key difference to the traditional PRP M/G/1 queueing theory.

Some assumptions are adopted for ease of analysis.

- In order to distribute the traffic loads of secondary network over all channels, we assume each secondary connection has a default operating channel to transmit data [6, 8]. If the secondary transmitter has data to send, it will transmit the control signal on the intended receiver's default channel to initialize the secondary connection. If default channel is busy, the secondary user must wait until its default channel becomes idle.
- When interruption event occurs, the secondary user must stay on the current operating channel if all channels are busy.

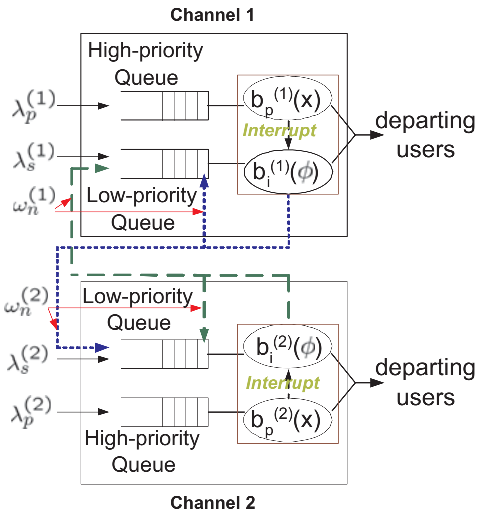

Figure 3: The PRP M/G/1 queueing network with two channels.

- It is assumed that the channel is error-free and only one user can transmit on each channel any time.

Figure 3 shows an example of the PRP M/G/1 queueing network with two channels, in which primary connections are put into the high-priority queue, and secondary connections are put into the low-priority queue. When the primary user appears at the channel occupied by the secondary users, the secondary user can either change to the other channel or stay on the current channel through one of two feedback paths. Firstly, in the change case, the unfinished transmission will be put into the tail of the low-priority queue of the other channel. On the other hand, the unfinished transmission can be inserted into the head of the low-priority queue of the current channel when the stay strategy is selected. In both cases, the unfinished transmission can be immediately resumed when the channel becomes idle.

The notations and definitions of the variables used in the PRP M/G/1 queueing networks are introduced as follows.

- Assume that the arrival processes of the primary and the secondary users are Poisson. Let $\lambda_p^{(k)}$ and $\lambda_s^{(k)}$ be the average arrival rates for the primary connections and secondary connections on channel k, respectively. Furthermore, $X_p^{(k)}$ and $X_s^{(k)}$ represent the transmission duration of the primary and the secondary connections on channel k, respectively; and $b_p^{(k)}(x)$ and $b_s^{(k)}(x)$ are the probability density functions (pdfs) of $X_p^{(k)}$ and $X_s^{(k)}$, respectively. Note that we assume the system parameters $\lambda_p^{(k)}$, $\lambda_s^{(k)}$, $b_p^{(k)}(x)$, and $b_s^{(k)}(x)$ are given in advance. They can be estimated by the existing models [2].

- Denote $\omega_i^{(k)}$ as the arrival rate of the redirected traffic from the secondary connections having i interruptions ($i \geq 0$) to channel k. Note that $\omega_0^{(k)} = \lambda_s^{(k)}$.

- Denote $\Phi_i^{(k)}$ as the transmission duration of a secondary connection between the i-th and the $(i+1)$-th interruptions $i \geq 0$, and let $b_i^{(k)}(\phi)$ be the pdf of $\Phi_i^{(k)}$.

- Denote $\rho_p^{(k)}$ and $\rho_i^{(k)}$ as the busy probability resulted from the primary connections and the secondary connections with i interruptions ($i \geq 0$) on channel k, respectively. The total utilization factor of channel k is denoted by $\rho^{(k)}$. Then, the following constraint shall be satisfied.

$$\rho^{(k)} \equiv \rho_p^{(k)} + \sum_{i=0}^{\infty} \rho_i^{(k)} < 1 \ , \tag{1}$$

where $1 \leq k \leq M$. Hence, $\rho^{(k)}$ can be also interpreted as the busy probability of channel k. Note that $\rho_p^{(k)} = \lambda_p^{(k)} \mathbf{E}[X_p^{(k)}]$ and $\rho_i^{(k)} = \omega_i^{(k)} \mathbf{E}[\Phi_i^{(k)}]$ for each i.

IV Derivation of Spectrum Utilization

In this section, we show how to evaluate spectrum utilization in CR networks with spectrum handoff based on the proposed PRP M/G/1 queuing network model. To simplify the analysis, we assume that transmission duration of all secondary connection over all channels follows the same exponential distribution. That is, $b_s^{(k)}(x) = \mu_s e^{-\mu_s x}$ where $\mu_s = \frac{1}{\mathbf{E}[X_s]}$. Referring to (1), in order to evaluate the spectrum utilization factor $\rho^{(k)}$, we must derive the unknown term $\rho_i^{(k)}$. Equivalently, we must derive $\mathbf{E}[\Phi_i^{(k)}]$ and $\omega_i^{(k)}$ firstly.

IV.A Derivation of Interrupted Probability $p^{(k)}$

Before calculating $\mathbf{E}[\Phi_i^{(k)}]$, we firstly derive the interrupted probability of the secondary connections. When a secondary connection is transmitting on channel k, it will be interrupted if primary users arrive during its transmission interval. Because the arrival of primary connections is a Poisson process, the event that no primary connection arrives during time interval x occurs with probability $e^{-\lambda_p^{(k)} x}$. Thus, for the secondary connection with 0 interruption on channel k, it is interrupted with probability:

$$\begin{aligned} p_0^{(k)} &= 1 - \int_0^{\infty} e^{-\lambda_p^{(k)} x} \cdot b_s(x) dx \\ &= 1 - \int_0^{\infty} e^{-\lambda_p^{(k)} x} \cdot \mu_s e^{-\mu_s x} dx \\ &= \frac{\lambda_p^{(k)}}{\lambda_p^{(k)} + \mu_s} \ . \end{aligned} \tag{2}$$

Here, we denote $p_i^{(k)}$ as the probability that the secondary connection with i interruption is interrupted on channel k.

For each secondary connection, because its transmission duration follows the exponential distribution, its remaining transmission duration when it is interrupted also follows the same exponential distribution [4]. That is, the transmission duration of all secondary connections with any interruptions is identical. Hence, the interrupted probability is independent of the number of interruptions. Let $p^{(k)}$ is the probability that the secondary connection is interrupted. We have,

$$p^{(k)} \equiv p_i^{(k)} = p_0^{(k)} = \frac{\lambda_p^{(k)}}{\lambda_p^{(k)} + \mu_s} \quad , \tag{3}$$

where $p^{(k)}$ is only related to k, $\lambda_p^{(k)}$, and μ_s.

IV.B Derivation of $\mathbf{E}[\Phi_i^{(k)}]$

Now, we show how to derive the expression of $\mathbf{E}[\Phi_i^{(k)}]$. We consider the time interval $[0, t]$ on channel k. Total $\lambda_p^{(k)} t$ primary connections and $\omega_i^{(k)} t$ secondary connections with i interruptions arrive during this interval. Hence, there are total $\omega_i^{(k)} t \cdot p^{(k)}$ secondary connections with i interruptions will be interrupted again on average during this interval. On the other hand, we apply the Poisson arrivals see time average (PASTA) property on the arrivals of the primary connections. When a primary connection arrives, the probability that it will see a busy channel which is used by the secondary connections with i interruptions is $\rho_i^{(k)}$. Thus, during this interval, total $\lambda_p^{(k)} t \cdot \rho_i^{(k)}$ primary connections can see a busy channel which results from the secondary connections with i interruptions. For each primary connection, it can only interrupt one secondary connection at most when it arrives on a busy channel because only one user can transmit at any time instant. Thus, the total number of the interrupted secondary connections is also $\lambda_p^{(k)} t \cdot \rho_i^{(k)}$. Hence, we have $\omega_i^{(k)} t \cdot p^{(k)} = \lambda_p^{(k)} t \cdot \rho_i^{(k)}$. That is,

$$\rho_i^{(k)} = \frac{\omega_i^{(k)}}{\lambda_p^{(k)}} \cdot p^{(k)} \quad . \tag{4}$$

Next, according to the definition of utilization, we have

$$\rho_i^{(k)} = \omega_i^{(k)} \mathbf{E}[\Phi_i^{(k)}] \quad . \tag{5}$$

Comparing (4) and (5), we can have

$$p^{(k)} = \lambda_p^{(k)} \mathbf{E}[\Phi_i^{(k)}] \quad . \tag{6}$$

Finally, substituting (3) into (6) , we have

$$\mathbf{E}[\Phi_i^{(k)}] = \frac{1}{\lambda_p^{(k)} + \mu_s} \quad . \tag{7}$$

IV.C Derivation of $\omega_i^{(k)}$

Consider a secondary connection with i interruptions on channel n. When it is interrupted again, it can stay on channel n or change its operating channel to another channel k ($k \neq n$). If all channels are busy, it stays on channel n. In this case, the interrupted secondary connection will wait at the head of the low-priority queue of channel n and be a new arrival of secondary connection with $i+1$ interruptions. Let M is the total number of channels. This stay case occurs with probability $\prod_{1 \le i \le M, i \neq n} \rho^{(i)}$. Hence, on channel n, the arrival rate (denoted by $\omega_{i+1}^{(n \to n)}$) of the secondary connections with $i+1$ interruptions which come from channel n can be expressed as follows:

$$\omega_{i+1}^{(n \to n)} = \omega_i^{(n)} p \times \prod_{1 \le m \le M, m \neq n} \rho^{(m)} \quad . \tag{8}$$

On the other hand, when the secondary connection with i interruptions is interrupted, it will change its operating channel to channel k ($k \neq n$) if channel k is idle. Note that the interrupted connection will uniformly select one channel to be the target channel form all idle channels if more than one channel is idle. Let $\Omega = \{1, 2, \cdots, M\}$. Then, on channel k, the arrival rate (denoted by $\omega_{i+1}^{(n \to k)}$) of the secondary connections with $i+1$ interruptions which come from channel n can be expressed as follows:

$$\begin{aligned} & \omega_{i+1}^{(n \to k)} \\ = \; & \omega_i^{(n)} p \times \\ & (1 - \rho^{(k)}) \left[\sum_{S \subseteq \Omega - \{n,k\}} \frac{1}{1 + |S|} \prod_{m \in S} (1 - \rho^{(m)}) \prod_{j \notin S} \rho^{(j)} \right] \quad , \end{aligned} \tag{9}$$

where the second term is the probability that channel k is selected to be the target channel.

Next, because the secondary connections with i interruptions can come from any one of M channels, we must accumulate them to obtain the total arrival rate of the secondary connections with i interruptions on channel k. That is, it follows that

$$\omega_{i+1}^{(k)} = \sum_{n=1}^{M} \omega_{i+1}^{(n \to k)} \quad . \tag{10}$$

When the unknown term $\rho^{(k)}$ in (8) and (9) is given, we can derive the value of $\omega_{i+1}^{(k)}$ in (10).

IV.D Derivation of $\rho_i^{(k)}$ and $\rho^{(k)}$

Firstly, we derive the busy probability $\rho_i^{(k)}$ resulted from the secondary connection with i interruption by substituting (7) into (5). Hence, we have

$$\rho_i^{(k)} = \frac{\omega_i^{(k)}}{\lambda_p^{(k)} + \mu_s} \quad , \tag{11}$$

where $k \geq 0$.

Next, substituting (11) into (1), the channel utilization factor of channel k can be expressed as follows.

$$\rho^{(k)} = \rho_p^{(k)} + \sum_{i=0}^{\infty} \rho_i^{(k)} = \lambda_p^{(k)} \mathbf{E}[X_p^{(k)}] + \frac{1}{\lambda_p^{(k)} + \mu_s} \sum_{i=0}^{\infty} \omega_i^{(k)} \quad . \tag{12}$$

Note that $\rho^{(k)}$ is a function of $\omega_i^{(k)}$ according to (12) and $\omega_i^{(k)}$ is a function of $\rho^{(k)}$ according to (10). Hence, we can obtain $\omega_i^{(k)}$ and $\rho^{(k)}$ by solving (10) and (12) iteratively.

Here, we consider a special case. When the primary and the secondary users have the same traffic model in a two-channel system (i.e., $\lambda_p^{(1)} = \lambda_p^{(2)} \equiv \lambda_p$, $\lambda_s^{(1)} = \lambda_s^{(2)} \equiv \lambda_s$, and $\mathbf{E}[X_p^{(1)}] = \mathbf{E}[X_p^{(2)}] \equiv \mathbf{E}[X_p]$), two channels have the same performance measures. Hence, the superscript (k) will be dropped to ease the notations. Then, one can obtain $p = \frac{\lambda_p}{\lambda_p + \mu_s}$,

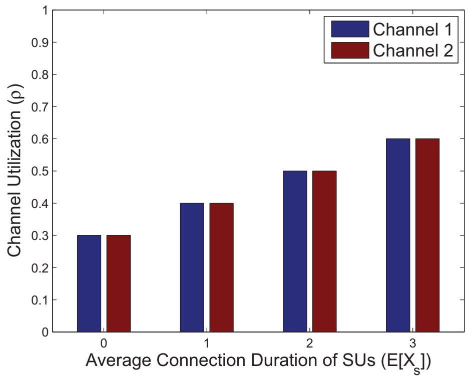

Figure 4: The effect of average connection duration of the secondary users (SUs) on channel utilization where $\lambda_p = 0.1$, $\mathbf{E}[X_p] = 3$, and $\lambda_s = 0.1$.

$\mathbf{E}[\Phi_i] = \frac{1}{\lambda_p+\mu_s}$, $\omega_i = \lambda_s(\frac{\lambda_p}{\lambda_p+\mu_s})^i$, and

$$\rho = \lambda_p \mathbf{E}[X_p] + \frac{\lambda_s}{\lambda_p + \mu_s}(1 + \frac{\lambda_p}{\mu_s}) = \lambda_p \mathbf{E}[X_p] + \lambda_s \mathbf{E}[X_s] \ , \quad (13)$$

respectively.

V Numerical Results

Firstly, we demonstrate the effect of homogeneous traffic load on channel utilization in a two-channel system. We assume that all channels have the same traffic patterns as follows: $\lambda_p = 0.1$, $\mathbf{E}[X_p] = 3$, and $\lambda_s = 0.1$. If CR technique is not implemented, each channel has only 30% utilization because only the primary users can use spectra. This situation is equivalent to the case that $\mathbf{E}[X_s] = 0$. However, when CR technique is implemented, channel utilization can be improved. An example is shown in Fig. 4. The channel utilization is calculated according to (13). Clearly, the channel utilization increases as the average transmission duration of the secondary connections increases. Furthermore, because all channels have the same performance measures, all of them have the same channel utilization.

Next, we consider the heterogeneous case for the traffic patterns of the primary users. Let $\lambda_p^{(1)} = 0.1$, $\lambda_p^{(2)} = 0.3$, $\mathbf{E}[X_p^{(1)}] = 3$, $\mathbf{E}[X_p^{(2)}] = 1$, and $\lambda_s^{(1)} = \lambda_s^{(2)} = 0.1$. In this case, we have $\rho_p^{(1)} = \rho_p^{(2)} = 0.3$. Although both of two channels have the same traffic loading resulted from the primary connections, the both channels have different utilization factor when CR technique is implemented. As shown in Fig. 5, when allowing the secondary users to access channels, the utilization factor of channel 1 is always higher than that of channel 2. Because channel 2 has larger arrival rate of the primary connection, the secondary connections of channel 2 encounter higher interrupted probability. Hence, the time that the secondary users use channel 2 is shorter than the time that the secondary users use channel 1. Thus, the channel utilization of channel 2 is lower than that of channel 1 when $\mathbf{E}[X_s] > 0$.

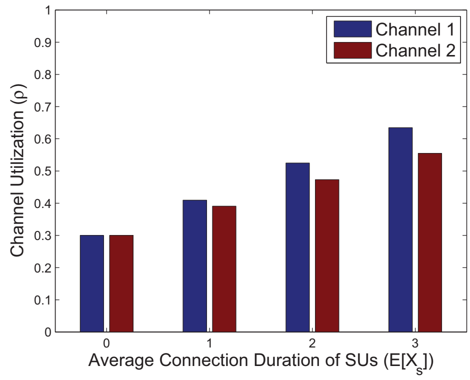

Figure 5: The effect of average connection duration of the secondary users (SUs) on channel utilization where $\lambda_p^{(1)} = 0.1$, $\lambda_p^{(2)} = 0.3$, $\mathbf{E}[X_p^{(1)}] = 3$, $\mathbf{E}[X_p^{(2)}] = 1$, and $\lambda_s^{(1)} = \lambda_s^{(2)} = 0.1$.

VI Conclusions

In CR networks, the most basic issue is how much CR technique can improve spectrum utilization. In order to quantify this gain, we propose a PRP M/G/1 queueing network model to characterize the spectrum usage behavior with multiple spectrum handoffs between the primary and the secondary users. Based on this model, we show how to evaluate spectrum utilization under different traffic loads in CR networks. From the numerical results, we find that the utilization improvement on the channel with lower arrival rate of the primary connections is larger than the channel with higher arrival rate of the primary connections because higher arrival rate will result in higher interrupted probability for the secondary connection.

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