Modeling and Analysis for Proactive-decision Spectrum Handoff in Cognitive Radio Networks

Chung-Wei Wang[*+], Li-Chun Wang[*], and Fumiyuki Adachi [+]
[*] National Chiao Tung University, Hsinchu, Taiwan
[+] Tohoku University, Sendai, Japan

***Abstract*— Spectrum handoff occurs when the primary users appear in the licensed band occupied by the secondary users. Spectrum handoff procedures aim to help the secondary users to vacate the occupied licensed spectrum and find suitable target channel to resume the unfinished transmission. In this paper, we discuss how to select the target channels to minimize the total service time with multiple spectrum handoffs. We propose a preemptive resume priority (PRP) M/G/1 queueing network model to evaluate total service time for various target channels selections. Then, we suggest a low-complexity greedy algorithm to select target channels. Numerical results show that a spectrum handoff scheme based on greedy selection strategy can reduce total service time compared to the randomly selection scheme.**

I. Introduction

Cognitive radio (CR) can improve spectrum efficiency through intelligent spectrum management technologies by allowing secondary users to temporarily access primary users' unutilized licensed spectrum. In order to enhance spectrum management, CR systems require many capabilities such as spectrum mobility (or called spectrum handoff) [1]. Spectrum handoff occurs when the high-priority primary users appear at its licensed band occupied by the secondary users. Spectrum handoff procedures aim to help the secondary users to vacate the occupied licensed spectrum and find suitable target channel to resume the unfinished transmission.

In general, according to the target channel decision methods, spectrum handoff mechanisms can be categorized into [2], [3]: (1) proactive-decision spectrum handoff: make the target channels for spectrum handoff ready *before* data transmission according to the long-term observation outcomes, and (2) reactive-decision spectrum handoff: determine the target channel according to the results from *on-demand* wideband sensing.

Compared to the reactive-decision spectrum handoff, the proactive-decision spectrum handoff may be able to reduce handoff delay because the time-consuming wideband sensing is not required [4]. Furthermore, it is easier to let both transmitter and receiver have a consensus on their target channel for the proactive-decision spectrum handoff than for the reactive-decision spectrum sensing. Nevertheless, when the spectrum handoff process is initiated, the proactive-decision spectrum handoff needs to resolve the issue that the pre-selected target channel may no longer be available. Hence, one challenge for the proactive-decision handoff is to determine the optimal target channels sequences to minimize total service time.

In this paper, we focus on finding the optimal target channels sequences for the *proactive-decision spectrum handoff* in CR networks, while leave the reactive-decision spectrum handoff in the further work. The main objectives of this paper are described as follows:

- A preemptive resume priority (PRP) M/G/1 queueing network model is proposed to characterize the spectrum usage interactions between primary and secondary users with multiple spectrum handoffs. Based on this model, the total service time for various target channels sequences can be evaluated, and then the optimal target channels sequences can be found.
- A suboptimal greedy target channel selection scheme is proposed to reduce the complexity for finding optimal target channels. The complexity of the proposed greedy target channel selection scheme is independent of the total number of channels.

The optimal sequences for target channels can be determined by exhaustive search for all possible permutations of target channels, but this method is obviously too complicated. Based on the proposed PRP M/G/1 analytical model, it will be shown that the proposed low-complexity greedy target channel selection scheme can reduce the total service time compared to the randomly selection scheme.

The rest of this paper is organized as follows. In Section II, we formulate an optimization problem of target channels selection aiming to minimize total service time with multiple spectrum handoffs. Next, we propose a PRP M/G/1 queueing network model to evaluate total service time for various target channels sequences in Section III. Then, a low-complexity greedy target channel selection scheme is discussed in Section IV. In Section V, we derive the total service time resulted from the proposed greedy target channel selection scheme in a simplified case. Numerical and simulation results are given in Section VI. Finally, we give our concluding remarks in Section VII.

II. Problem Formulation

A. An Illustrative Example for proactive-decision Spectrum Handoffs

We consider a slotted-based CR network where each slot consists of sensing phase and transmission phase. Before data transmission, secondary users must perform sensing procedure to check availability of the current operating channel. Furthermore, the spectrum handoff protocol proposed in [2] is considered. This

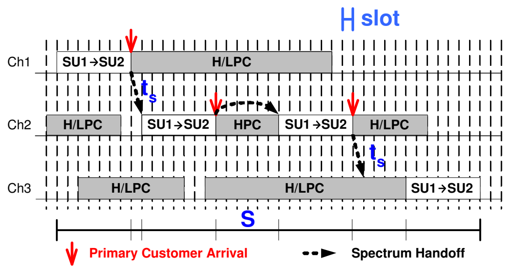

Fig. 1. An example of packet transmission process with three interruptions, where t_s is the channel switch time. The whole data packet is partitioned into four parts due to spectrum handoff.

protocol assumes each secondary user must wait on the selected target channel until it becomes idle.

Figure 1 shows an example where multiple spectrum handoffs occur during a packet transmission. In this figure, HPC and LPC stands for the high-priority customers (i.e., primary customers) and the low-priority customers (i.e., secondary customers), respectively. Consider secondary user 1 (SU1), whose *default channel* is channel Ch1. In the beginning, SU1 transmits its packet to the corresponding receiver SU2. SU1 requires total 28 time slots to transmit the whole packet. Assume that SU1's *target channels sequence* (denoted by Θ) is (Ch2, Ch2, Ch3). The multiple handoffs process is described as follows. At the first interruption, SU1 changes to the idle channel Ch2 from channel Ch1. The handoff delay in this case is the channel switching time (denoted by t_s). At the second interruption, SU1 stays on the current channel Ch2. SU2 can access the channel only after the high-priority primary customers of Ch2 finish their transmissions. In this case, handoff delay is the busy period resulted from the primary customers of Ch2 (denoted by $Y_0^{(2)}$). At the third interruption, SU1 changes to Ch3. Because Ch3 is busy, SU1 cannot be served until all the other customers in the present queue of Ch3 have been served. In this case, handoff delay is the sum of t_s plus the waiting time in Ch3 (denoted by $W_s^{(3)}$). Finally, the transmission of SU1 is finished on Ch3. The total service time (denoted by S) is defined as the duration from the instant of starting transmitting packets until the instant of finishing the transmission. Furthermore, handoff delay is defined as the duration from the instant of pausing transmission until the instant of resuming the unfinished transmission.

B. Total Service Time Minimizing Problem

We formulate a **Total Service Time Minimizing Problem** for spectrum handoff as follows. Given the default channel as well as the arrival and departure models for both the primary and secondary customers, ***find an optimal target channels sequence (denoted by*** Θ^****) to minimize the total service time S.*** Formally,

$$\Theta^* = \arg\min_{\forall\Theta} S(\Theta) \ . \tag{1}$$

III. PRP M/G/1 Queueing Network

In Section II, we formulate a total service time minimizing problem. However, we do not mention how to evaluate total service time. In this section, a PRP M/G/1 queueing network model is proposed to characterize the spectrum usage interactions between primary and secondary users with multiple spectrum handoffs. Based on this model, the total service time for various target channels sequences can be evaluated, and then the optimal target channels sequences can be found. Some important properties for PRP M/G/1 queueing network model are listed below:

- Primary customers have the preemptive priority to interrupt the transmission of secondary customers.
- The interrupted secondary customer is designed to resume the unfinished transmission, instead of retransmitting the whole packet.
- The interrupted secondary customer'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.
- The first-come-first-served (FCFS) scheduling discipline is adopted to arrange the channel access schedule among all secondary customers.

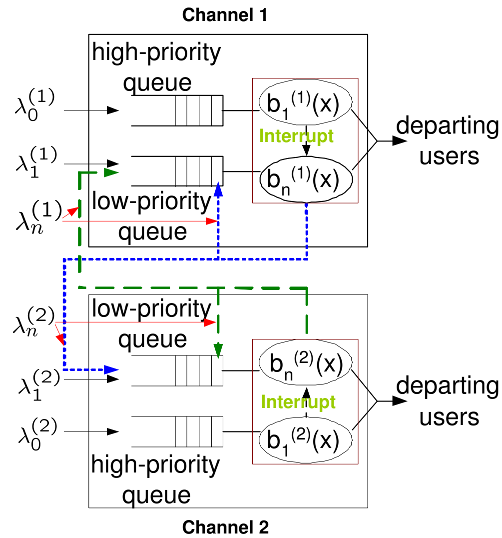

Fig. 2. The PRP M/G/1 queueing network for two-channel system where $n \geq 1$.

Figure 2 shows an example of the PRP M/G/1 queueing network with two channels, in which primary customers are put into the high-priority queue, and secondary customers are put into the low-priority queue. When secondary customers are interrupted by primary customers, they can stay on the current channel or change their operating channels to another channel. Firstly, in the change case, the unfinished transmission will be put into the tail of the low-priority queue of another 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.

In this model, one of key parameters is the effective packet length. It is the transmission duration from the instant that packet is transmitted or resumed until the instant that interruption event occurs. For example, if a secondary user finishes its packet transmission without interruption, the effective packet length is the whole packet length. On the other hand, only partial packet can be transmitted when interruption event occurs. In this case, the effective packet length is the transmission duration of this partial packet.

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

- We assume the arrivals of primary and secondary customers whose default channels are channel k follow the Poisson processes with rates $\lambda_p^{(k)}$ and $\lambda_s^{(k)}$, respectively. Furthermore, their packet length distributions are denoted by $b_p^{(k)}(x)$ and $b_s^{(k)}(x)$ with means $\mathbf{E}[X_p^{(k)}]$ and $\mathbf{E}[X_s^{(k)}]$ time slots, respectively.
- Denote $\lambda_i^{(k)}$ as the arrival rate of the secondary customers with $i-1$ interruptions ($i \geq 1$) at channel k. Furthermore, these customers' effective packet lengths are denoted by $b_i^{(k)}(x)$ with mean $\mathbf{E}[X_i^{(k)}]$ time slots.
- Denote $\rho_p^{(k)}$ and $\rho_i^{(k)}$ as the busy probability resulted from primary customers and the secondary customers with $i-1$ interruptions ($i \geq 1$) at channel k, respectively. The total utilization factor for channel k is represented as $\rho^{(k)}$. Then, the following constraint shall be satisfied.

$$\rho^{(k)} \equiv \rho_p^{(k)} + \sum_{i=1}^{\infty} \rho_i^{(k)} < 1 \ , \tag{2}$$

  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 $\rho_i^{(k)} = \lambda_i^{(k)}\mathbf{E}[X_i^{(k)}]$ for all i.

Note that the system parameters, such as $\lambda_p^{(k)}$, $\lambda_s^{(k)}$, $b_p^{(k)}(x)$, and $b_s^{(k)}(x)$, can be estimated by the existing models such as [5]. Hereafter, the subscript 0 will replace p to represent the primary user's valuables to ease the notations.

According to this model, we can evaluate the total service time of secondary users for various target channels selections. Intuitively, based on the brute force method, we must compare all possible permutations of target channels sequences in order to find the optimal solution. Let M be the total number of channels which can be selected for spectrum handoff and ξ be the number of interruptions during the whole packet transmission. The brute force method needs to compare M^{ξ} permutations and has the time complexity of $O(M^{\xi})$.

IV. Greedy Target Channel Selection

In order to reduce the complexity for solving **Total Service Time Minimizing Problem**, we suggest a sub-optimal greedy strategy for target channels selection. Specifically, we select the channel with *shortest handoff delay* to be the target channel at each spectrum handoff [6]. Furthermore, in the considered spectrum handoff protocol [2], we assume each secondary user must wait on the selected target channel until this channel becomes idle such as the cases of the second and the third interruptions in Fig. 1.

The above optimization problem can be solved by the sub-optimal greedy target channels selection scheme with time complexity of $O(1)$. This can be proved with the help of the following theorems.

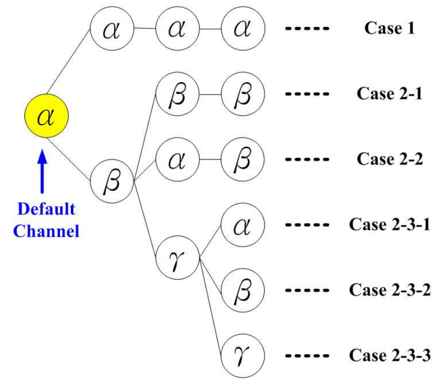

Fig. 3. There are only six permutations for the target channel sequence based on the principle of shortest handoff delay.

Theorem 1: Let $\Omega = \{1, 2, \ldots, M\}$ and $W_s^{(k)}$ be the expected time spent in the waiting queue for a secondary customer on channel k ($k \in \Omega$) . Assume $W_s^{(k)}$ is independent of the channels availabilities in the previous tracks of target channels sequence. When the shortest-handoff-delay principle is adopted to select the target channel, the size of *feasible solution set* of **Total Service Time Minimizing Problem** is six as shown in Fig. 3.

Proof: Assume that the secondary customer is transmitted on channel α in the beginning. For the first interruption, the expected handoff delay for staying on the current channel α equals to the busy period resulted from the primary users of channel α only. On the other hand, the handoff delay for changing its operating channel to channel k ($k \in \Omega/\{\alpha\}$) is the sum of channel switch time (denoted by t_s) plus the waiting time of secondary customers on channel k. Hence, there are two possible cases for target channels selection in the first interruption. In Case 1, we have

$$Y_0^{(\alpha)} < \min_{\forall k \in \Omega/\{\alpha\}} \{W_s^{(k)} + t_s\} \ , \tag{3}$$

where $Y_0^{(k)}$ is the busy period resulted from the primary users of channel k. In this case, the interrupted secondary customer prefers staying on the current channel because it can produce minimal expected handoff delay. Thus, the first target channel in the target channels sequence is channel α. With this decision, the interrupted secondary customer can resume its transmission when all the primary customers are served on channel α. If the statistics of traffic pattern on each channel are stable, (3) holds when the interrupted secondary customer is preempted by primary customers again. Hence, the interrupted secondary customer will always stay on channel α until it is transmitted completely. On the other hand, in Case 2,

$$\exists \beta \neq \alpha \ni W_s^{(\beta)} + t_s < \min\{\min_{\forall k \in \Omega/\{\alpha,\beta\}} \{W_s^{(k)} + t_s\}, Y_0^{(\alpha)}\} \ . \tag{4}$$

In this case, the interrupted customer prefers changing to channel β because it can produce minimal expected handoff delay. Thus, the first target channel in the target channels sequence is channel β.

Case 2 can be further partitioned into three subcases if the second interruption occurs. Firstly, the handoff delays for staying on channel β and changing to channel γ ($\gamma \neq \alpha$ and β) are $Y_0^{(\beta)}$ and $W_s^{(\gamma)} + t_s$, respectively. They are similar to the situation of the first interruption. Furthermore, because $W_s^{(\alpha)}$ in independent of the channels availabilities in the previous tracks of target channels sequence, the handoff delay for switching back to channel α is $W_s^{(\alpha)} + t_s$ approximately. From the above observations, there exist three possibilities in Case 2. In Case 2-1, we have

$$Y_0^{(\beta)} < \min_{\forall k \in \Omega / \{\beta\}} \{W_s^{(k)} + t_s\} \ . \tag{5}$$

This case is similar to Case 1. Hence, the interrupted secondary customer prefers staying on channel β thereafter until it is transmitted successfully. Furthermore, in Case 2-2, we have

$$W_s^{(\alpha)} + t_s < \min\{\min_{\forall k \in \Omega / \{\alpha,\beta\}} \{W_s^{(k)} + t_s\}, Y_0^{(\beta)}\} \ . \tag{6}$$

In this case, the interrupted secondary customer will switch back to channel α. The target channels in the target channels sequence will alternately switch between channels β and α. In the traditional cellular network, switching the target channel back and forth leads to the degradation of network performance [7]. However, in this case, it can result in shorter total service time. Finally, in Case 2-3, we have

$$\exists \gamma \neq \alpha, \beta, \ni W_s^{(\gamma)} + t_s < \min\{\min_{\forall k \in \Omega / \{\beta,\gamma\}} \{W_s^{(k)} + t_s\}, Y_0^{(\beta)}\} \ . \tag{7}$$

In this case, the interrupted secondary customer prefers changing to channel γ. That is, the second target channel in the target channels sequence is channel γ.

Similarly, Case 2-3 can be also further partitioned according to system parameters when the third interruption occurs. In the third interruption, the expected handoff delays for switching back to channels α and β approximate $W_s^{(\alpha)} + t_s$ and $W_s^{(\beta)} + t_s$, respectively. On the other hand, the expected handoff delay for staying on the current channel γ and changing to channel η ($\eta \neq \alpha$, β, and γ) are $Y_0^{(\gamma)}$ and $W_s^{(\eta)} + t_s$, respectively. Hence, there exist three possibilities in Case 2-3 as follows. In Case 2-3-1, we have

$$Y_0^{(\gamma)} < \min_{\forall k \in \Omega / \{\gamma\}} \{W_s^{(k)} + t_s\} \ . \tag{8}$$

In this case, the interrupted secondary customer prefers staying on channel γ thereafter until it is transmitted completely. Furthermore, in Cases 2-3-2 and 2-3-3, we have

$$W_s^{(\alpha)} + t_s < \min\{\min_{\forall k \in \Omega / \{\alpha,\gamma\}} \{W_s^{(k)} + t_s\}, Y_0^{(\gamma)}\} \ , \tag{9}$$

and

$$W_s^{(\beta)} + t_s < \min\{\min_{\forall k \in \Omega / \{\beta,\gamma\}} \{W_s^{(k)} + t_s\}, Y_0^{(\gamma)}\} \ , \tag{10}$$

respectively. Thus, the interrupted secondary customer switches back to channels α and β, respectively. These two subcases will repeat the discussions in Cases 1 and 2 when the secondary customer is interrupted again.

According to Lemma 1 in Appendix I, there are not any subcases in Case 2-3. Hence, we conclude that *there are only six permutations for target channels sequence when the principle of shortest handoff delay is adopted*. The six permutations are shown in Fig. 3. Hence, the time complexity of the proposed greedy algorithm is $O(1)$. Once the system parameters are given, **Total Service Time Minimizing Problem** can be solved from the only six permutations. Note that the similar discussions can be applied on other greedy strategies for target channels selection such as the strategy that the channel with longest idle period is selected firstly. ■

Not only can this theorem prove the low-complexity advantage for the proposed greedy target channel selection approach, but also be helpful to resolve the so-called transmitter-receiver channel synchronization issue in CR networks [4], [8]. That is, the transmitter and the receiver must have a consensus on the operating channel. Based on this theorem, the transmitter and the receiver only need to consider three channels in the suboptimal sense.

V. Performance Analysis

In this section, we evaluate total service time of secondary users. Based on the proposed PRP M/G/1 analytical model, it will be shown that the proposed low-complexity greedy target channel selection scheme can reduce the total service time compared to the randomly selection scheme. To simplify the analysis, we assume that each channel has identical traffic patterns. Hence, the notation (k) in all system parameters can be dropped.

Our goal is to derive total service time of secondary users in the two-channel system. Because each channel has identical traffic patterns, the possible permutations of target channels sequence can be further reduced into two cases. One is the *always-change* case, i.e. case 2-2 of Fig. 3. Another one is the "*always-stay*", i.e., case 1 of Fig. 3. Based on the estimated total service time provided by this analytical model, one can decide whether the always-change strategy is better than the always-stay strategy or vice versa.

A. Total Service Time of Secondary Customers

Let S and $\mathbf{E}[D]$ be the average total service time and handoff delay of secondary customers. Then, we have

$$S = \mathbf{E}[X_s] + \mathbf{E}[N]\mathbf{E}[D] \ , \tag{11}$$

where $\mathbf{E}[N]$ is the average number of interruptions.

If the always-stay strategy (i.e., case 1 of Fig. 3) is adopted, the average handoff delay is the average busy period (Y_0) resulted from primary users of each channel. That is, we have

$$\mathbf{E}[S_{stay}] = \mathbf{E}[X_s] + \mathbf{E}[N]Y_0 \ . \tag{12}$$

On the other hand, if the always-change strategy is adopted, the handoff delay is $W_s + t_s$ where W_s is the waiting time of secondary users. Thus, we have

$$\mathbf{E}[S_{change}] = \mathbf{E}[X_s] + \mathbf{E}[N](W_s + t_s) \ . \tag{13}$$

The unknown terms such as Y_0, $\mathbf{E}[N]$, and W_s in (12) and (13) will be derived in the following subsections.

In addition, we also consider a baseline case that the interrupted secondary customer will uniformly select a target channel from all channels. Thus, it follows that

$$\mathbf{E}[S_{random}] = \mathbf{E}[X_s] + \frac{\mathbf{E}[N]}{2} Y_0 + \frac{\mathbf{E}[N]}{2}(W_s + t_s) \ . \quad (14)$$

Based on the analytical results, a better target channel can be decided to minimize the total service time. Hence, the optimal total service time (denoted by S^*) can be expressed as follows:

$$S^* = \begin{cases} \mathbf{E}[S_{stay}] & , \quad Y_0 \leq W_s + t_s \\ \mathbf{E}[S_{change}] & , \quad Y_0 \geq W_s + t_s \end{cases} \ . \quad (15)$$

Note that if $Y_0 = W_s + t_s$, the stay or change decision is equivalent in terms of total service time.

B. Derivation of $\mathbf{E}[N]$ in (12) and (13)

For deriving $\mathbf{E}[N]$, recall that the transmission of a secondary customer will be interrupted if primary customers appear during its transmission duration. Thus, the average number of interruptions for a secondary packet within a period of $E[X_s]$ can be obtained as

$$\mathbf{E}[N] = \lambda_0 \mathbf{E}[X_s] \ . \quad (16)$$

C. Derivation of Y_0 in (12)

According to the definition of utilization, we have

$$\rho_0 = \lambda_0 \mathbf{E}[X_0] \ . \quad (17)$$

Denote I_0 as the idle period of each channel for the primary network. Because of the memoryless property, the duration from the termination of busy period to the arrival of the next primary customer follows the exponential distribution with mean λ_0. Hence, we have

$$I_0 = \frac{1}{\lambda_0} \ . \quad (18)$$

Then, substituting (17) and (18) into $\rho_0 = \frac{Y_0}{Y_0 + I_0}$ yields

$$Y_0 = \frac{\mathbf{E}[X_0]}{1-\rho_0} = \frac{\mathbf{E}[X_0]}{1-\lambda_0 \mathbf{E}[X_0]} \ . \quad (19)$$

D. Derivation of W_s in (13)

Next, let Q_0 be the average length of high-priority queue and Q_i be the average number of secondary customers with $i-1$ interruptions ($i \geq 1$) waiting in the queue, respectively. Because the incoming secondary user must wait until all these Q_i secondary users and the primary users have been served, the waiting time (W_s) for secondary users in always-change case can be expressed as

$$W_s = R_s + \sum_{i=0}^{\infty} Q_i \mathbf{E}[X_i] + \lambda_0 W_s \mathbf{E}[X_0] \ , \quad (20)$$

where R_s is the average residual effective packet length. It is the remaining time to complete service of the customer which is serving. This customer can be the primary customer or the secondary customer with $i-1$ interruptions. Furthermore, the second and the third terms are the accumulated workload resulted from all customers in the present queue and the newly arriving primary users, respectively. According to [9], we have $R_s = \frac{1}{2}\sum_{i=1}^{\infty} \lambda_i \mathbf{E}[(X_i)^2]$. Furthermore, according to Little's formula, it follows that

$$Q_i = \begin{cases} \lambda_0 W_0 & , \quad i = 0 \\ \lambda_i W_s & , \quad i \geq 1 \end{cases} \ , \quad (21)$$

where W_0 is the average waiting time of primary customers. Hence, we have

$$W_0 = R_0 + Q_0 \mathbf{E}[X_0] \ , \quad (22)$$

where the first term is average residual packet length resulted from primary customers only and the second term is the total workload of primary customers in the present high-priority queue. Similarly, since $R_0 = \frac{1}{2}\lambda_0 \mathbf{E}[(X_0)^2]$ according to [9], solving (21) and (22) simultaneously yields

$$W_0 = \frac{\lambda_0 \mathbf{E}[(X_0)^2]}{2(1-\rho_0)} \ , \ \text{and} \ \ Q_0 = \frac{\lambda_0^2 \mathbf{E}[(X_0)^2]}{2(1-\rho_0)} \ . \quad (23)$$

Last, if λ_i and $\mathbf{E}[X_i]$ can be known, one can obtain W by solving (20) and (21) iteratively. In the special case when the secondary customer has an exponentially distributed packet length, i.e., $b_s(x) = \mu_s e^{-\mu_s x}$ where $\mu_s = \frac{1}{\mathbf{E}[X_s]}$, one can obtain $\lambda_i = \lambda_s (\frac{\lambda_0}{\lambda_0 + \mu_s})^{i-1}$, $\mathbf{E}[X_i] = \frac{1}{\lambda_0 + \mu_s}$, and $\mathbf{E}[(X_i)^2] = \frac{2}{(\lambda_0+\mu_s)^2}$ for all $i \geq 1$. Thus, the closed-form expression for W_s is

$$W_s = \frac{\frac{1}{2}\lambda_0(\mathbf{E}[(X_0)^2]) + \frac{\lambda_s}{(\lambda_0+\mu_s)\mu_s} + \frac{\lambda_0^2 \mathbf{E}[(X_0)^2]}{2(1-\rho_0)}\mathbf{E}[X_0]}{1-\rho_0-\rho_s} \ . \quad (24)$$

VI. Numerical and Simulation Results

A. Simulation Setup

We use MATLAB software to simulate a two-channel system. In each channel, two types of customers are generated with Poisson process. The high-priority customers can interrupt the transmission of low-priority customers. Furthermore, we assume the customers with identical priority access channel with first-come-first-served (FCFS) scheduling discipline. Hence, each channel is collision-free. Finally, we assume all primary and secondary customers have the exponentially distributed packet lengths in our simulations.

B. Performance Evaluation

Figure 4 shows the total service time in the always-stay and the always-change cases. Based on (15), our proposed greedy selection can intelligently operate on the best target channel with shortest total service time. With a lower value of λ_p, the interrupted customer prefers to change the operating channel. By contrast, when λ_p is large, the interrupted customer prefers the always-stay strategy. This phenomenon can be also interpreted by the renewal theory as follows: As λ_p increases, the busy period Y_0 increases. Thus, it is more likely that the randomly interrupted secondary customer will see a longer busy period. Hence, in this case, the interrupted customer prefers staying on the current channel. 5

Figure 5 compares the total service time of spectrum handoff with two different target channel selection methods: 1) the

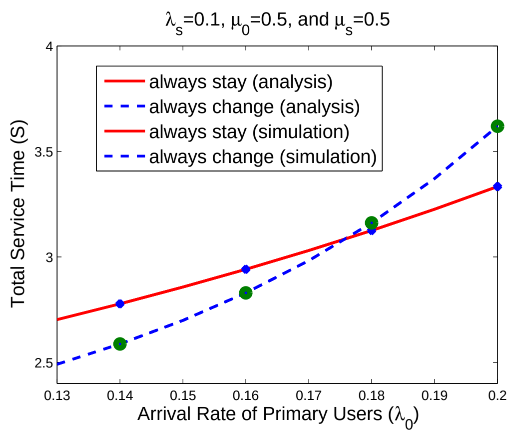

Fig. 4. Comparison of total service time in the always-stay and the always-change cases. The value of t_s is assumed be 0.

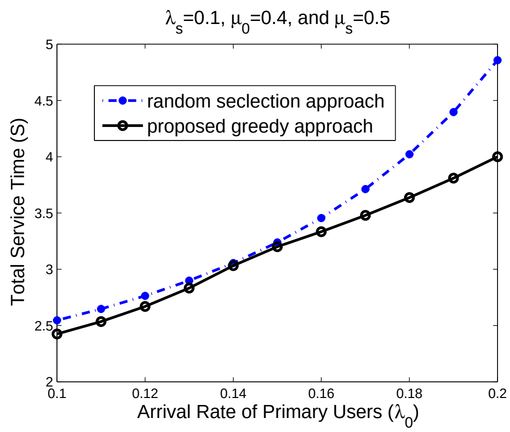

Fig. 5. Comparison of total service time for random and greedy strategies. The value of t_s is assumed be 0.

random target channel selection and 2) the proposed greedy target channel selection. For $\lambda_p \leq 0.2$, it is shown that the total service time can be shortened about $5 \sim 20\%$ comparing to the case of random selection. For larger λ_p, one can expect that the proposed greedy target channel selection strategy can improve total service time more significantly.

Figure 6 shows the effect of μ_s on the total service time of the proposed greedy target channel selection approach. As shown in this figure, when μ_s is small, it is preferable to make the interrupted customer prefers stay on the same channel because the waiting time may be longer after changing to another channel. Thus, the decision cross-point moves toward left-hand side as μ_s decreases.

VII. Conclusions

In this paper, we have investigated **Total Service Time Minimizing Problem**. We propose a preemptive resume priority (PRP) M/G/1 queueing network model to evaluate total service time for various target channels sequences. Then, we suggest a low-complexity greedy algorithm to select target channels. According to the greedy target channel selection approach, it is only required to maintain a candidate target channels sequence

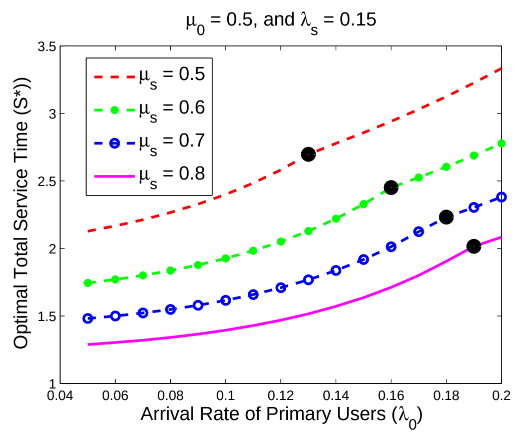

Fig. 6. Effect of μ_s on the total service time of the proposed greedy target channel selection. The value of t_s is assumed be 0.

consisting of at most three channels. Numerical results show that a spectrum handoff scheme based on greedy selection strategy can reduce the total service time compared to the randomly selection scheme.

Appendix I
The Proof of Lemma 1

Lemma 1: Case 2-3 can only be further partitioned into three sub-cases (sub-cases 2-3-1, 2-3-2, and 2-3-3).

Proof: Assume that there exists another subcase in case 2-3. That is,

$$\exists \eta \neq \alpha, \beta, \gamma, \ni W^{(\eta)} + t_s < \min\{ \min_{\forall k \neq \eta, \gamma} \{W^{(k)} + t_s\}, Y_1^{(\gamma)}\} \ . \tag{25}$$

Then, it follows that $W^{(\eta)} + t_s < W^{(k)} + t_s$ for all $k \neq \eta, \gamma$. However, from (4) in case 2, we obtain $W^{(\beta)} + t_s < W^{(k)} + t_s$ for all $k \neq \alpha, \beta$. It leads to a contradiction. ■

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