行政院國家科學委員會補助專題研究計畫期中進度報告

廣義的機會式通訊：無線行動網路中之競爭、合作與感知–子計畫四:感知無線行動網路之合作式媒體存取控制協定設計與用戶/基地台選取研究

Cooperative MAC Protocol Design and User/Base Station Selection in Cognitive Wireless Mobile Networks

計畫類別： □ 個別型計畫　　■ 整合型計畫

計畫編號： NSC 96-2628-E-009-004-MY3

執行期間： 97 年 8 月 1 日至 98 年 7 月 31 日

計畫主持人：王蒞君 教授

共同主持人：

計畫參與人員： 王中瑋, Samer Talat

成果報告類型(依經費核定清單規定繳交)：■ 精簡報告　□完整報告

本成果報告包括以下應繳交之附件：

□赴國外出差或研習心得報告一份

□赴大陸地區出差或研習心得報告一份

□出席國際學術會議心得報告及發表之論文各一份

□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢

□涉及專利或其他智慧財產權，□一年 □二年後可公開查詢

執行單位：國立交通大學電信工程學系

中 華 民 國 98 年 7 月 31 日

計畫執行概要:

感知無線網路（Cognitive Radio Networks）是近年來新興起的無線通訊技術。在感知無線網路中，通訊設備必須能夠智慧地感知週遭通訊環境中所有的頻譜機會（Spectrum Opportunity），並讓使用者能適當地分享所感知到的頻譜機會，以達到頻譜最佳化的利用。

在感知無線網路中，頻譜切換（Spectrum Handoff）發生在主要使用者（Primary User）需要重新使用頻帶時，運作在此頻帶的感知次要使用者（Secondary User）必須轉換至其他閒置頻帶。頻譜切換機制必須能夠在不干擾其他主要使用者的前提下，動態智慧地分配閒置頻帶給次要使用者。這需要智慧型的感知技術以感測並判定出主要使用者的傳輸。此外，當頻譜切換發生時，次要使用者也需要能夠即時的轉換至最佳的頻帶。最佳頻帶的選取取決於頻譜感測及頻帶帶寬。本計劃著重於無間隙高服務品質的頻譜切換。

本分項今年度的目標在探討異質感知協力式無線網路中的頻譜切換議題。主要的工作有三方面:

第一、 我們研究了被動式頻譜切換 (Reactive-sensing Spectrum Handoff)與主動式頻譜切換 (Reactive-sensing Spectrum Handoff)機制。並比較其性能。

第二、 我們研究了在主動式頻譜切換方法中，如何減少封包傳輸延遲。

第三、 我們也提出了在一個頻道帶寬不固定的情況下，利用延遲帶寬乘積（Delay Bandwidth Product）為判斷準則的頻譜切換機制。

Executive Summary:

Cognitive radio (CR) networks are emerging wireless communication technology. In CR networks, the users can intelligently sense, learn, and identify all the possible spectrum opportunities, and share the spectrum opportunities properly to achieve the optimal spectrum efficiency.

In CR network, spectrum handoff process arises when CR users wish or need to transfer their connections to an unused spectrum band. The spectrum handoff mechanism should dynamically allocate secondary user with licensed spectrum without interfering with primary users. This requires sophisticated techniques in order to sense and detect the primary user. If spectrum handoff occurs, secondary user moves to the best available spectrum band. The best available spectrum band depends on handoff decision in both spectrum sensing and variable channel bandwidth. Our handoff methods focus on the seamless transition with minimum quality degradation.

In this project, the main goal is to investigate the spectrum handoff for heterogeneous cognitive cooperative wireless systems.
Specific tasks include three folds:

First, we investigated the reactive-sensing and proactive-sensing spectrum handoff, and compared their performance.

Second, we investigated how to minimise the packet latency in proactive sensing spectrum.

Third, we also examined using delay bandwidth product (DBP) as a criteria for handoff channel selection in variable channel bandwidth.

計畫成果 (Achievements):

Conference paper

[1] Li-Chun Wang and Chung-Wei Wang, “Spectrum Handoff for Cognitive Radio Networks: Reactive-Sensing or Proactive-Sensing?,” IEEE IPCCC, 2008.

[2] Chung-Wei Wang and Li-Chun Wang, “Modeling and Analysis for Proactive Spectrum Handoff in Cognitive Radio Networks,” IEEE ICC, 2009.

[3] Samer T. Talat and Li-Chun Wang, “QoS-guaranteed Channel Selection Scheme for Cognitive Radio Networks With Variable Channel Bandwidths”, ICCCAS 2009.

Spectrum Handoff for Cognitive Radio Networks: Reactive-Sensing or Proactive-Sensing?

中文摘要

在這篇文章中，我們研究感知無線電網路中的『頻譜切換 (Spectrum Handoff)』問題。當次要使用者運作在執照頻帶時，若主要使用者想進行傳送，則次要使用者必須執行頻譜切換機制以避免干擾主要使用者。本文章將比較兩種不同的頻譜切換機制。首先，我們研究被動式頻譜切換 (Reactive-sensing Spectrum Handoff)。在這種機制下，當頻譜切換被執行時，次要使用者才去尋找切換的目標頻道。接下來，我們探討主動式頻譜切換 (Reactive-sensing Spectrum Handoff)。在這種機制下，在頻譜切換被執行前，次要使用者就必須先決定好目標頻道。基本上，這兩種機制各有優缺點。在本文章中，我們將利用排隊理論來針對此問題作一有系統的分析並設計最佳的頻譜切換機制。目前，根據提出的模型，我們已經可以順利量化不同頻譜切換策略的優劣。

English Abstract

In this paper, we will investigate the spectrum handoff schemes for the cognitive radio networks. Spectrum handoff occurs when the primary users appear and the secondary users are using this particular primary user's licensed channel. We compare two major types of spectrum handoff schemes. One is the reactive-sensing spectrum handoff, where the target channel for spectrum handoff is selected or sensed only after the spectrum handoff request is made. The other one is the proactive-sensing spectrum handoff, for which the target channel is pre-determined. The advantage of the reactive spectrum handoff is the accuracy of the selected target channel, but pays the cost of sensing time. By contrast, the proactive spectrum handoff avoids the sensing time, but the pre-determined target channel may not be available. We will provide a Preemptive Resume Priority M/G/1 queueing network model to analyze in which condition that the reactive- or proactive-sensing spectrum handoff should be used dependent of sensing time.

1 Introduction

Cognitive radio (CR) can improve spectrum efficiency by allowing secondary users to temporarily access primary users' unused licensed spectrum [7, 14, 21]. Cognitive radio (CR) system requires four important functionalities [1]: (1) spectrum sensing (detecting unused spectrum); (2) spectrum management (selecting the best channel); (3) spectrum sharing (coordinating the channel access among multiple users) [27]; and (4) spectrum mobility (switching to other available channel when a licensed user appears).

In this paper, we focus on the spectrum mobility (or called spectrum handoff) issue, which is discussed less often in the literature than other spectrum issues of CR networks. Spectrum handoff occurs when the high-priority primary user appear at its licensed channel and find that the channel is occupied by secondary users [28]. In this case, secondary users are forced to vacate the occupied licensed spectrum. Spectrum handoff procedures aim to help secondary users find suitable target channels to resume the unfinished transmission. In general, according to the target channel selection methods, spectrum handoff mechanisms can be categorized into: (1) proactive-sensing spectrum handoff; and (2) reactive-sensing spectrum handoff.

• For the proactive-sensing spectrum handoff, secondary users make the target channels for spectrum handoff ready before its transmission. In this case, secondary users periodically observe all channels to obtain the channel usage statistics, and determine the candidate set of target channels for spectrum handoff according to the long-term observation outcomes [5, 12].

• For the reactive-sensing spectrum handoff, the target channels are searched by the on-demand manner. In this case, the instantaneous outcomes from wideband sensing will be used to determine the target channel selection for spectrum handoff [9, 22, 26, 29].

Although many spectrum handoff schemes are proposed, the analytical model for characterizing these algorithms is not seen too much yet.

In this paper, we focus on developing an analytical model for the spectrum handoff in CR networks. The main contribution of this paper is to propose a preemptive resume priority (PRP) M/G/1 queueing network model to characterize the spectrum usage behaviors between primary and secondary users in CR networks. Based on this model, we can compare two major types of spectrum handoff schemes. Furthermore, we can also analyze in which condition that the reactive- or proactive-sensing spectrum handoff should be used dependent of sensing time.

The rest of this paper is organized as follows. Section 2 reviews the related literature about the spectrum usage models. In Section 3, we introduce the basic operations of spectrum handoff protocols. Next, we propose a PRP M/G/1 queueing network to evaluate the latency performance in Section 4. Finally, we give our concluding remarks in 5.

2 Related Work

The concept of spectrum handoff in CR networks is different from the traditional handoff mechanisms in wireless networks. In spectrum handoff, two types of users with different priorities are considered. The high-priority users have the right to interrupt the transmission of the low-priority users and ask them to leave the channel even though the signal strength of the low-priority user is still acceptable. In the traditional handoff, all users have the same priorities and the decision of changing channels is made mainly due to the deterioration of the current channel signal quality.

Basically, the modeling for spectrum handoff in the current literature can be categorized into four methods. Their advantages and disadvantages are discussed as follows.

2.1 Independent Channel Access Probability Model

In [4, 23], authors assumed the access probability of primary users in each slot is independent. Based on this simplification, the distributions of both busy and idle periods are exponentially-distributed. Hence, the complex probability model for channel usage in CR networks can be simplified due to the memoryless property of exponential distribution. However, this analytical approach cannot extend to the general traffic patterns.

2.2 Two-Dimensional Markov Chain

The authors in [2, 10, 19, 20, 32] used the two-dimensional Markov chain to analyze the performance measure of CR networks such as the blocking and the forced termination probabilities. In their models, each state corresponds the total numbers of primary users and secondary users in CR system. That is, in each state, we cannot distinguish which specific channels are used by users. Hence, their models are usually quite difficult to analyze the delay performance of secondary users for the proactive-sensing based spectrum handoff. Further, the overhead of the spectrum sensing was also not considered.

2.3 Markov Decision Process

In [30, 31], the frameworks of Markov decision process were proposed to select the target channel to maximize throughput of secondary users. They assumed the traffic statistics of the primary network are such that the channel occupancy follows a discrete-time Markov process. Then, based on the decision-theoretic approach, secondary users can adaptively select the best target channel. However, this approach ignores the effect of secondary users' traffic load. In fact, the past and future decisions of secondary users will affect the secondary users' traffic load on each channel and thus also affect the statistics of channel occupancy.

2.4 PRP M/G/1 queueing Model

In [8, 11, 15, 16], authors used PRP M/G/1 queueing model to characterize the spectrum usage behaviors. In [11], authors assumed primary users have not the preemptive priority. Next, in [15, 16], the secondary user is forced to stay on the current to resume its transmission when it is interrupted. Finally, although [8] allowed that secondary user can change its operating channel when it is interrupted, it does not consider the traffic load of interrupted users which come from other channels on each channel. Hence, this model cannot handle the interaction between different channels.

3 Spectrum Handoff Procedure

Spectrum handoff occurs when the primary customers appear in the channel occupied by the secondary customers. In this situation, the secondary customer shall immediately handoff (transit) from the current channel to the target channel.

3.1 Spectrum Handoff Mechanism for CR Networks

The spectrum handoff mechanism has been discussed in many literature [6, 13, 17]. They consist of five key steps as follows.

1. Firstly, we assume the secondary users SU1 and SU2 communicate on the channel Ch1 as shown in Fig. 3.1(a).
2. Furthermore, when primary users appear on Ch1, SU1 can detect this appearance event and prepare to perform spectrum handoff procedure as shown in Fig. 3.1(b).
3.Next, SU1 pauses its current communication within a predefined duration as shown in Fig. 3.1(c). Furthermore, it must also notify SU2 of the interruption event before another predefined time interval.
4.Then, SU1 and SU2 can resume its transmission on the selected target channel as as shown in Figs. 3.1(d)-(f).
5.Finally, because a frame may be interrupted many times during its transmission duration, the similar spectrum handoff procedure may be performed many

times.

Note that the target channel can be selected by different target channel selection methods for spectrum handoff as discussed in Section 1. The different selection will lead to different handoff delays.

3.2 Handoff Delay for Spectrum Handoffs

The handoff delay of the interrupted customer is dominated by the selected target channel. In this paper, handoff delay is defined as the duration from the instant of pausing frame transmission until the instant of resuming the transmission. Figures 3.1(d)-(f) show the handoff delay for different selections of target channel under a two-channel system. In general, when SU1 is interrupted by primary users, it will change its operating channel to the other channels, like Ch2. Hence, the remaining frame of SU1 will be a newly arriving secondary customer of Ch2. In this situation, there are two possible cases. In case 1, if the target channel Ch2 is idle, SU1 can immediately start transmitting its data frame as shown in Fig. 3.1(d). However, in case 2, if Ch2 is busy, SU1 needs to wait until all the other secondary users waiting for Ch2 in queue have been served as shown in Fig. 3.1(e). On the other hand, when choosing the target channel, the current channel (Ch1) can be also one of candidates as shown in Fig. 3.1(f). Hence, the remaining transmission of SU1 will be a newly arriving secondary customer of Ch1. In this situation, SU1 can continue accessing the channel only after the primary users finish the transmission because it is in the head of low-priority queue. Note that the similar procedure will be applied if this secondary customer is interrupted again on the selected target channel.

4 PRP M/G/1 queueing Network and Analysis Results

4.1 PRP M/G/1 queueing Network

In this paper, we use PRP M/G/1 queueing network which is proposed in [24, 25] to analyze in which condition that the reactive- or proactive-sensing spectrum handoff should be used dependent of sensing time. Some important properties for the 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 data frame.
- 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 [3].

Figure 1 shows the 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. First, in the change case, the unfinished data will be put into the tail of the low-priority queue of another channel. Second, the unfinished data can also be inserted into the head of the low-priority queue of the current channel when the stay case occurs. In both case, the unfinished transmission can be resumed when the channel becomes idle.

In this model, one of key parameters is the effective transmission time. It is the transmission duration from the time instant that frame is transmitted or resumed until the time instant that the interruption event occurs. For example, if a secondary customer finishes its frame transmission without any interruption, the effective transmission time is its whole frame length. On the other hand, a secondary customer can successfully transmit only partial frame to the corresponding receiver when it is interrupted by primary customers. In this case, the effective transmission time is the transmission duration of this partial frame.

4.2 Relationship between Spectrum Handoff Procedure and PRP M/G/1 queueing Network

The proposed PRP M/G/1 queueing network can modeled the five key steps of spectrum handoff mechanism as discussed in Section 3.1. They are summarized as follows.

1. Secondary customer arrival event as shown in Fig. 3.1(a): The arrivals of secondary customers whose default channel is channel k are modeled by the Poisson processes with mean rates $\lambda_s^{(k)}$. Furthermore, their service time distributions are denoted by $b_s^{(k)}(x)$ with mean $E[X_s^{(k)}]$.

2. Primary customer arrival event as shown in Fig. 3.1(b): The arrivals of primary customers whose default channel is channel k are modeled by the Poisson processes with mean rates $\lambda_0^{(k)}$. Furthermore, their service time distributions are denoted by $b_0^{(k)}(x)$ with mean $E[X_0^{(k)}]$.

3. Interruption event as shown in Fig. 3.1(c): In the proposed queueing network model, primary customers have the preemptive priority and thus can interrupt the transmission of secondary users. Hence, secondary customers must pause their transmission when primary customers appear.

4. Resumption on target channel as shown in Figs. 3.1(d)-(f): Secondary frame must be resumed on the selected target channel. This model can handle different results of target channel selection through different feedback paths. For example, in Fig. 1(f), when secondary customer selects to stay on the current channel, it will be inserted into the head of the low-priority queue of the current channel through the feedback path.

5. Multiple handoff event: The interrupted secondary frame will resume its transmission on the target channel. Hence, this unfinished frame will be the newly arriving secondary customer. For channel k, the arrival rate of the secondary customers with $i-1$ interruptions ($i \geq 1$) is denoted by $\lambda_i^{(k)}$. Furthermore, its effective transmission time is denoted by $b_i^{(k)}(x)$ with mean $E[X_i^{(k)}]$.

4.3 Analysis Results of Transmission Latency

The closed-form expressions of transmission latency for reactive- and proactive-sensing spectrum handoff have been derived in [25] and [24], respectively. Now, we consider a two-channel system as shown in Fig. 1. We assume that each channel has the identical traffic patterns. Hence, the notation (k) in all system parameters can be dropped. Let $\mu_s = 1/E[X_s]$. Then, the transmission latency for reactive-sensing spectrum handoff can be expressed as follow:

$$E[L_{reactive}]$$

$$= E[X_s] + \frac{\lambda_0 \left[t_p \mu_s + (E[X_0])^2 \lambda_0 \mu_s + E[X_0](\lambda_s - t_p \lambda_0 \mu_s) \right]}{(1 - \lambda_0 E[X_0])(\mu_s)^2},$$

where t_p is the processing time which is the sum of channel switch time (t_s) plus channel sensing time (t_f).

On the other hand, we have proved that there exist only two predetermined target channels sequences to minimize the handoff latency when we select the channel with the shortest handoff delay to be the target channel at each spectrum handoff. The first one is the always-stay case where the interrupted customer will always stay on its default channel until its packet is transmitted completely. In this case, the average transmission latency can be expressed as follows:

$$E[L_{stay}] = E[X_s] + \lambda_0 E[X_s] \frac{E[X_0]}{1 - \lambda_0 E[X_0]}. \quad (2)$$

Furthermore, the second one is the always-change case where the target channels will alternately switch between two channels. In this case, the average transmission latency can be expressed as follows:

$$E[L_{change}]$$

$$= E[X_s] + E[N]\left(\frac{\lambda_0 (E[(X_0)])^2 + \frac{\lambda_s}{(\lambda_0 + \mu_s)\mu_s} + \frac{\rho_0^2}{1 - \rho_0} E[X_0]}{1 - \rho_0 - \rho_s} + t_s \right), \quad (3)$$

where t_s is the channel switch time, $\rho_0 = \lambda_0 E[X_0]$, and $\rho_s = \lambda_s E[X_s]$. Hence, in the proactive-sensing spectrum handoff scheme, the optimal transmission latency can be expressed as follows

$$L_{proactive} = \min\{E[L_{stay}], E[L_{change}]\}. \quad (4)$$

4.4 Numerical Results

Figure 2 shows the transmission latency in the always-stay and the always-change cases. Based on (4), our proposed greedy selection can intelligently operate on the best target channel with the lowest transmission latency.

With a lower value of λ_0, the interrupted customer prefers to change the operating channel. By contrast, λ_0 is large, the interrupted customer prefers the always-stay strategy. This phenomenon can be also interpreted by the renewal theory as follows [18]: As λ_0 increases, the busy period 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 original channel.

Fig. 3 compares the transmission latency of spectrum handoff with reactive- and proactive-sensing spectrum handoff schemes.

When the sensing time (t_f) for spectrum handoff is zero, the reactive-sensing spectrum handoff scheme has the shortest transmission latency. However, the transmission latency increases as sensing time increases. For example, when $t_f = 0.7$, the transmission latency with reactive-sensing spectrum handoff scheme is not always better than that with proactive-sensing spectrum handoff scheme. As shown in this figure, when λ_0 is smaller than 0.13, the proactive-sensing spectrum handoff scheme has shorter transmission latency because the selected target channel is idle with higher probability.

5 Conclusions

In this paper, we compare two major types of spectrum handoff schemes. One is the reactive-sensing spectrum handoff, and the other is proactive-sensing spectrum handoff. We provide a Preemptive Resume Priority M/G/1 queueing network model to analyze in which condition that the reactive- or proactive-sensing spectrum handoff should be used dependent of sensing time. Because this model can handle the case when the interrupted secondary users need to change their operating channels, the interaction between different channels can be elaborated exactly. Furthermore, the effects of traffic patterns and target channels selection strategies on transmission latency can be also considered simultaneously.

6 References

[1] I. F. Akyildiz and W. Y. Lee and M. C. Vuran and S. Mohanty. NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey. *Computer Networks Journal (Elsevier)*, 50:2127-2159, 2006.

[2] F. Capar and I. Martoyo and T. Weiss and F. Jondral. Comparison of Bandwidth Utilization for Controlled and Uncontrolled Channel Assignment in a Spectrum Pooling System. IEEE VTC, :1069-1073, 2002.

[3] Bong Dae Choi and Gang Uk Hwang. The AP, $M/G_1, G_2/1$ Queue with Preemptive Priority. Journal of Applied Mathematics and Stochastic Analysis, 10(4):407-421, 1997.

[4] Chun-Ting Chou and Sai Shankar N and H. Kim and K. G. Shin. What and How Much to Gain From Spectral Agility?. IEEE Journal on Selected Areas in Communications, 25(3):576-588, 2007.

[5] J. Gambini and O. Simeone and U. Spagnolini and Y. Bar-Ness and Y. Kim. Cognitive Radio with Secondary Packet-By-Packet Vertical Handover. IEEE International Conference on Communications, :1050-1054, 2008.

[6] Chuan Han and Jun Wang and Shaoqian Li. A Spectrum Exchange Mechanism in Cognitive Radio Contexts. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, :1-5, 2006.

[7] Simon Haykin. Cognitive Radio: Brain-Empowered Wireless Communications. IEEE Journal on Selected Areas in Communications, 23(2):201-220, 2005.

[8] Junghyun Heo and Jungchae Shin and Jihee Nam and Yutae Lee and Joon Goo Park and Ho-Shin Cho. Mathematical Analysis of Secondary User Traffic in Cognitive Radio System. IEEE VTC, 2008.

[9] Wendong Hu and Daniel Willkomm and George Vlantis and Mario Gerla and Adam Wolisz. Dynamic Frequency Hopping Communities for Efficient IEEE 802.22 Operation. IEEE Communications Magazine, :80-87, 2007.

[10] B. Ishibashi and N. Bouabdallah and R. Boutaba. QoS Performance Analysis of Cognitive Radio-based Virtual Wireless Networks. IEEE INFOCOM, :2423-2431, 2008.

[11] S. Keshavamurthy and K. Chandra. Multiplexing Analysis for Dynamic Spectrum Access. MILCOM, :1-7, 2006.

[12] Hyoil Kim and Kang G. Shin. Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks. IEEE Transactions on Mobile Computing,

7(5):533-545, 2008.

[13] Xin Liu and Zhi Ding. ESCAPE: A Channel Evacuation Protocol for Spectrum-Agile Networks. IEEE DySPAN, :292-302, 2007.

[14] Joseph Mitola and Gerald Q. Maguire. Cognitive Radio: Making Software Radios More Personal. IEEE Personal Communications, 6:13-18, 1999.

[15] Ping Zhu and Jinglong Li and Xufa Wang. A New Channel Parameter For Cognitive Radio. CrownCom, :482-486, 2007.

[16] Ping Zhu and Jinglong Li and Xufa Wang. Scheduling Model for Cognitive Radio. CrownCom, :1-6, 2008.

[17] Qicai Shi and David Taubenheim and Spyros Kyperountas and Paul Gorday and Neiyer Correal. Link Maintenance Protocol for Cognitive Radio System with OFDM PHY. IEEE DySPAN, :440-443, 2007.

[18] W. L. Smith. Renewal Theory and its Ramifications. Journal of the Royal Statistical Society, 20:243-302, 1958.

[19] S. Tang and Brian L. Mark. Performance Analysis of a Wireless Network with Opportunistic Spectrum Sharing. Proceedings of IEEE Global Telecommunications Conference, 2007.

[20] Shensheng Tang and Brian L. Mark. An Analytical Performance Model of Opportunistic Spectrum Access in a Military Environment. IEEE Wireless Communications and Networking Conference, 2008.

[21] Ryan W. Thomas and Luiz A. DaSilva and Allen B. MacKenzie. Cognitive Networks. IEEE DySPAN, :352-360, 2005.

[22] Jin Tian and Guangguo Bi. A New Link Maintenance and Compensation Model for Cognitive UWB Radio Systems. International Conference on ITS Telecommunications Proceedings, :254-257, 2006.

[23] Li-Chun Wang and Anderson Chen. On the Performance of Spectrum Handoff for Link Maintenance in Cognitive Radio. International Symposium on Wireless Pervasive Computing, 2008.

[24] Li-Chun Wang and Chung-Wei Wang. Modeling and Analysis for Proactive-Sensing Spectrum Handoff in Cognitive Radio Networks. submitted to ICC'09.

[25] Li-Chun Wang and Chung-Wei Wang. Modeling and Analysis for Reactive-Sensing Spectrum Handoff in Cognitive Radio Networks. submitted to INFOCOM'09.

[26] Li-Chun Wang and Chung-Wei Wang. Spectrum Handoff for Cognitive Radio Networks with Reactive Sensing. IEEE APWCS, 2008.

[27] Li-Chun Wang and Chung-Wei Wang and Yin-Chih Lu and Chuan-Ming Liu. A Concurrent Transmission MAC Protocol for Enhancing Throughout and Avoiding Spectrum Sensing in Cognitive Radio. IEEE Wireless Communications and Networking Conference, :121-126, 2007.

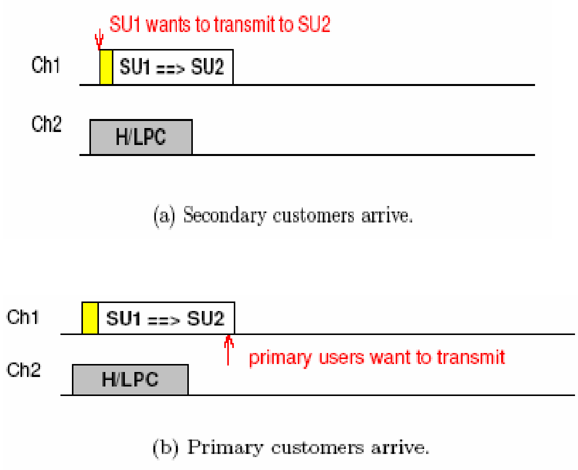
[28] T. A. Weiss and F. K. Jondral. Spectrum Pooling: An Innovative Dtrategy for the Enhancement of Spectrum Efficiency. IEEE Communications Magazine, 42(3):S8-S14, 2004.

[29] Daniel Willkomm and James Gross and Adam Wolisz. Reliable Link Maintenance in Cognitive Radio Systems. IEEE DySPAN, :371- 378, 2005.

[30] Q. Zhao and L. Tong and A. Swami and Y. Chen. Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework. IEEE Journal on Selected Areas in Communications, 25(3):589-600, 2007.

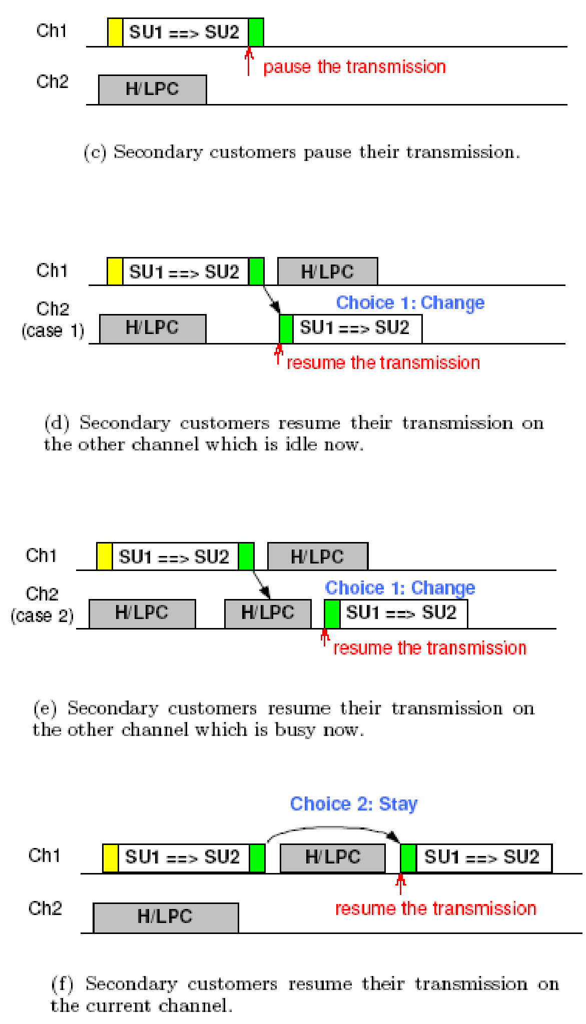
[31] Qianchuan Zhao and S. Geirhofer and Lang Tong and B. M. Sadler. Opportunistic Spectrum Access via Periodic Channel Sensing. IEEE Transactions on Signal Processing, 56(2):785-796, 2008.

[32] Xiaorong Zhu and Lianfeng Shen and Tak-Shing Peter Yum. Analysis of Cognitive Radio Spectrum Access with Optimal Channel Reservation. IEEE Communications Letter, 11(4):304-306, 2007.



(a) Secondary customers arrive.

(b) Primary customers arrive.



(c) Secondary customers pause their transmission.

(d) Secondary customers resume their transmission on the other channel which is idle now.

(e) Secondary customers resume their transmission on the other channel which is busy now.

(f) Secondary customers resume their transmission on the current channel.

Figure 1: An example of target channel selection under a two-channel system. The notations ``H/LPC" represents the occupation duration resulted from primary and secondary users.

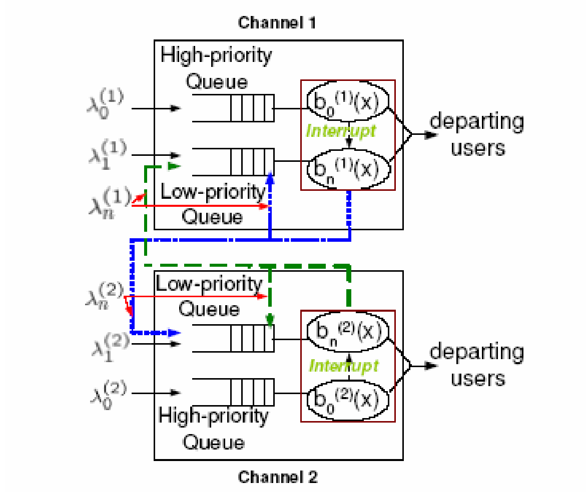


Figure 2: The PRP M/G/1 queueing network for two-channel system where $n \geq 1$.

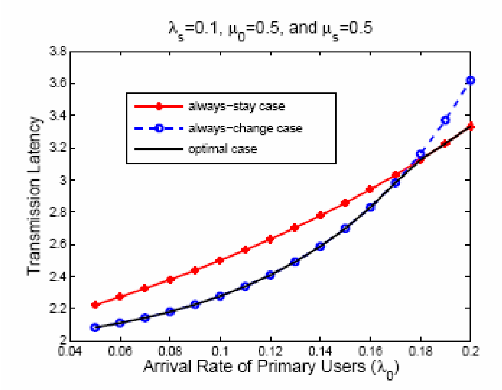


Figure 3: Comparison of transmission latency in the always-stay and the always-change cases where $t_s = 0$ and $\mu_0 = 1/E[X_0]$.

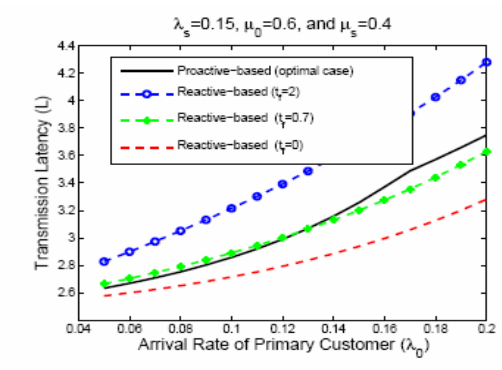


Figure 4: Comparison of transmission latency for different spectrum handoff schemes where $t_s = 0$ and $\mu_0 = 1/E[X_0]$.

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

中文摘要

在感知無線電網路中，當次要使用者運作在執照頻帶時，一個重要的課題是如何避免影響主要權使用者的傳輸。因此，一旦主要使用者想進行傳送時，次要使用者必須立即停止目前的傳輸並且將這個未完成的封包傳輸轉換到其他適合的頻帶上繼續傳送，以便將它對主要使用者的影響降到最低。這樣的行為叫做『頻譜切換(Spectrum Handoff)』。在本文章中，我們討論如何預先選擇最好的頻譜切換的目標頻道，使得封包的傳輸延遲能夠被最小化。首先，我們利用排隊理論來分析不同的目標頻道選擇對傳輸延遲的影響。然後，我們提出一個低複雜度的演算法來選擇目標頻道。從數值分析的結果可以發現，我們提出的機制確實能夠大大的降低封包的傳輸延遲。

English 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.

1 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 [7, 8]: (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 [10]. 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 to 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 2, 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 3. Then, a low-complexity greedy target channel selection scheme is discussed in Section 4. In Section 5, 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 6. Finally, we give our concluding remarks in Section 7.

2 Problem Formulation

2.1 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 [8] is considered. This 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.

2.2 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,

$$\Theta^* = \underset{\forall\Theta}{\operatorname{argmin}}\ S(\Theta). \tag{1}$$

3 PRP M/G/1 queueing Network

In Section 2, 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.

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 $E[X_p^{(k)}]$ and $E[X_s^{(k)}]$ 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 $E[X_i^{(k)}]$ 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.

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

where $1 \leq k \leq M$. Hence, $\rho^{(k)}$ can be also interpreted as the busy probability of channel k. Note that $\rho_p^{(k)} = \lambda_p^{(k)} E[X_p^{(k)}]$ and $\rho_i^{(k)} = \lambda_i^{(k)} E[X_i^{(k)}]$ 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 $O(M^{\xi})$.

4 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 [2]. Furthermore, in the considered spectrum handoff protocol [8], 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.

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 [9]. 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 8, there are not any sub-cases 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 [6, 10]. 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.

5 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.

5.1 Total Service Time of Secondary Customers

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

$$S = E[X_s] + E[N]E[D], \quad (11)$$

where $E[N]$ 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

$$E[S_{stay}] = E[X_s] + E[N]Y_0. \quad (12)$$

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

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

The unknown terms such as Y_0, $E[N]$, 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

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

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:

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

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

5.2 Derivation of $E[N]$ in (12) and (13)

For deriving $E[N]$, 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

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

5.3 Derivation of Y_0 in (12)

According to the definition of utilization, we have

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

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

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

5.4 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 ($i \ge 1$) 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

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

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 [3], we have $R_s = \frac{1}{2}\sum_{i=1}^{\infty}\lambda_i E[(X_i)^2]$. Furthermore, according to Little's formula, it follows that

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

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

$$W_0 = R_0 + Q_0 E[X_0], \qquad (22)$$

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 $R_0 = \frac{1}{2}\lambda_0 E[(X_0)^2]$ according to [3], solving (21) and (22) simultaneously yields

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

Last, if λ_i and $E[X_i]$ 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 $\mu_s = \frac{1}{E[X_s]}$, one can obtain $\lambda_i = \lambda_s(\frac{\lambda_0}{\lambda_0 + \mu_s})^{i-1}$, $E[X_i] = \frac{1}{\lambda_0 + \mu_s}$, and $E[(X_i)^2] = \frac{2}{(\lambda_0 + \mu_s)^2}$ for all $i \ge 1$. Thus, the closed-form expression for W_s is

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

6 Numerical and Simulation Results

6.1 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.

6.2 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 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 $5:20\%$ 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.

7 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 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.

8 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,

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

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+

References

[1] I. F. Akyildiz and Won-Yeol Lee and M. C. Vuran and S. Mohanty. A Survey on Spectrum Management in Cognitive Radio Networks. IEEE Communications Magazine, 50:40-48, 2008.

[2] Alex Chia-Chun Hsu and David S. L. Wei and C.-C. Jay Kuo. A Cognitive MAC Protocol Using Statistical Channel Allocation for Wireless Ad-Hoc Networks. IEEE Wireless Communications and Networking Conference, :105-110, 2007.

[3] An Introduction to Queueing Systems. Kluwer Academic/Plenum Publishers, New York, 2002.

[4] Xiukui Li and S. A. Zekavat. Traffic Pattern Prediction and Performance Investigation for Cognitive Radio Systems. IEEE Wireless Communications and Networking Conference, :894-899, 2008.

[5] Xiukui Li and Seyed A. Zekavat. Traffic Pattern Prediction and Performance Investigation for Cognitive Radio Systems. IEEE Wireless Communications and Networking Conference, 2008.

[6] Li-Chun Wang and Yin-Chih Lu and Chung-Wei Wang and David S. L. Wei. Latency Analysis for Dynamic Spectrum Access in Cognitive Radio: Dedicated or Embedded Control Channel?. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2007.

[7] Li-Chun Wang and Chung-Wei Wang. Spectrum Handoff for Cognitive Radio Networks with Reactive Sensing. IEEE APWCS, 2008.

[8] Li-Chun Wang and Chung-Wei Wang. Spectrum Handoff

for Cognitive Radio Networks: Reactive-Sensing or Proactive-Sensing?. IEEE IPCCC, 2008.

[9] T. A. Weiss and F. K. Jondral. Spectrum Pooling: An Innovative Dtrategy for the Enhancement of Spectrum Efficiency. IEEE Communications Magazine, 42(3):S8-S14, 2004.

[10] Q. Zhao and L. Tong and A. Swami and Y. Chen. Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework. IEEE Journal on Selected Areas in Communications, 25(3):589-600, 2007.

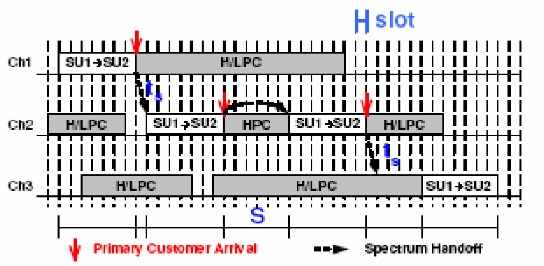


Figure 1: An example of packet transmission process with three interruptions, where t_s is the channel switch time. The whole data packet is partitioned into four parts due to spectrum handoff.

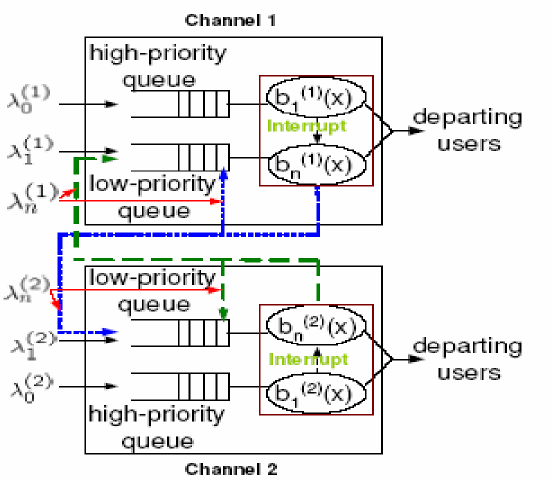


Figure 2: The PRP M/G/1 queueing network for two-channel system where $n \geq 1$.

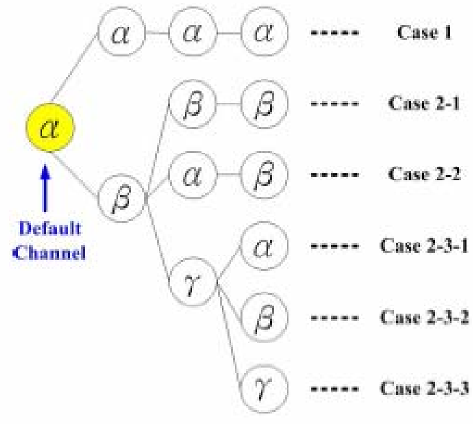


Figure 3: There are only six permutations for the target channel sequence based on the principle of shortest handoff delay.

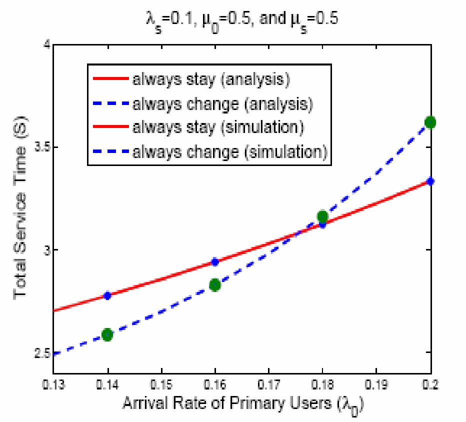


Figure 4: Comparison of total service time in the always-stay and the always-change cases. The value of t_s is assumed be 0 .

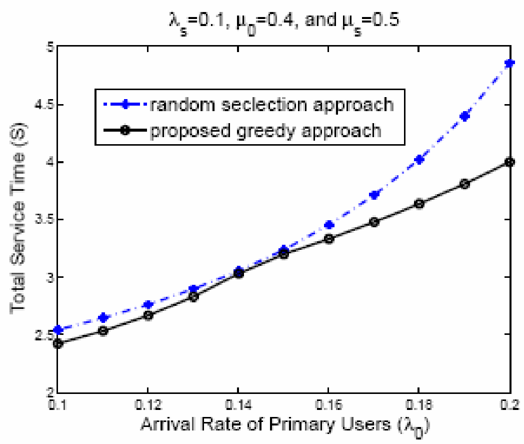


Figure 5: Comparison of total service time for random and greedy strategies. The value of t_s is assumed be 0.

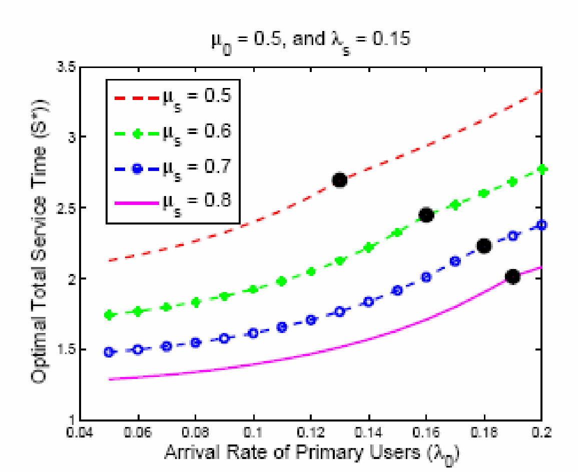


Figure 6: Effect of μ_s on the total service time of the proposed greedy target channel selection. The value of t_s is assumed be 0.

QoS-guaranteed Channel Selection Scheme for Cognitive Radio Networks With Variable Channel Bandwidths

中文摘要

感知無線電網路是能夠快速佈建的無線技術，其能有效率地使用頻譜頻道，並對現有的主要使用者有最小影響。頻譜切換問題是感知無線電網路的一項挑戰。當主要用戶（Primary user, PU）出現在正被次要用戶（Secondary user, SU）所使用的頻帶時，次要用戶必須進行頻譜切換，以在其他閒置頻道中繼續傳輸。不同於過去的研究，主要是考慮了所有頻道皆有相同的頻道帶寬(Fixed channel bandwidth)。在本研究中，考慮了變動頻道帶寬（Variable channel bandwidth）的情形下，我們提出了利用延遲頻寬乘積（Delay bandwidth product, DBP）為判斷準則的頻譜切換機制。在所提出的方法中，Delay 定義為次要用主要用戶可容忍之延遲和主要用戶之平均佔用時間之差。在變動頻道帶寬之系統中，次要用戶將依據DBP 指標選取能達成較高傳輸量並能夠滿足服務品質的頻道。考慮到支持語音和網頁瀏覽等服務的延遲要求下，我們所提出以延遲頻寬乘積為選取指標的頻譜切換機制能比其他現有的頻譜切換機制高出 100 %至 200 %的傳輸量。

English Abstract

Cognitive radio (CR) network allows fast deployment of wireless technologies to utilize spectrum channels, all with minimal impact on existing primary users. Another challenge in CR networks is the spectrum handoff issue when the primary user (PU) appears in the spectrum band being used by the secondary user (SU). In this paper, unlike the existing spectrum handoff schemes suitable for fixed channel bandwidth, we introduce the concept of the delay bandwidth product (DBP) to prioritize the channels with variable bandwidths. The delay in the proposed DBP index is defined as the difference of the maximum tolerable delay of the SU and the average occupation time of the PU. Based on the DBP index for the variable bandwidth channels, the SU selects the optimal channel and bandwidth that can deliver the highest throughput and guarantee its QoS requirement. Compared with other existing spectrum handoff schemes, the proposed DBP-based spectrum handoff can achieve 100% to 200% higher throughput subject to the delay requirements for supporting voice and web browsing services.

1 Introduction

Cognitive radio (CR) is an intelligent adaptive opportunistic radio which can increase spectrum efficiency by dynamically identify the unused spectrum of the primary user (PU), and configuring it for the secondary user (SU). Moreover, CR networks should decide the best spectrum band to meet the QoS requirements [1]. To address these goals, the spectrum mobility protocol in CR networks should be designed to switch SU to other available channels when a PU appears. The efficiency of the spectrum mobility determines both the network throughput as well as the overall spectrum utilization.

Spectrum mobility is a key challenge in the design of CR networks. Intuitively, the purpose of spectrum mobility management is to make sure that such transitions can be as seamless as possible so that the CR user can perceive minimum performance degradation during spectrum handoff. However, this task is not easy since each time a SU changes its operational frequency, the network protocol may need to shift from one mode of operation to another. Also, the CR network protocols must adapt to the channel parameters of the operating frequency, and they should be transparent to spectrum handoff and the associated latency.

Although some spectrum mobility schemes have been proposed, current spectrum mobility solutions may not be suitable for the variable channel bandwidth case. Thus, we investigate that the variable channel-bandwidth spectrum handoff in CR network. To our knowledge, such adaptation has been issued by Microsoft research group: kognitiv networking over white spaces (KNOWS) in [2, 3]. Adapting channel-bandwidths provide unique benefits, such as reducing power and increasing range simultaneously, improving flow throughput, fairness and balance load in WLANs, and enhancing the network capacity [2].

Several existing spectrum handoff schemes have been reported to achieve Cognitive radio goals, such as channel sensing [4, 5, 6], CSMA-like [7, 8, 9], channel allocation optimization [10, 11], and cross-layer optimization [12, 13]. The elegant option to achieve the goal for CR is the channel selection algorithm. Intuitively, the SU selects the optimal decision to stay in the same channel or switch to one of the candidate sensed channels when the PU appears. Through this selection process, the SU selects the optimal service channel which maximizes the total deliver bits [14]-[20].

The contribution of this paper is to design a feasible channel selection scheme from the SU perspective that allocate variable bandwidths to users effectively based on the concept of delay bandwidth product (DBP). The rest of this paper is organized as follows: Section 2 elaborates the DBP. Section 3 introduces the system model of DBP in the CR networks. Section 4 discusses the system evaluation for the DBP. Section 5 presents simulation results. Finally, the conclusion is given in Section 6.

2 Delay Bandwidth Product

There are many situations in which it is more important to know how long it takes to send a message from one end of a network to the other and back, rather than the one-way latency. Perceptively, it is also useful to consider the product of these two metrics, often called the delay bandwidth product. Intuitively, if we think of a channel between a pair of processes as a hollow pipe where the latency corresponds to the length of the pipe and the bandwidth gives the diameter of the pipe, then the delay bandwidth product gives the volume of the pipe the number of bits it holds [21].

In this paper, we develop a DBP-based channel selection scheme. Refereing to Fig. 1, the total delay time (D_i) is defined as the elapsed time until the SU can transmit its data again. In the proposed channel selection scheme, when the PU apperas, the SU can stay at the current channel and wait for the PU to leave the spectrum band. The other option for SU is to move to other sensed channels as shown in Fig. 1. Clearly, the total delay D_i is dependent on sensing time in the candidate sensed channel (W_j), the handoff execution time (t_0), and the transmission time of PU (T_k).

In the proposed spectrum handoff scheme, suppose the SU successfully establishes a connection. The SU will use the current channel. If the PU appears, the SU measures the channel priority index for the current channel and the candidate sensed channel. This priority index depends on the delay bandwidth product. As a result, the SU will be allocated with the channel that has the highest channel priority index. The proposed spectrum handoff scheme ensures the optimal throughput for SU. Inherently, the less sensing time, the longer the transmission time. On the other hand, the higher the channel bandwidth is, the more the delivered bits are. Thus, it is required to compromise between the bandwidth of the channel and the effective delay required by the channel itself, especially in the variable channel bandwidth case.

3 System Model

In this paper, the CR multiuser network consists of N variable bandwidth channels, each with bandwidth B_i $(i = 1,...,N)$. Each of these N channels is allocated to a PU. Assume the Current Channel (k) is defined as the channel which is at the present moment being used by the SU. The Candidate Sensed Channel (j) is defined as the channel which is sensed by the SU. Besides the option that the SU switches from the current channel to one of the sensed channels when the PU appears, we will study the option if SU stays in the channel till PU deactivates. Our concern is to select the optimal channel for the SU rather than to detect or sense the channel. Therefore, we assume that the SU is capable of listening to the channel and is aware that the PU transmits in the legacy system. For simplicity, we suppose each base station has one PU. Also, we assume a slotted system in which the user's transmissions on the channel are partitioned into slots.

On the other hand, every SU contends for the available channel. However, just one transmission is permitted at one slot. In addition, we assume that SU performs reliable spectrum sensing whenever needed and there will be at least one available candidate sense channel. Then, we will consider that the SU switches among those channel with variable bandwidths. As mentioned earlier, in a cognitive radio network, the SU performance depends on channel selection criteria (see Section 2) and the PUs traffic behavior in the N channels. Over a period of time, these N channels can either carry traffic or be idle. In this paper, we consider two different traffic scenarios for PU transmission. This assumption is reasonable because we want to measure the DBP performance within various channel conditions. In the first traffic scenario, the PU follows the Pareto distribution model [22]. The Pareto distribution is a simple model for many practical applications. In addition, Pareto distribution belongs to the so-called long-tailed distribution in which it has two parameters that can be easily determined to model different traffic models.

In the second channel traffic model, a commonly accepted model for artificial conversational speech/voice channel is used in which the channel availability can be modelled using a simple two-state Markov chain [14, 23] as shown in Fig. 2 (a), where the states I and B represent a channel being available and unavailable respectively at the current channel k. Symbols P_I and P_B represent respectively the probability that the channel state stays available or busy. $(1-P_I)$ and $(1-P_B)$ represent their transition probability from the state of availability to that of unavailability, and vice versa, respectively. In other words, when the channel is in the available state, the SU can transmit. Otherwise, the PU can transmit as shown in Fig. 2 (b).

4 System Evaluation

In this section, we consider the two traffic scenarios for the PU: the Pareto distribution model and Markov state model. According to the channel selection decision of the SU as shown in Fig. 1. Then, the total delay time D_i of SU i can be expressed as:

$$D_i = \begin{cases} t_0 + W_j, & if\ \ 1 \le j \le N,\ j \ne k; \\ T_k, & j = k \end{cases} \qquad (1)$$

The values of T_k and W_j are dependent on the traffic models as discussed in the following.

First, we choose the Pareto distribution model to describe the PU transmission time. The distribution probability density function and the distribution cumulative distribution function for Pareto distribution [22] are described in the following formulas:

$$f(x) = \frac{\lambda K^{\lambda}}{x^{\lambda+1}}, x \ge K \qquad (2)$$

$$F(x) = \begin{cases} 1-(\frac{K}{x})^{\lambda}, & x > 0 \\ 0, & otherwise \end{cases} \qquad (3)$$

where $\lambda > 0, K > 0$.

The Pareto distribution is characterized by a shape parameter K and a scale parameter λ. The density $f(x)$ is a decreasing function of x and achieves its maximum when x is smallest, i.e., when $x = K$. The web-browsing packet transmission model with Pareto distribution packet length has been commonly used to assess the traffic carriage requirements for 3G cellular systems. According to [22], the values of K, λ are assumed to be 81.5 and 1.1 respectively. Moreover, W_j is assumed to be variable in the range from 1 msec to 25 msec.

Second, another widely-used traffic model for voice conversation is the Markov state model [22]. Fig. 2(a) shows the state transition between PU appearance and SU availability. Let $Prob(state = B)(i)$ be the state probability that the channel i is busy for sending PU's traffic. Assume that the SU probability transmission on different channels are identical. We know that the P_B represents the transition probability for the channel to be busy. Then, the probability $\Pi_B(i) =$ $Prob(state = B)(i)$ can be expressed as:

$$\Pi_B(i) = p_B(1-p_B). \qquad (4)$$

In this paper, we assume the SU spends T_s slots for sensing the available channel. Also, the SU maximum channel sensing tolerant number of slot is $T_{Threshold}$. Notice that T_s is dependent on the $\Pi_B(i)$, we can express the mean of T_s as:

$$E[T_s] = \sum_{L=1}^{\infty} LP(T_s = L). \qquad (5)$$

The probability of T_s being equal to L slots can be expressed as:

$$P(T_s = L) = (\Pi_B(i))^{L-1}(1-\Pi_B(i)). \qquad (6)$$

Besides, the probability of T_s to be less than $T_{Threshold}$ slots is equal to

$$P(T_s < T_{Threshold}) = \sum_{L=1}^{T_{Threshold}} P(T_s = L). \qquad (7)$$

Then, the average sensing time of a SU W_i can be written by:

$$W_i = E[T_s < T_{Threshold}] \qquad (8)$$

$$= \sum_{L=1}^{T_{Threshold}} LP(T_s = L). \qquad (9)$$

Similarly, the T_k can be calculated.

We also provide control parameter for the DBP priority index which builds on top of existing techniques for adapting channel conditions. The operation of this control parameter (C_i) is illustrated in Fig. 3. The main idea is to increase or decrease the DBP index according to the channel conditions and the channel bandwidth ratio in reference to other channels' bandwidth.

In Fig. 3, C_i is used to track the fast variations of the channels caused by fading and mobility, and also, it is used to track the differences date rate between the different channels. The value of C_i starts from one for all the channels and updates as the PU appears in the channel i. This will help SU to improve throughput. It is assumed that the successful transmission probability is P_i, which is defined as the percentage of successful completed transmitted slots to the total transmitted slot in the channel i. The short term updates of instant data rate (R_i) of channel i can be expressed as:

$$R_i = \begin{cases} R_i(1-\alpha), & if\ P_i \le 0.8\,; \\ R_i(1+\alpha), & if\ P_i \ge 0.9\,. \end{cases} \qquad (10)$$

where $i = 1,2,...,N$. α is the rate smoothing parameter, and α is equal to 0.001. If the channel i has P_i higher 0.9, which means the successful transmission rate is high, the value of instant data rate (R_i) will increase. But if it is less than 0.8, the channel condition is bad and we choose to decrease the instant data rate (R_i) value.

Herein, the long term updating is made every 50 time slots, the long term updating of C_i is adjusted according to the difference between the ratio of the updated instant rate R_i to the target rate (R^*) in the current channel k to the ratio f the updated instant rate R_j to the target rate (R^*) in the sensed channels j . Therefore, the C_i is performed according to the following rule:

$$C_i = \begin{cases} C_i - \Delta C, & if\,[\frac{R_i}{R^*} - \frac{1}{N}\sum_{j=1} N\frac{R_j}{R^*}] < -\varepsilon; \\ C_i + \Delta C, & f\ [\frac{R_i}{R^*} - \frac{1}{N}\sum_{j=1} N\frac{R_j}{R^*}] > \varepsilon \end{cases} \qquad (11)$$

ε is the threshold limit. The value of ε is assumed to be 0.001. The ΔC is the step parameter which is fixed at 0.01. The values of both ε and ΔC are designed parameter which are chosen to achieve accurate channel measurement, where the choice of ΔC decide the C_i adjustment for channel

i. Also, B_i is the average bandwidth of channel i. T_{max} is the maximum delay allowed of SU. In addition, the priority index differs according to predetermined average time (T_{avg}). It is statical time that SU spend to switch for other channel. Now, the priority index η_i can be expressed as:

$$\eta_i = \begin{cases} (T_{max} - D_i)B_i, & if\ D_i \le T_{avg}\ ; \\ C_i(T_{max} - D_i)B_i, & otherwise; \end{cases} \qquad (12)$$

where $i = 1,2,...,N$.

The priority index represents the DBP-based scheme, where $(T_{max} - D_i)$ part of this equation represents the maximum allowable time for SU to transmit, while the second part represents the B_i of SU. The priority index increases as much as the DBP increases. It can be said the priority index represents the maximum capacity of channel i. Moreover, If the D_i is larger than the T_{avg}, the weight of SU will be increased by the control parameter C_i. The C_i ensures the channel with higher bandwidth as well higher successful transmission probability to have higher weight.

Now the channel selection in the time when PU appears is defined according to:

$$Channel_i = \mathbf{max}\{\eta_i\} \qquad (13)$$

then

$$k = Channel_i. \qquad (14)$$

Finally, we calculate the performance of this proposed DBP-based scheme to determine whether it meets the required service and reliability objectives. Now consider the impact of DBP allocation scheme on the delivered information bits during a given period of time. It is assumed that the successful transmission slot is ts_i. Also, t_{total} is the total transmission time which is given by:

$$t_{total} = \sum_{i=1}^{N} ts_i + \sum_{i=1}^{N} D_i. \qquad (15)$$

Thus, the Effective Data Rate R_{eff} for SU is given by:

$$R_{eff} = \frac{\sum_{i=1}^{N} ts_i B_i}{t_{total}}, \qquad (16)$$

5 Simulation Results

In this section we show in a CR network with variable bandwidth channels the effective data rate of SU. The transmissions of both PU and SU are partitioned into slots. The PU adopts the connection-oriented MAC protocol in which the user will establish a connection to transmit data according to the information broadcasted by the base station.

We consider the situation where the SU switches among variable bandwidth channels range between 2Mbps to 54 Mbps. Moreover, the SU overhears the broadcasted message to synchronize the timing with the legacy system and acquire the schedule in order to avoid interfering with the PU transmissions. Here, we assume that the slot time, frame error rate, radio sensing time, handoff execution time t_0 are 10 μsec, $10^{-2}:10^{-1}$, 1 $m$sec : 25 $m$sec, and 1 $m$sec : 100 $m$sec respectively.

In the numerical results, we refer to the DBP using the control parameter C_i as adaptive delay bandwidth product (ADBP) scheme, and the direct switch scheme as the traditional behavior of the SU when the PU appears, which is to switch to another channel directly. We compare them with the stochastic channel selection (SCS) algorithm [15]. One can see that SCS scheme does not achieve effective data rate as well as the ADBP does nor direct switching scheme, because the main goal of the SCS is to converge SU to maintain the chosen channel with the highest successful probability. Nevertheless, the channel with the highest successful probability may be not efficient for the SU to achieve better performance, especially if we use the SCS within variable channel bandwidth case. Moreover, the SCS scheme may not perform well when user mobility speeds is high, or the channel behavior has fast fading. Thus, in our simulation, we consider the users with random walk mobility in a time-varying channel.

As we can expect, if the Pareto distribution model is used, the effective secondary user data rate increases as W_j decreases. The ADBP scheme performs quite well as W_j increases, compare to other schemes. Fig. 4 illustrates the impact of W_j where the probability of PU appearance in any time slot takes the value of 0.3. It shows that the adaptive channel allocation scheme performs well under the condition of a busy channel in respect to the Direct Switch scheme up to 200%. It is clear that the ADBP can ensure the SU throughput even if W_j increases because it can adapt to the channel condition as well as it ensures that the channel with higher bandwidth has more transmission time for the SUs.

In Markov state model, the effective SU data rate increases and W_i decreases. The ADBP scheme performs quite well as W_i increases compares with other schemes. Fig. 5 illustrate the impact of W_i when the probability of which the channel state is busy P_B takes the value of 0.3. The ADBP outperforms other schemes up to 100%. It is obvious that the DBP-based scheme performs well under different channel models. We conclude that the total effective data rate will be maximized as long as we stay over the channel with the highest DBP index.

6 Conclusions

In this work, delay bandwidth product-based channel selection scheme helps to select the optimal channels for the secondary user in a CR network with variable bandwidth channels. Even with totally random exponential traffic patterns, the effective data rate in the DBP-based channel selection scheme is higher than that in direct switch or stochastic channel selection (SCS) schemes. Numerical results give evidence of the desired behaviors of our proposed algorithm and also demonstrate that the algorithm can deliver a higher throughput subject to the delay requirements for supporting voice and web browsing services.

Reference:

[1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey,” Comput. Netw., vol. 50, no. 13, pp.

2127–2159, 2006.

[2] Y. Yuan, P. Bahl, R. Chandra, T. Moscibroda, and Y. Wu, “Allocating dynamic time-spectrum blocks in cognitive radio networks,” in MobiHoc ’07: Proceedings of the 8th ACM international symposium on Mobile ad hoc networking and computing. New York, NY, USA ACM, 2007, pp. 130–139.

[3] R. Chandra, R. Mahajan, T. Moscibroda, R. Raghavendra, and P. Bahl, “A case for adapting channel width in wireless networks,” in SIGCOMM’08: Proceedings of the ACM SIGCOMM 2008 conference on Data communication. New York, NY, USA: ACM, 2008, pp.135–146.

[4] E. Peh and Y.-C. Liang, “Optimization for cooperative sensing in cognitive radio networks,” Wireless Communications and Networking Conference, 2007.WCNC 2007. IEEE, pp. 27–32, March 2007.

[5] G. Ganesan and Y. Li, “Cooperative spectrum sensing in cognitive radio, part i: Two user networks,” Wireless Communications, IEEE Transactions on, vol. 6, no. 6, pp. 2204–2213, June 2007.

[6] J. Yang, R. Brodersen, and D. Tse, “Addressing the dynamic range problem in cognitive radios,” Communications, 2007. ICC ’07. IEEE International Conference on, pp. 5183–5188, June 2007.

[7] C. Han, J. Wang, and S. Li, “A spectrum exchange mechanism in cognitive radio contexts,” Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on, pp. 1–5, Sept. 2006.

[8] O. Holland, A. Attar, N. Olaziregi, N. Sattari, and A. Aghvami, “A universal resource awareness channel for cognitive radio,” Personal, Indoor and Mobile Radio Communications, 2006 IEEE 17th International Symposium on, pp. 1–5, Sept. 2006.

[9] J. Acharya and R. Yates, “A framework for dynamic spectrum sharing between cognitive radios,” Communications, 2007. ICC ’07. IEEE International Conference on, pp. 5166–5171, June 2007.

[10] M. Thoppian, S. Venkatesan, R. Prakash, and R. Chandrasekaran, “Mac-layer scheduling in cognitive radio based multi-hop wireless networks,” World of Wireless, Mobile and Multimedia Networks, 2006. WoWMoM 2006. International Symposium on a, pp. 10 pp.–202, 2006.

[11] A. T. Hoang, Y.-C. Liang, and M. Islam, “Maximizing throughput of cognitive radio networks with limited primary users’ cooperation,” Communications, 2007. ICC ’07. IEEE International Conference on, pp. 5177–5182, June 2007.

[12] F.-S. Chu and K.-C. Chen, “Radio resource allocation in ofdma cognitive radio systems,” Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposiumon, pp. 1–5, Sept. 2007.

[13] S.-Y. Lien, C.-C. Tseng, and K.-C. Chen, “Novel rate-distance adaptation of multiple access protocols in cognitive radio,” Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on, pp. 1–5, Sept. 2007.

[14] Q. Zhao, L. Tong, and A. Swami, “Decentralized cognitive mac for dynamic spectrum access,” New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on, pp. 224–232, Nov. 2005.

[15] Y. Song, Y. Fang, and Y. Zhang, “Stochastic channel selection in cognitive radio networks,” Global Telecommunications Conference, 2007. GLOBECOM ’07. IEEE, pp. 4878–4882, Nov. 2007.

[16] S.-C. Lo and C.-W. Tseng, “A novel multi-channel mac protocol for wireless ad hoc networks,” Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th, pp. 46–50, April 2007.

[17] A. Al-Fuqaha, B. Khan, A. Rayes, M. Guizani, O. Awwad, and G. Ben Brahim, “Opportunistic channel selection strategy for better qos in cooperative networks with cognitive radio capabilities,” Selected Areas in Communications, IEEE Journal on, vol. 26, no. 1, pp. 156– 167, Jan. 2008.

[18] P. Zhu, J. Li, K. Han, and X. Wang, “A new channel parameter for cognitive radio,” Cognitive Radio Oriented Wireless Networks and Communications, 2007. CrownCom 2007. 2nd International Conference on, pp. 482–486, Aug. 2007.

[19] L.-C. Wang and C.-W. Wang, “Spectrum handoff for cognitive radio networks: Reactive-sensing or proactive-sensins?” Performance, Computing and Communications Conference, 2008. IPCCC 2008. IEEE International, pp. 343–348, Dec. 2008.

[20] M. Hoyhtya, S. Pollin, and A. Mammela, “Performance improvement with predictive channel selection for cognitive

radios," Cognitive Radio and Advanced Spectrum Management, 2008. CogART 2008. First International Workshop on, pp. 1–5, Feb. 2008.

[21] L. Peterson and B. Davie, Computer Networks: A System Approach, 3rd ed. Elsevier Science and Technology Books, 2003.

[22] V. Paxson and S. Floyd, "Wide area traffic: the failure of poisson modeling," Networking, IEEE/ACM Transactions on, vol. 3, no. 3, pp. 226–244, Jun 1995.

[23] M. Sharma, A. Sahoo, and K. Nayak, "Channel selection under interference temperature model in multi-hop cognitive mesh networks," New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007. 2nd IEEE International Symposium on, pp. 133–136, April 2007.

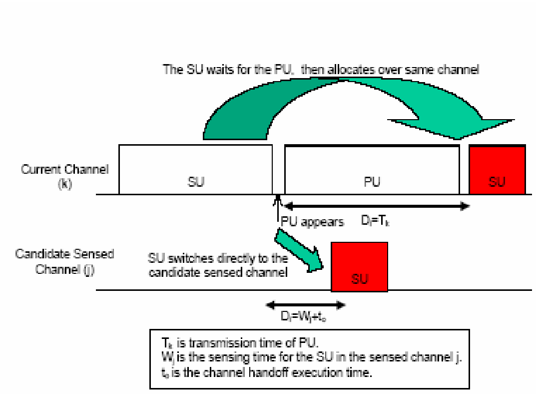


Figure 1: The secondary user channel options.

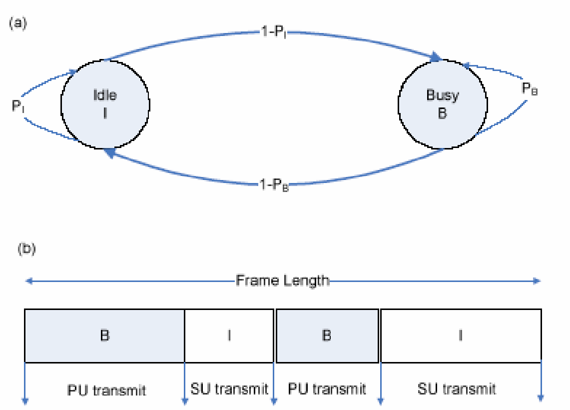


Figure 2: (a) A two-state Markov chain to model a channel. (b) Slotted frame structure.

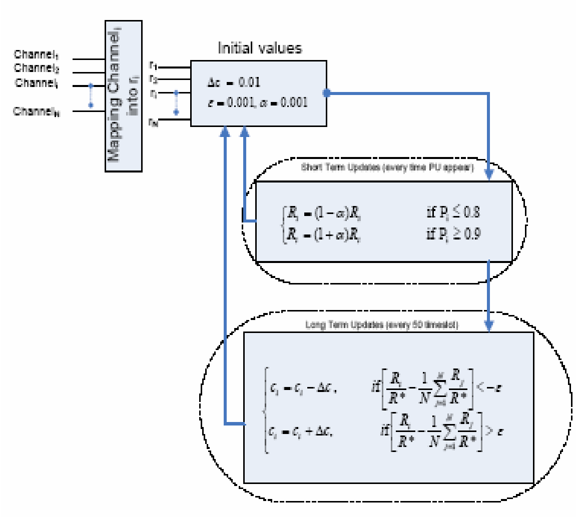


Figure 3: The delay bandwidth product control parameter.

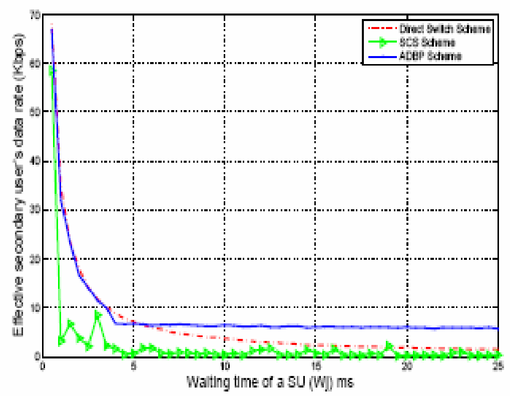


Figure 4: Impact of *Wj* when probability of PU appearance is 0.3

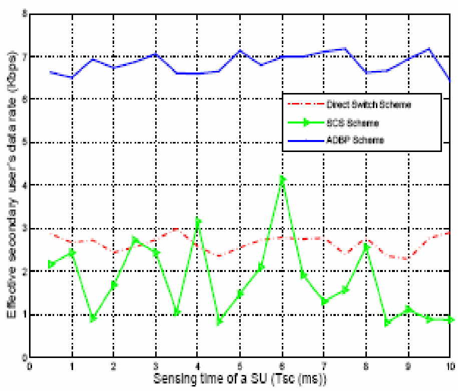


Figure 5: Effective secondary user's data rate when the probability busy state (P_B) is 0.3