Load-Balancing Spectrum Decision for Cognitive Radio Networks with Unequal-Width Channels

Samer T. Talat, and Li-Chun Wang,
Department of Electrical Engineering
National Chiao Tung University, Hsinchu, Taiwan
Email:stalat.cm92g@nctu.edu.tw

***Abstract*—A cognitive radio (CR) system scans the wide spectrum to find available spectrum. One of key challenges in using these temporarily available spectrums is that the bandwidth of the available spectrum are not equally wide. The other challenge for spectrum decision scheme in CR systems is that many secondary users (SUs) may choose the same channel simultaneously, resulting in channel contention. In this paper, we develop a load balancing spectrum decision scheme for unequal-bandwidth CR networks. We apply the concept of the delay bandwidth (DB) product to select a suitable channel for each user among many unequal-width channels. Compared with other existing unequal bandwidth spectrum decision schemes, our simulation results show that the proposed DB-based spectrum decision can improve the overall system throughput up to 40% in the considered case.**

***Index Terms*—Cognitive radio, variable-bandwidth, channel selection, spectrum decision.**

I. Introduction

Spectrum management in cognitive radio (CR) networks poses many challenges due to dynamic spectrum environments. Spectrum management techniques in CR networks include spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [1]. After sensing the wide spectrum, a CR network can find available spectrums with different widths at various carrier frequencies. Unlike wireless systems utilizing conventional fixed and equal-bandwidth channel allocation, a CR system may operate at a dynamic and variable-bandwidth channel. Thus, how to determine a suitable channel with unequal bandwidths becomes an issue in a general CR networks.

If all the SUs choose the same channel, this situation will increase collision probability and hence degrade the system performance. Most spectrum decision techniques in CR network have not focused on both unequal-width channels and load balancing capabilities simultaneously.

The objective of this paper is to develop a spectrum decision scheme for a general CR network with unequal-bandwidth channels that can maximize the data throughput of the SU and achieve load balancing for the other SUs. The delay bandwidth product (**DB**) concept [2] is applied in our spectrum decision scheme for unequal bandwidth. In spectrum decision scheme, each SU will determine the most appropriate operation channel in each frame based on the **DB**-index. Moreover, hence the collision probability is function of the **DB**-index, it is necessary to find the optimal distribution of serving SUs at each channel. An exhaustive search approach is hold to find the optimal distribution which guarantees each SU has the maximum throughput and the minimum collision probability simultaneously.

The rest of this paper is organized as follows. Section II presents the related works in CR networks. Section III introduces the system model. Section IV presents the performance analysis for the DB-oriented spectrum decision. Section V shows numerical results. Finally, our concluding remarks are given in Section VI.

II. Related Work

In spectrum decision, adapting channel-bandwidths provides the benefits of power reduction, coverage range extension, load balance, fairness and network capacity enhancement. In [3], [4], a practical variable channel-bandwidth cognitive radio was built to demonstrate the advantages of variable channel-bandwidth allocation in CR networks. Most current spectrum decision management techniques in CR networks consider either an unequal-width channels or load balancing techniques.

Spectrum decision approaches considering unequal-width were introduced in [5]–[8]. The channel bandwidth is used as spectrum management metric in [5]. However, this spectrum decision did not consider if the primary user's traffic load can be high. In [6], an interesting game-theory based on an unequal-width channels spectrum decision was proposed, but this approach may require a lot of network topology information. Additionally, [7] proposed that the SU

apply partially observable Markov decision process (POMDP) to recognize spectrum opportunity based on sensing history and channel statistics such as the idle channel probability of the CR network. Then, the SU decides which frequency band(s) can maximize the overall network throughput. In our previous work, we use the **DB**-based concept [8] to maximize the throughput in unequal-width channel in CR network. Although unequal-width channels were considered, the main goal of the previous works were to decide which channel(s) to sense and access to maximize the total capacity. All the previous works did not consider the effects of load balancing when multiple secondary users are using the same spectrum simultaneously.

Spectrum decision approaches considering the equal-width channels and load balancing effect were introduced in [9]–[12]. A stochastic channel selection algorithm based on learning automata techniques was proposed in [9] to adjust the selecting probability for each available band. Although this algorithm can converge to the optimal solution asymptotically, it may not be the best option in an unequal-width channel environment because this algorithm chooses the band with the highest successful transmission probability, rather than the band which achieves the highest throughput. In [10]–[12] M/G/l queue models were proposed from a view point of connection rather than time slot. However, these analytical approaches do not consider the effects of unequal-width channels. In this work, we consider both load balancing effect and variable bandwidth using the **DB**-based metric.

III. System Model

A. System Architecture

In this section, the CR multi-user network consists of M unequal-width channels, where each channel has PUs and SUs. This common system model adopts the time-slotted CR network structure, in which the SUs transmissions on the channel are partitioned into slots and the SU performs a reliable spectrum sensing in each frame as shown in Fig. 1. Each SU performs spectrum sensing at the beginning of each time slot to detect the presence of PU. If the current operating channel is idle and has the highest DB-index, the SU must transmit one slot-sized frame in this time slot over this operating channel. Otherwise, the SU must perform spectrum handoff procedures to resume its unfinished transmission, where the SU can dynamically change its operating frequency and bandwidth to the idle channel with the highest DB-index. For simplicity, we also consider only one PU passes it traffic for each channel m, ($m \in \{1, 2, ...M\}$).

B. Frame structure

In this paper, the total number of SUs is N. where each SU_i ($i \in \{1, 2, ...N\}$) switches among the available free of error bands and transmit their fixed power. When a SU selects to move to the best channel m with the highest DB-index, this spectrum decision is based on the SU frame structure as shown in Fig. 1, where this frame (T_f) consist of four parts: channel sense time T_s, channel execution time t_o, waiting time T_w, and the transmission time.

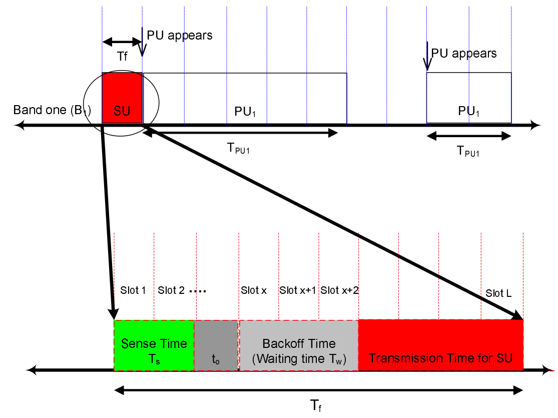

Fig. 1. The secondary user frame structure.

C. Channel Selection

At any moment, several system elements determine the best band opportunity for the SU. The first element is the PU traffic pattern, where each channel can be in either a busy or idle state, which refers respectively to times when a PU occupies the channel or does not. The distribution of PU is independent and identically distributed (i.i.d.) ON/OFF renewal process. Moreover, some channels may be highly occupied by the PU such as with browsing activity, while others channels are less occupied by the PU such as with voice call activities. In our system model, we assume each channel has different busy probability ($\rho^{(m)}$) of the PU. The value of $\rho^{(m)}$ at the channel m is constant, it does not depend on the previous time slots (Memory less probability). Basically, if $\rho^{(m)}$ decreases at channel m, then the transmission time for SU_i increases. Intuitively, all the SUs will try to transmit on the channel with the smallest $\rho^{(m)}$.

The second element is the unequal-width bands, these unequal-width bands can be represented by the vector $\overrightarrow{B}$ as

$$\overrightarrow{B} = \left[B^{(1)} \quad B^{(2)} \quad B^{(3)} \quad \ldots B^{(M)}\right] \tag{1}$$

Intuitively, if the $B^{(m)}$ increases, the delivered bit increases. All the SUs will try to transmit on the channel with the highest $B^{(m)}$.

The third element is ($n^{(m)}$), which represents the total number of SUs at channel m. Then, $\overrightarrow{n}$ represent the total number of the SUs at each channel as

$$\overrightarrow{n} = \left[n^{(1)} \quad n^{(2)} \quad \ldots \quad n^{(M)}\right] \tag{2}$$

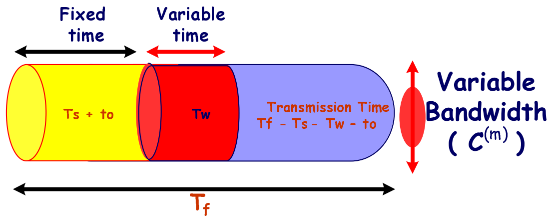

Fig. 2. The DB-based deliverable bits $R^{(m)}$.

If the $n^{(m)}$ increases, the delivered bits will decrease since more SUs will share the same band m. Each SU will try to transmit on the channel with the minimum $n^{(m)}$. The main challenge for the SU to increase the total deliverable bits is to select the best channel m among M channels taking into account all the previous elements. The focus here is to study the tradeoff between the previous elements. We show how to represent those system elements as a function of the tolerable transmission time ($D^{(m)}$) and the capacity ($C^{(m)}$) at the channel m in (3) and (4), respectively. The $D^{(m)}$ is defined as

$$D^{(m)} = \begin{cases} T_f - T_s^{(m)} - T_w^{(m)} - t_o, & \text{if } s_i \neq s_{i+1} \\ T_f - T_s^{(m)} - T_w^{(m)}, & \text{if } s_i = s_{i+1} \end{cases} \tag{3}$$

where s_i is the target channel of the SU at the i^{th} slot, $T_w^{(m)}$ is the waiting time of secondary user (SU_i) at the channel m to avoid collision with the other SUs. $T_s^{(m)}$ is the sensing time of the SU_i at the channel m. In equation (3), note that T_s, t_o and T_f are constant, while the waiting time $T_w^{(m)}$ at channel m is variable as shown in Fig. 2 The $C^{(m)}$ is defined as

$$C^{(m)} = B^{(m)} log_2(1 + SINR) \tag{4}$$

where $SINR$ is the signal to interference plus noise ratio. In Fig. 2, if we think of a channel as a hollow pipe, where the delay corresponds to the tolerable transmission time ($D^{(m)}$) of the pipe and the capacity ($C^{(m)}$) gives the diameter of the pipe. Then the volume of the pipe gives the number of bits that it can hold. Based on the DB concept, we define the deliverable bits ($R^{(m)}$) for SU_i at channel m as

$$R^{(m)} = D^{(m)} C^{(m)}. \tag{5}$$

In equation (3), the value of $T_w^{(m)}$ is defined as

$$T_w^{(m)} = W_{backoff}^{(m)} * T_{slot}. \tag{6}$$

In addition, the $W_{backoff}^{(m)}$ is the backoff window size, and T_{slot} is Time slot where

$$W_{backoff}^{(m)} = \frac{1}{\tau^{(m)}} - 1. \tag{7}$$

where $\tau^{(m)}$ is the probability that the SU transmits a packet in a randomly chosen slot time in channel m. According to the IEEE 802.11-based cognitive radio network [13], the collision probability ($p_c^{(m)}$) is the probability that $n^{(m)}$ SUs transmit in the channel m at the same time, which is defined as

$$p_c^{(m)} = 1 - (1 - \tau^{(m)})^{n^{(m)}} \tag{8}$$

also, τ is function of $p_c^{(m)}$ as shown below

$$\tau^{(m)} = \frac{2}{1 + W + p_c^{(m)} W \sum_{l=1}^{x-1} (2p_c^{(m)})^l} \tag{9}$$

where W is the initial contention window and is defined as the minimum contention window ($W = CW_{min}$); x is the maximum backoff stage; $2^x W = CW_{max}$.

D. Problem Formulation

The first question raised here is: which channel will deliver the highest $R^{(m)}$ if the number of SUs at each channel is known? The Second question raised here is : what is the best SUs distribution at each channel if the number of the SUs at each channel is unknown? The overall CR network utilization is a function of channel selection probability in those two cases.

This section investigates the channel selection probability on the estimated deliverable bits for the SU, based on the equations (3), (5) and (6) we can predicate the channel selection probability. Let the *channel selection probability vector* ($\overrightarrow{P}$), which is defined as the best channel m to maximize the throughput

$$\overrightarrow{P} = \begin{bmatrix} p^{(1)} & p^{(2)} & \dots & p^{(M)} \end{bmatrix} \tag{10}$$

and $p^{(m)}$ is the channel selection probability of channel $m \in \{1, 2, ...M\}$. The *channel selection probability vector* ($\overrightarrow{P}$) represent the probability to move to channel M.

Finally, we calculate the allocated bit for a certain time of transmission. Let the *Average deliverable bit* ($E[R]$) be

$$E[R] = \sum_{m=1}^{M} p^{(m)} R^{(m)}. \tag{11}$$

IV. Performance Analysis

In the section, we will analysis the performance of traditional spectrum decision approaches such as the random switch (**RS**) [10], [11] and bandwidth switch (**BS**) [5], [6]. In the **RS**, the SU channel selection probability is equally for all channels as shown in equation (12). In the other hand, the **BS** selects the operating channel for SU based on the highest bandwidth as shown in equation (14). In case of the random switch (**RS**), the $\overrightarrow{P}(RS)$ for a single SU can be expressed as

$$\overrightarrow{P}(RS) = \begin{bmatrix} \frac{1}{M} & \frac{1}{M} & \dots & \frac{1}{M} \end{bmatrix}. \tag{12}$$

and the *Average deliverable bit* ($E[R(\mathbf{RS})]$) be

$$E[R(\mathbf{RS})] = \sum_{m=1}^{M} \frac{1}{M} C^{(m)}. \tag{13}$$

In the bandwidth switch (**BS**) case, if $B^{(1)} > B^{(2)} > \ldots > B^{(M)}$, then $\overrightarrow{P}(BS)$ is the function of bandwidth and channel busy probability ($\rho^{(m)}$) at channel m, where the SU will choose the highest bandwidth channel if it is not busy by the PU. Otherwise, the SU will choose the second highest bandwidth channel if it is not busy by the PU, and so on. This channel selection probability can be expressed as follow

$$\overrightarrow{P}(BS) = \begin{bmatrix} 1-\rho^{(1)} \\ \rho^{(1)}(1-\rho^{(2)}) \\ \vdots \\ \rho^{(1)}\rho^{(2)}\ldots(1-\rho^{(M)}) \end{bmatrix} \tag{14}$$

and

$$p^{(m)} = (1-\rho^{(m)}) \prod_{j=1}^{m-1} \rho^{(j)} \tag{15}$$

The *Average deliverable bit* ($E[R(\mathbf{BS})]$) be

$$E[R(\mathbf{BS})] = \sum_{m=1}^{M} p^{(m)} C^{(m)}. \tag{16}$$

In the deliverable bit switch (**DB**) case, the channel selection is determined by which channel can achieve the highest allocated bit for a certain time of transmission. If $R^{(1)} > R^{(2)} > \ldots > R^{(M)}$, the channel selection probability of $\overrightarrow{P}(DB)$ is equal to $\overrightarrow{P}(BS)$. Then we calculate the **DB** performance scheme. Let the *Average deliverable bit* ($E[R(\mathbf{DB})]$) be

$$E[R(\mathbf{DB})] = \sum_{m=1}^{M} \widetilde{p}^{(m)} R^{(m)}. \tag{17}$$

where, $\widetilde{p}^{(m)}$ defined as:

$$\widetilde{p}^{(m)} = \frac{n^{(m)}}{N} p^{(m)}, \forall m \in \{1, 2, \ldots M\}. \tag{18}$$

The DB-based scheme does not only choose the band according to the highest bandwidth, but also chooses the band according to the PU traffic transmission and available transmission time due to number of SUs. Moreover, we study the spectrum decision in two different scenarios as shown in the following subsection IV-A and IV-B.

A. Scenario 1: Number of SU at each channel is known

If $n^{(m)}$ is **known**, we need to find the best channel to maximize the throughput of CR systems. The value of $n^{(m)}$ can be calculated by solving equation (8) and (9) iteratively [13].

Our first problem for the DB-oriented band selection is formulated as follows:

$$m^* = \arg\max_{1 \le m \le M} (E[R(\mathbf{DB})]). \tag{19}$$

B. Scenario 2: Number of SU at each channel is unknown

If $n^{(m)}$ is **unknown**, it is needed to find the best $\overrightarrow{P}$ to maximize the throughput of CR systems. Note that $n^{(m)}$ is defined as

$$n^{(m)} = N p^{(m)} \widetilde{p}^{(m)}, \forall m \in \{1, 2, \ldots M\}. \tag{20}$$

Then problem for the DB-oriented band selection is defined according to

$$m^* = \arg\max_{\overrightarrow{P}} (E[R(\mathbf{DB})]). \tag{21}$$

The optimal value of $\overrightarrow{P}$ is calculated by the exhaustive search approach of the best ($E[R(\mathbf{DB})]$) with all possible $\widetilde{p}^{(m)}$. It is necessary to perform this exhaustive search periodically in CR system. This will eliminate complexity of this search and ensure the load balancing among all the SUs.

V. NUMERICAL RESULTS

In this section, we consider a CR network with three unequal-width channels and compare the total allocated bits of the SU using the **RS**, the **BS** and the **DB** spectrum decision schemes. The transmissions of both the PU and the 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. Moreover, the SU overhears the broadcasted message to synchronize timing with the legacy system and acquires the schedule in order to avoid interfering with the PU transmissions. Here, we assume that the SU frame transmission time is 5 $msec.$

In the numerical results, one can see that the BS scheme and the RS scheme do not achieve the highest data rate compared to the DB-based because the main goal of the BS is to converge the SU to maintain the selected channel at the highest bandwidth without considering the waiting time of the SU in this channel. While the RS scheme only focuses on minimizing the waiting time of the SU without taking into consideration the channel that has the highest deliverable

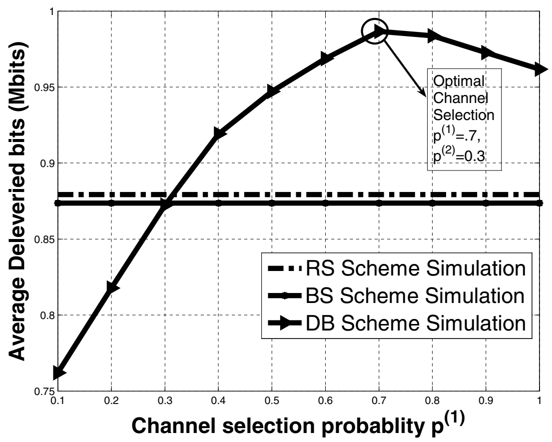

Fig. 3. The optimal channel selection value, when $\rho^{(m)}$ equal 0.1.

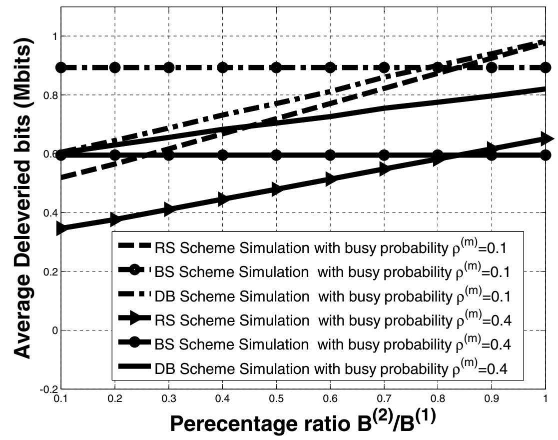

Fig. 4. Unequal-width channels effect with a fixed channel selection vector $= [0.5\ 0.5]$, and $T_s = 1$msec.

bits. Nevertheless, the DB-based chooses the highest deliverable bit by maintaining all the channels load and width.

In the first scenario, with the given $n^{(m)}$, the deliverable bit for the SU increases as $T_w^{(m)}$ decreases. In addition, as T_s increases, DB-based scheme achieves up to 40% more compared to other schemes. As we can expect, the DB-based outperforms other techniques by adapting the channel condition and distribute the SU accordingly. In the second scenario, the DB-based scheme investigates what is the best $\overrightarrow{P}$ to increase the total CR throughput. Fig. 3 illustrates the impact of $p^{(m)}$, where fixed $\rho^{(m)}$ is given and $C^{(m)}$ for the two channels case are 48 and 36 Mbits. The optimal $\overrightarrow{P}$ equal to $[0.7\ 0.3]$ for the 10 SUs. Fig. 4 illustrates the relationship between the unequal-width channels with fixed channel selection vector ($\overrightarrow{P} = [0.5\ 0.5]$) within different busy period vs $\rho^{(m)}$. where $C^{(1)}$ is 54 Mbits and $C^{(2)}$ is variable. As the $C^{(2)}$ increases, the total average bit delivered in the DB-based method increases because the DB scheme consider the load balance effect. Also, in Fig. 4, it proves that the DB-based outperforms the BS and the RS with fix transmission time. Since the DB-based scheme ensures load balancing among the unequal-width channels.

VI. Conclusions

In this paper we provide new insights into the design of unequal-width channels in cognitive radio network systems. We have learned that the average deliverable bits depends on a wide variety of variables, such as transmission rate ratio, the total delay time ratio, and channel conditions. Our numerical results have proved the correctness of our analysis. We conclude that average deliverable bits will be maximized as long as we select the DB-based spectrum decision mechanism.

References

[1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Computer Network*, vol. 50, no. 13, pp. 2127–2159, 2006.

[2] L. Peterson and B. Davie, *Computer networks: A system approach*, 3rd ed. Elsevier Science and Technology Books, 2003.

[3] Y. Yuan, P. Bahl, R. Chandra, T. Moscibroda, and Y. Wu, "Allocating dynamic time-spectrum blocks in cognitive radio networks," *Proceedings of the 8th ACM International Symposium on Mobile ad hoc Networking and Computing*, pp. 130–139.

[4] R. Chandra, R. Mahajan, T. Moscibroda, R. Raghavendra, and P. Bahl, "A case for adapting channel width in wireless networks," *Proceedings of the ACM SIGCOMM 2008 conference on Data communication*, pp. 135–146, 2008.

[5] P. N. Anggraeni, N. H. Mahmood, J. Berthod, N. Chaussonniere, L. My, and H. Yomo, "Dynamic channel selection for cognitive radios with heterogenous primary bands," *Wireless Perss Communacation*, vol. 45, no. 3, pp. 369–384, 2008.

[6] W. Yuan, W. Liu, W. Cheng, and S. Wang, "Variable-width channel allocation in wireless LAN: A game-theoretic perspective," *IEEE International Conference on Communications*, Jun. 2009.

[7] Q. Zhao, L. Tong, 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*, vol. 25, no. 3, pp. 589 –600, Apr. 2007.

[8] S. Talat and L.-C. Wang, "QoS-guaranteed channel selection scheme for cognitive radio networks with variable channel bandwidths," *International Conference on Communications, Circuits and Systems, 2009. ICCCAS 2009.*, Jul. 2009.

[9] Y. Song, Y. Fang, and Y. Zhang, "Stochastic channel selection in cognitive radio networks," *IEEE Global Telecommunications Conference*, Nov. 2007.

[10] L.-C. Wang and C.-W. Wang, "Spectrum handoff for cognitive radio networks: reactive-sensing or proactive-sensing?" *IEEE International on Performance, Computing and Communications Conference (IPCCC 2008)*, Dec. 2008.

[11] M. Hoyhtya, S. Pollin, and A. Mammela, "Performance improvement with predictive channel selection for cognitive radios," *First International Workshop on Cognitive Radio and Advanced Spectrum Management*, Feb. 2008.

[12] L.-C. Wang, C.-W. Wang, and F. Adachi, "Load-balancing spectrum decision for cognitive radio networks," *IEEE Journal on Selected Areas in Communications (JSAC)*, pp. 757–769, Apr. 2011.

[13] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535 –547, Mar. 2000.