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

Samer T. Talat and Li-Chun Wang

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.**

I. 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], [15], [16], [17], [18], [19], [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 II elaborates the DBP. Section III introduces the system model of DBP in the CR networks. Section IV discusses the system evaluation for the DBP. Section V presents simulation results. Finally, the conclusion is given in Section VI.

II. 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

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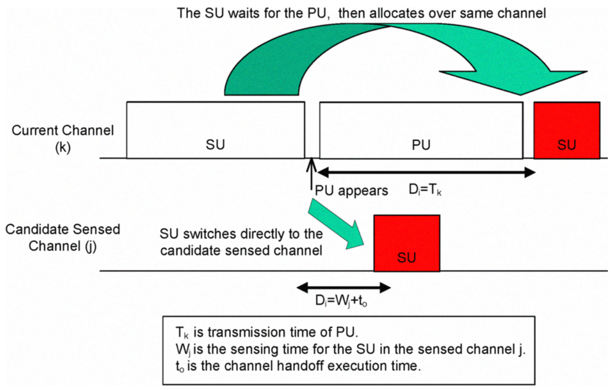

Fig. 1. The secondary user channel options.

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.

III. 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 users 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 II) 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).

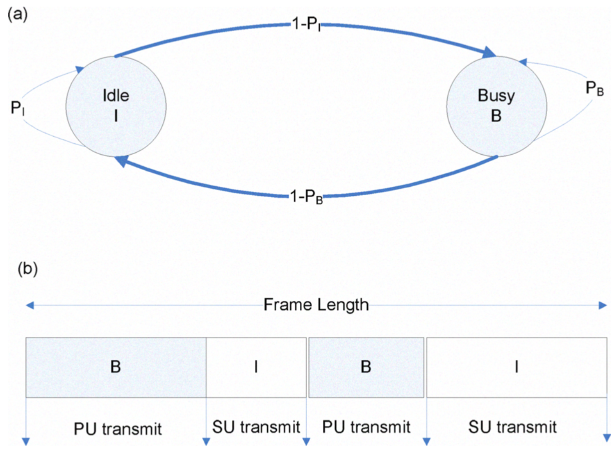

Fig. 2. (a) A two-state Markov chain to model a channel. (b) Slotted frame structure.

IV. 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:

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

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:

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

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

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 [23]. 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:

$$\Pi_B(i) = p_B(1 - p_B). \tag{4}$$

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:

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

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

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

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

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

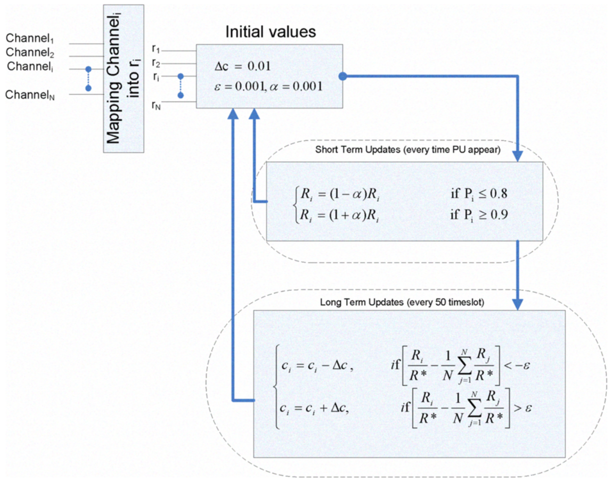

Fig. 3. The delay bandwidth product control parameter.

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

$$W_i = E[T_s < T_{Threshold}] \tag{8}$$

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

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:

$$R_i = \begin{cases} R_i(1 - \alpha), & \text{if } P_i \leq 0.8 \text{ ;} \\ R_i(1 + \alpha), & \text{if } P_i \geq 0.9 \text{ .} \end{cases} \tag{10}$$

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:

$$C_i = \begin{cases} C_i - \Delta C, & \text{if } [\frac{R_i}{R^*} - \frac{1}{N}\sum_{j=1}^{N}\frac{R_j}{R^*}] < -\epsilon \ ; \\ C_i + \Delta C, & \text{if } [\frac{R_i}{R^*} - \frac{1}{N}\sum_{j=1}^{N}\frac{R_j}{R^*}] > \epsilon \ . \end{cases} \tag{11}$$

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:

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

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:

$$Channel_i = \mathbf{max}\{\eta_i\} \tag{13}$$

then

$$k = Channel_i. \tag{14}$$

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:

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

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

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

V. 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, $10^{-2} \sim 10^{-1}$, 1 $m$sec $\sim$ 25 $m$sec, and 1 $m$sec $\sim$ 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.

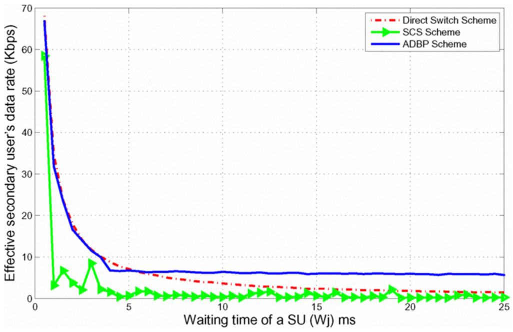

Fig. 4. Impact of W_j when probability of PU appearance is 0.3

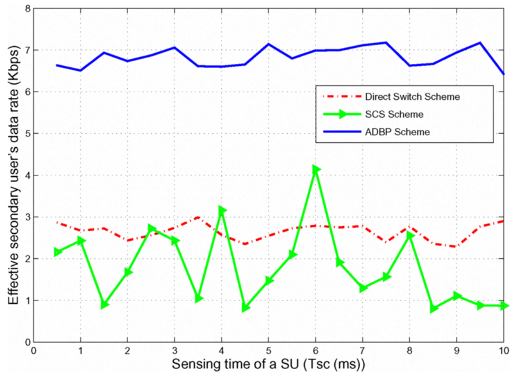

Fig. 5. Effective secondary users data rate when the probability busy state (P_B) is 0.3

VI. 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.

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