Channel Prediction-Based Channel Allocation Scheme for Multichannel Cognitive Radio Networks

Juhyeon Lee and Hyung-Kun Park

Abstract: **Cognitive radio (CR) has been proposed to solve the spectrum utilization problem by dynamically exploiting the unused spectrum. In CR networks, a spectrum selection scheme is an important process to efficiently exploit the spectrum holes, and an efficient channel allocation scheme must be designed to minimize interference to the primary network as well as to achieve better spectrum utilization. In this paper, we propose a multichannel selection algorithm that uses spectrum hole prediction to limit the interference to the primary network and to exploit channel characteristics in order to enhance channel utilization. The proposed scheme considers both the interference length and the channel capacity to limit the interference to primary users and to enhance system performance. By using the proposed scheme, channel utilization is improved whereas the system limits the collision rate of the CR packets.**

Index Terms: **Multichannel selection, opportunistic spectrum access, spectrum hole prediction.**

I. INTRODUCTION

As new wireless service and applications increase, the need for spectral resources has increased. Many spectrum resources are allocated to conventional networks, and the utilization of a wireless spectrum becomes an important issue in wireless communications. The Federal Communication Commission (FCC) observation results show that most of the allocated spectrum is not used most of the time whereas an unlicensed spectrum is being exhausted by emerging wireless service and applications [1]. To solve the problem of spectrum shortage and to utilize more efficiently the spectrum, the FCC has recently suggested a new concept for dynamically allocating the spectrum resource, which is called the cognitive radio (CR) technology.

The CR technology is expected to solve the limitation by exploiting the spectrum hole in conventional wireless networks [2], [3]. A CR user monitors the spectrum owned by a licensed user, also called primary user (PU), to find the spectrum hole and exploits it for communication. To efficiently utilize the spectrum holes, a channel allocation scheme is important and must be designed to minimize interference to the primary network as well as to achieve similar purposes as those in traditional wireless networks.

Channel prediction methods can be useful for channel allocation because they can reduce interference to PUs and processing time for finding optimal spectrum holes [4]. There are many research efforts for channel prediction based spectrum decision [5]–[8] in the CR area. They prove that using the channel prediction methods can improve performance of CR system including channel utilization, channel switching latency and interference to PU. According to the literatures, finding proper spectrum holes among idle channels based on channel prediction can enhance the performance of channel allocation in CR networks.

Many papers have presented studies on the topic of efficient spectrum allocation in CR networks. Opportunistic spectrum access-media access control (MAC) [9] proposes an opportunistic channel selection in multichannel environment but does not consider the characteristics of the channel, such as utilization traffic and transmission rate, and chooses the available channels randomly. Statistical channel allocation for adhoc CR networks [10] predicts a successful transmission rate for all idle channels and their combinations on the basis of channel utilization. The complexity of a statistical channel allocation-MAC exponentially increases as the number of idle channels increases. An opportunistic cognitive MAC (OC-MAC) using spectrum-hole prediction was proposed [11]. The OC-MAC protocol predicts the remaining idle time using channel utilization and probability theory. However, it does not support multichannel transmission. Proactive channel access approach [12] proposes proactive channel prediction and intelligent channel switching techniques to minimize interference to primary users under the exponential ON-OFF model. A Spectrum matching algorithms [13] are proposed to support quality of service (QoS) of CR users. The spectrum decision is based on statistical characteristics of spectrum bands. Although these researches well utilized the characteristic of channels, they do not relate their channel modeling to appropriate multichannel allocation. Some approaches exploit optimization algorithms [14], [15]. Each CR user adapts its transmission parameters to changes of the wireless environment, in order to efficiently exploit the available resource. However, finding the system optimum that takes into account all the constraints of a cognitive system requires prohibitively computational cost and a complete knowledge on the network status.

In this paper, we propose a spectrum hole prediction-based channel selection algorithm that supports multichannel transmission. By using the predicted spectrum hole, interference to the PU can be limited to the defined channel success rate. We introduce the interference length that is directly related to the success rate, and show that allocation that minimizes the total interference length is necessary to maximize the channel success rate of multiple channel allocation. We propose a channel allocation algorithm to achieve our channel allocation goal that minimizes the interference length. In addition, we consider the

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channel capacity of each channel and propose a method to apply channel quality factors for channel selection to improve the efficiency of channel utilization. Our research includes the following aspects.

– Prediction of the number of spectrum hole slots that satisfies the required channel success rate

– Channel allocation strategy to maximize the channel success rate for multichannel transmission

– Channel allocation algorithm to achieve the proposed allocation strategy

– Method to apply channel quality factors to channel selection to improve channel utilization.

The rest of this paper is organized as follows. In Section II, we present the proposed prediction method and channel allocation strategy. In Section III, we propose the channel allocation algorithm to achieve our allocation goal. At this point, we also describe how channel quality factors can be applied to the channel selection procedure. In Section IV , we describe the simulation environment and the results. Finally, we conclude our work in Section V.

II. SPECTRUM HOLE PREDICTION-BASED CHANNEL ALLOCATION

A. Spectrum Hole Prediction

Because of the dynamic nature of a cognitive network system, secondary users have relatively unstable channel access characteristics. Upon the beginning transmission or spectrum handoff, secondary users must decide to find the appropriate available channels for data transmission. To more opportunistically use the spectrum and reduce interference to the primary networks, the statistical properties of the primary networks can be used. By using the statistics of the primary network traffic, we can predict the spectrum hole and reduce the interference to the primary network.

In this section, we predict the number of time slots of a spectrum hole that satisfies the minimum channel success rate of a packet transmission. We assume that the secondary users know the statistical property of each channel by collecting channel usage information for a long time. To predict the spectrum hole, developing a detailed understanding of the traffic characteristics of the primary network is important. One of the most widely used traffic model is the Poisson model. The memoryless Poisson distribution is the predominant model used for analyzing traffic in traditional telephony networks. In this study, we modeled the PU's traffic pattern in each channel as a Poisson distribution model. Although the Poisson model is not a real traffic model, we expect the Poisson model is enough to prove the performance of the proposed channel allocation scheme.

The Poisson process is characterized as a renewal process. In this process, the inter-arrival times are exponentially distributed using the rate parameter λ. To predict the spectrum hole of channel i, we should obtain the probability that the PU's packets do not appear until the time t.

$$s_i(t) = A_i e^{-\lambda_i t}, \text{ where } A_i = e^{-\lambda_i t_o} \tag{1}$$

where λ_i is the PU's packet arrival rate in channel i and t_o is the time duration between the previous arrival time of a PU's packet and the spectrum sensing time. Each channel may have different arrival rates.

We define spectrum hole t_h as the time duration that satisfies the minimum channel success rate α. Threshold α is the required minimum success rate of each subchannel. The minimum success rate α denotes the success rate of each single channel, and not the success rate of a multichannel transmission. The success rate is the probability that a CR user transmits the packet without interference to the PU.

Each channel is divided into several small time slots, and spectrum hole t_h can be represented as the number of time slots N_h. When a CR user transmits a packet using spectrum hole N_h, the success rate must be greater than threshold α. Threshold α limits the interference to the PU in a channel.

$$\alpha \leq s_i(N_{d,i} t_{\mathrm{slot}}) = A_i e^{-\lambda_i N_{h,i} t_{\mathrm{slot}}} \tag{2}$$

where t_{slot} is the time duration of the time slot. The spectrum hole is the maximum number of slots that satisfies (2), and we can obtain the number of time slots of the spectrum hole as follows.

$$N_{h,i} = \left\lfloor -\frac{1}{t_{\mathrm{slot}}} \left(t_{o,i} + \frac{\log \alpha}{\lambda_i} \right) \right\rfloor . \tag{3}$$

The spectrum hole slot number N_h indicates the maximum number of time slots that can be used by the CR users while maintaining the channel success rate α. Spectrum hole N_h can differ according to the packet arrival rate λ, and each channel may have different N_h values.

To obtain the spectrum hole, each CR user should know the initial time value $t_{o,i}$. To obtain this value, multiple CR users within a certain area should share channel information. Each CR user in the area periodically senses the channel. If a CR user detects the arrival of a PU, it broadcasts the arrival time and enables the other CR users to update the channel information table. Signaling overhead can be increased due to the broadcasting of the channel information. However, we expect that the channel overhead is not so high as compared with the traffic of the CR users because CR users transmit channel information only when the channel is idle.

B. Multichannel Allocation Strategy

In a CR network, minimizing the interference to the primary network is the most important factor. In a multichannel transmission, the CR users should select the channels to minimize the interference to the PU and to maximize the success rate. If a CR user needs N_D time slots to transmit its own packet using M channels, the success rate of transmission is expressed as

$$S = \prod_{t=0}^{M-1} s_i \left(N_{d,i} t_{\mathrm{slot}} \right) = \exp \left[-t_{\mathrm{slot}} \sum_i \lambda_i \left(N_{d,i} + N_{o,i} \right) \right],$$

$$N_{d,i} \leq N_{h,i},\ N_{d,0} + N_{d,1} + \cdots + N_{d,L-1} = N_D, \tag{4}$$

where $N_{d,i}$ is the number of time slots allocated to channel i, and $N_{o,i}$ is the number of time slots for $t_{o,i}$. We define the interference length L_i of channel i [16] as (5) to simply obtain the

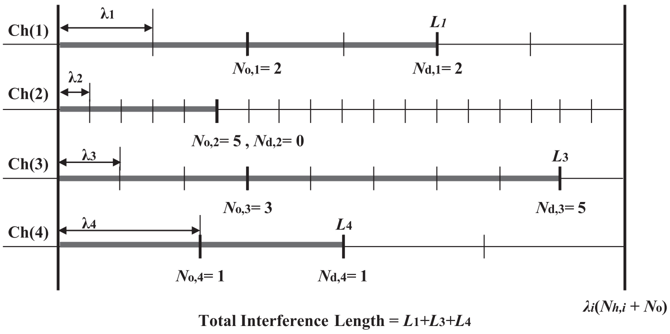

Fig. 1. Example of the interference length.

success rate. Then, we can express the success rate as a function of the sum of the interference lengths as

$$L_i(N_{d,i}) = \lambda_i\left(N_{d,i} + N_{o,i}\right), \tag{5}$$

$$S = \exp\left[-t_{\text{slot}}\sum_i L_i\right]. \tag{6}$$

From (6), we find that the total interference length is directly related to the success rate. As the total interference length increases, the success rate decreases. Fig. 1 shows an example of the interference length and the relationship among λ_i, $N_{d,i}$, $N_{o,i}$, and L_i. The total interference length is the sum of all interference lengths. If no time slots are allocated in a channel, its interference length becomes zero and is not included in the total interference length because the channel does not affect the success rate.

The CR users should determine the $N_{d,i}$ values that minimize the total interference length in order to maximize the success rate. We define vector $\bar{N_d} = [N_{d,0}, N_{d,1}, \cdots, N_{d,M-1}]$ as the set of time slots to be transmitted for each channel. Using (7), we can find vector $\bar{N_d^*} = [N_{d,0}^*, N_{d,1}^*, \cdots, N_{d,M-1}^*]$ that maximizes the success rate.

$$\bar{N_d^*} = \arg\min_{\bar{N_d}} \sum_{i=0}^{M-1} L_i(N_{d,i}) \tag{7}$$

$$\text{subject to } \sum_{i=0}^{M-1} N_{d,i}^* = N_D \text{ and } \mathrm{N}_{\mathrm{d,i}}^* \le \mathrm{N}_{\mathrm{h,i}}.$$

III. CHANNEL ALLOCATION ALGORITHMS

In this chapter, we propose channel allocation algorithms to achieve the allocation goal we suggested in (7). The chapter consists of two parts. In subsection A, we propose the algorithm to achieve minimum interference length. Subsection B shows another modified algorithm that considers channel quality to improve channel utilization.

A. Minimum Interference Length Channel Allocation Algorithm (MIL Selection)

To find $\bar{N_d^*}$, we should select as small as possible the number of channels because a large number of selected channels would contain large $N_{o,i}$ values and will increase the interference length. Therefore, we will determine the least number of channels with a large $N_{h,i}$ value to minimize the interference length.

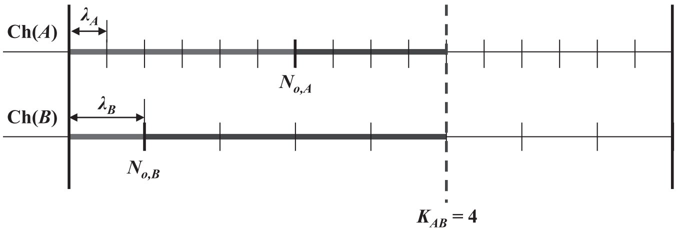

Fig. 2. Concept of the boundary value K.

Generally, if we have a large amount of data to transmit, the channel with the smallest λ_i is the best selection because the channel with smaller λ_i has larger $N_{h,i}$. However, an exception occurs if $N_{d,i}$, the number of slots to be allocated to channel i, is not large enough. Fig. 2 shows the interference length of two channels. Channel B, which has a larger λ_i, has a smaller interference length when $N_{d,i}$ is smaller than four slots, whereas Channel A's interference length is smaller in the opposite case. If we allocate more than four slots, we should select Channel A; otherwise, Channel B would be a better selection to minimize the interference length. We set this boundary number of slots (four slots in this case) as K_{AB}.

K_{AB}, K value of channel A and B, is the number of slots that makes the interference length of Channel A smaller than that of Channel B when more slots than K_{AB} are allocated. We can obtain K_{AB} by expanding (8), and the result is expressed in (9). If the K_{AB} value is negative, Channel A is optimal. If the K_{AB} value is positive, the optimal channel depends on $N_{d,i}$. Here, λ_A must be smaller than λ_B.

$$\lambda_A(N_{o,A} + K_{AB}) = \lambda_B(N_{o,B} + K_{AB}) \tag{8}$$

$$K_{AB} = \frac{\lambda_A N_{o,A} - \lambda_B N_{o,B}}{\lambda_B - \lambda_A},\ \lambda_A < \lambda_B \tag{9}$$

If a channel with N_h larger than data N_D exists, using a single channel with the shortest interference length is better because the additional channels add initial slots $N_{o,i}$, and they increase the interference length by $\lambda_i N_{o,i}$. If data N_D are larger than any other $N_{h,i}$ of each channel i, we should select multiple channels that can minimize the interference length.

Our goal is to find a set of channels that can transmit data N_D with the minimum interference length. We extend the proposed channel selection principle using K values to a multichannel case. First, we determine the channel with the smallest λ_i and call it Channel S. Second, using (9), we calculate the K value of Channel S and the other channels. Then, we determine the channel with the largest K value, which is Channel R. The selection criteria for Channels S and R are expressed by (10) and (11), respectively.

$$\text{Channel } S = \arg\min_i \lambda_i, \tag{10}$$

$$\text{Channel } R = \arg\max_i K_{Si}. \tag{11}$$

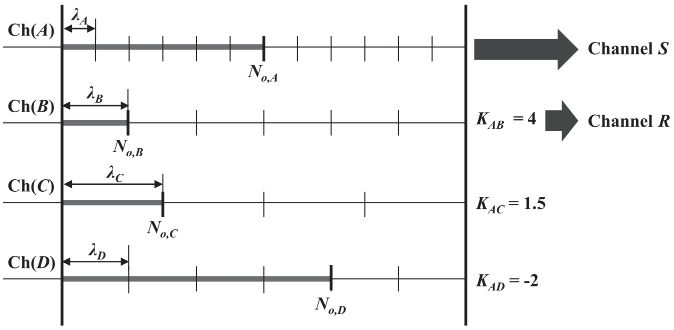

Fig. 3. Multichannel selection procedure.

If the number of slots to be transmitted is smaller than the K value, the best choice is Channel R; otherwise, Channel S is the best choice for smaller interference lengths. This multichannel selection procedure is shown in Fig. 3.

Fig. 3 shows an example of the channel selection procedure. According to our channel selection criteria described above, the first step is to find the Channel S which has the smallest λ_i. In this case, Channel A is selected as Channel S because Channel A has the smallest λ_i. If multiple channels with smallest λ_i exist, we simply choose the channel with the smallest $N_{o,i}$ among them because a smaller $N_{o,i}$ causes shorter interference length. With the selected Channel S, the K value of each channel can be determined. The next step is to find the Channel R which has the largest K_{Si}. In this case, Channel B is selected as Channel R because Channel B has the largest K value.

From the figure, the channel with small $\lambda_i N_{o,i}$ shows a large K value. If $\lambda_i N_{o,i}$ is greater than $\lambda_A N_{o,A}$, channel i has a negative K value. Hence, if every channel shows a negative K value, Channel S is the best choice. However, if more than one channel shows a positive K value, we select either Channel S or R depending on the number of slots to be allocated. If the finally selected channel has large $N_{h,i}$ value enough to transmit all remaining slots, the selection procedure is finished at this point. Otherwise, we should select the other channels to allocate the remaining data. We can use the iterative channel selection using the above procedure.

In case every channel has larger N_h than K values, the above procedure can properly work. However, we cannot guarantee that every channel has always a larger N_h than the K value because the K value is derived from λ_i and $N_{o,i}$ factors. Thus, we consider additional cases as follows.

1) If $N_{\text{rem}} < K_{SR}$
    1-1) $N_{h,R} > N_{\text{rem}}$
    1-2) $N_{h,R} < N_{\text{rem}}$

2) If $N_{\text{rem}} > K_{SR}$
    2-1) $N_{h,S} > K_{SR}$
    2-2) $N_{h,S} < K_{SR}$

where N_{rem} is the number of remaining slots to be transmitted. In Case 1), i.e., $N_{\text{rem}} < K_{SR}$, selecting Channel R is better if Channel R has sufficient $N_{h,R}$. Therefore, the selection in Case 1-1) is Channel R. However, if Channel R does not have enough $N_{h,R}$ as in Case 1-2, Channel S would be a better choice if it has more N_h. For certainty, we measure how many N_h could Channel S have when $N_{h,R} < N_{\text{rem}}$. First, (12) is satisfied because $N_{\text{rem}} < K_{SR}$ and $N_{h,R} < N_{\text{rem}}$.

$$N_{h,R} < K_{SR}. \tag{12}$$

The predicted number of spectrum hole slots N_h is the number of slots that satisfies the success rate α in (3). From this fact, it is found that the $L_i(N_{h,i}) = \lambda_i(N_{o,i} + N_{h,i})$ values of each channel i are identical, and consequently, (13) is satisfied. Using (9), (12), and (13), we can finally obtain the result, as expressed by (14).

$$\begin{aligned} L_S(N_{h,S}) &= L_R(N_{h,R}) \qquad (13) \\ &= \lambda_S(N_{o,S} + N_{h,S}) = \lambda_R(N_{o,R} + N_{h,R}), \end{aligned}$$

$$N_{h,R} > N_{h,S}. \tag{14}$$

Equation (14) means that Channel R always has more N_h than Channel S when $N_{rem} < K_{SR}$ and $N_{h,R} < N_{\text{rem}}$. This result shows that Channel R should be selected in Case 1), i.e., $N_{\text{rem}} < K_{SR}$.

In Case 2), i.e., $N_{\text{rem}} > K_{SR}$, selecting Channel S is better if Channel S has sufficient N_h, as in Case 2-1) $N_{h,S} > K_{SR}$. However, if Channel S does not have enough N_h, as in Case 2-2), we should determine which channel has more N_h. Using the condition$N_{h,S} < K_{SR}$ and (13), we can obtain the same result as that shown in (14). This result also leads to the conclusion that Channel R is the best choice for Case 2-2).

The results discussed above can be summarized as follows.

1) If $N_{\text{rem}} < K_{SR}$: $i^* =$ Channel R

2) If $N_{\text{rem}} > K_{SR}$
    2-1) $N_{h,S} > K_{SR}$: $i^* =$ Channel S
    2-2) $N_{h,S} < K_{SR}$: $i^* =$ Channel R

Finally, the multichannel-selection procedure is presented as follows. First, we determine the channel with the smallest λ_i and designate it as Channel S. Second, using (9), we calculate the K_{Si} value of each channel i. Then, we determine the channel with the largest K value and designate it as Channel R. If no positive K value exists, Channel S is optimal. Otherwise, we should compare K_{SR} and the remaining number of slots. If K_{SR} is larger, Channel R is optimal; otherwise, we check if Channel S has enough spectrum hole $N_{h,S}$. If $N_{h,S}$ is larger than K_{SR}, the optimal channel is Channel S; otherwise, Channel R is the optimal channel. After we find the optimal channel, we update $\bar{N}_d$. If more data remain to be sent, we go back to the Channel S selection step and repeat the process. If no more data have to be sent or if no more spectrum holes exist, we end the selection process and transmit data $\bar{N}_d$ over selected channels. Fig. 4 shows the multichannel-selection procedure.

B. Channel Capacity-Based Channel Allocation Algorithm (CCB Selection)

Aside from the PU's probability distribution, each CR channel may have different channel conditions. To transmit a cer-

```
At each channel allocation instance {

  for every user $i$ {
        update $N_{h,i}$, $N_{o,i}$}

  while (number of idle channels > 0 && size of buffer > 0) {

      channel $S = \text{argmin}_i \lambda_i$            // channel $S$ selection

      for every user $i$ {
          update $K_{Si} = \frac{\lambda_S N_{o,S} - \lambda_i N_{o,i}}{\lambda_i - \lambda_S}$}

      channel $R = \arg\max_i K_{Si}$            // channel $R$ selection

       if ($K_{SR}$ < 0 )                         // final channel selection
          selected = channel S
       else if ($K_{SR}$ < size of buffer )
          selected = channel $R$
       else if ($N_{h,S}$ < size of buffer )
            selected = channel $R$
       else
            selected = channel $S$

     // determining number of slots to transmit over the selected channel
      if $N_{d,\text{selected}}$ > size of buffer
              $N_{d,\text{selected}}$ = size of buffer
      else
              $N_{d,\text{selected}} = N_{h,\text{selected}}$

      update $\overline{N_d} = \overline{N_d} + N_{d,\text{selected}}$
      size of buffer = size of buffer - $N_{d,\text{selected}}$
      }

   channel allocation $\overline{N_d}$ }// End of channel allocation
```

Fig. 4. MIL Selection.

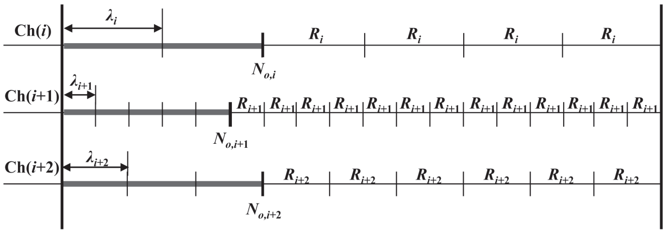

Fig. 5. Interference length under different channel conditions.

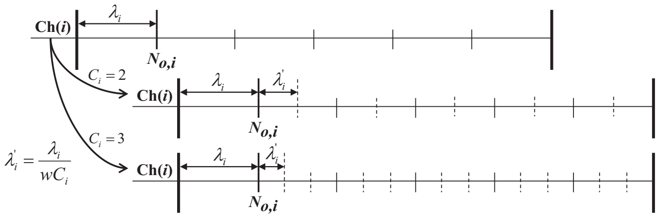

Fig. 6. Example of λ_i' modification ($w = 1$).

tain amount of data, channels with good channel condition need smaller time slots or smaller interference length than those with poor channel conditions because the good channels can transmit more data within a single time slot. In this section, we propose a channel allocation method that considers both channel conditions and the PU's statistical characteristic, by simple modification of previous algorithm.

We assume that the secondary users know each channel's condition by receiving channel estimation results; they then calculate the data rate for transmission. Further, the system supports variable data rate; thus, it has a certain level of data rates. The secondary node determines the appropriate channel level for each channel using the channel estimation result, and the node transmits the data with a certain amount of predefined data rate R_i according to each channel level. Fig. 5 shows the interference length of each channel under different channel conditions. Each channel i has its data rate R_i according to its channel condition.

The idea presented in this section is that we modify λ_i using data rate R_i. However, data rate R_i cannot be simply applied to our method. Hence, we first define the concept of relative channel capacity in (15).

$$C_i = \frac{R_i}{R_{\min}}. \tag{15}$$

C_i is the relative channel capacity of channel i and is defined as the ratio of R_i to the minimum data rate $R_{\min}$, which is the minimum data rate among the variable data rates supported by the system. The relative channel capacity factor C_i shows how much more data can be allocated in a spectrum hole slot compared with the minimum data rate of the system. In other words, one slot of a channel with R_i has the same capacity of C_i slots as that of a channel with $R_{\min}$, or channel i needs C_i times less slots to transmit the data. Using this characteristic, we modify λ_i as (16).

$$\lambda_i' = \begin{cases} \lambda_i, & \text{if } wC_i < 1, \\ \frac{\lambda_i}{wC_i}, & \text{else} \end{cases} \tag{16}$$

where w is a parameter that gives weight to the capacity. We do not modify λ_i when $wC_i < 1$ to make λ_i maximize the value of λ_i'. The effect of the modification of λ_i is shown in Fig. 6.

Using the modified λ_i' does not mean that the predicted number of spectrum holes $N_{h,i}$ in (3) should be modified along with λ_i'. In Fig. 6, the channel with $C_i = 3$ can transmit more data than the others; however, its $N_{h,i}$ should be 5 and not 15 because its predicted number of slots that satisfies α is 5, as derived from (3). The modified λ_i' will only affect the channel selection.

To apply the proposed method to the channel-selection algorithm, we need additional computational effort to determine the channel-related parameters such as R_i, C_i, and λ_i'. The channel capacity-based channel allocation algorithm is shown in Fig. 7.

IV. SIMULATIONS AND RESULTS

We evaluated the performance of the proposed channel selection scheme via computer simulation. For the simulation environment, we considered one primary network and one CR network. We did not specify the primary network but considered a general primary network. The simulation consisted of two parts. One part assumed that every channel has the same capacity whereas the other part adopted variable capacities for each channel. In the first part of simulation, we examine the performance of MIL selection that is shown in subsection III-A whereas both of MIL and CCB selection is evaluated in the other

```
At each channel allocation instance {

  for every user $i$ {
          update $R_i,\ C_i,\ \lambda'_i,\ N_{o,i}$}

  while (number of idle channels > 0 && size of buffer > 0) {

      $S$ = arg min$_i\,\lambda_i{}'$                    // channel $S$ selection

      for every user $i$ {
          update   $K_{Si} = \frac{\lambda'_S N_{o,S} - \lambda'_i N_{o,i}}{\lambda'_i - \lambda'_S}$}

      $R$ = arg max$_i\,K_{Si}$                    // channel $R$ selection

    if ($K_{SR}$< 0 )                         // final channel selection
          selected = channel $S$
       else if ($K_{SR}$< size of buffer )
          selected = channel $R$
       else if ($N_{h,S}$< size of buffer )
          selected = channel $R$
       else
          selected = channel $S$

     // determining number of slots to transmit over the selected channel
      if  $N_{h,\mathrm{selected}}$  > size of buffer
              $N_{d,\mathrm{selected}}$  = size of buffer
      else
              $N_{d,\mathrm{selected}}$  = $N_{h,\mathrm{selected}}$
     update $\overline{N_d} = \overline{N_d} + N_{d,\mathrm{selected}}$
     size of buffer = size of buffer -  $N_{d,\mathrm{selected}}$
     }

    channel allocation  $\overline{N_d}$  } // End of channel allocation
```

Fig. 7. CCB Selection.

part of simulation. The multichannel was composed of 16 channels, and the channel rate was 2 Mbps. The arrival process of the primary service was modeled as an independent Poisson process with mean arrival rate λ_i for channel i, and the service duration had an exponential distribution with a mean service duration of 500 slots. The load of the primary traffic was calculated by multiplying the mean arrival rate and the mean service duration.

We compared the performance of the proposed selection scheme with that of the Random channel selection and the Statistical channel selection. The Random channel selection scheme randomly selects multiple idle channels among all sensed idle channels. On the other hand, the Statistical channel selection scheme selects channels to transmit according to each channel's statistical characteristic such as arrival rate of a channel. For both selection approach, the number of idle channels to be selected is determined depends on the packet length to transmit, and the equal number of times slots are allocated to each selected channel.

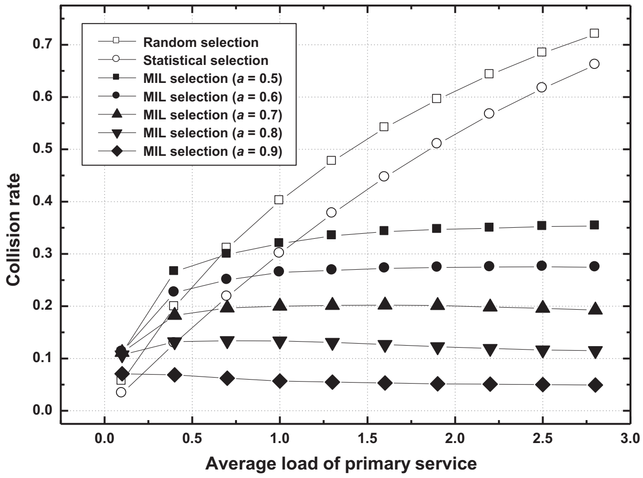

Fig. 8. Collision probability according to the load of the primary service.

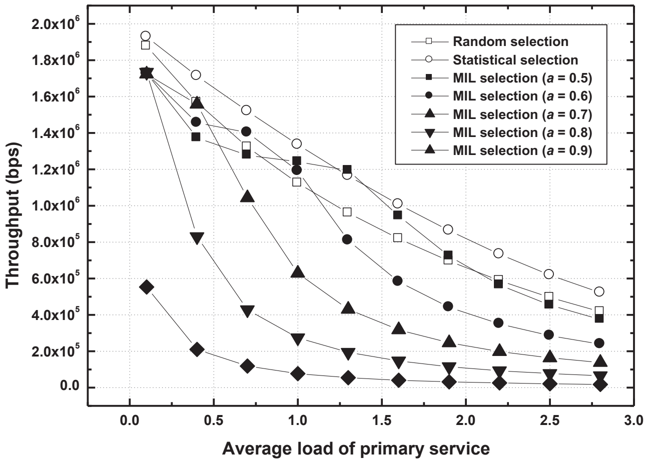

Fig. 9. Throughput according to the load of the primary service.

Fig. 8 shows the collision probability of the proposed and other channel selection strategies. As the load of the primary service increases, the interference to the PU increases. When the channel success rate threshold α increases, the collision probability is reduced because the CR user can have less opportunity to exploit the spectrum holes. For all the success rate threshold values α, the proposed algorithm successfully keeps the collision probability lower than a certain point. In the Random selection, however, it shows higher collision rate than the proposed channel selection scheme because it does not utilize the traffic characteristics but randomly selects channels. On the other hand, the Statistical selection can have lower collision rate than the proposed one depending on α value when the traffic load is very low. It also has better performance than that of the Random selection by selecting channels according to the channel's statistical characteristic. However the collision of the Statistical selection becomes higher as the channel load is increased while the proposed selection limits the collision rate even in the heavy traffic load.

Fig. 9 shows the throughput according to the average load of the primary service. If the channel load is greater, the throughput of all selection schemes becomes worse because few idle channels exist in the heavy traffic. The throughput of the proposed channel selection is generally lower than those of the other selections. However, the proposed selection with $\alpha = 0.5$ shows similar performance to those of the other selections, while

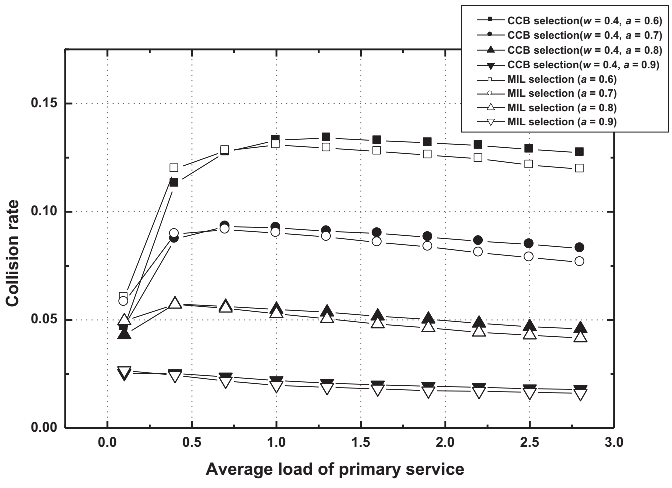

Fig. 10. Collision probability according to the load of the primary service ($w = 0.4$).

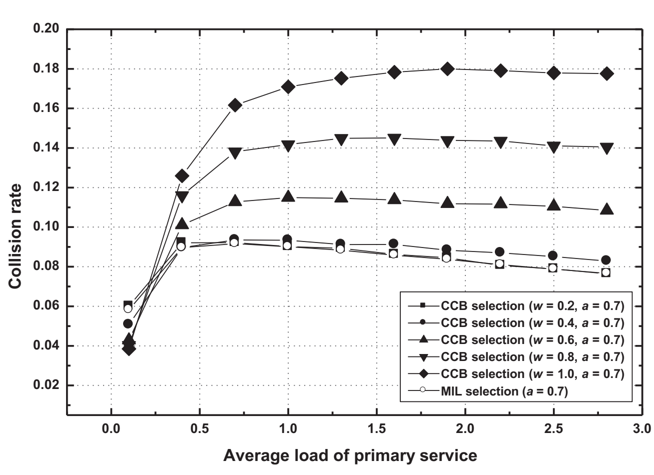

Fig. 12. Collision probability according to the load of the primary service for each w.

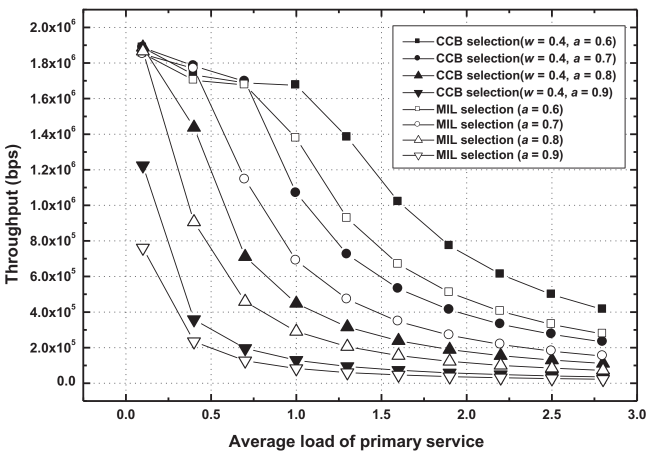

Fig. 11. Throughput according to the load of the primary service ($w = 0.4$).

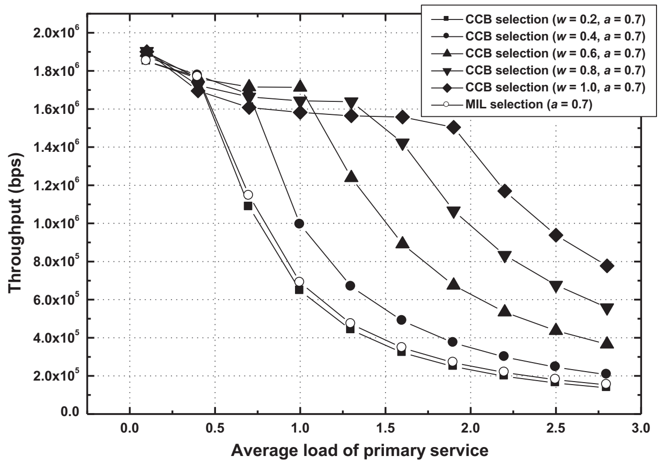

Fig. 13. Throughput according to the load of the primary service for each w.

it can successfully lower the collision rate than the other selections. As the channel success threshold increases, the predicted length of the spectrum hole decreases, and the amount of transmitted data is limited. A decrease in collision with the primary data can cause a decrease in the channel throughput. In the CR, the collision with primary service is a more serious problem than the throughput reduction of the CR data, and the throughput should be maximized under the allowed collision probability. In the proposed channel selection, we can control the collision probability and the throughput by controlling the channel success rate threshold α.

In the second part of the simulation, we assumed that every channel had different channel conditions. We used a four-level variable data rate; thus, each channel could have a different channel rate according to its channel condition. The other simulation parameters were the same as those in the previous simulation. We compared the performance of the channel capacity-based channel selection using modified $\lambda_i^{'}$, CCB selection, with that of the channel selection using unmodified λ_i, MIL selection.

Figs. 10 and 11 show the collision rate and the average throughput of the algorithm. Parameter w represents the weight of the channel capacity in (9), and α is the minimum channel success rate. Fig. 10 shows that the MIL selection that does not consider the channel quality has a lower collision rate because the modified $\lambda_i^{'}$ can reduce the interference length of a channel with large capacity, and it makes the node select a high-capacity channel more frequently than to select a channel with minimum interference length. For the same reason, the CCB selection shows a higher throughput than the unmodified version shown in Fig. 11, that means modifying the statistic parameter along with channel condition does improve the efficiency of resource allocation. Both simulation results show that the enhancing channel utilization can cause the increasing of interference to the PU, thus choosing the appropriate system parameters are necessary.

Figs. 12 and 13 show the collision rate and the average throughput according to each weight factor w. The smaller w value shows more results similar to that of the MIL selection, whereas the larger w value shows higher collision rate and throughput because the larger w value results in a much larger $\lambda_i^{'}$ modification. The node with larger w selects more high-capacity channels, which could be not quite optimal in terms of the interference length. The selection of the w value can result in different collision rates and throughput performance, and we can control the performance with an appropriate selection of the w value.

V. CONCLUSIONS

Channel selection is one of the most important processes in CR networks. Cognitive users should select channels not only to utilize the spectrum more efficiently but also to minimize interference to the primary network. In this paper, we have proposed a channel selection scheme that uses spectrum hole prediction to limit the interference to the primary network and to exploit the channel characteristics in order to enhance channel utilization. The simulation results show that the proposed channel selection scheme successfully limits interference to the PUs than the conventional channel selection scheme such as the Random selection and Statistical selection. Furthermore, with simple adjusting of statistic parameter along with the channel quality, the proposed scheme achieves higher throughput while limiting the collision rate. The selection of the channel success rate threshold α and weight factor w can result in different collision rates and throughput performance, and we can control the performance by appropriate selection of the α and w values.

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