

Dynamic selection of CWmin in cognitive radio networks for protecting IEEE 802.11 primary users

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Abstract—Time domain spectrum sharing between primary user (PU) and cognitive radio (CR) networks is considered. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol is suitable for this type of spectrum sharing with unslotted access in which PUs and secondary users (SUs) are asynchronous. The goal is to maximize the average throughput of the SUs while guaranteeing the average throughput of the PUs. To achieve this, in our proposal the CR network adaptively changes its minimum contention window size (CWmin), depending on the channel occupancy rate (COR) from the PU network. The COR is approximately proportional to the average throughput and is estimated based on the observed traffic. In this paper, we analytically derive the optimum CWmin to maximize the COR of the CR network, while guaranteeing the COR of the PU network. In addition, to further protect saturated (high load) PUs, we also propose using a margin in the CWmin selection process. The simulation results show that the proposed approach does maximize the COR of the CR network and that it does converge faster in dynamic situations than the previous proposals. Also, the simulation results show the effectiveness of the proposed approach with margin.

I. INTRODUCTION

Due to the rapid development of the wireless communication technology, the need to use frequency resources is increasing drastically. However, most of the limited frequency resources have already been allocated to existing wireless systems (primary user: PU), and there is lack of frequency bands for new wireless systems leading to the so-called spectral scarcity problem. A report sponsored by FCC in [1] shows that the spectrum has not been effectively utilized by the PUs in the time or space domain. As a solution to the spectral scarcity problem, spectrum sharing technique has attracted much attention, in which the unlicensed SU opportunistically uses the white spaces as long as negative impact on the PU is constrained.

Spectrum sharing techniques utilizing the white spaces in spatial domain [2], [3] or time domain [4]–[10] have been studied. This paper focuses on time domain spectrum sharing. In [4], three random access schemes for time domain spectrum sharing are proposed with PUs which are not equipped with any reactive function such as carrier sense. In the case of PU in a distributed wireless network, PU is usually reactive and equipped with the carrier sense [5]–[10]. This reactivity is a useful characteristic for SUs to achieve effective time domain spectrum sharing since the PU innately has an ability to avoid

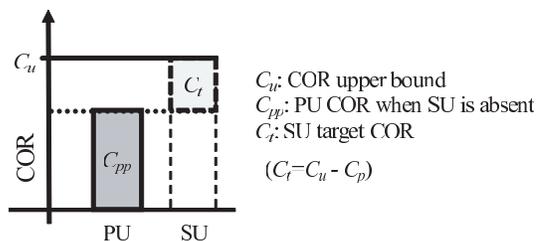


Fig. 1. A concept of time domain spectrum sharing using COR.

a collision by the carrier sense.

Several metrics to protect PUs have been introduced. In [5] and [6], delay performance to capture the impact of SU activity on PU is evaluated. They show that increasing throughput of SUs leads to more delay at PU. In [7], cognitive medium access (CMA) was proposed with interference constrain depending on a rate of collision between SU and PU. In the case of reactive PUs, the average throughput of PU is also important metric [9], [10]. One reason for this is that an accurate carrier sensing by PUs and SUs would achieve significantly low rate of collisions but it may leads to degradation of average throughput in PU. In [9], Levorato et al. proposed a framework for analysis and optimization of the average throughputs. However in [9], the carrier sense multiple access with collision avoidance (CSMA/CA) which is widely used was not assumed.

In [10] and this paper, the PU and the SU behave according to the CSMA/CA protocol. Therein, we proposed to use the channel occupancy rate (COR) information for optimizing the aggressiveness of the SU by the selection of the minimum contention window size CW_{min} . The COR of the PUs indicates the amount of time the channel is busy due to transmission of the PUs and it is approximately proportional to the average throughput of the PUs. As shown in [11], CW_{min} affects the throughput performance in CSMA/CA networks.

The concept of the spectrum sharing employing the COR information is shown in Fig. 1. The left bar graph indicates the COR by the PU when no SUs are present and this COR is denoted as C_{pp} . The upper bound value C_u refers to the maximum possible combined COR when both PUs and SUs are simultaneously operating without a significant COR

degradation in PUs. In this case, the method proposed in [10] aims to make $C_s = C_u$ where C_s denotes the COR by the SUs and C_t is the SU target COR given by $C_t = C_u - C_{pp}$. There are still two issues that remain to be solved in [10] as follows. Actually, the upper bound of utilization C_u is not a static value as it varies with the change of environment such as C_{pp} . In [10], we utilized the worst possible value of C_u . Due to this assumption, the C_s cannot fully reach the optimal value of C_t . Furthermore, the heuristic approach used in [10] for selecting the CW_{min} may lead to slower convergence speeds.

In this paper, we propose a new method for the selection of the CW_{min} to solve the two issues. We derive the optimum CW_{min} based on C_{pp} based on analysis. Based on this derivation, we propose the CW_{min} selection method which can approximately achieve the upper bound of COR C_u based on an estimated C_p and improves convergence speeds.

The estimation error of C_p , especially in a case of saturated PUs, degrades PU average throughput performance. For improved protection of the PU network, we also propose using margin COR C_m , i.e., target COR is reduced by C_m . This method enhances the ability of protecting even saturated PU with only small reduction in C_s .

II. NETWORK MODEL

PUs and SUs are WLANs based on IEEE 802.11a and communicating through CSMA/CA protocol [12]. Each of the primary and secondary networks consists of one access point (AP) as the transmitter and one terminal as the receiver as in [9]. An extension to larger networks requires to consider other issues such as resource sharing among SUs and these are out of the scope of this paper. We assume single channel shared by the PU network and the SU network. All the users (SUs and PUs) are located close to each other, thus, they can sense the channel occupancy perfectly. Therefore, a collision between the SU and the PU is only caused by back-off time setting. An example of the collision will be introduced in the next section. The data packets of each active user are generated randomly and independently according to the Poisson's process. The generation of packets is carried out on one time slot unit where length of one time slot is denoted as T_{slot} and $T_{slot} = 9\mu$ sec as in IEEE 802.11a. The other assumed parameters are as follows: the data packet length, $T_{DATA} = 28$ time slots, the time length of SIFS, $T_{SIFS} = 2$ time slots, the time length of DIFS, $T_{DIFS} = 4$ time slots and ACK signal length, $T_{ACK} = 3$ time slots [12]. Average incidence rates per T_{slot} of PU and SU are denoted with λ_p and λ_s , respectively. SU is capable of selecting their CW_{min} to control its own COR C_s and estimating the PU COR C_p .

III. CHANNEL OCCUPANCY RATE (COR) AND OPTIMIZATION PROBLEM

First, COR and related characteristics of the CSMA/CA protocol are introduced. Then, the relationship between the optimum CW_{min} and C_u is shown. In addition, the addressed optimization problem in the proposed method is presented.

A. Channel Occupancy Rate (COR)

Let the user's signal be sensed every time slot by carrier sense and the channel status at an arbitrary time slot k is given by $A(k)$ defined as follows,

$$A(k) = \begin{cases} 1 & (\text{if signal is sensed}) \\ 0 & (\text{else}). \end{cases} \quad (1)$$

Then, the estimated value of COR \hat{C} if the channel is observed for a time period of K time slots can be calculated as follows,

$$\hat{C} = \frac{\sum_{k=1}^K A(k)}{K}. \quad (2)$$

An example of random access by CSMA/CA with SUs and PUs is shown in Fig. 2 to show important characteristics of CSMA/CA. In the example, at the TIME 1 (Fig. 2) the transmitters have to sense the channel status for DIFS duration. If the channel status is idle for that duration, next the transmitters set Back-off time (BT). The value of BT is a uniformly distributed random number ranging from 0 to an integer determined by contention window size CW . In the example, since the PU AP set $BT = 6$ smaller than $BT = 9$ of the SU AP, the PU AP sends a data packet to the PU terminal. Then, the SU AP senses that channel is busy. Therefore the SU AP stops counting down the BT and waits until channel is idle, i.e., TIME 2 (Fig. 2). At the TIME 2, the SU AP again senses the channel status for DIFS duration and restarts counting down the rest of BT , i.e., $BT = 3$. But the new BT set by the PU AP is also $BT = 3$, therefore, they send data packets simultaneously and a collision occurs.

Let $Random(CW)$ be a function that produces uniformly distributed random numbers in the range of 0 to an integer CW , then BT can be given by

$$BT = Random(CW). \quad (3)$$

The initial value of CW is set as CW_{min} before a transmission but when there is a collision, the contention window size is doubled, up to the maximum value CW_{max} , i.e., $CW_{min} \leq CW \leq CW_{max}$ and $CW = 2n \times (CW_{min} + 1) - 1$ where n is

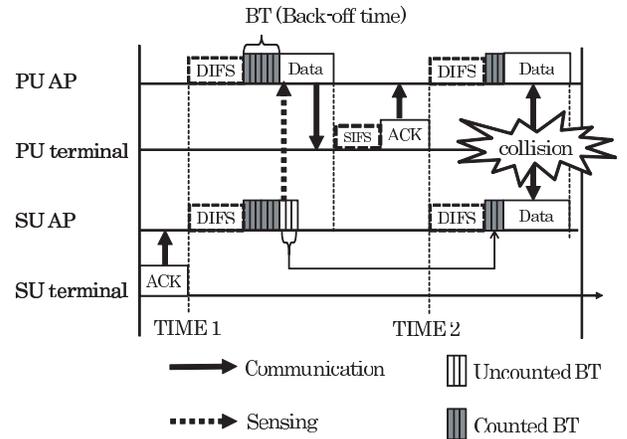


Fig. 2. an example of CSMA/CA protocol.

positive integer indicating the number of continuous collisions. In primary network, $CW_{min} = 15$ and $CW_{max} = 1023$.

There are two important characteristics in \hat{C} under the CSMA/CA protocol. First, \hat{C} is always less than 1 because there are DIFS, SIFS and BT intervals where signal does not exist. Second, the COR depends on CW_{min} . It is possible to understand intuitively that smaller CW_{min} leads to higher COR and vice versa. The second characteristic indicates that by selecting suitable CW_{min} it may be possible to maximize C_s while keeping $C_p \simeq C_{pp}$ and this is the idea used in the CW_{min} selection method [10]. In the SU, CW_{min} is adjustable in the region $0 \leq CW_{min} \leq 1023$ and $CW_{max} = 1023$ to control C_s finely.

B. COR upper bound

The meaning of COR upper bound C_u is explained as follows with the help of Fig. 3. In Fig. 3, CORs of C_p , C_s and the total COR given by $C_p + C_s$ are plotted as a function of the SU's CW_{min} . The COR performances are evaluated by the network simulator developed with MATLAB and following parameters are assumed; $\lambda_p=0.015$ and $\lambda_s=0.03$.

In this evaluation, the CW_{min} of the SU is fixed as mentioned on the horizontal axis in Fig. 3 to show C_u and the optimum CW_{min} . In the region where $CW_{min}^* < CW_{min}$ where CW_{min}^* is shown in Fig. 3, C_p is constant although C_s is increased by decreasing its CW_{min} . This fact implies that C_p is most likely constant at its original value C_{pp} thus the PU is protected. On the other hand, in the region where $CW_{min} < CW_{min}^*$, C_p is decreasing by decreasing the SU's CW_{min} hence the PU is harmed by SU.

Here, we define the total COR at CW_{min}^* as the COR upper bound C_u . At C_u , a usage of CW_{min}^* can achieve the maximization of C_s and this C_s corresponds to the target COR, C_t .

The other important fact is that the value of C_u can be varied due to C_{pp} . Finally, our optimization problem is represented

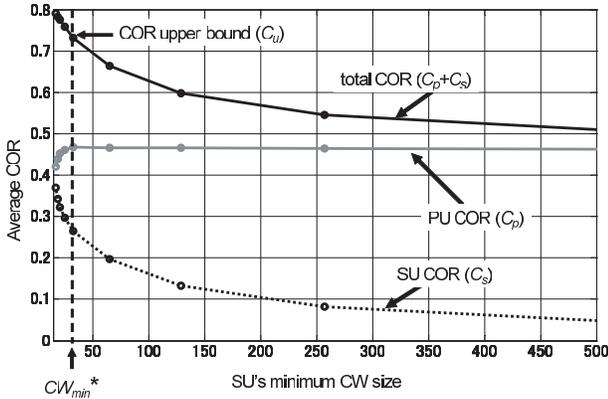


Fig. 3. COR performances (C_s , C_p and total COR) as a function of CW_{min} to show COR upper bound which is the total COR at CW_{min}^* . ($\lambda_p=0.015$ and $\lambda_s=0.03$)

by

$$CW_{min}^* = \arg \max_{CW_{min}} C_p + C_s \quad (4)$$

subject to

$$C_p \geq (1 - \epsilon)C_{pp} \quad (5)$$

where ϵ is the maximum fraction of COR loss in PU and $0 < \epsilon < 1$.

IV. PROCESS OF THE TIME DOMAIN SPECTRUM SHARING

A process of the time domain spectrum sharing is divided into two phases; the first phase is C_p estimation and the second phase is CW_{min} selection. In the first phase, C_p is estimated by the SU over i th estimation time duration T_{cor} where $T_{cor} = KT_{slot}$. In this paper, investigation of estimation period K is out of scope but based on Monte Carlo simulation sufficient length of K to avoid significant effect of the estimation error is derived. In the second phase, based on the estimated value $\hat{C}_p(i)$, the SU sets CW_{min} to be used in the $(i+1)$ th T_{cor} period based on a CW_{min} selection method. In this paper, two CW_{min} selection methods are introduced and details are shown in section V. In the numerical evaluation, we will show a comparison between the proposed method and the conventional CW_{min} selection method in [10].

There are two differences between the conventional CW_{min} selection method proposed in [10] and the method proposed in this paper. The first difference is that the conventional method does not use the actual C_u but the worst case C_u which is usually less than actual C_u . Due to this fact, the conventional method can not maximize the C_s . The second difference is that the conventional method updates CW_{min} in heuristic manner. On the other hand, the proposed method can achieve CW_{min}^* instantaneously based on $\hat{C}_p(i)$. These difference will be confirmed by computer simulations in the section VI.

As mentioned in section III-B, CW_{min}^* is the CW_{min} when the total CORs, $(C_p + C_s)$, is equal to C_u . In other words, CW_{min}^* can achieve that $C_s = C_u - C_p$ where $C_p \simeq C_{pp}$.

V. OPTIMUM CW_{min}

In this section we first give a derivation of the CW_{min}^* without considering margin. After that, the CW_{min} selection method with margin is introduced.

A. CW_{min} without margin

As the data packet occurs according to the Poisson's distribution, the average time interval between two consecutive packets follows exponential distribution and is given as follows

$$\bar{T}_{p,int} = \frac{(T_{DATA} + T_{ACK})}{C_{pp}} = \frac{T_{slot}}{\lambda_p}. \quad (6)$$

Let the average time length of one data packet transmission of the PU be $\bar{T}_{p,trans}$ given as

$$\bar{T}_{p,trans} = T_{DIFS} + B\bar{T}_p + T_{DATA} + T_{SIFS} + T_{ACK}, \quad (7)$$

where $B\bar{T}_p$ is the average BT of PU which is approximated by $CW_{min,p}/2$, where $CW_{min,p}$ is PU's CW_{min} . The time

$\bar{T}_{p,int} - \bar{T}_{p,trans}$ indicates the average length of time for which PU's channel is idle and denoted as $\bar{T}_{p,idle}$. The case $\bar{T}_{p,idle} < 0$ means that there is no space for SU since PU is saturated and $C_{pp} = C_u$.

The SU's minimum time length of one data packet transmission is given by $T_{s,min} = T_{DIFS} + T_{DATA} + T_{ACK} + T_{SIFS}$ where the SU's BT is zero. Then, N_s which is the SU's maximum average possible number of transmissions in $\bar{T}_{p,idle} > 0$ is given by

$$N_s = \frac{\bar{T}_{p,idle}}{T_{s,min}}. \quad (8)$$

In other words, if the average number of transmissions by SU per T_{slot}/λ_p is N_s , the channel is fully occupied in the time domain without degradation of C_p . The CW_{min} for achieving N_s corresponding to $CW_{min,s}^*$ where the suffix s indicates SU is given by

$$\frac{CW_{min,s}^*}{1} = \lfloor \frac{CW_{min,p}}{N_s} \rfloor. \quad (9)$$

where 1 indicates the average number of transmissions by PU and $\lfloor \cdot \rfloor$ is the floor function. This implies that the ratio of the number of transmissions is inversely proportional to the ratio of CW_{min} . The approximated SU's COR with CW_{min}^* is given by

$$C_s^* \simeq \frac{(T_{DATA} + T_{ACK}) \times N_s}{T_{slot}/\lambda_p} \quad (10)$$

such that C_u can be given as

$$C_u \simeq C_{pp} + C_s^*. \quad (11)$$

In fact, this C_s^* corresponds to the target COR C_t . In the proposed CW_{min} selection method, $CW_{min,s}^*$ can be obtained by substituting $\hat{C}_p(i)$ to C_{pp} in (6).

Base on the analysis, in the case of Fig. 3, we can obtain that $CW_{min}^* = 26$ and $C_u = 0.74$ which are consistent with the results in Fig. 3.

B. CW_{min} with margin

Let us take a margin C_m from C_s^* such that

$$C_{s,m}^* = C_s^* - C_m. \quad (12)$$

Then, by using (9) and (10), the selected CW_{min} which can achieve $C_{s,m}^*$ is denoted as $CW_{min,m}^*$ and can be derived as follows

$$CW_{min,m}^* = \lfloor \frac{CW_{min,p}}{N_s - C_m/C_p} \rfloor. \quad (13)$$

Note that $CW_{min,m}^*$ is greater than CW_{min}^* due to the margin and it is possible to enhance the protection performance for PUs. This fact will be confirmed in the following section.

VI. NUMERICAL EVALUATIONS

In this section, we show the performance of our proposed method by the simulation results, and compare it with the conventional method proposed in [10] in two cases; 1) static case where λ_p is time invariant and 2) dynamic case where λ_p is time variant. The estimation period is set as $T_{cor} = 560T_{slot}$ which is long enough to avoid significant COR estimation error.

A. Static case

In Fig. 4, COR performances of PU and SU as a function of λ_p in a static environment are shown. Upper bound of COR, C_u is also plotted in the figure. Three important things can be confirmed by the result. First, C_u is increased with decreasing C_{pp} . This fact means that setting target COR as C_s^* based on estimated C_p is reasonable approach. Second, the proposed method can outperform the conventional method in terms of C_s performance. In the conventional method, the SU sets C_t by using the worst case upper bound \hat{C}_u , i.e., the smallest value of C_u . In this case, $\hat{C}_u = 0.698$ at $\lambda_p = 0.03$. Third, the C_p performances in both the proposed and the conventional methods are equivalent but there is a slight difference between C_p and C_{pp} at $\lambda_p = 0.03$ where buffer of PU is saturated. For this problem, the CW_{min} selection method with margin is proposed and the performance will be shown in the next section.

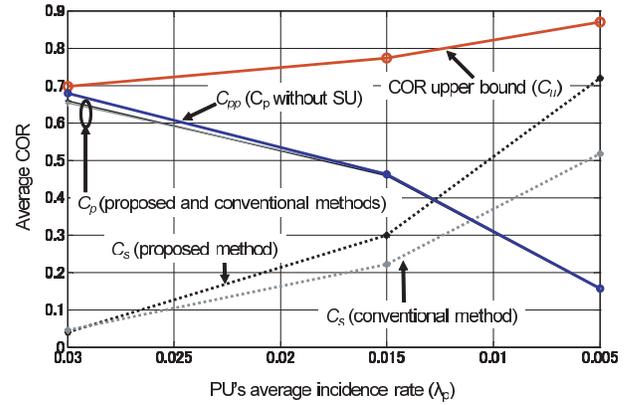


Fig. 4. A comparison of achieved COR performances between the proposed method without margin and the conventional method under static case.

B. Dynamic case

In Fig. 5, COR performances of PU and SU as a function of time are shown. The PU's average incidence rate λ_p changes from a higher value of 0.03 to a lower value of 0.0032 at time=0.4 sec.

From the result, it can be seen that there are two differences between the C_s performances of the proposed and the conventional methods. The first difference is the convergence speed of C_s ; the proposed method is faster than the conventional method. The conventional method updates its CW_{min} heuristically with an update ratio of 10%. On the other hand,

the proposed method selects CW_{min}^* which can achieve the C_s^* instantaneously. The second difference is the converged COR value of C_s of both the methods. Its reason is the same as the second thing explained for Fig. 5 in the section VI-A.

Furthermore, it can be seen that C_p is not guaranteed to its original value C_{pp} when time is less than 0.42. In the situation $\lambda_p = 0.03$, PU's buffer is saturated and SU in fact is not supposed to use the channel. However, due to the estimation error in \hat{C}_p SU may use the channel and it degrades the C_p slightly. That is why we introduced the CW_{min} selection with margin and the evaluation of this method is shown as follows. Fig. 6 shows COR performances of PU and SU for the same environment as considered in the above case of Fig. 5. In this result, a comparison between the proposed method with margin and the proposed method without margin is shown. In the region where time is less than 0.42, the C_p with margin is larger than C_p without margin. It indicates that the margin can enhance the protection of PU's performance in proposed method. On the other hand, in the region where time is greater than 0.55, C_s with margin is less than C_s without margin. This is the price for the protection of PU's performance.

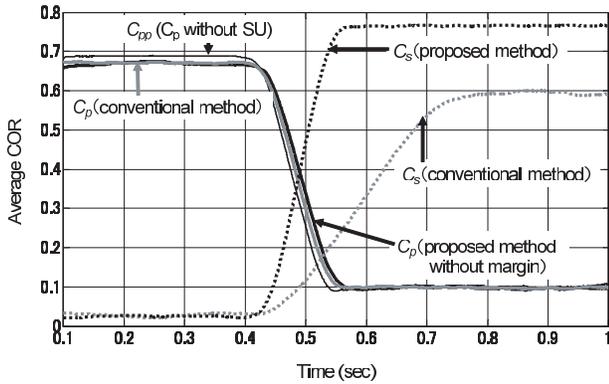


Fig. 5. A comparison of achieved COR performances between the proposed method without margin and the conventional method under dynamic case. In the region where time < 0.4 , $\lambda_p = 0.03$ and in the region where time ≥ 0.4 , $\lambda_p = 0.0032$.

VII. CONCLUSIONS

In this work, a time domain spectrum sharing based on COR information for cognitive radio network using CSMA/CA to co-exist with primary networks also using CSMA/CA such as wireless LAN was considered. The optimal CW_{min} CW_{min}^* was derived based on analysis and it was also shown that CW_{min}^* can achieve the COR upper bound where SU COR is maximized while guaranteeing the PU COR. Based on this analysis the CW_{min} selection method was proposed. The simulation results under the static case showed that the proposed method outperforms the conventional one in terms of C_s performance. In dynamic case, the simulations result showed that the convergence speed of the proposed method is faster than the conventional method. In addition, it was shown that the proposed method with margin can protect the saturated PUs with only small loss in SU's performance.

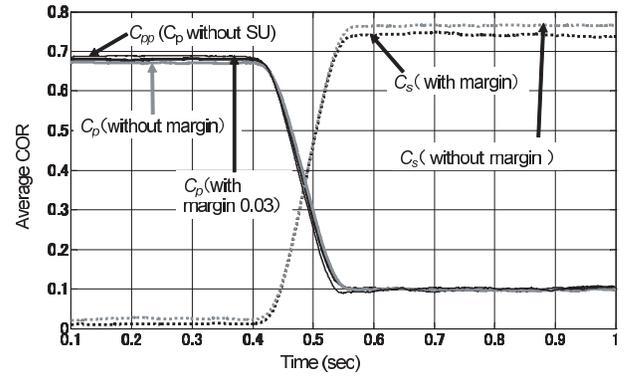


Fig. 6. A comparison of achieved COR performances between the proposed method without margin and the proposed method with margin under dynamic case. In the region where time < 0.4 , $\lambda_p = 0.03$ and in the region where time ≥ 0.4 , $\lambda_p = 0.0032$.

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