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Maximizing Communication Opportunity for Collaborative Spectrum Sensing in Cognitive Radio Networks

Tomohiro Nishida, Masahiro Sasabe, and Shoji Kasahara
Graduate School of Information Science, Nara Institute of Science and Technology,
8916-5 Takayama-cho, Ikoma, Nara 630-0192, Japan.
nishida.tomohiro.nl3@is.naist.jp, {m-sasabe, kasahara}@ieee.org

***Abstract*—In cognitive radio networks, secondary users (SUs) must accurately sense the spectrum of primary user (PU) to acquire their own communication opportunities without interfering PU's communication. Collaborative spectrum sensing (CSS) among SUs can improve the probability to detect PU's communication, compared to non-collaborative spectrum sensing, where each SU senses signal independently. In this paper, we propose a communication opportunity maximization scheme for CSS in multiple PUs cognitive radio networks. First, we define an objective function that represents SU's communication opportunity and a constraint on miss detection probability. In the proposed scheme, each SU forms a group with other SUs to meet the constraint and maximize its own communication opportunity according to the objective function and the constraint. Through simulation experiments with a two-PU scenario, we show that the proposed scheme can improve the ratio of winning SUs, that can use PU's channel, to the whole SUs, in comparison with the non-collaborative spectrum sensing. We also show that it can quickly increase the overall throughput of winning SUs up to the theoretical upper bound.**

***Index Terms*—Cognitive radio networks; collaborative spectrum sensing; communication opportunity; group formation**

I. INTRODUCTION

The demand for wireless communication systems has been significantly increasing due to the proliferation of smart phones and the advent of Internet of Things (IoT). In order to utilize the limited radio resources effectively, cognitive radio has been proposed as a technique to improve the utilization of the frequency band [1]. In a cognitive radio network, there exist two types of users: primary users (PUs) and secondary users (SUs). PUs utilize licensed spectrum channels, while SUs try to use the spectrum channels during unoccupied period. Each SU recognizes the usage status of the PU's spectrum by spectrum sensing, and attempts communication only when he/she judges that the spectrum is idle. Therefore, the accuracy of the SU's spectrum sensing is important to avoid interference in PU's communication.

The results of the spectrum sensing may include errors, due to propagation loss of the PU signal, fading and noise. Spectrum sensing errors are classified into two types: miss detection and false alarm. The miss detection is a sensing error that an SU recognizes the spectrum of the PU is idle even though it is actually used by the PU. Therefore, it is important for the PU to suppress the probability of miss detection. The false alarm is a sensing error that an SU judges the spectrum of the PU is busy even though it is actually unused by the PU. Thus, it is important for the SU to suppress the probability of false alarm, in order to acquire communication opportunities.

In [2], Ghasemi and Sousa have proposed collaborative spectrum sensing (CSS), where multiple SUs share the sensing results and derive a sensing result from them. They have also shown that CSS can reduce the probability of miss detection. Although CSS requires group formation for collaboration among SUs, centralized approaches to form groups among all SUs become impractical with the increase in the number of SUs, due to the exponential growth of computational overhead. To tackle this problem, Saad et al. have proposed a distributed group formation scheme using a game theoretic approach for single-PU cognitive radio networks [3]. However, there may be more than one PU in actual systems.

In this paper, we propose a communication opportunity maximization scheme based on group formation for CSS in multi-PU cognitive radio networks. The objective of SUs is to increase its own communication opportunities, but there also exists a constraint that the SUs should not interfere with the PUs' communication. We assume that the PUs impose an upper limit of the probability of miss detection on SUs. Each SU aims to meet the constraint on the probability of miss detection by performing single spectrum sensing or CSS with other SUs. SUs that meet the constraint select a PU such that they can maximize their own communication opportunities. We evaluate the effectiveness of the proposed scheme through several simulation experiments.

The rest of the paper is organized as follows: Section II presents related work. In Section III, we propose a communication opportunity maximization scheme and we show simulation results in Section IV. Finally, conclusions and future work are given in Section V.

II. RELATED WORK

CSS in cognitive radio networks is an effective method to reduce the probability of miss detection of PU's signal by exploiting spatial diversity [4]. There are several fusion rules, e.g., AND, OR, K-out-of-N and majority rules, to derive a cooperative decision from individual decisions of SUs in

CSS [4]. In [2], Ghasemi and Sousa have shown that an OR-based fusion method can suppress the probability of miss detection with the sacrifice of the probability of false alarm when the number of SUs increases. Zhang and Letaief have proposed CSS based on transmission diversity to suppress the channel errors, which are caused by fading, during information sharing about sensing results [5].

Since CSS requires collection of individual sensing results from SUs and distribution of the cooperative decision to SUs, the communication overhead will increase with the number of SUs. To tackle this problem, group formation of SUs for CSS is effective [3], [6]–[9]. Such group formation schemes are classified into a centralized approach and a decentralized approach. In the centralized approach, a server that manages SUs derives an optimal group formation by calculating all possible group patterns among all SUs. In [6], the server calculates all possible group patterns among all SUs and forms the group with the highest utility. In the succeeding process, the server continues the same approach until the group formation is completed. In [3], it has been reported that the exhaustive search of optimal group formation becomes intractable when the number of SUs is over eight.

In the distributed approach, each SU tries to form a group with neighboring SUs based on its own incentive for CSS. Saad et al. have proposed a distributed scheme to form groups among SUs based on the utility function that exhibits the trade-off between decrease of the miss detection probability and increase of the false alarm probability [3]. They have modeled the problem of group formation among SUs as a coalition formation (CF) game with a nontransferable utility (NTU) in game theory. A CF game is a type of cooperative games in which each player participating in the game forms a coalition with other players based on the utility of the coalition [10]. The utility of a coalition cannot be apportioned between the coalition's players in CF-game with NTU [10], [11]. In [7], Wang et al. have proposed a group formation scheme that considers the limited transmission power and bandwidth of SUs. The group formation among SUs is formulated as an overlapping CF (OCF) game in which it allows each SU to belong to multiple coalitions. Although these distributed group formation schemes are designed for single-PU cognitive radio networks, there may be more than one PU in actual systems.

Some group formation schemes in cognitive radio networks with multiple PUs have been studied [6], [8], [9]. Jing et al. have proposed a group formation scheme for cooperative spectrum prediction in multi-PU cognitive radio networks [6]. Each SU predicts the spectrum status of each PU, and selects a PU with the highest spectrum prediction accuracy. For each PU, a group is formed among all SUs selecting the corresponding PU in a centralized manner. In [8], a group formation scheme based on sensing accuracy and energy efficiency in multi-PU cognitive networks have been proposed. The groups are formed by using the utility function that takes into account both sensing accuracy and energy required to communication and sensing. Wang et al. have studied a distributed cooperative multi-channel spectrum sensing scheme for multi-PU cognitive radio networks. Each SU selects the channel with the highest Signal-to-Noise Ratio (SNR) of PU signals and forms a group with other SUs selecting the same channel. In this paper, we assume multi-PU cognitive radio networks as in [6], [8], [9], and propose a communication opportunity maximization scheme in which each SU forms a group to maximize its own communication opportunities.

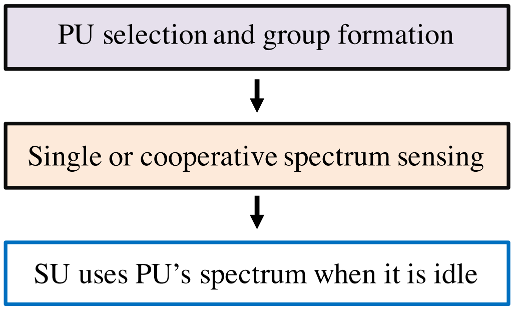

Fig. 1: The flow of cognitive radio networks.

III. PROPOSED SCHEME

In general, SU's miss detection probability and PU's utilization of its own spectrum are different among PUs, in case of cognitive radio networks with multiple PUs. Therefore, it is required for each SU to appropriately select a PU and form a group with other SUs such that it can maximize its own transmission rate without interfering with the corresponding PU's communication. Fig. 1 shows the flow of cognitive radio networks assumed in this paper. First, each SU selects a PU and forms a group, and then performs single or cooperative spectrum sensing. Each SU that could detect the idle state of PU's spectrum attempts to use it. This flow is repeated at a certain interval.

In what follows, we first present the system model. Next, we propose a communication opportunity maximization scheme based on group formation among SUs and PU selection.

A. *System Model*

We consider a cognitive radio network consisting of L PUs, labeled 1 to L, and N SUs, labeled 1 to N. Let $\mathcal{L} = \{1, \ldots, L\}$ and $\mathcal{N} = \{1, \ldots, N\}$ denote the set of all PUs and that of all SUs, respectively. Each SU recognizes the busy state of PU's spectrum when it detects the PU's signal. Each PU imposes the upper limit of miss detection probability, χ $(0 \leq \chi \leq 1)$, on SUs [12]. SUs that satisfy this requirement can obtain the communication opportunities. As in [13], we assume a Rayleigh fading environment where SU i's miss detection probability to PU l, $P_{i,l}^{\mathrm{miss}}$, and SU i's false alarm probability, P^{false}_i, are given by

$$P^{\text{miss}}_{i,l} = 1 - e^{-\frac{\lambda}{2}} \sum_{n=0}^{m-2} \frac{1}{n!} \left(\frac{\lambda}{2}\right)^n - \left(\frac{1+\bar{\gamma}_{i,l}}{\bar{\gamma}_{i,l}}\right)^{m-1} \cdot \left[e^{-\frac{\lambda}{2(1+\bar{\gamma}_{i,l})}} - e^{-\frac{\lambda}{2}} \sum_{n=0}^{m-2} \frac{1}{n!} \left(\frac{\lambda\bar{\gamma}_{i,l}}{2(1+\bar{\gamma}_{i,l})}\right)^n\right], \quad (1)$$

$$P^{\text{false}}_i = P^{\text{false}} = \frac{\Gamma(m, \frac{\lambda}{2})}{\Gamma(m)}, \quad (2)$$

where m is the time-bandwidth product and λ is the energy detection threshold. Moreover, $\overline{\gamma}_{i,l}$ represents the average SNR of received signal from PU l to SU i, which is given by $\overline{\gamma}_{i,l} = P_l h_{l,i}/\sigma^2$, where P_l is the transmit power of PU l, σ^2 is the Gaussian noise variance, and $h_{l,i}$ is the path loss between SU i and PU l. $h_{i,l}$ is given by $h_{l,i} = \kappa/d^{\mu}_{l,i}$, where κ is the path loss constant, μ is the path loss exponent, and $d^{\mu}_{l,i}$ is the distance between PU l and SU i. $\Gamma()$ is the gamma function and $\Gamma(,)$ is the incomplete gamma function.

When SU i's miss detection probability to PU l, $P^{\text{miss}}_{i,l}$, exceeds upper limit χ, SU i should form a group with other SUs and perform CSS to reduce the miss detection probability. Suppose that each group $\mathcal{S} \subseteq 2^{\mathcal{N}}$ elects an SU called *head* from all SUs of the group. The head collects individual sensing results from other SUs in the group, which are called *members*, and makes a group decision by combining the obtained results. We apply the OR-based fusion rule to the group decision, which is effective to reduce the miss detection probability.

As in [3], group S's miss detection probability to PU l, $Q^{\text{miss}}_{\mathcal{S},l}$, and group S's false alarm probability to PU l, $Q^{\text{false}}_{\mathcal{S}}$, are given by

$$Q^{\text{miss}}_{\mathcal{S},l} = \prod_{i \in \mathcal{S}} [P^{\text{miss}}_{i,l}(1 - P_{e,i,k}) + (1 - P^{\text{miss}}_{i,l})P_{e,i,k}], \quad (3)$$

$$Q^{\text{false}}_{\mathcal{S}} = 1 - \prod_{i \in \mathcal{S}} [(1 - P^{\text{false}})(1 - P_{e,i,k}) + P^{\text{false}} P_{e,i,k}], \quad (4)$$

where $P_{e,i,k}$ is the error probability on the reporting channel between member i and head k, which is given as the error probability of BPSK (Binary Phase Shift Keying) modulation in Rayleigh fading environments [14].

$$P_{e,i,k} = \frac{1}{2}\left(1 - \sqrt{\frac{\overline{\gamma}_{i,k}}{1 + \overline{\gamma}_{i,k}}}\right), \quad (5)$$

where $\overline{\gamma}_{i,k}$ represents the average SNR between member i and head k. As in [3], we select the most reliable SU, which has the minimum miss detection probability to the corresponding PU, as a head, in order to avoid the risk that the sensing result of that SU is wrongly reported during the information sharing.

To form a group, each SU i first requires to discover the candidates of SUs for the group formation. As in [7], we assume that the set of SU i's candidate SUs, $\mathcal{N}_i$, consists of SUs within SU i's transmission range $\tilde{d}$,

$$\tilde{d} = \sqrt[\mu]{\kappa P_{\text{SU}}/\gamma_0 \sigma^2},$$

where P_{SU} is SU's transmit power to report its sensing result to the corresponding head.

B. Communication Opportunity Based Group Formation and PU Selection

Recall that each SU can use the PU's spectrum only when it satisfies the PU's requirement for miss detection probability. As in [3], we call SUs that satisfy the PU's requirement *winning* and the remaining SUs *losing*. We also call an SU that does not require to form a group *single SU*.

In the proposed scheme, SU i first must meet the constraint on miss detection probability. Next, SU i meeting the constraint selects a PU such that it can maximize its own communication opportunities. These can be represented by the following objective function and constraint:

$$\max_{l \in \mathcal{L}_{\mathcal{S}_i,\chi}} \; (1 - R^{\text{use,PU}}_l)\,(1 - Q^{\text{false}}_{\mathcal{S}_i})\, r_{l,\mathcal{S}_i}, \quad (6)$$

$$\mathcal{L}_{\mathcal{S}_i,\chi} = \{l \in \mathcal{L} \mid Q^{\text{miss}}_{\mathcal{S}_i,l} \leq \chi\}, \quad (7)$$

where $\mathcal{L}_{\mathcal{S}_i,\chi}$ is the set of PUs to which SU i's group $\mathcal{S}_i$ can meet the constraint on miss detection probability. Moreover, $R^{\text{use,PU}}_l$ is the probability that PU l uses its own spectrum and $r_{l,\mathcal{S}_i}$ is the transmission rate of SU i in a winning group selecting PU l.

Fig. 2 shows the flowchart of SU i's PU selection and group formation. First, each SU $i \in \mathcal{N}$ forms a group by itself and discovers SUs in its transmission range $\tilde{d}$ as the set of neighboring SUs $\mathcal{N}_i$. Next, each SU i checks whether it meets the constraint on miss detection probability under single spectrum sensing (step (i) in Fig. 2). If SU i can become winning by meeting at least one of the constraints imposed by PUs, it selects a PU to maximize the expected value of its own communication rate, according to (6) (step (ii) in Fig. 2). Otherwise, it becomes losing and selects a PU with the minimum value of miss detection probability (step (iii) in Fig. 2).

Each losing SU i attempts to perform CSS with other losing SUs. First, each SU i searches for possible group candidates $\mathcal{W}_i$ for cooperation. Note that the group candidates must also be losing. If SU i finds appropriate groups with which it can become winning, it selects a PU and forms a group to maximize the expected value of its own communication rate according to (6) (step (iv) in Fig. 2). Otherwise, it still stays losing and forms a group with a losing group to minimize the miss detection probability (step (v) in Fig. 2). Note that this group formation is repeated until losing groups do not change. As the result, there is a possibility that some SUs remain losing depending on the positions of PUs and SUs.

IV. PERFORMANCE EVALUATION

In this section, we show the effectiveness of the proposed scheme through simulation experiments.

A. Simulation Settings

We use Netlogo [15] as the simulator. We show the simulation parameters in Table I. The values of

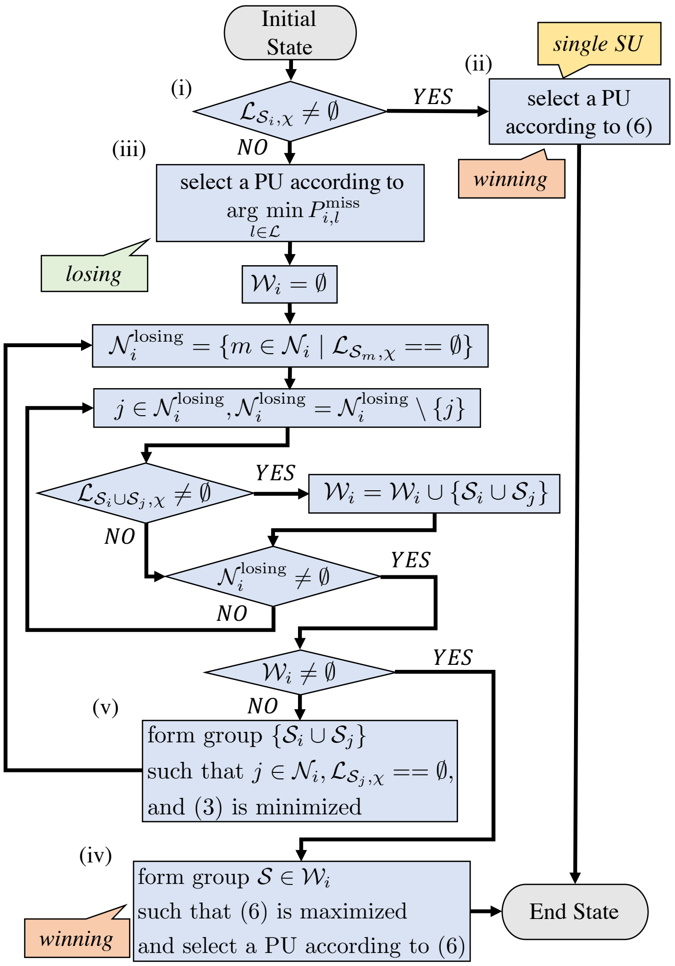

Fig. 2: SU i's PU selection and group formation.

TABLE I: Simulation parameters.

Parameter	Value
Simulation region	3 [km] × 3 [km] square area
The number of SUs, N	$2, 3, 4, 5, 6, 7, 10, 15, 20, 30, 40, 50$
Transmit power of SU, P_{SU}	10 [mW]
Transmit power of PU l, P_l	100 [mW]
Gaussian noise variance σ^2	-90 [dBm]
Path loss constant κ	1
Path loss exponent μ	3
Time-bandwidth product m	5
Energy detection threshold λ	21.51 [mW]
False alarm probability P^{false}	0.018 (1.8%)
Upper limit of miss detection probability, χ	0.05
The number of PU, L	2
Probability that PU 0 uses its own spectrum, $R_0^{\text{use,PU}}$	0.3
Probability that PU 1 uses its own spectrum, $R_1^{\text{use,PU}}$	0.5
Transmission range of SU, $\tilde{d}$	2,154 [m]

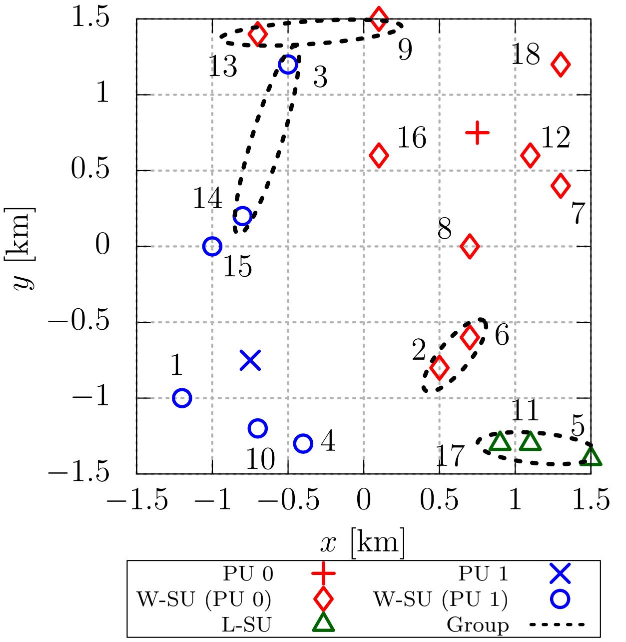

Fig. 3: An example of PU selection and group formation (W-SU (PU l) means winning SU selecting PU l and L-SU means losing SU).

$N, P_{SU}, P_l, \sigma^2, \kappa, \mu, m, \lambda$ and P^{false} are determined according to [3], and the value of $\tilde{d}$ is determined according to [7]. To evaluate the fundamental characteristics of the proposed scheme, we make the following assumptions: (1) $R_l^{\text{use,PU}}$ is constant and known among SUs, (2) all SUs recognize the number of winning SUs selecting PU l N_l, and (3) the transmission rate $r_{l,\mathcal{S}_i}$ of SU i in a winning group selecting PU l is given by $1/N_l$.

We use two evaluation criteria: the ratio of winning SUs and the total throughput. The ratio of winning SUs is the ratio of the number of winning SUs to that of all SUs. The total throughput represents the sum of values of objective functions among winning SUs that select the same PU. For comparison purpose, we use a *non-cooperative scheme*, which is the proposed scheme where each SU only performs single spectrum sensing.

B. Example of PU Selection and Group Formation

Fig. 3 shows an example of PU selection and group formation, which is obtained by the proposed scheme, in case of $N = 18$. We observe that each SU i near PU 0 or 1, i.e., $i = 1, 4, 7, 8, 10, 12, 15, 16, 18$, becomes a single SU because it can satisfy the constraint on miss detection probability under single spectrum sensing. In addition, we find that SUs located near the diagonal line from left top to right bottom tend to form groups with neighboring SUs, i.e., $\{2, 6\}, \{3, 14\}, \{5, 11, 17\}, \{9, 13\}$. This is because two PUs are arranged such that the square region is equally divided according to that diagonal line. We should also note here that $R_0^{\text{use,PU}}$ is smaller than $R_1^{\text{use,PU}}$ as in Table I. Thus, more SUs are likely to select PU 0 due to a large idle probability of PU 0's channel. Finally, we also observe that some SUs, i.e., $\{5, 11, 17\}$, remain losing even if they form groups. This

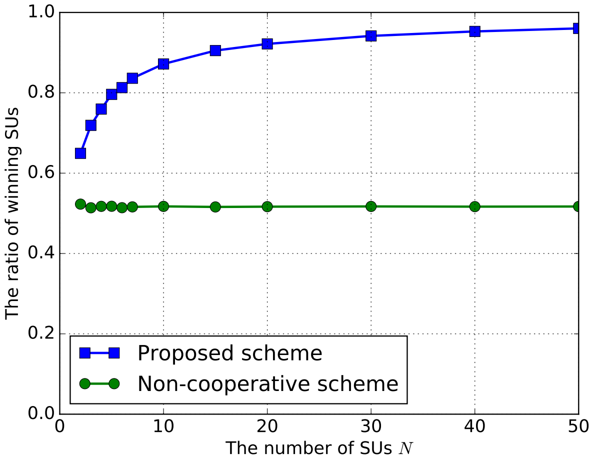

Fig. 4: Relationship between the number of SUs N and the ratio of winning SUs $(\chi = 0.05)$.

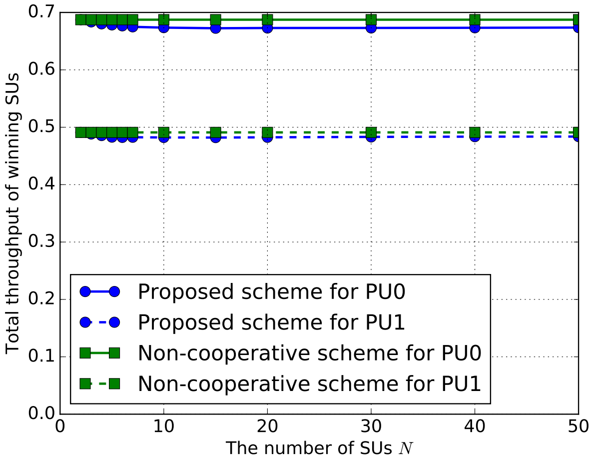

Fig. 5: Relationship between the number of SUs N and total throughput $(\chi = 0.05)$.

is because they cannot meet the constraint on miss detection probability.

The performance of the proposed scheme depends on the positions and the number of PUs and SUs. In what follows, we evaluate the fundamental characteristics of the proposed scheme by setting the number of PUs L to be two and the positions of PUs as in Fig. 3. We show the average of 5000 independent simulation runs for each evaluation criterion.

C. Ratio of winning SUs

Fig. 4 illustrates the relationship between the number of SUs N and the ratio of winning SUs when $\chi = 0.05$. We show the results of the proposed scheme and the non-cooperative scheme. First, the proposed scheme can significantly improve the ratio of the number of winning SUs to that of all the SUs compared to the non-cooperative scheme, regardless of the number of SUs. In particular, the degree of improvement increases with increase of the number of SUs, e.g., 45% improvement at $N = 50$. As a result, we can conclude that the proposed scheme is effective to give communication opportunities to losing SUs with single spectrum sensing by making appropriate groups among them. In addition, the effectiveness of the proposed scheme grows with increase of the number of SUs.

D. Total throughput

Fig. 5 illustrates the relationship between the number of SUs N and total throughput when $\chi = 0.05$. According to the parameter settings in Table I, SUs can theoretically use the spectrum of PU 0 with probability $1 - R_0^{\text{use,PU}}$, i.e., 0.7, and that of PU 1 with probability $1 - R_1^{\text{use,PU}}$, i.e., 0.5, respectively. In Fig. 5, The total throughput can be almost the same as the theoretical value in both schemes, regardless of PU selection. Comparing the results of both schemes, we also observe that the total throughput of the non-cooperative scheme does not change regardless of the number of SUs while that of the proposed scheme slightly decreases with increase of the number of SUs until $N = 15$, and then it converges. This is due to the false alarm probability given by (6). Since the non-cooperative scheme does not form groups, the false alarm probability is constant, i.e., 0.018. On the contrary, the average false alarm probability of the proposed scheme changes depending on the number of SUs, as shown in Fig. 6. We can confirm the similar tendency in Fig. 6, where the false alarm probability of the proposed scheme increases until $N = 15$, and then it almost converges.

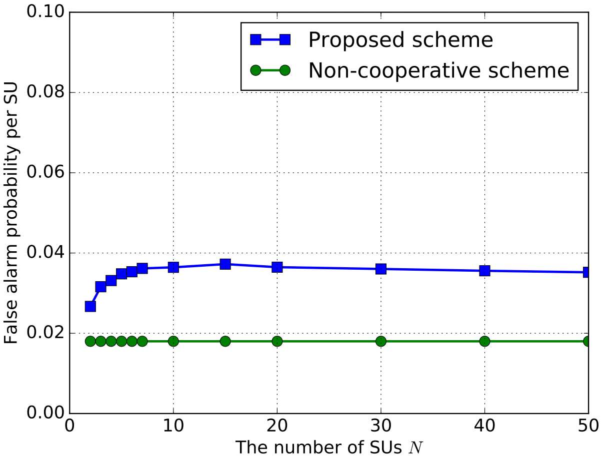

Fig. 6: Relationship between the number of SUs N and false alarm probability $(\chi = 0.05)$.

E. Convergence property

Fig. 7 illustrates the relationship between the number of iterations and total throughput when $N = 50$ and $\chi = 0.05$. At each iteration, each losing SU attempts to form a new group and select a PU once, according to the proposed scheme.

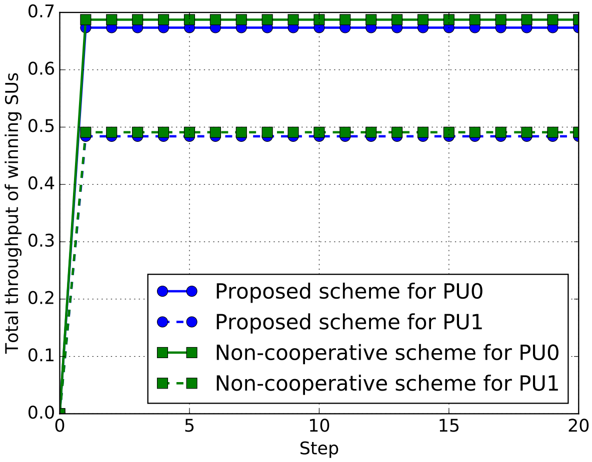

Fig. 7: Relationship between the number of iterations and total throughput $(N = 50, \chi = 0.05)$.

We observe that the total throughput steeply increases at the first iteration, and then it converges. Thus, the proposed scheme has fast convergence property. Since we assume in this paper that there is no environmental changes such as mobility of SUs and arrivals/departures of SUs, we plan to examine the effectiveness of the proposed scheme in such dynamic environments for future work.

V. CONCLUSION

In this paper, we proposed a communication opportunity maximization scheme for CSS in multi-PU cognitive radio networks. First, we defined the constraint on the upper limit of miss detection probability χ, which is imposed by PU, and the objective function to select a PU such that the SU maximizes its own communication opportunities. If an SU can meet the constraint with single spectrum sensing, it selects a PU to maximize its own objective function from the candidates. Otherwise, it forms a group with other SUs and selects a PU such that it can maximize its own objective function under the constraint.

Through several simulation experiments, we showed that the proposed scheme can improve the ratio of winning SUs, which can use PU's spectrum, compared to the proposed scheme without cooperation, i.e., non-cooperative scheme. In addition, we also showed that the proposed scheme can quickly achieve the total throughput competitive with the theoretical value. As a future work, we plan to examine the effectiveness of the proposed scheme against environmental dynamics, e.g., mobility of SUs and arrivals/departures of SUs.

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REFERENCES

[1] S. Haykin, "Cognitive Radio: Brain-Empowered Wireless Communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201–220, 2005.

[2] A. Ghasemi and E. S. Sousa, "Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments," in *Proc. of 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, 2005, pp. 131–136.

[3] W. Saad, Z. Han, T. Baar, M. Debbah, and A. Hjørungnes, "Coalition Formation Games for Collaborative Spectrum Sensing," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 1, pp. 276–297, 2011.

[4] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative Spectrum Sensing in Cognitive Radio Networks: A Survey," *Physical Communication*, vol. 4, no. 1, pp. 40–62, 2011.

[5] W. Zhang and K. Letaief, "Cooperative Spectrum Sensing with Transmit and Relay Diversity in Cognitive Radio Networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 12, pp. 4761–4766, 2008.

[6] T. Jing, X. Xing, W. Cheng, Y. Huo, and T. Znati, "Cooperative Spectrum Prediction in Multi-PU Multi-SU Cognitive Radio Networks," in *Proc. of 8th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, 2013, pp. 25–30.

[7] T. Wang, L. Song, Z. Han, and W. Saad, "Distributed Cooperative Sensing in Cognitive Radio Networks: An Overlapping Coalition Formation Approach," *IEEE Transactions on Communications*, vol. 62, no. 9, pp. 3144–3160, 2014.

[8] H. Xiaolei, C. Man Hon, V. W. S. Wong, and V. C. M. Leung, "A Coalition Formation Game for Energy-Efficient Cooperative Spectrum Sensing in Cognitive Radio Networks with Multiple Channels," in *Proc. of IEEE GLOBECOM 2011*, 2011, pp. 1–6.

[9] W. Wang, B. Kasiri, J. Cai, and A. S. Alfa, "Distributed Cooperative Multi-Channel Spectrum Sensing Based on Dynamic Coalitional Game," in *Proc. of IEEE GLOBECOM 2010*, 2010, pp. 1–5.

[10] R. B. Myerson, *Game Theory, Analysis of Conflict*. Cambridge: Harvard University Press, 1991.

[11] D. Ray, *A Game-Theoretic Perspective on Coalition Formation*. New York: Oxford University Press, 2007.

[12] E. Hossain, D. Niyato, and Z. Han, *Dynamic Spectrum Access and Management in Cognitive Radio Networks*. Cambridge University Press, 2009.

[13] F. F. Digham, M. S. Alouini, and M. K. Simon, "On the Energy Detection of Unknown Signals over Fading Channels," *IEEE Transactions on Communications*, vol. 55, no. 1, pp. 21–24, 2007.

[14] J. G. Proakis and M. Salehi, *Digital Communications 5th ed.* New York: McGraw-Hill, 2007.

[15] S. Tisue and U. Wilensky, "NetLogo: Design and Implementation of a Multi-Agent Modeling Environment," in *Proc. of Agent*, 2004, pp. 7–9.