Coalition Formation and Spectrum Sharing of Cooperative Spectrum Sensing Participants

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***Abstract*—In cognitive radio networks, self-interested secondary users (SUs) desire to maximize their own throughput. They compete with each other for transmit time once the absence of primary users (PUs) is detected. To satisfy the requirement of PU protection, on the other hand, they have to form some coalitions and cooperate to conduct spectrum sensing. Such dilemma of SUs between competition and cooperation motivates us to study two interesting issues: 1) how to appropriately form some coalitions for cooperative spectrum sensing (CSS) and 2) how to share transmit time among SUs. We jointly consider these two issues, and propose a noncooperative game model with 2-D strategies. The first dimension determines coalition formation, and the second indicates transmit time allocation. Considering the complexity of solving this game, we decompose the game into two more tractable ones: one deals with the formation of CSS coalitions, and the other focuses on the allocation of transmit time. We characterize the Nash equilibria (NEs) of both games, and show that the combination of these two NEs corresponds to the NE of the original game. We also develop a distributed algorithm to achieve a desirable NE of the original game. When this NE is achieved, the SUs obtain a D_{hp}-stable coalition structure and a fair transmit time allocation. Numerical results verify our analyses, and demonstrate the effectiveness of our algorithm.**

***Index Terms*—Coalition formation, cognitive radio, game theory, spectrum sensing.**

I. INTRODUCTION

THE COGNITIVE radio (CR) technique remarkably improves spectrum utilization by allowing secondary users (SUs) to temporarily access the licensed channel owned by primary users (PUs) [1]–[6]. In a CR network (CRN), SUs conduct spectrum sensing [7]–[9] to identify transmission opportunities. Only when the licensed channel is detected to be idle can SUs transmit their data. Since spectrum sensing is imperfect, missed detection and false alarm may take place in practice.

When missed detection occurs, the communication of PUs will be interfered. To protect PUs, SUs are required to keep their detection probabilities above a threshold (e.g., 0.9). In fading environment, however, an individual SU usually cannot meet this requirement alone. To address this problem, multiple SUs can form a coalition (or group), and collaborate to conduct spectrum sensing, which is termed cooperative spectrum sensing (CSS) [10]–[21]. In this way, they can increase their detection probability above the threshold.[1]

In general, an increase in detection probability is accompanied by a raise in false alarm probability, which diminishes some potential transmission opportunities of SUs. Hence, a CSS coalition often keeps its false alarm probability below a threshold (e.g., 0.1). Under the most common fusion rule OR, more CSS participants generate a higher false alarm probability. Therefore, the maximum size of a CSS coalition is actually limited in practice. When many SUs participate in CSS, they usually form multiple coalitions to independently sense the spectrum, and then share the channel for transmission.

In practice, SUs may belong to different authorities and act selfishly [14]–[17]. To maximize their own throughput, they compete with each other for transmission opportunities. Their competition in transmitting imposes an inevitable impact on their collaboration in sensing. And this arises two interesting questions.

1) How to appropriately form multiple coalitions to conduct CSS?
2) How to efficiently and fairly share the transmission opportunities among SUs?

Notice that the amount of transmission opportunities depends on sensing performance, and the latter is determined by CSS coalition formation outcome. On the other hand, to decide which coalition to join, an SU needs to figure out its transmission opportunities when joining every candidate coalition. Hence, the two questions above are interdependent and should be jointly studied.

To shed some insights on this complicated design problem, we consider an infrastructure-based CRN with multiple self-interested SUs. Considering concurrent transmissions severely limit the overall network performance [22], [23], we assume that the licensed channel is shared among the SUs in a time-division fashion. We aim to answer the following questions.

1) How many coalitions should be formed, and which coalition should an SU join?

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[1]When conducting CSS, all participants share the same sensing results, and hence, have the identical detection probability and false alarm probability. Please refer to (6) and (7) for details.

2) How long should an SU occupy the licensed channel for transmission in various situations?

To study the interactions among the SUs, we formulate the considered problem as a noncooperative game [24]–[35] with 2-D strategies[2]: 1) 1-D indicates the decision on coalition formation and 2) the other quantifies transmit time allocation. The Nash equilibrium (NE) of this game corresponds to a stable decision outcome, which no individual SU has an incentive to deviate from. Hence, NE is considered as the desired solution to our problem.

However, the proposed game is hard to analyze due to its complicated strategies. To overcome this challenge, we decompose this game into two more tractable ones: 1) transmit time allocation game (TAG) and 2) coalition formation game (CFG). We show that the combination of the NEs of TAG and CFG solves the original game. We also develop a distributed algorithm to achieve the NEs of TAG, CFG, and the original game.

Our main contributions are summarized as follows.

1) *Problem:* This paper jointly studies the formation of CSS coalitions and the allocation of transmit time for self-interested SUs, which have not been thoroughly investigated in existing literature.
2) *Scenario:* This paper considers a practical scenario where various coalition patterns emerge.[3] Up to now, the transmission opportunity allocation of SUs in this complicated situation has not been thoroughly studied in existing literature.
3) *Solution:* Most existing game theoretical approaches on CSS aim to find an NE, i.e., a stable decision outcome. In this paper, we take both stability and fairness into account when studying transmit time allocation of SUs. More specifically, we select the fair NE using Shapley value[4] and Nash bargaining.[5]
4) *Method:* We propose a game decomposition framework to solve our game. This decomposition framework illustrates some insights for analyzing the complicated game with multidimensional strategies. In addition, we develop an algorithm with good scalability and low complexity to achieve the desired decision outcome of SUs.

The rest of this paper is organized as follows. Section II discusses the related work. The system model and problem formulation are introduced in Section III, and the game model is presented in Section IV. In Sections V and VI, we analyze the derivative games and obtain their NEs. We also develop a merge-and-split-based algorithm (MSBA) in Section VII. Computer simulation results are provided in Section VIII, followed by the concluding remarks in Section IX.

II. Related Work

Existing literature on CSS coalition formation can be divided into two categories: 1) single coalition and 2) multiple coalitions.

A. Single CSS Coalition

Sun *et al.* [14] studied how to determine the probability of attending CSS for selfish SUs. They considered one single CSS coalition, and assumed that only one SU was chosen for transmit every time the absence of PUs was detected. Their utility function represented the average throughput of an SU.

Wang *et al.* [15] investigated the choices of SUs between performing CSS and overhearing. They considered one single CSS coalition, and defined the utility function as the throughput of an SU.

Yuan *et al.* [16] focused on a unique CSS coalition, and studied the choice of SUs between CSS and independent spectrum sensing. In their model, the utility function included three terms: 1) throughput; 2) delay; and 3) energy consumption. Yuan *et al.* [16] assumed that the total data rate of the licensed channel was equally shared among SUs via time division multiple access or other protocols.

B. Multiple CSS Coalitions

Mukherjee [17] studied the formation of multiple CSS coalitions. In his model, the strategies of an SU were: 1) conducting CSS and 2) conducting local spectrum sensing (LSS). The objective of an SU was to minimize its false alarm probability.

To study the formation of multiple CSS coalitions, Saad *et al.* [18] proposed two game models. In the first model, the utility function was set to a function decreasing with the false alarm probability. In the second model, the utility function was set to 1 when the constraints on false alarm and missed detection are satisfied, and 0 otherwise.

Wang *et al.* [19] investigated the formation of multiple CSS coalitions under the assumption that an SU could participate in multiple CSS coalitions simultaneously. In this paper, the authors introduced two criteria (i.e., Q_m+Q_f and Q_m/Q_f), and set their objective functions accordingly.

Saad *et al.* [20], assumed that SUs conducted spectrum sensing independently, and formed coalitions to share the channel knowledge. They also assumed that different SUs could transmit over the same channel simultaneously. They studied the formation of channel knowledge sharing coalitions, and also investigated how to appropriately select the transmit power for SUs to mitigate the interference among the SUs operating on the same channel.

[2]Here the term “2-D strategies” means two heterogeneous strategies.

[3]Please refer to Section III-A for more details.

[4]The Shapley value is a game-theoretic solution concept of great importance due to its “fairness” properties. It is usually used in cooperative game theory and its applications. As a fairness criterion, however, Shapley value can also be used in noncooperative games. In fact, the concept of Shapley value has been used in some existing literature on noncooperative game theory such as [36]. In this paper, we introduce Shapley value to identify the NE with a good fairness property.

[5]Nash bargaining falls in the category of cooperative game theory. The Nash bargaining problem is formulated as a constrained optimization model, and its solution possess some appealing properties including fairness and efficiency. In this paper, we aim to assign transmit time to CSS coalitions in a fair and efficient fashion. Hence, we introduce the optimization model used in Nash bargaining, and derive a fair and efficient allocation for SUs. In addition, we show that the derived allocation corresponds to an fair NE of our noncooperative game. Please refer to Section V-B for details.

TABLE I
DIFFERENCE BETWEEN THIS PAPER AND EXISTING LITERATURE

Paper	Coalition	Spectrum Sensing	Spectrum Sharing	Throughput-oriented	Fair Allocation
Ours	Multiple	Cooperative	Time Division	Yes	Yes
[14]	Single	Cooperative	Exclusive Use	Yes	-
[15]	Single	Cooperative	Exclusive Use	Yes	-
[16]	Single	Cooperative	Equally shared	Yes	-
[17]	Multiple	Cooperative	-	-	-
[18]	Multiple	Cooperative	-	-	-
[19]	Multiple	Cooperative	-	-	-
[20]	Multiple	Independent	Concurrent Transmit	Yes	-

C. Difference Between This Paper and Existing Literature

This paper differs from the existing literature in several aspects.

1) This paper jointly studies the formation of multiple cooperative spectrum sensing coalitions and the transmit time allocation among SUs. References [14]–[16] only consider a single CSS coalition, and [17]–[19] only study the formation of multiple CSS coalitions.
2) Saad *et al.* [20] assumes that SUs conduct spectrum sensing independently, and jointly studies the formation of multiple channel knowledge sharing coalitions and the transmit power allocation among SUs. This paper differs from [20] in both spectrum sensing and spectrum sharing.

The differences between this paper and the existing literature are summarized in Table I.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Description

Consider a time-slotted CRN with L heterogenous SUs, a secondary base station (BS) [37][6] and a licensed channel. The SUs are under different authorities and act selfishly. The licensed channel is occasionally occupied by its PUs. Only when the channel is detected to be idle, the SUs are allowed to transmit.

To improve sensing performance, the SUs form some coalitions to conduct CSS. For each coalition, CSS is conducted as follows.

1) Every member (i.e., SU) performs spectrum sensing locally, and makes a binary decision to indicate whether the licensed channel is idle or not.
2) All members report their decisions to a fusion center (FC) through a common control channel (i.e., reporting channel).[7]
3) The FC combines the decisions and makes a final (global) decision according to a fusion rule.

[6]A CRN may or may not contain a secondary BS. As the first worldwide standard based on the CR technology, for example, IEEE 802.22 introduces the secondary BS to manage its cell. In general, the secondary BS provides single hop connection to SUs. Through this connection, an SU can access other networks such as Internet.

[7]In CSS, the common control channel can be implemented as a dedicated channel in licensed or unlicensed bands [3].

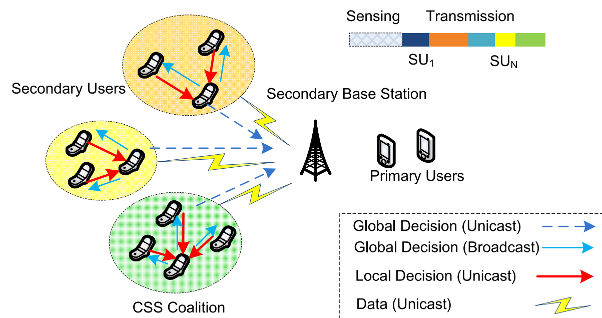

Fig. 1. CRN system model.

4) The FC broadcasts the final decisions to the corresponding members.

The fusion rules of “OR” and “AND” are commonly used in existing literature on CSS. With the OR rule, the FC declares the licensed channel is busy if any SU detects the presence of PUs. Accordingly, both detection probability and false alarm probability rise, as compared to the case of independent spectrum sensing. With the AND rule, on the other hand, the FC declares the licensed channel is busy only when all SUs detect the presence of PUs. When AND is adopted, both detection probability and false alarm probability decrease.

It is noted that the system with OR or AND is vulnerable to the spectrum sensing data falsification or Byzantine attacks [38]. For example, if OR is adopted and some malicious SU always declares the presence of PUs (i.e., ALWAYS YES attacker), the false alarm probability will be high or even 1. To address this problem, some trust factor-based method can be deployed to identify the attackers [39]. This issue exceeds the scope of this paper, and hence is omitted here. Considering that PU protection is mandatory and critical for SUs, we select OR as the fusion rule, as in many existing literature such as [15], [16], and [18].

In our secondary system, either the secondary BS or a coalition member can act as the FC. In this paper, we assume that every coalition selects one coalition member as its FC [18], as shown in Fig. 1.[8] Note that our proposed method can be

[8]Some existing cluster-head election algorithms can be employed to appropriately elect a coalition member as the FC. We refer the readers to [40] and [41] for details. In addition, a good method for electing an FC in a coalition is provided in [19].

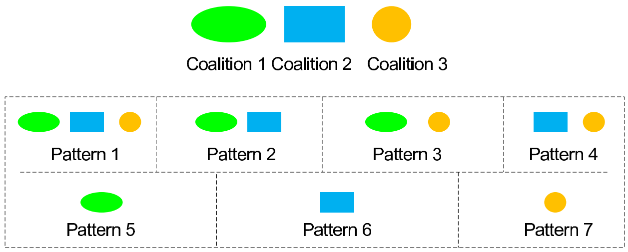

Fig. 2. Coalition patterns.

easily extended for the case where the secondary BS is chosen as the FC by all coalitions.

To capture the transient transmission opportunities, the time is divided into an infinite number of time slots with length $T > 0$. Every time slot consists of two phases: 1) sensing phase with length τ and 2) transmission phase with length $T - \tau$ $(0 < \tau < T)$. The secondary system works as follows.

1) *Initial Stage:*
   a) before the system runs, the SUs appropriately form multiple CSS coalitions and associate themselves with the secondary BS.
2) *Running Stage:*
   a) in every sensing phase, the coalitions independently conduct CSS;
   b) the FC of every coalition delivers its final decision to the secondary BS through the common control channel;
   c) in every transmission phase, the secondary BS schedules the SUs in the coalitions declaring the absence of PUs to transmit their packets to itself in a time-division fashion.

In our secondary system, the transmission phase is partitioned into multiple mini-slots, each of which is exclusively assigned to one SU for transmission. For illustration, consider three CSS coalitions shown in Fig. 2. Suppose only coalitions 1 and 2 declare the channel is idle in a certain time slot (this case is denoted by "Pattern 2" in Fig. 2). In this situation, all the SUs in these two coalitions compete for transmit time. Accordingly, each of them is assigned one mini-slot for transmission. As for the members in coalition 3, they think the channel is busy and hence will not transmit. Therefore, the length of their mini-slots is set to zero. We will discuss this issue in detail in Section III-C.

B. Constraints

In this paper, we consider two kinds of constraints: 1) system constraint and 2) individual constraint.

1) System Constraint: A secondary system is allowed to work only if the detection probability of every coalition is above a threshold θ. Let $\mathcal{C}_j$ represent the jth CSS coalition. Let P_d^j and P_f^j denote the detection and false alarm probability of $\mathcal{C}_j$, respectively. The secondary system needs to satisfy the following constraints:

$$\forall j, P_d^j \geq \theta. \tag{1}$$

As will be shown in (6), (7), and (13), the satisfaction of the constraints $P_d^j \geq \theta$ actually depends on the choices of all SUs. If $\exists j, P_d^j < \theta$, the secondary BS will be forbidden from working. As a result, all the coalitions associated with the secondary BS cannot transmit at all. Therefore, the set of constraints $P_d^j \geq \theta$ is imposed on every SU.

2) Individual Constraint: To reduce the unemployed transmission opportunities yielded by false alarms, every coalition attempts to keep its false alarm probability below a threshold γ, that is

$$P_f^j \leq \gamma. \tag{2}$$

Constraint (2) reflects the desire of an individual SU to obtain more transmission opportunities. Therefore, it is imposed on a single SU (instead of all SUs).

Considering the system and individual constraints, we require every CSS coalition satisfy constraints (1) and (2). In some cases, an SU, who cannot satisfy the constraints alone, may be excluded by all coalitions. Accordingly, the SU will be ruled out by the secondary system. In this paper, such SU is termed zombie SU.[9]

C. Throughput

In this section, we derive the expression of the average (or expected) throughput of a non-zombie SU. With no particular emphasis, we use SUs to represent non-zombie SUs in the sequel.

Faced with the same channel, the coalitions may generate different detection results. The coalition who declares the absence of the PUs is termed active coalition, since it will transmit in the following transmission phase. The other coalitions, who detect the presence of the PUs, are inactive. When the coalitions repeatedly conduct CSS, various coalition patterns may emerge. Consider the example in Fig. 2, where SUs form three coalitions and generate seven coalition patterns.[10] For instance, under coalition pattern 1, all the coalitions are active, and their members can transmit in the transmission phase. Under coalition pattern 2, coalitions 1 and 2 are active. Accordingly, only the SUs in coalitions 1 and 2 will transmit. In this paper, we consider the general scenario with Q coalitions and $\Delta = 2^Q - 1$ coalition patterns. Accordingly, the throughput of an SU should be averaged over all coalition patterns.

In general, an SU can transmit under two cases [11], [12]: 1) the absence of PUs is detected and 2) the presence of PUs is not detected. Let r_i^1 and r_i^2 $(r_i^1 > r_i^2)$ be the throughput of SU_i in cases 1 and 2, respectively. We use t_i^q to denote the mini-slot length of SU_i under the qth coalition pattern. Then, the average throughput of SU_i can be calculated as

$$\bar{r}_i = \frac{1}{T}\sum_{q=1}^{\Delta} \Lambda_i^q \left(\Theta_q^1 r_i^1 + \Theta_q^2 r_i^2\right) t_i^q \tag{3}$$

where $\Lambda_i^q = 1$ if SU_i is in a certain active coalition under the qth coalition pattern, and $\Lambda_i^q = 0$ otherwise.

[9] In Section VII, our proposed algorithm can identify the zombie SUs.

[10] We ignore the case where no coalition declares the absence of PUs since no SUs transmit in this case.

In (3), Θ_q^1 (Θ_q^2) is the probability that the qth coalition pattern emerges and the PUs are absent (present). Let $\mathcal{CP}_q$ be the set of the active coalitions under the qth coalition pattern. We have

$$\Theta_q^1 = P_{H_0} \prod_{\mathcal{C}_j \in \mathcal{CP}_q} \left(1 - P_f^j\right) \prod_{\mathcal{C}_v \notin \mathcal{CP}_q} P_f^v \tag{4}$$

and

$$\Theta_q^2 = \left(1 - P_{H_0}\right) \prod_{\mathcal{C}_j \in \mathcal{CP}_q} \left(1 - P_d^j\right) \prod_{\mathcal{C}_v \notin \mathcal{CP}_q} P_d^v \tag{5}$$

where P_{H_0} represents the probability that the licensed channel is not occupied by the PUs.

Suppose SU_i is included in $\mathcal{C}_j$, i.e., $\text{SU}_i \in \mathcal{C}_j$. Clearly, $\bar{r}_i$ increases with the increment of t_i^q and decreases with the increment of P_d^j and P_f^j.

D. Detection and False Alarm Probabilities

Let $\mathcal{N}$ denote the set of non-zombie SUs and $N = |\mathcal{N}|$ ($N \leq L$) represent the number of non-zombie SUs. We use an N-dimensional vector $\vec{s}_i = (s_i^1, \ldots, s_i^j, \ldots, s_i^N)$ to represent the coalition that SU_i joins. Here, $s_i^j = 1$ if SU_i joins $\mathcal{C}_j$, and $s_i^j = 0$ otherwise. The maximum number of coalitions is N. When the maximum number is reached, every coalition contains only one non-zombie SU.

With $\vec{s}_i$, the number of coalitions can be calculated as $Q = \sum_{j=1}^{N} \min\{1, \sum_{i=1}^{N} \vec{s}_i \vec{e}_j^T\}$, where $\vec{e}_j$ represents the unit row vector with 1 at the jth position, and 0 otherwise. We denote by p_d^k and p_f^k the detection probability and false alarm probability of SU_k when conducting local spectrum sensing, respectively. Next, we will derive the detection probability and false alarm probability of a CSS coalition.

Consider an SU SU_k and a CSS coalition $\mathcal{C}_j$. If $\vec{s}_k \vec{e}_j^T = 1$, SU_k joins $\mathcal{C}_j$. If $\vec{s}_k \vec{e}_j^T = 0$, SU_k does not select $\mathcal{C}_j$. Hence, the detection probability and false alarm probability of $\mathcal{C}_j$ are calculated as

$$P_d^j = 1 - \prod_{k=1}^{N} \left(1 - \vec{s}_k \vec{e}_j^T p_d^k\right) \tag{6}$$

and

$$P_f^j = 1 - \prod_{k=1}^{N} \left(1 - \vec{s}_k \vec{e}_j^T p_f^k\right) \tag{7}$$

respectively.

Similarly, the detection probability and false alarm probability of SU_i when conducting CSS are given by

$$\tilde{p}_d^i = 1 - \prod_{k=1}^{N} \left(1 - \vec{s}_i \vec{s}_k^T p_d^k\right) \tag{8}$$

and

$$\tilde{p}_f^i = 1 - \prod_{k=1}^{N} \left(1 - \vec{s}_i \vec{s}_k^T p_f^k\right) \tag{9}$$

respectively. In (8) and (9), $\vec{s}_i \vec{s}_k^T = 1$ indicates that SU_i and SU_k join the same coalition.

E. Design Objective

Under the system and individual constraints, every SU optimally determines its coalition selection and transmit time allocation to maximize its average throughput. We use $\vec{t}_i = (t_i^1, \ldots, t_i^\Delta)$ to denote the transmit time allocation of SU_i. Then, every SU, say SU_i, aims to solve the following problem:

$$\max_{\vec{s}_i, \vec{t}_i} \bar{r}_i = \frac{1}{T} \sum_{q=1}^{2^Q - 1} \Lambda_i^q \left(\Theta_q^1 r_i^1 + \Theta_q^2 r_i^2\right) t_i^q \tag{10}$$

$$\text{s.t.} \quad \sum_{j=1}^{N} s_i^j = 1 \tag{11}$$

$$\forall q \in \left[1, 2^Q - 1\right], \sum_{k=1}^{N} \Lambda_i^q t_k^q \leq T - \tau \tag{12}$$

$$\forall i \in [1, N], 1 - \prod_{k=1}^{N} \left(1 - \vec{s}_i \vec{s}_k^T p_d^k\right) \geq \theta \tag{13}$$

$$1 - \prod_{k=1}^{N} \left(1 - \vec{s}_i \vec{s}_k^T p_f^k\right) \leq \gamma. \tag{14}$$

In the above formulation, constraint (11) stipulates that an SU belongs to one unique coalition. Constraint (12) states that under every coalition pattern, transmit time is shared among all the members of active coalitions.

IV. Game Model and its Decomposition

It can be seen from (10)–(14) that the decisions of all the SUs (i.e., $\vec{s}_i$ and $\vec{t}_i$) are interdependent. Hence, the interactive decision-making procedure of the SUs can be formulated as a noncooperative game: coalition formation and transmit time allocation game (CF − TA). In this game, the SUs act as the players, $\bar{r}_i$ is used as the utility (payoff) function, and the strategy of the ith player is denoted by $(\vec{s}_i, \vec{t}_i)$.

NE is the most widely used "solution concept" in noncooperative game theory [24], [35]. When an NE is achieved, no player has an incentive to unilaterally change its strategy. Therefore, the NE of CF − TA corresponds to a stable decision outcome of SUs. In this paper, we consider NE as the solution to our problem. It should be pointed out that we do not attempt to obtain the global optimal solution to our problem, since the SUs may resist and deviate from this optimal solution due to individual rationality.

Different from most existing game models, CF − TA adopts 2-D strategies (i.e., binary strategy $\vec{s}_i$ and continuous strategy $\vec{t}_i$), which makes it hard to analyze. To overcome this challenge, we decompose the game into two derivational noncooperative ones.

1) *CFG:* The SUs act as the players, $\vec{s}_i$ is the strategy, and $\bar{r}_i$ is the utility function. CFG only deals with coalition formation.
2) *TAG:* The SUs are the players, $\vec{t}_i$ is the strategy, and $\bar{r}_i$ is the utility function. TAG only considers transmit time allocation under a given coalition structure.

Here, the coalition structure is defined as follows.

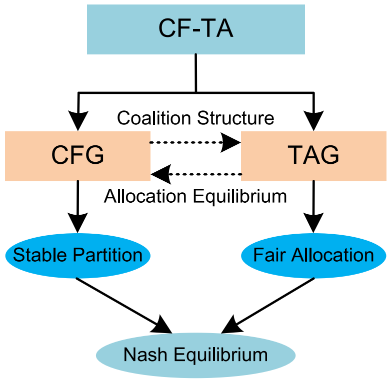

Fig. 3. Game decomposition.

Definition 1: A coalition structure over $\mathcal{N}$ is a collection of nonempty subsets $\mathcal{CS} = \{\mathcal{C}_1, \mathcal{C}_2, \ldots, \mathcal{C}_k\}$ $(1 \le k \le N)$ such that 1) $\bigcup_{j=1}^{k} \mathcal{C}_j = \mathcal{N}$ and 2) $\mathcal{C}_i \bigcap \mathcal{C}_j = \varnothing$ for any $i \ne j$.

In our model, the coalition structure can be characterized by the SUs' strategies $\{\vec{s}_i\}$. The decomposition framework is shown in Fig. 3. The interconnection between CFG and TAG is described as follows.

1) In TAG, the transmit time allocation depends on the considered coalition structure. To solve TAG, one first gets a coalition structure from CFG.
2) In CFG, the utility of every SU depends on its transmit time length. When calculating the utility, one treats the NE of TAG under the considered coalition structure as the transmit time allocation.

The motivations of introducing this decomposition framework include the following.

1) The derivational games, i.e., TAG and CFG, adopt 1-D strategy, and hence are easy to solve.
2) The combination of the NEs in TAG and CFG solves the game $\mathrm{CF-TA}$, if the above interconnection is established. We will discuss it in Section VII.

With the decomposition, we can obtain the NE of $\mathrm{CF-TA}$ as follows.

1) Given the coalition structure, solve TAG and find an NE.
2) With the NE of TAG, calculate the utilities of the SUs.
3) If the current coalition structure corresponds to an NE of CFG, then terminate. Otherwise, update the current coalition structure and go back to step 1).

The rest of the problem include: 1) how to solve TAG in step 1) and 2) how to update the current coalition structure in step 3). We will discuss these issues in the following two sections.

V. Transmit Time Allocation Game

TAG deals with how to allocate transmit time to the SUs under a given coalition structure.

Theorem 1: The transmit time allocation $(\vec{t}_1, \vec{t}_2, \ldots, \vec{t}_N)$ is an NE of TAG if $\forall i$, $\vec{t}_i \succeq 0$ and $\forall q$, $\sum_{i=1}^{N} \Lambda_i^q t_i^q = T - \tau$ hold.

The proof is straightforward and is omitted here. According to Theorem 1, there exists an infinite number of NEs in TAG. Every NE in Theorem 1 is efficient and Pareto optimal, since all transmit time is utilized for transmission by the SUs.

When multiple NEs exist, a stable outcome may not be achieved if players do not agree on the selection of NEs. In this situation, one needs to introduce some NE refinement (or selection) method to lead the players to achieve one desirable NE. To select an appropriate NE, we consider fairness as the NE refinement criterion.[11]

In practice, transmit time allocation can be implemented in two stages.

1) The coalitions compete for transmit time.
2) The members of each coalition competitively share the transmit time obtained by their coalition.

In the following, we start with stage 2) and study the fair transmit time allocation among the coalition members, under the assumption that each allocation has obtained its transmit time. Then, we look at stage 1) and derive the fair transmit time allocation among the coalitions. With these two steps, we can derive a fair transmit time allocation for the SUs. We will show such allocation is an NE of TAG.

A. Transmit Time Allocation Among Coalition Members

Since inactive coalitions do not transmit, we only consider active coalitions. To obtain a fair transmit time allocation, one needs to take into account the contribution of each member to its coalition. Here, we introduce the concept of Shapley value to measure the contribution of a coalition member [44], [45]. Accordingly, the length of the mini-slot assigned to each member is proportional to its Shapley value.

1) Brief Introduction to Shapley Value: Let $\tilde{\mathcal{C}}_j$ be the jth active coalition. The Shapley value of a member in $\tilde{\mathcal{C}}_j$ is defined as follows.

Definition 2: The Shapley value of the kth member of $\tilde{\mathcal{C}}_j$ is $(1/(|\tilde{\mathcal{C}}_j|!)) \sum_{\pi \in \prod_{\tilde{\mathcal{C}}_j}} \Delta_\pi^j(k)$, where $|\tilde{\mathcal{C}}_j|$ is the number of members in $\tilde{\mathcal{C}}_j$, $\prod_{\tilde{\mathcal{C}}_j}$ is the set of all permutations of the members in $\tilde{\mathcal{C}}_j$, and $\Delta_\pi^j(k)$ is the marginal contribution of the kth member to $\tilde{\mathcal{C}}_j$ under permutation π.

We denote by $S_\pi(k)$ the set of all predecessors of the kth member in permutation π. We refer $\mathrm{SU}_{\tilde{k}}$ to the kth member. The marginal contribution of the kth member with respect to permutation π is given by

$$\Delta_\pi^j(k) = \nu\big(S_\pi(k) \cup \mathrm{SU}_{\tilde{k}}\big) - \nu(S_\pi(k)) \tag{15}$$

where ν corresponds to the coalition value [44]. Clearly, the marginal contribution measures how much $\mathrm{SU}_{\tilde{k}}$ increases the value of the coalition consisting of its predecessors in permutation π when it joins them [44]. Accordingly, the Shapley value can be considered as an average marginal contribution, where the average is taken over all the permutations.

Next, we will design two types of Shapley values for our problem.

2) Throughput Oriented Shapley Value: In general, the coalition value can be defined as the sum of member values.

[11] As shown in [42] and [43], efficiency and fairness are usually considered as the NE refinement criterion. Since all the NEs characterized by Theorem 1 are efficient, here we focus on the fairness criterion.

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Hence, we define the coalition value of our problem as

$$\nu\left(\tilde{\mathcal{C}}_j\right) = \sum_{i \in \tilde{\mathcal{C}}_j} \bar{r}_i. \tag{16}$$

Accordingly, this Shapley value is termed throughput oriented Shapley value.

Proposition 1: Suppose $\nu(\tilde{\mathcal{C}}_j) = \sum_{i\in\tilde{\mathcal{C}}_j} \bar{r}_i$ holds. The Shapley value of every member in $\tilde{\mathcal{C}}_j$ is $\Phi_j^k = (\sum_{i\in\tilde{\mathcal{C}}_j} \bar{r}_i)/(|\tilde{\mathcal{C}}_j|)$.

The proof of Proposition 1 follows [44, Proposition 2.14]. The intuition behind Proposition 1 is that every coalition member is of equal importance since it is indispensable for satisfying the sensing performance requirements.[12]

Let T_j^q be the transmit time of $\tilde{\mathcal{C}}_j$ under the qth coalition pattern. With Proposition 1, we conclude that the transmit time allocation for the members of $\tilde{\mathcal{C}}_j$ is

$$\left(\frac{T_j^q}{|\tilde{\mathcal{C}}_j|}, \frac{T_j^q}{|\tilde{\mathcal{C}}_j|}, \ldots, \frac{T_j^q}{|\tilde{\mathcal{C}}_j|}\right). \tag{17}$$

3) Sensing Performance Oriented Shapley Value: From the perspective of PU protection, however, the coalition members generally play different roles. Accordingly, we can allocate the transmit time to the members according to their contributions to the detection probability. This motivates us to propose the concept of sensing performance oriented Shapley value by defining the coalition value as the detection probability of the CSS coalition.

Proposition 2: Suppose $\nu(\tilde{\mathcal{C}}_j) = 1 - \prod_{k\in\tilde{\mathcal{C}}_j}(1-p_d^k)$ holds. Let $\bar{\mathcal{C}}_a$ $(0 \le a \le |\tilde{\mathcal{C}}_j| - 1)$ represent an active coalition consisting of a members who are not the kth member of $\tilde{\mathcal{C}}_j$. Let $\{\bar{\mathcal{C}}_a\}$ denote the set of all such coalitions (i.e., $\bar{\mathcal{C}}_a$). The Shapley value of the kth member of $\tilde{\mathcal{C}}_j$ is

$$\Phi_j^k = \frac{p_d^{\tilde{k}}}{|\tilde{\mathcal{C}}_j|!} \sum_{a=0}^{|\tilde{\mathcal{C}}_j|-1} \sum_{\bar{\mathcal{C}}_a \in \left\{\bar{\mathcal{C}}_a\right\}} a!\left(|\tilde{\mathcal{C}}_j| - 1 - a\right)! \prod_{i\in\bar{\mathcal{C}}_a}\left(1 - p_d^i\right) \tag{18}$$

where $p_d^{\tilde{k}}$ is the detection probability of the kth member of $\tilde{\mathcal{C}}_j$.

The proof of Proposition 2 can be found in [46]. With Proposition 2, we conclude that the transmit time allocation for the members of $\mathcal{C}_j$ is

$$\left(\frac{\Phi_j^1 T_j^q}{1 - \prod_{i\in\mathcal{C}_j}\left(1 - p_d^i\right)}, \frac{\Phi_j^2 T_j^q}{1 - \prod_{i\in\mathcal{C}_j}\left(1 - p_d^i\right)}, \ldots, \frac{\Phi_j^{|\mathcal{C}_j|} T_j^q}{1 - \prod_{i\in\mathcal{C}_j}\left(1 - p_d^i\right)}\right). \tag{19}$$

Now we evaluate the stability of the transmit time allocation corresponding to Shapley values.[13]

[12]In Section VII, we will show that if an SU leaves its coalition, constraint (1) will be violated. Hence, every coalition member is indispensable for the coalition.

[13]The stability discussed in Proposition 3 is inspired by the concept of core, which has been widely used in cooperative games. The core is the set of imputations such that each coalition receives at least as much as it can create on its own, i.e., $\sum_{i\in\mathcal{S}} x_i \ge \nu(\mathcal{S}), \forall \mathcal{S} \in \mathcal{C}$, where x_i is the payoff of member i. It is noted that some cooperative games have empty cores.

Proposition 3: For any coalition $\tilde{\mathcal{C}}_j$ and the transmit time allocations described in (17) or (18), we have

$$\sum_{\tilde{i}\in\mathcal{S}} \bar{r}_{\tilde{i}} \ge \nu(\mathcal{S}), \forall \mathcal{S} \subseteq \tilde{\mathcal{C}}_j \tag{20}$$

where $\mathcal{S}$ denotes any subset of the members in $\tilde{\mathcal{C}}_j$ and $\bar{r}_{\tilde{i}}$ refers to the utility of the coalition member $\mathrm{SU}_{\tilde{i}}$.

The proof of Proposition 3 is given in [46]. Proposition 3 implies that the transmit time allocations described in (17) and (18) are stable in the sense that no subset of members can benefit from rejecting it and forming a new coalition.

B. Transmit Time Allocation Among Coalitions

Now, we consider the fair transmit time allocation among active coalitions. If a coalition is not satisfied with its transmit time allocation, it has two possible choices: 1) leaving the secondary system and acting alone[14] or 2) staying in the secondary system, but colluding with at least one coalition to compete with the others. If it chooses the second, both detection probability and false alarm probability will arise. Accordingly, the amount of its transmission opportunities will decrease. In this paper, we mainly consider the first choice. We aim to obtain a transmit time allocation that is fair such that no coalition is willing to act alone. To do it, we introduce the Nash bargaining theory.

Nash bargaining aims to reach an agreement over the sharing of a resource but has a conflicting interest on how to reach this agreement [24], [47], [48]. If the agreement cannot be reached, each player acts alone and reaches its disagreement point. Let M be the number of active coalitions under a coalition pattern. Let $\check{r}_i^q$ be the achievable average throughput of SU_i when acting alone under the qth coalition pattern. The Nash bargaining problem for transmit time allocation among coalitions can be formulated as

$$\max_{T_j^q} \prod_{j=1}^{M} \left(\sum_{i\in\mathcal{C}_j} \bar{r}_i^q\left(t_i^q\left(T_j^q\right)\right) - \varpi_j^q\right)^{\alpha_j} \tag{21}$$

s.t.

$$\sum_{j=1}^{M} T_j^q \le T - \tau \tag{22}$$

$$\forall j, \sum_{i\in\mathcal{C}_j} \bar{r}_i^q\left(t_i^q\left(T_j^q\right)\right) \ge \varpi_j^q = \sum_{i\in\mathcal{C}_j} \check{r}_i^q. \tag{23}$$

This formulation is explained as follows.

1) $\sum_{i\in\mathcal{C}_j} \bar{r}_i^q(t_i^q(T_j^q))$ denotes the throughput of $\mathcal{C}_j$. $t_i^q(T_j)$ is the function of T_j, which is given in (17) or (19). ϖ_j^q corresponds to the disagreement point of $\mathcal{C}_j$. It is defined as the achievable throughput of a coalition that acts alone, i.e., $\varpi_j^q = \sum_{i\in\mathcal{C}_j} \check{r}_i^q$.
2) α_j is generally set to 1 for every j. In rare cases, one may want to give different weights to the coalitions. Accordingly, α_j represents the bargaining power of $\mathcal{C}_j$ [24], and the coalitions may have different α_j.

[14]In practice, a coalition acting alone may give up transmission since it is not associated with a BS.

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3) Constraint (22) states that the total transmit time allocated to the coalitions cannot exceed $T-\tau$. Constraint (23) stipulates that every coalition should satisfy their individual rationality, i.e., participating in transmit time allocation is not worse than acting alone.

The solution to the above Nash bargaining problem is termed Nash bargaining solution (NBS). It satisfies some nice properties such as Pareto efficiency and fairness [24], [47], [48]. Hence, NBS corresponds to a desirable transmit time allocation among coalitions.

Now, we propose Theorem 2 to derive the NBS of our problem. Some notations used in this theorem are explained as follows.

1) With the throughput oriented Shapley value, we have $t_i^q(T_j^q) = ((T_j^q)/(|\mathcal{C}_j|))$ and

$$\bar{r}_i^q\left(t_i^q\left(T_j^q\right)\right) = \frac{T_j^q}{T|\mathcal{C}_j|}\left(\Theta_q^1 r_i^1 + \Theta_q^2 r_i^2\right). \tag{24}$$

In this case, we use k_j to denote $\sum_{i\in\mathcal{C}_j}(1/(T|\mathcal{C}_j|))(\Theta_q^1 r_i^1 + \Theta_q^2 r_i^2)$.

2) With the sensing performance oriented Shapley value, we have

$$t_i^q(T_j^q) = \frac{\Phi_j^i T_j^q}{1-\prod_{i\in\mathcal{C}_j}(1-p_d^i)} \quad \text{and}$$

$$\bar{r}_i^q\left(t_i^q\left(T_j^q\right)\right) = \frac{1}{T}\frac{\Phi_j^i T_j^q}{1-\prod_{i\in\mathcal{C}_j}(1-p_d^i)}\left(\Theta_q^1 r_i^1 + \Theta_q^2 r_i^2\right). \tag{25}$$

In this case, we use k_j to represent $\sum_{i\in\mathcal{C}_j}((\Phi_j^i)/T)((\Theta_q^1 r_i^1 + \Theta_q^2 r_i^2)/(1-\prod_{i\in\mathcal{C}_j}(1-p_d^i)))$.

Theorem 2: Under the qth coalition pattern, the transmit time allocation of coalitions corresponding to the NBS is

$$T_j^q = \frac{\varpi_j^q}{k_j} + \frac{\alpha_j}{\sum_{j=1}^M \alpha_j}\left(T-\tau-\sum_{j=1}^M \frac{\varpi_j^q}{k_j}\right),\ j = 1,2,\ldots,M. \tag{26}$$

The proof of Theorem 2 can be found in [46].

C. Transmit Time Allocation Equilibrium of TAG

According to (17), (19), and Theorem 2, we can derive the transmit time allocation equilibrium of TAG. Suppose that SU_i is included in $\mathcal{C}_j$. At such equilibrium, the transmit time allocated to SU_i under $\mathcal{CP}_q$, denoted by $\tilde{t}_i^q$, is described as follows.

1) With the throughput oriented Shapley value

$$\tilde{t}_i^q = \begin{cases} \frac{\varpi_j^q}{k_j|\mathcal{C}_j|} + \frac{\alpha_j}{\sum_{j=1}^M \alpha_j}\dfrac{T-\tau-\sum_{j=1}^M \frac{\varpi_j^q}{k_j}}{|\mathcal{C}_j|}, & \Lambda_i^q = 1 \\ 0, & \Lambda_i^q = 0. \end{cases} \tag{27}$$

2) With the sensing performance oriented Shapley value

$$\tilde{t}_i^q = \begin{cases} \dfrac{\Phi_j^i\left[\frac{\varpi_j^q}{k_j} + \frac{\alpha_j}{\sum_{j=1}^M \alpha_j}\left(T-\tau-\sum_{j=1}^M \frac{\varpi_j^q}{k_j}\right)\right]}{1-\prod_{k\in\mathcal{C}_j}(1-p_d^k)}, & \Lambda_i^q = 1 \\ 0, & \Lambda_i^q = 0. \end{cases} \tag{28}$$

Clearly, the transmit time allocation described by (27) or (28) satisfies the conditions in Theorem 1, and hence corresponds to an NE of TAG.

VI. Coalition Formation Game

In CFG, every SU decides which coalition to join, with the goal of its average throughput maximization. We denote by $(\mathcal{C}_1,\ldots,\mathcal{C}_J)$ $(0 < J \le N)$ a general coalition formation outcome (i.e., coalition structure). A coalition formation equilibrium has two properties.

1) *Feasibility:* Every coalition meets the sensing performance requirements [i.e., constraints (13) and (14)].
2) *Stability:* Every SU has no incentive to unilaterally deviate from the coalition formation equilibrium.

Here, we propose Theorem 3 to identify an NE of CFG.

Theorem 3: The coalition formation outcome satisfying the following conditions corresponds to an NE of CFG:

$$\forall j \in [1,J],\ \min\left\{P_d^j-\theta,\gamma-P_f^j\right\} \ge 0 \tag{29}$$

$$\forall\, j \in [1,J],\ \forall\ \text{SU}_i \in \mathcal{C}_j,\ \frac{P_d^j - p_d^i}{1-p_d^i} < \theta. \tag{30}$$

The proof of Theorem 3 is straightforward, and hence is omitted.

To achieve a coalition formation equilibrium, we introduce two types of operations: merge and split.[15] The merge operation combines one or more SUs with another SU or coalition. The split operation divides a coalition into noncoalitional SUs[16] (and a new smaller coalition). Merge enhances both detection probability and false alarm probability. Contrarily, split decreases these two probabilities. The motivation of introducing merge and split is twofold. First, merge and split can be used to form any coalition structure. Second, merge and split can be used to meet constraints (29) and (30).

Before describing the operations of merge and split, we first introduce the concept of Pareto order $\succ_p$ [18], [51]. Consider two coalition structure $\mathcal{A} = \{\mathcal{C}_1,\mathcal{C}_2,\ldots,\mathcal{C}_l\}$ and $\mathcal{B} = \{\mathcal{C}'_1,\mathcal{C}'_2,\ldots,\mathcal{C}'_k\}$, where $\{\cup_{i=1}^l \mathcal{C}_i\} = \{\cup_{i=1}^k \mathcal{C}'_k\}$. Let $\bar{r}_i^{\mathcal{A}}$ and $\bar{r}_i^{\mathcal{B}}$ represent the utility of SU_i under the coalition structure $\mathcal{A}$ and $\mathcal{B}$, respectively. $\mathcal{A} \succ_p \mathcal{B}$ means $\forall \text{SU}_i \in \{\cup_{i=1}^l \mathcal{C}_i\}$, $\bar{r}_i^{\mathcal{A}} \ge \bar{r}_i^{\mathcal{B}}$ and $\exists \text{SU}_j \in \{\cup_{i=1}^l \mathcal{C}_i\}$, $\bar{r}_j^{\mathcal{A}} > \bar{r}_j^{\mathcal{B}}$.

Let P be a partition [51] of the SU set $\{\text{SU}_1,\ldots,\text{SU}_l\}$. Accordingly, $\{\text{SU}_1,\ldots,\text{SU}_l\} \cap P$ corresponds to a coalition structure defined by P. Then, the merge operation is described in the following.

A. Merge

$$\{\text{SU}_1,\ldots,\text{SU}_l\} \cap P \xrightarrow{\text{merge}} \left\{\cup_{i=1}^l \text{SU}_i\right\} \tag{31}$$

if $\{\cup_{i=1}^l \text{SU}_i\} \succ_p \{\text{SU}_1,\ldots,\text{SU}_l\} \cap P$.

[15] Merge and split are the operations that can be used to form a coalition structure. Although they have been employed in some algorithms developed for cooperative games, they are also applicable for our problem. In the next section, we will use them in our proposed algorithm.

[16] The noncoalitional SUs are those SUs who are temporarily excluded by all coalitions.

It is noted that merge occurs only when it is beneficial for at least one SU and harmless for the others.

In the following, we consider two kinds of split operations: 1) classical split and 2) specifical split, which are described by (32) and (33), respectively.

B. Classical Split

$$\left\{\cup_{i=1}^{l}\mathrm{SU}_i\right\} \xrightarrow{\text{split}} \{\mathrm{SU}_1, \ldots, \mathrm{SU}_l\} \cap P \qquad (32)$$

if $\{\mathrm{SU}_1, \ldots, \mathrm{SU}_l\} \cap P \succ_P \{\cup_{i=1}^{l}\mathrm{SU}_i\}$.

C. Specifical Split

$$\left\{\cup_{i=1}^{l}\mathrm{SU}_i\right\} \xrightarrow{\text{split}} \mathcal{C}' \cup \left\{\mathrm{SU}_j\right\} \cup \cdots \cup \{\mathrm{SU}_k\} \qquad (33)$$

if 1) $\mathcal{C}'$ is feasible and 2) no subset of $\mathcal{C}'$ is feasible, where $\mathcal{C}' = \{\cup_{i=1}^{l}\mathrm{SU}_i\}\backslash\{\mathrm{SU}_j, \ldots, \mathrm{SU}_k\}$.

It can be seen that the classical split operation is contrary to the merge operation. As for the special split operation, it refines a coalition by excluding some SUs (e.g., SU_j and SU_k). It occurs only when the remaining coalition (i.e., $\mathcal{C}'$) is feasible.

VII. Proposed Algorithm

In this section, we develop a distributed algorithm [52] to lead the SUs to obtain the NE of CF − TA. This algorithm adopts the merge/split operations to obtain the NE of CFG. Meanwhile, it employs (27) or (28) to calculate the NE of TAG. It will be shown that the combination of these two NEs corresponds to the NE of CF − TA.

A. Algorithm Description

Our MSBA is described in Algorithm 1. In step 1), every SU obtains the detection probability and false alarm probability of the others via a common control channel. In step 2), the algorithm leads the SUs to form some feasible coalitions. Since these feasible coalitions are not optimal in terms of individual throughput maximization, the SUs repeatedly conduct merge and specifical split until a coalition formation equilibrium is achieved. The details are shown in step 3). When step 3) terminates, the SUs excluded by all coalitions are considered as the zombie SUs. They do nothing in step 4).

The details of step 3) are shown in Fig. 4. The noncoalitional SUs derived by specifical split act as the input of the next merge operation, and the feasible coalitions derived by merge are considered as the input of the next specifical split operation. The new coalitions derived by specifical split will never be further merged or split in the following rounds. Instead, they will be output by MSBA and remain unchanged. As a result, when MSBA runs, the number of noncoalitional SUs will be gradually reduced. The merge and split operations terminate once no feasible coalition can be formed by merge. This explains why step 3) in MSBA will not lead to an infinite number of cycles.

When conducting merge or split, SUs need to calculate their utilities under various coalition structures. To do it, they calculate their own transmit time with (27) or (28). Furthermore, the merge operation in MSBA can be conducted locally. That is, the coalitions attempt to merge with their neighboring SUs.

It should be pointed out that although there exists a centralized entity (i.e., the secondary BS) in our system, one should not run MSBA in a centralized fashion [53]. In steps 1)–3) of MSBA, the SUs exchange messages via their common control channel, and calculate their own utilities using r_i^1 and r_i^2.

Algorithm 1 MSBA

1) *Exchanging information*:
  for each SU_i **do**
    SU_i broadcasts its ID, p_d^i and p_f^i ;
  end for
2) *Forming feasible coalitions*:
  for each coalition $\mathcal{C}_j$ **do**
    if ($P_d^j \le \theta$ and $P_f^j > \gamma$) or ($P_d^j < \theta$ and $P_f^j \ge \gamma$)
      Divide $\mathcal{C}_j$ into non-coalitional SUs;
    else if $P_d^j > \theta$ and $P_f^j > \gamma$
      Apply classical split to $\mathcal{C}_j$;
    else if $P_d^j < \theta$ and $P_f^j < \gamma$
      Merge SUs with $\mathcal{C}_j$ for feasibility;
    end if
  end for
3) *Repeating merge and split*:
  repeat
    Apply merge to the non-coalitional SUs;
    Apply specifical split to each coalition;
  until no change takes place
  Output SUs excluded by all coalitions as zombie SUs;
4) *Sensing and Transmitting in one time slot*:
  Coalitions conduct CSS in the sensing phase;
  SUs in active coalitions transmit in their own mini-slots;
5) *Adapting to network dynamics*:
  if p_d^i or p_f^i is changed due to mobility
    SU_i broadcasts its ID, current p_d^i and p_f^i;
    Go back to step 2);
  end if
  if network structure is changed due to network dynamics
    Go back to step 1);
  end if
  Go back to step 4);

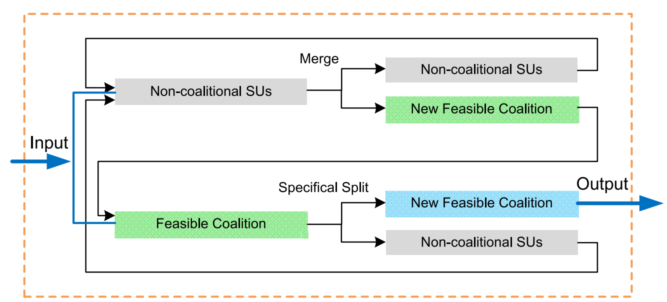

Fig. 4. Merge-and-split operation in step 3.

The BS is not involved in these steps. Furthermore, every SU does not need to reveal its r_i^1 and r_i^2 to the BS or the other SUs.

B. Algorithm Properties

MSBA has some nice properties, which makes it implementable in practice.

1) Good Scalability and Low Complexity: The maximum coalition size does not increase with the total number of SUs. In addition, the coalitions conduct merge and split concurrently. Hence, MSBA can converges within reasonable time even if it is deployed in a large-scale system. On the other hand, the BS can use broadcast (through the common control channel) to schedule the SUs for transmission. Therefore, MSBA does not require precise clock synchronization among the SUs, and is easy to implement in practice [54].

2) Adaptation to Network Dynamics: When the secondary system changes (e.g., some SUs move, leave or join), either the network structure or the sensing performance of SUs may change.[17] In this situation, the equilibrium derived by the algorithm is not needed any more. To address this problem, MSBA conducts the previous steps again to achieve a new outcome, as shown in step 5).

C. Theoretical Analysis

Proposition 4: Given p_d^i and p_f^i $(i = 1, 2, \ldots, L)$, the merge/split operations in MSBA converge to an NE of CFG within a finite number of steps.

The proof of Proposition 4 is given in [46].

An NE outcome is stable since it can resist unilateral deviation of any player. However, the concept of NE does not take into account the concurrent deviation of multiple players. To evaluate the stability of our NE under concurrent deviation, we introduce a different stability concept D_{hp}-stability [18], [51].

Definition 3: A coalition structure is D_{hp}-stabile if no coalition has an incentive to split or merge one or more other coalitions.

D_{hp}-stability means that a coalition structure can resist these two kinds of deviations: 1) a coalition is split into smaller coalitions and 2) a coalition merges with other coalitions.

Theorem 4: The coalition formation equilibrium derived by our MSBA algorithm is D_{hp}-stable.

When MSBA terminates, the NEs of both CFG and TAG are actually obtained at the same time. We denote by $(\vec{s}_1^*, \ldots, \vec{s}_N^*)$ and $(\vec{t}_1^*, \ldots, \vec{t}_N^*)$ the NEs of CFG and TAG derived by MSBA, respectively.

Theorem 5: The combination of $(\vec{s}_1^*, \ldots, \vec{s}_N^*)$ and $(\vec{t}_1^*, \ldots, \vec{t}_N^*)$, i.e., $((\vec{s}_1^*, \vec{t}_1^*), \ldots, (\vec{s}_N^*, \vec{t}_N^*))$, is an NE of the $\mathrm{CF-TA}$ game.

The proofs of Theorems 4 and 5 are given in [46]. With Proposition 4 and Theorem 5, we can conclude that MSBA converges to an NE of $\mathrm{CF-TA}$.

[17] The existing neighbor discovery mechanisms in wireless *ad hoc* networks can be used to detect the network change. This issue has been thoroughly investigated and hence is omitted here.

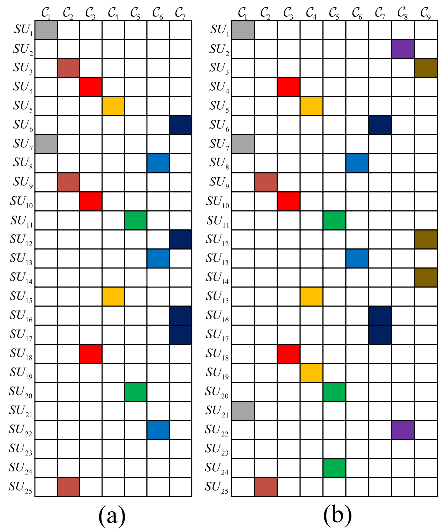

Fig. 5. (a) Initial and (b) final coalition structures.

VIII. Performance Evaluation

In this section, we use simulations to verify the previous equilibrium analyzes, and demonstrate the effectiveness of the proposed algorithm. The key parameters are set as follows: $L = 25$, $T = 10$, $\tau = 2$, $\theta = 0.9$, $\gamma = 0.1$, $P_{H_0} = 0.6$, $\omega_j^q = 0$, and $\alpha_j = 1$.

A. Coalition Formation Equilibrium

The initial coalition structure and the coalition formation equilibrium derived by MSBA are shown in Fig. 5(a) and (b), respectively. In both figures, each colored box represents an SU, and the boxes with the same color belong to the same coalition. It can be seen from Fig. 5(b) that the SUs finally form nine coalitions. Note that SU_{23}, which cannot meet the sensing performance requirements alone, does not belong to any coalition. Hence, it is a zombie SU and should be ruled out from the secondary system.

Next, we will verify that the final coalition formation outcome derived by MSBA is an NE. Each SU can change its equilibrium strategy by joining another coalition. However, the deviation is not allowed, since it violates the constraints on detection probability. Hence, the coalition formation outcome derived by MSBA is stable. For illustration, we consider Fig. 6, where the horizontal axis represents the SUs, and the vertical axis denotes the detection probability of the coalition ruling out a certain SU. For example, the bar at SU_{11} indicates the detection probability of the coalition ruling out SU_{11}. It can be seen that the detection probability of every coalition falls below the required threshold 0.9 if one of its members leaves. If the deviation is allowed, the secondary system will be forbidden from accessing the licensed channel. As a result, all the SUs will lose their transmission opportunities. Clearly, a rational SU will avoid it, and hence refuse to deviate from its equilibrium strategy.

B. Transmit Time Allocation Equilibrium

Now, we evaluate the transmit time allocation derived by MSBA. It is observed in our simulations that

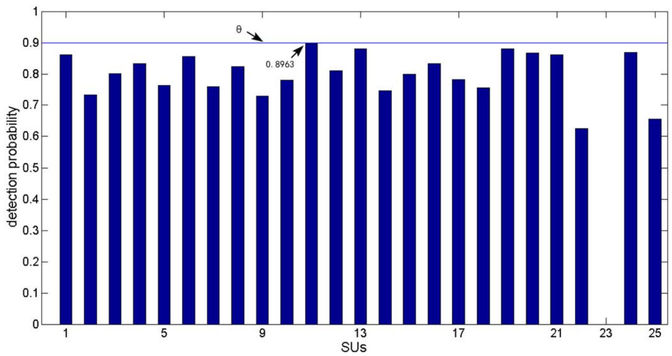

Fig. 6. P_d of each coalition ruling out one SU.

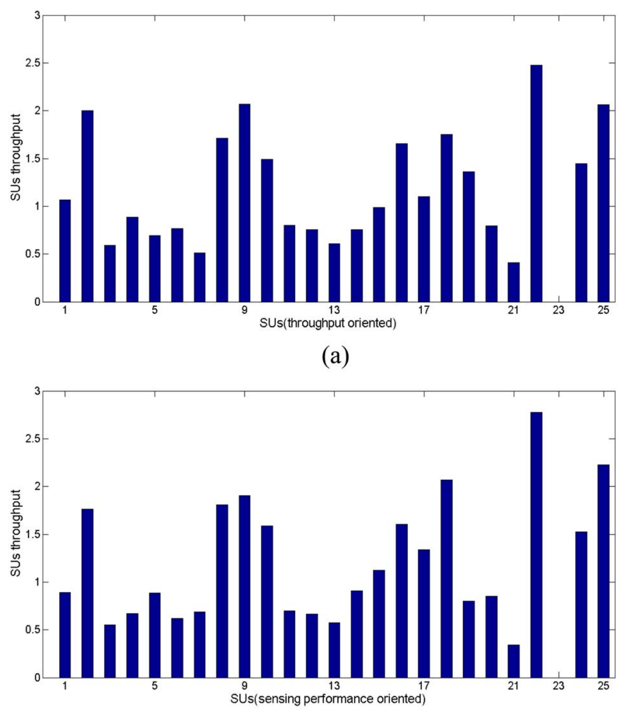

Fig. 7. Average throughput of SUs. (a) With throughput oriented Shapley value. (b) With sensing performance oriented Shapley value.

$\sum_{i=1}^{N} \Lambda_i^q t_i^q = T - \tau$ holds under every coalition pattern. According to Theorem 1, we know that the transmit time allocation outcome derived by MSBA is an NE of TAG.

Then, we evaluate the transmit time allocation equilibrium in terms of fairness. To do it, we introduce the concept of Jain's fairness [55], [56], which is defined as

$$\mathcal{F} = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} (x_i)^2}. \tag{34}$$

Jain's fairness rates the fairness of a set of values where there are n users and x_i is the value allocated to user i. This definition shows that $\mathcal{F}$ lies in $[(1/N), 1]$. In this interval, $(1/N)$ corresponds to the least fair allocation in which only one user obtains a nonzero value, and 1 corresponds to the fairest allocation in which all users receive the same value.

Before we apply the Jain's fairness to our problem, we introduce a capability factor ψ^i to measure the capability of an SU competing for its transmit time. The intuition behind the capability factor is that an SU with stronger capability should obtain more transmit time. Here, we use the difference between detection probability and false alarm probability as the capability factor, i.e., $\psi^i = p_d^i - p_f^i$. Accordingly, x_i is set to $((\bar{t}_i)/(\psi^i))$, where $\bar{t}_i = \sum_{q=1}^{2^Q-1} \Lambda_i^q (\Theta_q^1 P_{H_0} + \Theta_q^2 (1 - P_{H_0})) t_i^q$ is the average mini-slot length under all coalition patterns.

TABLE II
JAIN'S FAIRNESS INDEX

Coalition	Fairness 1	Fairness 2
$\mathcal{C}_1$	0.9805	0.9944
$\mathcal{C}_2$	0.9974	0.9992
$\mathcal{C}_3$	0.9777	0.9981
$\mathcal{C}_4$	0.9273	0.9945
$\mathcal{C}_5$	0.9976	0.9977
$\mathcal{C}_6$	0.9987	0.9995
$\mathcal{C}_7$	0.9837	0.9987
$\mathcal{C}_8$	0.9949	0.9977
$\mathcal{C}_9$	0.9914	0.9983

The Jain's fairness indices of all the nine coalitions corresponding to Fig. 5(b) are shown in Table II. The second column of this table shows the Jain's fairness indices in the case where throughput oriented Shapley value is used. And the third column indicates the Jain's fairness indices corresponding to the sensing performance oriented Shapley value. It can be seen that the Jain's fairness index of every coalition is close to 1. Therefore, the transmit time allocation equilibrium is fair for all the coalition members.

It should be pointed out that the fairness indices in the third column are better than those in the second column. This is because that the throughput oriented Shapley value does not take into account the detection probability of each coalition member and allocates each member the same transmit time. As for the sensing performance oriented Shapley value, it assigns transmit time to each coalition member according to its detection probability. Hence, the sensing performance oriented Shapley value usually results in a fairer allocation.

In the following, we compare these two kinds of Shapley values from the view point of SUs. Intuitively, an SU with more contribution to sensing accuracy should obtain higher throughput. Our comparison reveals that the sensing performance oriented Shapley value follows this intuition. We show the average throughput of every SU in Fig. 7(a) and (b). Fig. 7(a) indicates the average throughput of SUs when the throughput oriented Shapley value is used. And Fig. 7(b) corresponds to the sensing performance oriented Shapley value. For illustration, we consider SU_{12} and SU_{14}. Fig. 5(b) shows both SUs belong to the same coalition, i.e., $\mathcal{C}_9$. In our simulations, both SUs have the same data rates, i.e., $r_{12}^1 = r_{14}^1$ and $r_{12}^2 = r_{14}^2$. But they have different sensing accuracy ($p_d^{12} = 0.4838$ and $p_d^{14} = 0.6133$). With the throughput oriented Shapley value, we have $\bar{r}_{12} = \bar{r}_{14}$, as shown in Fig. 7(a). With the sensing performance oriented Shapley value, we have

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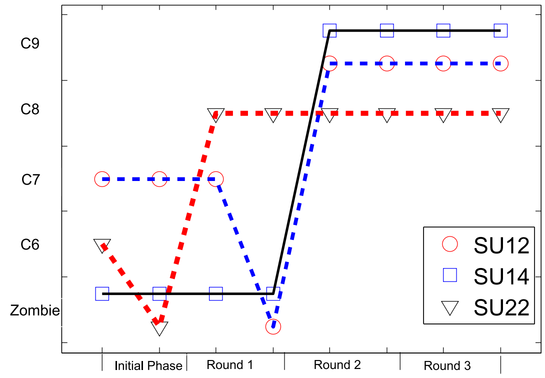

Fig. 8. Iterations of MSBA.

$\bar{r}_{12} < \bar{r}_{14}$, as shown in Fig. 7(b). Clearly, the sensing performance oriented Shapley value is more reasonable from the view point of SUs.

C. Merge-and-Split-Based Algorithm

Finally, we evaluate MSBA in terms of convergence and scalability.

1) Convergence: The convergence of MSBA under given p_d^i and p_f^i is observed in many simulations. For the illustration purpose, we show the coalition formation procedure of several SUs in Fig. 8. In this figure, the horizontal axis represents the operations of merge and split, and the vertical axis indicates which coalition an SU joins. As shown in Algorithm 1, MSBA contains two main phases: 1) initial phase and 2) iteration phase. In the initial phase, the SUs form some feasible coalitions. In the iteration phase, the SUs repeatedly conduct merge and split until a coalition formation equilibrium is achieved. Accordingly, the horizontal axis can be roughly divided into two segments: the first corresponds to the formation of feasible coalitions, and the second represents the formation of the coalition formation equilibrium.

1) Consider the first segment of the horizontal axis. To form feasible coalition, SU_{22} is split from $\mathcal{C}_6$. For SU_{14}, it is not included by any coalition.
2) The second segment contains three rounds. In round 1, SU_{22} joins $\mathcal{C}_8$ together with SU_2, and SU_{12} leaves $\mathcal{C}_7$ by conducting specifical split. In round 2, SU_3, SU_{12} and SU_{14} form a new coalition $\mathcal{C}_9$ using merge. In round 3, no SU changes its coalition selection and MSBA converges.

2) Scalability: To verify the scalability of MSBA, we run MSBA under seven scenarios, in which the number of SUs ranges from 19 to 37. In every scenario, we run MSBA for at least ten times with different p_d^i and p_f^i. It is observed that MSBA converges within a few rounds in all the simulations. The statistical results are given in Table III. The second column of this table represents the maximum size of the coalitions in the coalition formation equilibrium. The third column denotes the average size of the coalitions in the coalition formation equilibrium. The last column corresponds to the average number of iterations in step 3) of MSBA. Note that all the values are averaged over the simulations in every scenario.

TABLE III
CONVERGENCE OF MSBA IN VARIOUS SCENARIOS

N	Maximum $\lvert\mathcal{C}_i\rvert$	Average $\lvert\mathcal{C}_i\rvert$	Average iter. num.
19	3.30	2.40	2.00
22	3.50	2.56	2.00
25	3.70	2.54	2.00
28	3.80	2.52	2.00
31	3.80	2.55	2.05
34	3.90	2.57	2.05
37	4.00	2.58	2.10

According to Table III, we have the following observations and conclusions.

1) The SUs are not interested in large-size coalitions. This is because the SUs considered in this paper are self-interested, and they aim to maximize their own average throughput instead of detection probability. Since the large-size coalition usually results in less transmission opportunities (due to its high false alarm probability), a coalition refuses to adopt more members once the sensing performance requirements are met.
2) The iteration number of MSBA and the average coalition size do not rapidly increase with the network size (i.e., N). Even if the number of SUs is large, the coalitions will stop adopting more members after conducting a few merge-and-split operations. As a result, MSBA has good scalability.

In addition, we also compare our proposed algorithm with existing methods via simulations. Please find the results in [46].

IX. CONCLUSION

In this paper, we propose to jointly study the CSS coalition formation and transmit time allocation of self-interested SUs. We formulate the problem as a noncooperative game, and then decompose the game into two more tractable ones. We characterize the NEs of the derivative games, and show that the combination of both NEs corresponds to the NE of the original game. We also develop an algorithm to achieve the NEs of these games. The simulation results verify the correctness of our equilibrium analyzes, and demonstrate the convergence and scalability of our algorithm. In the future work, we will discuss the case where the other fusion rules such as AND or k-out-of-N [11] are adopted in the system.

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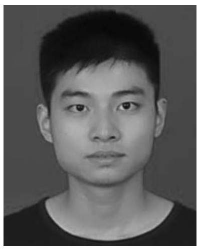

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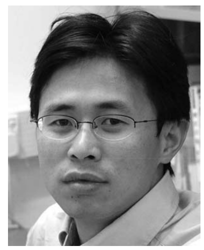

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