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Overlapping Coalition Formation Games for Joint Interference Management and Resource Allocation in D2D Communications

JINMING HU, (Student Member, IEEE), WEI HENG, (Member, IEEE), YAPING ZHU, (Student Member, IEEE), GANG WANG, (Member, IEEE), XIANG LI, (Student Member, IEEE), AND JING WU, (Student Member, IEEE)

National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, China

Corresponding author: Wei Heng (wheng@seu.edu.cn)

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ABSTRACT In this paper, an overlapping coalition formation game is proposed to conduct joint interference management and resource allocation in device-to-device (D2D) communications. We aim at improving the sum rate of all D2D links in D2D communications underlying cellular network without sacrificing the quality of service of each cellular user (CU) and D2D link. First, based on the cross-tier interference level between CUs and D2D links, each D2D link selects multiple best resource blocks (RBs) to reuse. Then, by dividing the user equipments (i.e., CU and D2D links) which share the same RB into one coalition, an initial overlapping coalitional structure is formed. A cooperative game with overlapping coalitions is further proposed to maximize the system utility in terms of sum rate of all D2D links. Finally, the characteristic analysis of the proposed algorithm is provided to validate that the user equipments can cooperate to form a stable and most beneficial coalitional structure with overlapping coalitions. Simulation results show that the proposed overlapping coalition formation game achieves a better performance compared with other existing schemes.

INDEX TERMS Device-to-device (D2D) communications, interference management, resource allocation, overlapping coalition formation games.

I. INTRODUCTION

As one of the most promising techniques in 5G communications, device-to-device (D2D) communication has attracted intensive interest in recent years. By sharing the uplink or downlink resource blocks (RBs) with cellular users (CUs), D2D communication achieves a great potential of improving spectral efficiency (SE) and increasing network capacity [1]. Different from the traditional cellular communications, D2D communication allows direct communication between two users which are geographically close to each other without being relayed by base station (BS). This technology leads to a network with a higher spectrum utilization efficiency, less power consumption and lower delay, which can well adapt to the increasing demand for larger network capacity and higher transmission rates [2], [3].

Although a higher spectral efficiency can be achieved by the reuse of resources in D2D communications, it may result in serious cross-tier interference (between CUs and D2D links) and co-tier interference (between different D2D links transmitting on the same RB) [4], [5]. If the interferences are not properly managed, the performance of whole system will be seriously affected. Therefore, effective interference management algorithms are needed to mitigate quality-of-service (QoS) degradation caused by the two above-mentioned types of interferences. A number of recent literatures have been effort on the problem of interference management in D2D communications underlaying cellular networks [6]–[10]. In [6], a guard zone based interference mitigation scheme was proposed, in which the BSs were capable of successive interference cancellation (SIC). By adaptively activating and deactivating the state of D2D links, the QoS requirement of CUs was also guaranteed. In order to control the interference caused by D2D transmission, Yin *et al.* [7] investigated a pricing-based interference coordination scheme for D2D communications in cellular networks. The analysis of transmission capacity region (TCR) was studied in [8], which could provide an insight to interference management in D2D systems when both power control and SIC methods were applied. By limiting the coexistence of CUs and D2D pairs which imposed serious interference to the cellular network, an interference management strategy was proposed in [9], which improved the system performance in terms of overall capacity of all user equipments. The algorithm in [10] considerd both uplink and downlink interferences through admission control and power allocation, which aimed at maximizing the total throughput of the D2D communications underlaying cellular network.

Due to the limited battery capacity of D2D devices, energy efficiency (EE) is regarded as important as the reliability in D2D communications. Proper resource allocation can not only improve EE of the network, but also reduce the interferences. Therefore, researching resource allocation algorithms is also critical to the D2D communications underlaying cellular network. Existing resource allocation algorithms generally consist of uplink ([11]–[14]) and downlink ([15]–[17]) resource allocation algorithms. A globally optimal uplink resource allocation scheme was proposed in [11], which aimed at better utilizing the resources of CUs while guaranteeing the QoS of the cellular communications. Nguyen *et al.* [12] proposed a distributed uplink resource allocation algorithm to solve the problems of interference mitigation and data rate maximization in D2D communications, in which a pricing scheme was used and each D2D pair competed to reuse the spectrum. In [13], a noncooperative game was modeled for the D2D communications underlaying cellular network with uplink resource reuse, which could tradeoff the EE and SE by distributed resource allocation. From a more practical perspective, Hoang *et al.* [14] proposed an uplink resource allocation algorithm to maximize the system throughput based on non-cooperative game theory in multicell D2D communications, in which, the proposed game-theoretic approach was based on an assumption that each player has incomplete information of others. When the D2D pairs reuse the downlink resources to communicate, the resource allocation strategies different from the ones in uplink scenario due to the change of interference. Yang *et al.* [15] investigated the downlink resource allocation problem in D2D communications underlaying single-cellular network, which aimed at maximizing the sum rate of D2D pairs while ensuring the minimum power requirements. A downlink resource reuse strategy was proposed in [16] between multiple D2D links and CUs, in which the D2D-CU matching and power control were jointly optimized to maximize the network utility. By considering downlink resource reuse and energy harvesting (EH), Gupta *et al.* [17] formulated a non-convex problem of joint RB and power allocation, and transformed it into a tractable optimization problem.

In recent years, some works try to solve the resource allocation problem in D2D communications from a game theory point of view. For example, the coalition game theory is utilized to realize interference management and resource reuse for D2D communications underlaying cellular networks [18]–[21]. Li *et al.* [18] proposed a coalition formation game in which the utility function was related to mutual interferences, transmission modes, and resource sharing policies. An uplink resource allocation algorithm for a large scale network with multiple D2D links and CUs was proposed in [19], which aims at maximizing the sum rate of system based on a coalition formation game. However, the aspect of power control was not considered in [19]. By jointly considering mode selection and power control strategies, Chen *et al.* [20] proposed a coalition formation game to maximize the system performance in terms of the EE of all users in the network. However, all these works assume that the coalitions are independent of each other, which may restrict the network from obtaining gain through cooperation.

In this paper, an overlapping coalition formation game is proposed to solve the problem of joint interference management and resource allocation in D2D communications, in which the coalitions are not limited to be disjoint. The proposed overlapping coalition formation game consists of two phases: initialization of overlapping coalitions and cooperative game with overlapping coalitions. In the first phase, user equipments (i.e., CU and D2D links) which share the same RB will be divided into one coalition and each D2D link is allowed to participate in more than one coalition simultaneously. In the second phase, each D2D link can make a decision on whether to leave the current coalition to join a new coalition or not. In D2D links reselection process, the individual payoff of each D2D link in terms of data rate and the total utility of coalitional structure in terms of sum rate of all coalitions are compared. Through these two phases, user equipments can cooperate to obtain the most beneficial coalitional structure consisting of overlapping coalitions.

The main contributions of this paper can be summarized as follows:

- A cooperative game with overlapping coalitions is proposed to solve the problem of joint interference management and resource allocation in D2D communications underlaying cellular network. Unlike most existing literatures, the coalitions in our proposed scheme may not be disjoint, which can improve the spectrum efficiency significantly and enable a higher flexibility in resource sharing;
- To mitigate the mutual interference between different user equipments, each D2D link chooses best CUs to reuse their RBs according to the cross-tier interference strength. That is, the QoS of each CU is guaranteed while overlapping coalitions are formed to improve the spectrum efficiency. In addition, the size of coalition is considered in the process of coalition formation, which can also mitigate the mutual interference;
- A novel switching scheme is introduced that each D2D link can autonomously decide whether to leave the current coalition or not. Each D2D link is allowed to join another existing coalition or form an independently

new coalition. The system utility is improved after each movement of D2D links is completed;

- The characteristic analysis of the proposed algorithm is given, which includes the convergence, stability and computational complexity. Simulation results show that in the proposed algorithm, user equipments can cooperate to form a stable and most beneficial coalitional structure with overlapping coalitions.

The remainder of this paper is organized as follows. The system model and problem formation are introduced in Section II. In Section III, an overlapping coalition formation game is introduced which includes two phases: initialization of overlapping coalitions and cooperative game with overlapping coalitions. Section IV provides the characteristic analysis. Simulation results are given in Section V and conclusions are drawn in Section VI.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

Consider an uplink hybrid macro-cell network composed of M CUs and L D2D links. In this network, there are T ($T \geq M$) time-frequency RBs and each CU is allocated a dedicated RB by BS initially. Let $\mathcal{M} = \{S_1, S_2, \ldots, S_M\}$, $\mathcal{L} = \{D_1, D_2, \cdots, D_L\}$ and $\mathcal{T} = \{1, 2, \cdots, T\}$ denote the set of CUs, D2D links and RBs, respectively. Different from the works [21]–[23] which assume each D2D link can only reuse one RB of CU, each D2D link in our work is allowed to reuse RBs of multiple CUs and each RB can be reused by different D2D links. In such a scenario, although a higher spectral efficiency can be achieved, the cross-tier inference and co-tier interference may be serious, which significantly affects the performance of system. To mitigate the mutual interference, it is feasible to divide user equipments which have less mutual interference into one coalition. Further, in order to improve the system utility, each D2D link is allowed to reselect several best coalitions to join simultaneously. Thus, the final resulted coalitional structure is overlapped. Some definitions related to the overlapping coalitional structure are stated as follows.

Definition 1: An overlapping coalitional structure is denoted by $\mathcal{CS}$, which can be defined as $\mathcal{CS} = \{C_1, C_2, \ldots, C_K\}$, where subscript K is the number of coalitions in $\mathcal{CS}$. Component $C_i, (i = 1, 2, \ldots, K)$ in $\mathcal{CS}$ is a coalition which consists of no more than one CU and several D2D links. Compared with the non-overlapping coalitional structure with $C_i \cap C_j = \emptyset$ for $\forall\, i \neq j$, the coalitions in the overlapping coalitional structure $\mathcal{CS}$ may not be disjoint, i.e., $\exists\, i \neq j$, $C_i \cap C_j \neq \emptyset$ ($C_i, C_j \in \mathcal{CS}$).[1]

D2D links are allowed to join multiple coalitions simultaneously to form the overlapping coalitional structure in this work. To indicate the participating status of D2D links corresponding to different coalitions, a definition of coalition participation indicator is given as follows.

[1]Components in $C_i \cap C_j$ can only be D2D links because each coalition consists of at most one CU.

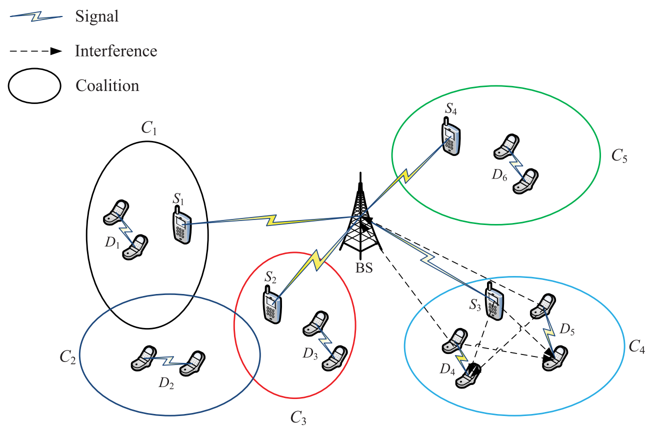

FIGURE 1. An illustration of overlapping coalition model in D2D communications underlaying cellular network.

Definition 2: A coalition participation indicator $\zeta_{lk} \in \{0, 1\}$ is defined to indicate whether the l-th D2D link D_l participates in coalition C_k. If D_l joins C_k, $\zeta_{lk} = 1$, otherwise, $\zeta_{lk} = 0$. Then, the coalition set that D_l participates in can be denoted by $Join(D_l) = \{C_k | \zeta_{lk} \neq 0, C_k \in \mathcal{CS}\}$, $Join(D_l) \subseteq \mathcal{CS}$.

To ensure each D2D link has access to the RBs (no matter directly allocated by BS or from sharing with CUs), we have $Join(D_l) \neq \emptyset, \forall\, D_l \in \mathcal{L}$. In addition, since one coalition can include several D2D links, $\exists\, i \neq j$, $Join(D_i) \cap Join(D_j) \neq \emptyset$, for example, if D_i and D_j are both included in C_k, $Join(D_i) \cap Join(D_j)$ has at least one component such as C_k.

An illustration of overlapping coalitional structure in D2D communications underlaying cellular network is given in Fig. 1. As shown in Fig. 1, in order to improve the spectral efficiency, D2D pair D_2 tends to join multiple coalitions (C_1, C_2 and C_3) simultaneously to form an overlapping coalitional structure. Moreover, D2D pair D_4 and D_5 reuse the same RB of CU S_3 which cooperate to form a coalition C_4.

B. PROBLEM FORMULATION

Let $h_{m,t}$ and $h^I_{m,l,t}$ be the normalized (by noise power) channel gain from the m-th CU S_m to BS and D_l on the t-th RB, respectively. Denote $g_{l,t}$, $g^I_{i,m,t}$ and $g^I_{i,l,t}$ as the normalized channel gain from the transmitter to its receiver of D_l, the transmitter of the i-th D2D link D_i to S_m and the transmitter of D_i to the receiver of D_l on the t-th RB, respectively. Then, the data rate of D2D link D_l on the t-th RB can be written as

$$r_{l,t} = \log_2\left(1 + \frac{\chi_{l,t} p_{l,t} g_{l,t}}{1 + p_{m,t} h^I_{m,l,t} + \sum\limits_{i \in \mathcal{L}, i \neq l} \chi_{i,t} p_{i,t} g^I_{i,l,t}}\right), \tag{1}$$

where, $p_{l,t}$, $p_{m,t}$ and $p_{i,t}$ are the transmitting power of D_l, CU S_m and D_i on RB t, respectively. The parameter $\chi_{l,t} \in \{0, 1\}$ is the RB selection indicator, if the t-th RB is reused by D_l, then $\chi_{l,t} = 1$, otherwise $\chi_{l,t} = 0$.

Note that, there exists a special case that a D2D link occupies a RB alone to transmit data since the number of RBs is larger than that of CUs. In this case, the data rate of D_l on the occupied RB t is given as

$$r'_{l,t} = \log_2 \left(1 + \chi_{l,t} p_{l,t} g_{l,t}\right). \quad (2)$$

Consequently, the sum data rate of D_l can be expressed as

$$R_l^D = \sum_{t \in \mathcal{T}} r_{l,t} \; or \; \sum_{t \in \mathcal{T}} r'_{l,t}, \quad \forall l. \quad (3)$$

For a CU $S_m \in \mathcal{M}$, its data rate on the t-th RB can be expressed as

$$r_m = \log_2 \left(1 + \frac{p_{m,t} h_{m,t}}{1 + \sum_{j \in \mathcal{L}} \chi_{j,t} p_{j,t} g_{j,m,t}^I}\right). \quad (4)$$

Therefore, the sum rate of all D2D links and CUs can be given as

$$R^D = \sum_{l \in \mathcal{L}} \sum_{t \in \mathcal{T}} \log_2 \left(1 + \frac{\chi_{l,t} p_{l,t} g_{l,t}}{1 + I_{SD}^t + I_{DD}^t}\right), \quad (5)$$

and

$$R^C = \sum_{m \in \mathcal{M}} \log_2 \left(1 + \frac{p_{m,t} h_{m,t}}{1 + \sum_{j \in \mathcal{L}} \chi_{j,t} p_{j,t} g_{j,m,t}^I}\right), \quad (6)$$

respectively, where $I_{SD}^t = p_{m,t} h_{m,l,t}^I$ and $I_{DD}^t = \sum_{i \in \mathcal{L}, i \neq l} \chi_{i,t} p_{i,t} g_{i,l,t}^I$ denote the cross-tier interference from S_m to the receiver of D_l on the t-th RB and the co-tier interference between different D2D links sharing the same RB t, respectively.

In this paper, we aim at achieving an improvement of the system utility in terms of sum rate achieved by all D2D links while ensuring the QoS of each CU and D2D link. Then, the optimization problem can be formulated as

$$\max_{\chi_{l,t}, p_{l,t}} \; R^D = \sum_{l \in \mathcal{L}} \sum_{t \in \mathcal{T}} \log_2 \left(1 + \frac{\chi_{l,t} p_{l,t} g_{l,t}}{1 + I_{SD}^t + I_{DD}^t}\right), \quad (7a)$$

$$s.t. \; r_m \geq R_{th}^C, \; \forall m, \quad (7b)$$

$$R_l^D \geq R_{th}^D, \; \forall l, \quad (7c)$$

$$\sum_{t \in \mathcal{T}} \chi_{l,t} p_{l,t} \leq P_{\max}^D, \forall l, \quad (7d)$$

$$\sum_{t \in \mathcal{T}} p_{m,t} \leq P_{\max}^S, \forall m, \quad (7e)$$

where R_{th}^C and R_{th}^D are the minimum data rate requirement of each CU and D2D link, respectively. Constraints (7b) and (7c) guarantee the QoS of each CU and D2D link, respectively. Constraint (7d) ensures that each D2D link reuses the RBs of CUs under the maximum transmitting power $P_{\max}^D$. Constraint (7e) forces the transmit power of each CU to be below the power limit $P_{\max}^S$. It is noted that the existence of subchannel selection indicator $\chi_{l,t}$ makes the optimization problem hard to solve, which is NP-hard [24].

III. OVERLAPPING COALITION FORMATION GAME

In this section, an overlapping coalition formation game (OCFG) is proposed to find an approximate solution of the problem which is described in Section II.B. In OCFG algorithm, the user equipments sharing the same RB will be divided into one coalition and each D2D link can join multiple coalitions simultaneously. We aim at maximizing the throughput of all D2D links while guaranteeing the QoS of each CU and D2D link. The proposed OCFG algorithm includes two phases: initialization of overlapping coalition and cooperative game with overlapping coalitions.

A. INITIALIZATION OF OVERLAPPING COALITIONS

As defined before, in our proposed scheme, each coalition consists of no more than one CU and several D2D links. That is, each D2D link can use the RBs directly allocated by BS or reuse the RBs of CUs. Therefore, the coalitions which D2D links decide to join can be categorized into two kinds: coalitions consist of one CU and several D2D links, and coalitions consist of only D2D links. For each D2D link, it is allowed to participate in more than one coalition simultaneously to ensure its minimum data rate requirement. Correspondingly, if the CU's date rate is decreased seriously due to the participation of some D2D links, it will refuse to share the RBs with them. Then, a criterion is given to illustrate the principles of overlapping coalition formation, which can provide a guideline for the initialization of overlapping coalitions.

Criterion 1: The overlapping coalitions that user equipments cooperate to form should satisfy the following conditions: (i) the potential cross-tier interference caused by D2D links sharing RBs with CUs should be as small as possible; (ii) the data rate of each D2D link should meet the minimum requirement; (iii) the QoS of each CU should be guaranteed.

To satisfy condition (i), each D2D link sorts an ascending order sequence of CUs depending on the potential cross-tier interference strength. For example, assume that the CU sequence for D_l is given as $\{S_1, S_2, \cdots, S_M\}$, it means that D_l potentially causes the most serious cross-tier interference to CU S_M and the lowest cross-tier interference to CU S_1. Therefore, D_l prefers to reuse the RB of S_1 rather than S_M, which implies that the condition (i) is applied. To satisfy condition (ii), each D2D link is allowed to join one or more coalitions simultaneously to guarantee its requirement of data rate. For example, D_l can choose CUs to form coalitions starting from S_1 up to S_M until $R_l^D \geq R_{th}^D$ is satisfied. Finally, the QoS of CUs should be guaranteed because D2D communications are just a complement to cellular networks. According to condition (iii), if the participation of D_l makes the date rate of CU S_m $(m = 1, 2, \cdots, M)$ under predefined threshold R_{th}^C, D_l will be refused to be a member of the coalition which S_m is currently in.

All in all, the user equipments sharing the same RB are divided into one coalition and each coalition is composed of several D2D links and at most one CU. Each D2D link is allowed to join multiple preferable coalitions to ensure its minimum requirement of data rate on the premise that the QoS of each CU is guaranteed. By forming overlapping coalitions, the cross-tier interference can be mitigated efficiently and the network is more flexible.

B. COOPERATIVE GAME WITH OVERLAPPING COALITIONS

Based on the initialization of overlapping coalitions, cooperative game with overlapping coalitions is given in this section, aiming at maximizing the system utility in terms of the sum rate of D2D links. In order to provide a better description of the proposed OCFG algorithm, several basic definitions are presented as follows.

Definition 3: An OCFG $G = (\mathcal{N}, v, \mathcal{CS})$ with a transferable utility[2] (TU) is defined by a finite set of players $\mathcal{N}$, a characteristic function v that describes the payoff available to each coalition, and an overlapping coalitional structure $\mathcal{CS}$.

In our game, the players $\mathcal{N}$ are the set of D2D links, i.e., $\mathcal{N} = \{D_1, D_2, \ldots, D_L\}$. Each player (i.e., D2D link) is allowed to switch from current coalition to another to achieve a higher system utility. The structure $\mathcal{CS}$ is defined in Definition 1 and denoted by $\mathcal{CS} = \{C_1, C_2, \ldots, C_K\}$ $(M \leq K \leq T)$.

The throughput of D_l corresponding to C_k $(k = 1, 2, \ldots, K)$ is denoted by $R^D_{l,k}$, which is given as

$$R^D_{l,k} = \begin{cases} 0, & R^D_l < R^D_{\text{th}}, R^D_{l,k} = \min\{R^D_{i,k}\}, \\ \delta_{l,k} \cdot \tilde{r}_{l,k}, & \text{otherwise}, \end{cases} \tag{8}$$

where $i = 1, 2, \ldots, N_k$ (N_k is the number of D2D pairs in C_k). According to the two kinds of coalitions aforementioned, if coalition C_k contains a CU occupying the t-th RB and D_l reuse the RB of CU, $\tilde{r}_{l,k} = r_{l,t}$ as given in Eq. (1); if coalition C_k contains no CU and D_l use the t-th RB directly, $\tilde{r}_{l,k} = r'_{l,t}$ as defined in Eq. (2). The parameter $\delta_{l,k}$ denotes the participation level of D_l in C_k, which is given as

$$\delta_{l,k} = \tilde{r}_{l,k} / \sum_{k \in Join(\mathcal{D}_l)} \tilde{r}_{l,k}, \tag{9}$$

where, $\sum_{k \in Join(\mathcal{D}_l)} \tilde{r}_{l,k}$ is the total data rate of D_l in all coalitions it participates in.

Then, the payoff of D_l in C_k is denoted by $v(D_{l,k})$, that is $v(D_{l,k}) = R^D_{l,k}$. It can be implied from Eq. (8) that, if the sum rate of D_l does not meet the desired requirement and its throughput is also the minimum among all D2D pairs in C_k, its payoff in C_k is 0. Eq. (8) demonstrates different payoffs of D2D link in each coalition according to its data rate achieved in that coalition. The total individual payoff obtained by D_l from coalitional structure $\mathcal{CS}$ is defined as the sum payoff of D_l from all coalitions it is currently participating in, which can be written as

$$v(D_l, \mathcal{CS}) = R^D_l = \sum_{k \in \{1, \ldots, K\}, C_k \in Join(D_l)} v(D_{l,k}). \tag{10}$$

The utility of a coalition C_k can be defined as the sum payoff of all D2D links in C_k, which is given as

$$v(C_k) = \sum_{i}^{N_k} v(D_{i,k}). \tag{11}$$

From Eq. (11), it can be seen that the utility of C_k depends on the size of coalition, i.e., the number of D2D links in the coalition. However, larger number of D2D links in one coalition may result in higher interference to CU. Consider the QoS constraint of CU, the utility of C_k in the current structure $\mathcal{CS}$ can be further written as

$$v(C_k, \mathcal{CS}) = \begin{cases} \sum_i^{N_k} v(D_{i,k}), & r_m \geq R^C_{\text{th}} \\ 0, & \text{otherwise}. \end{cases} \tag{12}$$

Consequently, the utility of a structure $\mathcal{CS}$ can be expressed as

$$v(\mathcal{CS}) = \sum_{k=1}^{K} v(C_k, \mathcal{CS}). \tag{13}$$

To achieve the goal of maximizing the sum rate of all D2D links, each D2D link is allowed to switch from current coalition to another existing coalition or to a new independent coalition which only consists of itself. Accordingly, two switching orders are proposed to compare two coalitional structures as follows.

Definition 4: Consider a coalitional structure $\mathcal{CS}_P = \{C_1, \ldots, C_f, \ldots, C_g, \ldots, C_K\}$, if a D2D pair D_l in C_f switches to another existing coalition C_g, a new structure $\mathcal{CS}_Q = \{C_1, \ldots, C^q_f, \ldots, C^q_g, \ldots, C_K\}$ is formed with $C^q_f = C_f \setminus \{D_l\}$ and $C^q_g = C_g \cup \{D_l\}$. Then, the switching order $\triangleright_C$ means that $\mathcal{CS}_Q$ prefers to $\mathcal{CS}_P$ for D_l, which is defined as

$$\mathcal{CS}_P \triangleright_C \mathcal{CS}_Q \Leftrightarrow \begin{cases} v(D_l, \mathcal{CS}_Q) > v(D_l, \mathcal{CS}_P)), \\ v(C^q_g, \mathcal{CS}_Q) \geq v(C_g, \mathcal{CS}_P)), \\ v(\mathcal{CS}_Q) > v(\mathcal{CS}_P). \end{cases} \tag{14}$$

From (14), the switching order $\triangleright_C$ implies that three conditions should be satisfied when D_l switches from one coalition to another existing coalition: (i) the individual payoff of D_l is increased, (ii) the utility of the coalition C^q_g which D_l newly joins is not decreased and (iii) the total utility of the new coalitional structure $\mathcal{CS}_Q$ is increased.

Definition 5: Consider a coalitional structure $\mathcal{CS}_P = \{C_1, \ldots, C_f, \ldots, C_K\}$ and a D2D link D_l is a member of coalition C_f, that is $C_f \in Join\,(D_l)$. Another new coalitional structure is defined as $\mathcal{CS}_E = \{C_1, \ldots, C^e_f, \ldots, C_K, C_{K+1}\}$ where $C^e_f = C_f \setminus \{D_l\}$ and $C_{K+1} = \{D_l\}$. To transform coalitional structure $\mathcal{CS}_P$ into $\mathcal{CS}_E$, D_l departs from coalition C_f and forms a new dependent coalition C_{K+1}

[2]The TU property means that the total utility can be appropriately apportioned among the coalition members in $\mathcal{CS}$ by adopting a feasible coding manner or different transmitting power.

consisting of only D_l. Then, the switching order $\triangleright_I$ can be given as

$$\mathcal{CS}_P \triangleright_I \mathcal{CS}_E \Leftrightarrow \begin{cases} v(D_l, \mathcal{CS}_E) > v(D_l, \mathcal{CS}_P)), \\ v(\mathcal{CS}_E) > v(\mathcal{CS}_P). \end{cases} \quad (15)$$

The switching order $\triangleright_I$ implies that two conditions should be satisfied when D_l splits to a newly independent coalition: (i) the individual payoff of D_l is increased and (ii) the total utility of the new coalitional structure $\mathcal{CS}_E$ is increased.

To summarize, the OCFG algorithm for joint interference management and resource allocation in D2D communications can be described explicitly in Algorithm 1. In this algorithm, a history information set $H(D_l)$ is introduced to record the coalitions that each D2D link $D_l, l = (1, 2, \cdots, L)$ has ever participated in. If a new coalition has already existed in the list of $H(D_l)$, D_l will not join this coalition even if one or two switching order conditions are satisfied.

Algorithm 1 OCFG Algorithm for Joint Interference Management and Resource Allocation

Initial Stage: At the beginning time $\tau = 0$, the network is initialized to be all singletons $CS = \{\{C_1\}, \{C_2\}, \ldots, \{C_M\}\}$.

Phase 1-Initialization of Overlapping Coalitions

1: Each D2D link maintains a cross-interference list of CUs sorted in ascending order, that is, from the lowest to the highest interference level;

2: Each D2D link sends a cooperation proposal to CU starting from the first one to the last one in the list, which ensures the QoS of CU, that is $r_m \geq R_{th}^C$;

3: Each D2D link participates in all possible coalitions to ensure $R_l^D \geq R_{th}^D$;

Phase 2-Cooperative Game with Overlapping Coalitions

1: **Repeat**

2: Update time index $\tau = \tau + 1$;

3: Each D2D link decides whether to switch from the current coalition to another existing coalition according to the switching order condition (14) and the history $H(D_l)$;

4: Each D2D link decides whether to leave the current coalition and participates in a completely new independent coalition according to the switching order condition (15) and the history $H(D_l)$;

5: **Until** convergence to a stable coalition CS^*.

The OCFG algorithm mainly consists of two parts: initialization of overlapping coalitions and cooperative game with overlapping coalitions. Initially, the network is partitioned by M singleton coalitions and each coalition contains a CU. Then, each D2D link finds its preferable RBs to reuse while guaranteeing the QoS of CUs. By forming overlapping coalitions, the potential cross-tier interference can be mitigated efficiently. Successively, D2D links decide whether to leave the current coalition to join another existing coalition or a new independent coalition only consisting of itself. Each time the D2D link changes the coalition which it is currently participating in, both the individual payoff of D2D link and the total payoff of new formed coalitional structure should be improved. In addition, the history information set $H(D_l)$ is introduced to prevent D2D link from joining the same coalition twice. When no D2D link has an incentive to change the coalitions it is currently participating in, a stable coalitional structure with overlapping coalitions is obtained and the corresponding resource reuse strategy is achieved.

IV. CHARACTERISTIC ANALYSIS OF THE OCFG ALGORITHM

To reveal more insight into the proposed OCFG algorithm, the analysis of its characteristics in terms of convergence, stability and computational complexity is provided in this section.

A. CONVERGENCE

Starting from any initial coalitional structure, the convergence of OCFG algorithm is guaranteed.

Proof: Assume that the numbers of D2D links, CUs and RBs are given, the total number of possible coalitions that can be formed is finite. It is noted that, each switch operation of a D2D link leads to a new coalitional structure with higher system utility than old ones, in addition, the history information set $H(D_l)$ is used to prevent D2D links from choosing previous coalitions. Therefore, given finite number of coalitional structure, the proposed OCFG algorithm is guaranteed to reach a final stable coalitional structure with overlapping coalitions. ■

Definition 6: For a given coalitional structure $\mathcal{CS}$ with K coalitions, an imputation for $\mathcal{CS}$ is defined as $\boldsymbol{\varphi}_{CS} = (\boldsymbol{\varphi}_1, \cdots, \boldsymbol{\varphi}_K)$, where $\boldsymbol{\varphi}_k = \left(v\left(D_{1,k}\right), \cdots, v\left(D_{L,k}\right)\right)^T$. Then, to evaluate the stability of the proposed algorithm, an outcome $\mathcal{O}(\mathcal{CS}, \boldsymbol{\varphi}_{CS})$ of the game with coalitional structure $\mathcal{CS}$ is proposed.

B. STABILITY

Given an OCFG $G = (\mathcal{N}, v, \mathcal{CS})$, if all the players in $\mathcal{N}$ has no incentive to take a switch operation, that is to say, no player has a profitable deviation from the current coalitional structure. Then, the outcome $\mathcal{O}(\mathcal{CS}, \boldsymbol{\varphi}_{CS})$ of current $\mathcal{CS}$ is stable. The proposed OCFG algorithm always converges to the stable overlapping coalitional strcture with a stable outcome.

Proof: The proof can be achieved by the analysis of stationary distribution of Markov chain [25]. Denote the transition matrix and the stationary probability vector for the Markov chain by $\mathbf{P}$ and $\boldsymbol{\Pi}$, respectively. The elements in $\mathbf{P}$ are the transfer probability $p_{\mathcal{CS}\rightarrow\mathcal{CS}^*}$ from coalitional structure $\mathcal{CS}$ to $\mathcal{CS}^*$, which is defined as

$$p_{\mathcal{CS}\rightarrow\mathcal{CS}^*} = \begin{cases} 1, & v(\mathcal{CS}^*) > v(\mathcal{CS}), \\ 0, & \text{otherwise}. \end{cases} \quad (16)$$

The stationary probability vector $\mathbf{\Pi}$ can be obtained by solving

$$\mathbf{\Pi}^{\mathrm{T}}\mathbf{P} = \mathbf{\Pi}^{\mathrm{T}}, \tag{17}$$

where, $\mathbf{\Pi}^{\mathrm{T}} = \{\pi_{\mathcal{CS}_1}, \ldots, \pi_{\mathcal{CS}_k}, \ldots, \pi_{\mathcal{CS}_K}\}$ and $\pi_{\mathcal{CS}_k}$ is the probability that $\mathcal{CS}_k$ will be formed. Hence, the stationary distribution of the Markov chain $\pi_{\mathcal{CS}_k} = \sum_{\mathcal{CS}^* \neq \mathcal{CS}} \pi_{\mathcal{CS}^*} p_{\mathcal{CS} \to \mathcal{CS}^*}$ can be acquired to prove the stability of the final coalitional structure. ■

C. COMPUTATIONAL COMPLEXITY

The computational complexity of OCFG algorithm is less than $O(L \times T)$.

Proof: In the proposed OCFG algorithm, each D2D link has a possibility of switching from the current coalition to a new coalition if such an operation can improve the system utility (i.e., the sum rate of network). Given a coalitional structure $\mathcal{CS}$, for each D2D link, the computational complexity of finding RB to reuse can be easily computed by $O(L \times T)$ in the worst case. It is noted that the worst case occurs only when all D2D links work in a non-cooperative way. After the initialization of overlapping coalition formation is completed and history information set $H(D_l)$ is introduced, the complexity will be reduced. Therefore, the computational complexity of OCFG algorithm is less than $O(L \times T)$ obviously. ■

V. SIMULATION RESULTS

In this section, simulation results are provided to evaluate the performance of the proposed OCFG algorithm. In the simulations, CUs and D2D links are distributed uniformly in a hybrid macrocell network with a radius of 500 m. The distance from transmitter to corresponding receiver of a D2D link is 50 m. The bandwidth of RB and the thermal noise level are set to be 15 KHz and -174 dBm/Hz, respectively. To make system model more practical, the path-loss channel model for CUs and D2D links are set to be $PL_{CU} = 15.3 + 37.6 \log 10(r)$ and $PL_{D2D} = 14.2 + 30 \log 10(r)$, respectively. Here, the parameter r denotes the distance from the transmitter to the corresponding receiver in meters. In addition, the maximum transmitting power of CU and D2D link are set to be 23 dBm and 13 dBm, respectively. The minimum data rate requirement of CU and D2D link are 4 bit/s/Hz and 1 bit/s/Hz, respectively.

In Fig. 2, a snapshot of a hybrid macrocell resulting from the proposed OCFG algorithm is presented, with four D2D links and CUs. The BS is located at (0,0) and user equipments are uniformly distributed in this area. By adopting OCFG algorithm, the user equipments can self-organize into a stable and the most beneficial coalitional structure as shown in Fig. 2. Here, the coalitional structure is composed of four coalitions $\{CU_1, D_3\}, \{CU_2, D_2, D_4\}, \{CU_3, D_4\}, \{CU_4, D_1\}$, which are denoted by C_1, C_2, C_3 and C_4, respectively. It is noted that the finally formed coalitional structure is an overlapping coalitional structure. For example, D2D link D_4 is an overlapping player because it participates in coalition C_2 and C_3 at the same time. In addition, we can see that the user equipments which are closely located tend to form different coalitions to mitigate the mutual interference. Fig. 2 shows that a stable overlapping coalitional structure can be obtained by using the proposed OCFG algorithm.

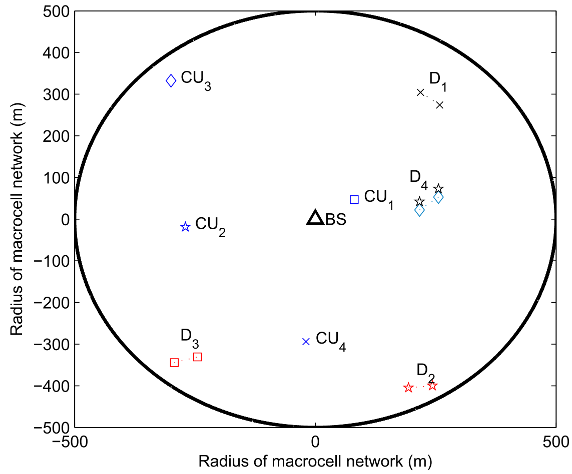

FIGURE 2. A snapshot of an overlapping coalitional structure resulting from OCFG algorithm.

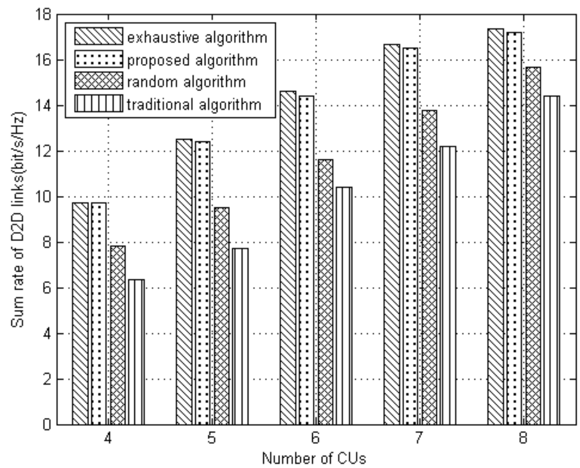

FIGURE 3. The sum rate of D2D links versus different number of CUs.

Fig. 3 and Fig. 4 show the variation of sum rate of all D2D links versus the number of CUs and D2D links, respectively. For both figures, the numbers of D2D links and CUs are fixed as 4, respectively. Here, the "traditional algorithm" represents the scheme in [23] that each D2D link can reuse RB of only one CU and each CU can not share its RB with more than one D2D link. The "random algorithm" means that D2D links randomly select CU to form coalition where the distance between the receiver of D2D link and CU is more than 200 m. The "exhaustive algorithm" refers to the scheme that D2D links choose appropriate RBs to reuse by exhaustive search and the "proposed algorithm" refers to the proposed OCFG algorithm. It can be seen from Fig. 3 that the sum rates of D2D links of all the methods increase when the number of CUs increases. The reason is that D2D links will have more RBs

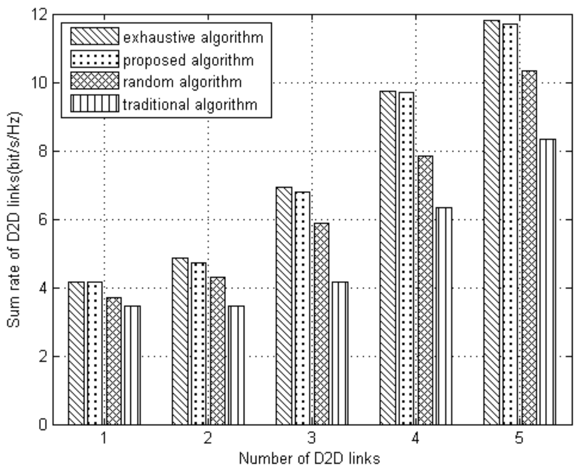

FIGURE 4. **The sum rate of D2D links versus different number of D2D links.**

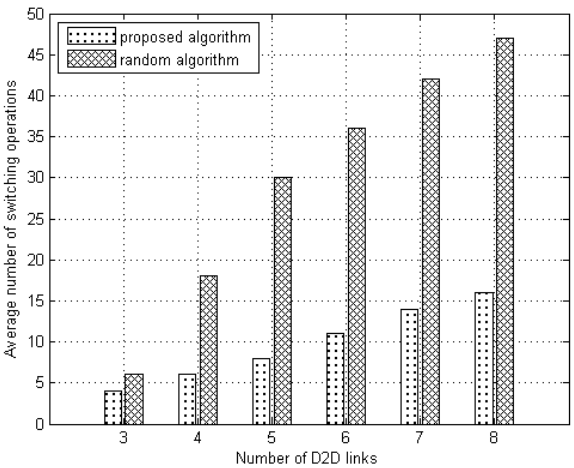

FIGURE 5. **Average number of switching operations versus different number of D2D links.**

to reuse when the number of CUs increase. As can be seen from Fig. 4, the sum rate of D2D links increase obviously as the number of D2D links increases. Specifically, we can also see that the performance of the proposed OCFG algorithm outperforms the other three algorithms on the condition of different number of CUs or D2D links. In addition, the performance gap between OCFG algorithm and the "exhaustive algorithm" can be negligible, however, the computational complexity of the proposed OCFG algorithm is obviously smaller than that of the exhaustive algorithm ($O\left(T^L\right)$).

Fig. 5 investigates the efficiency of OCFG algorithm as a function of the number of D2D links. Here, the efficiency is defined as the average number of switching operations to obtain the final coalitional structure. In Fig. 5, the number of CUs is set to be 8. It can be seen from Fig. 5 that the average number of switching operations increases as the number of D2D links increases. The reason is that the possibility of finding appropriate CUs to cooperate for each D2D link increases with the number of D2D links. Under the same simulation circumstance, we can see that the performance

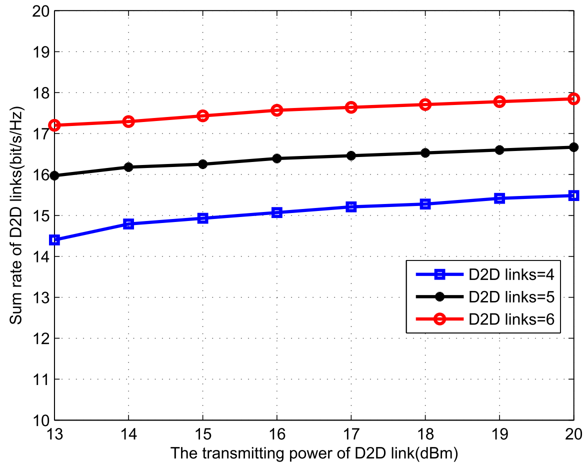

FIGURE 6. **The sum rate of D2D links versus different transmitting power of D2D links.**

of the proposed OCFG algorithm outperforms the "random algorithm".

Fig. 6 shows the impact of different transmitting power of D2D links on the performance of system. The maximum transmitting power of D2D links is set from 13 dBm to 20 dBm and the number of CUs is set to be 6. As can be seen from Fig. 6, the sum rate of D2D links increases with the transmitting power and the upward trend slows down when the transmitting power continues to increase. The reason is that the interference between user equipments will increase when the transmitting power of D2D links increases. Therefore, increasing transmitting power of D2D links can not improve the performance of system all the time.

VI. CONCLUSIONS

In this paper, the problem of joint interference management and resource allocation for D2D communications underlaying cellular networks has been studied. To maximize the throughput of all D2D links, a novel OCFG algorithm has been proposed to allow user equipments to cooperate to form a coalitional structure with overlapping coalitions. In this algorithm, each D2D link can autonomously decide whether to join or leave a coalition to obtain higher system utility. Moreover, the characteristics of the proposed OCFG algorithm have been analyzed, including convergence, stability and computational complexity. Based on the property analysis, it can be seen that user equipments cooperate to form a stable and most beneficial overlapping coalitional structure finally. Simulation results have demonstrated that the proposed OCFG algorithm can improve the performance significantly compared to other existing schemes.

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JINMING HU was born in 1986. He received the B.S. degree in communication and information systems from the University of Jinan, and the M.S. degree in communication and information systems from Nantong University. He is currently pursuing the Ph.D. degree with the National Mobile Communications Research Laboratory, Southeast University, Nanjing, China. His research interests include energy efficiency in heterogeneous networks and energy harvesting in wireless communication.

WEI HENG was born in 1965. He received the B.S. degree in information engineering from the Huazhong University of Science and Technology in 1987, and the M.S. degree in signal and information processing and the Ph.D. degree in communications and information system from Southeast University in 1990 and 1997, respectively. From 1997 to 2002, he was a Research Scholar with The Catholic University of America. Since 2002, he has been a Professor with the National Mobile Communications Research Laboratory, Southeast University. His research interests include wireless communication theory, cognitive radio, and signal processing.

YAPING ZHU was born in 1990. She received the B.S. degree and the M.S. degree in communication and information systems from Southeast University, Nanjing, China, where she is currently pursuing the Ph.D. degree with the National Mobile Communications Research Laboratory. Her research interests are in the area of broadband mobile communications and localization in mobile wireless sensor networks.

GANG WANG received the B.S. degree in electrical engineering and the M.S. degree in circuit and system from Southeast University, Nanjing, in 2000 and 2003, respectively, where he is currently pursuing the Ph.D. degree in communications and information systems. He is currently a Teacher with the National Mobile Communications Research Laboratory, Southeast University. His research interests include green communications, energy harvesting wireless communications, and wireless communication theory.

XIANG LI was born in 1990. He received the B.S. and M.S. degrees from the University of Electronic Science and Technology of China in 2012 and 2015, respectively. He is currently pursuing the Ph.D. degree with the National Mobile Communications Research Laboratory, Southeast University, Nanjing, China. His research interests include wireless transmission, wireless networking, signal processing, and its applications.

JING WU received the B.S. degree in electronic science and technology and the M.S. degree in communication and information system from the Nanjing University of Posts and Telecommunications, China, in 2013 and 2016, respectively. She is currently pursuing the Ph.D. degree with the Department of Information Science and Engineering, Southeast University, China. Her research interests include statistical signal processing and its applications in wireless communications and cyber-physical systems.