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Research Article

Game-Theoretic Social-Aware Resource Allocation for Device-to-Device Communications Underlaying Cellular Network

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Device-to-Device communication underlaying cellular network can increase the spectrum efficiency due to direct proximity communication and frequency reuse. However, such performance improvement is influenced by the power interference caused by spectrum sharing and social characteristics in each social community jointly. In this investigation, we present a dynamic game theory with complete information based D2D resource allocation scheme for D2D communication underlaying cellular network. In this resource allocation method, we quantify both the rate influence from the power interference caused by the D2D transmitter to cellular users and rate enhancement brought by the social relationships between mobile users. Then, the utility function maximization game is formulated to optimize the overall transmission rate performance of the network, which synthetically measures the final influence from both power interference and sociality enhancement. Simultaneously, we discuss the Nash Equilibrium of the proposed utility function maximization game from a theoretical point of view and further put forward a utility priority searching algorithm based resource allocation scheme. Simulation results show that our proposed scheme attains better performance compared with the other two advanced proposals.

1. Introduction

With the rapid spread of intelligence terminals and the explosive growth of communication capacity, local area services are considered as a popular issue. Traditional cellular networks can not meet the explosive demands for gigantic amount of mobile users in the following years. As Device-to-Device (D2D) communication enables direct communication between a pair of mobile users in proximity by occupying the cellular spectrum without traversing the BS or core network [1, 2], it becomes an important usage case through peer-to-peer scheme while nowadays mobile users in cellular networks need high-speed data service in which they could potentially be in range for direct communication [3–5]. For example, when friends close to each other want to exchange music, picture, or video via their own mobile phone, the D2D communication can provide a reasonable solution for the local media service as the same interested contents can be shared between mobile users. In this way, the throughput and spectral efficiency of the network can be highly increased [6–8].

In D2D communication underlaying cellular network, mobile users occupy the same licensed band of spectrum resource for cellular users to increase the system capacity. Hence, resource allocation becomes the key issue in D2D communication, and appropriate resource allocation schemes are imperative to be conducted to settle this issue [9]. Considering the fact that the D2D communication shares the uplink spectrum resource, Xu et al. utilize a reverse iterative combinatorial auction based mechanism to accomplish the resource allocation [10]. Ferdouse et al. propose a throughput efficient subcarrier allocation (TESA) proposal for multiclass cellular D2D systems [11]. Hoang et al. adopt graph-based approach to discuss the nonorthogonal dynamic spectrum sharing to maximize the weighted system sum rate [12].

Worth mentioning about the above studies [10–12] is that mobile users in social networks usually form stable social networks when communicating with others. They are grouped by social relationships or background to form different communities which have the same interested contents. Human beings in social communities share interested content through online social platforms, such as Weibo and WeChat. The more the interactions that take place in the community, the faster the transmission rate the community will consider. But these studies above all pay attention to improving the transmission rate in an overall perspective to restrict the interference cellular communication suffers [13]. The characteristics of high sociality may be able to improve the spectrum efficiency greatly; however, this has not been considered.

The sociality in D2D communication has been extensively studied for resource allocation optimization problem. Wang et al. model the strength of sociality of D2D links by counting contact time among mobile users [14]. The authors in [15] propose a social-aware resource allocation method based on two hops: communication with the BS (first hop) and extending communication with another device (second hop), but, with the iterations proceeding, the size of the master problem is also increasing. Li et al. quantitatively analyze the benefit taken by the incorporation of social features and propose a social-ware D2D communication framework by leveraging these social networking characteristics; this investigation has created the precedent for studying the problem of social-awareness based D2D resource allocation in [16].

The aforementioned works indicate that the rate performance of the network can be effectively improved by implementing proper interference control policy and fully using social networking characteristics. However, how to allocate cellular resource for each D2D pairs is much more complex. The difference of our work from all the works done by those predecessors is that we maximize the sum transmission rate of the system by jointly paying attention to the interference caused by the D2D transmitter to cellular user and rate performance enhanced by the social relationships between mobile users. Thus, we further design a priority searching algorithm based resource allocation scheme in D2D communications underlaying cellular network.

Generally, D2D pairs along with cellular users may be self-interested to maximize their own benefit through cooperation or competition in the underlaying D2D communication network. Consequently, it is needed to develop suitable solutions to the consideration we present above. At the same time, game theory is adopted for modeling and researching the resource allocation problem in recent works. Many kinds of game theory have been applied to the study of D2D resource allocation problems. In [17], a social-community utilization optimization game is proposed to optimize the utility of social community for each of the D2D pairs. But modeling the game in such a way seems quite a complex task. In [18], Stackelberg game has been applied to model the interactions between D2D users and cellular users. Since the Stackelberg game belongs to the category of cooperative game, its outcome is not social optimum. Further cooperative games such as Nash Bargaining Solution (NBS) are needed to improve the results. In [19], NBS is developed to tackle the inefficiency of the scheme in [18] where the assumption is not reasonable in practical environment.

Despite the popularity of game theory in recent resource allocation related investigation, the most common idea of these papers is to verify that any strategy that deviates from the Nash Equilibrium (NE) can not improve the system performance any more. This one-side proof may be not convincing enough when applying to resource allocation problem between two disjoint sets influenced by mutual interference. Accordingly, the matching theory provides a distributed solution to resource matching problem between two disjoint sets. In [20], the matching theory was employed to match D2D pairs with cellular users to address the energy efficiency optimization problem in D2D enabled cellular networks. Besides, this work was extended to large-scale networks and acquired significant performance gains. In [21], a 3D iterative matching algorithm was proposed to maximize the sum rate of D2D pairs while guaranteeing the QoS requirement of both cellular communication and D2D communication. In [22], the matching theory was used to model the network as a one-to-one matching market and each secondary user (SU) can maximize its utility by selecting the most suitable primary user (PU). However, it is confirmed that sociality-interference joint resource allocation problem has not been considered from the perspective of matching theory.

In this paper, in order to jointly compare the influence of sociality between the mobile users within the same community and power interference caused by D2D communication, we discuss the main problem existing in current resource allocation scheme and propose a utility function maximization (UFM) game for D2D communication underlaying cellular network by utility function construction, game establishment, providing relative proof for the existence of Nash Equilibrium. Inspired by one-to-one matching theory, we propose a priority searching algorithm based resource allocation scheme to acquire the final resource allocation proposal for the UFM game. We perform extensive simulations under realistic social network to evaluate the rate performance of our proposed scheme. The result shows that our proposed scheme improves system performance obviously, in terms of increasing the overall transmission rate and decreasing the transmission time.

The remainder of this paper is organized as follows: we introduce the system model and formulate the problem in Section 2. UFM game is formulated in Section 3. Then, in Section 4, a priority searching based resource allocation algorithm is proposed, and, in Section 5, simulation result and analysis are given, and finally we make the conclusion of the paper in Section 6.

2. Problem Formulation

2.1. System Model. We consider the D2D communication underlaying cellular network in which D2D links occupy the spectrum resource of uplink cellular communication. The reason why we choose uplink one is that when the cellular users (CUs) are in downlink transmission they will suffer from sophisticated interference caused by D2D communication [23]. Otherwise, we divide the investigation of social-awareness based resource allocation for D2D communication

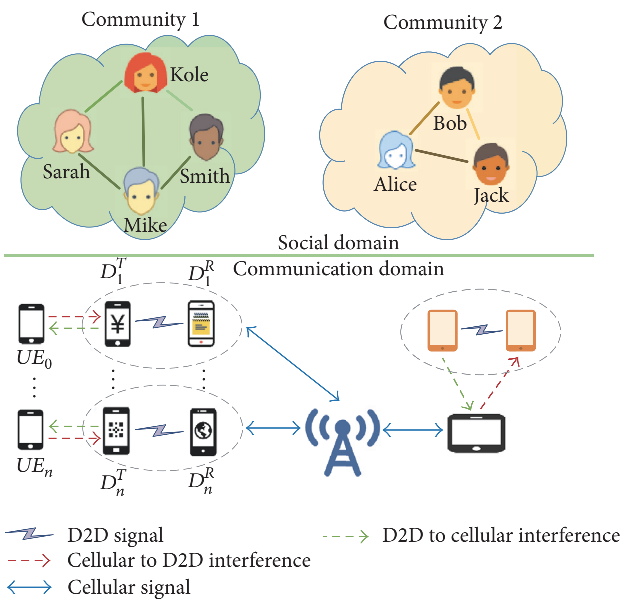

Figure 1: Illustration of social-aware D2D communications underlaying cellular network. In physical domain, wireless links are subject to the physical interference constraints, while social domain indicates the relationships between mobile users.

underlaying cellular networks into two domains in our work: physical domain and virtual social domain. More details about these are illustrated in Figure 1.

In the physical domain, the system contains N nodes labelled as the set of $\mathcal{N} = \{1, 2, \ldots, N\}$. Each node denotes a mobile user that can communicate with the BS or execute D2D communication with other users directly. For active mobile users, they can form $\mathcal{D} = \{1, 2, \ldots, D\}$ D2D pairs. The remaining, which is denoted by the set $\mathcal{C} = \{1, 2, \ldots, C\}$ can request for interested content toward BS via cellular communication. Those D2D pairs can choose to reuse the spectrum resource of any cellular users. But there exist physical constraints between mobile users, and only some of them can form D2D pairs (including D-Tx and D-Rx) [24].

In the social domain, for the reason that a community is combined by sophisticated relationship like friendship, kinship, or even classmates with each other [25], and they were physically in close proximity, we tend to make use of these characteristics to model the social relationship between the users. Users consider the strength of their social trust within a community and their properties of social trust between different communities, respectively, to make D2D communication more secure.

To ensure the practicality of our work, we set the channel scene as Rayleigh fading channel. Under the premise of the free space propagation model, the interference signal power level of cellular user which is introduced by D2D transmitter D-Tx sharing the same spectrum resource with cellular user can be expressed as follows according to Shannon theorem:

$$P_{\text{int},c} = P_d \cdot \zeta_{c,d}{}^{-\alpha} \cdot h_{c,d}^2, \quad (1)$$

while the interference signal of D2D receiver D-Rx is from the BS that establishes communication link with cellular users. Thus, the signal power can be expressed as

$$P_{\text{int},d} = P_B \cdot \zeta_{B,d}{}^{-\alpha} \cdot h_{B,d}^2, \quad (2)$$

where P_d and P_B are the transmitted power of BS and D2D transmitter, respectively. $\zeta_{c,d}$ denotes the distance between the D2D transmitter and cellular user and $\zeta_{B,d}$ denotes the distance between D2D receiver and the BS, α is the path loss exponent, and $h_{c,d}$ and $h_{B,d}$ are the complex Gaussian channel coefficients.

In our investigation, we assume there are one D2D pair and one cellular user within a single cell. By sharing cellular spectrum resource blocks with D2D pair, D2D communication and cellular communication can be conducted synchronously [26]. For the purpose of maximizing the overall system transmission rate, the Signal-to-Noise Ratio (SINR) of the two communication modes is regarded as important indicator. Based on (1) and (2), we can obtain the SINR of cellular user c and D2D receiver d as

$$\text{SINR}_{c,i} = \frac{p_c g_c}{P_{\text{int},c} + N_0}, \qquad \text{SINR}_{d,i} = \frac{p_d g_d}{P_{\text{int},d} + N_0} \quad (3)$$

p_c is the given transmission power of cellular user and p_d is the given transmission power of D2D transmitter; g_d and g_c are the channel gains of cellular link and D2D link, respectively. And N_0 is the noise power on each channel.

At the same time, we usually calculate the sum rate of the system to measure the quality of D2D communication underlaying cellular network. For uplink direction, let $R_{c,i}$ be the data transmission rate between the CU and the BS and $R_{d,i}$ be the data transmission rate between D-Tx and D-Rx. Since the transmission rate of each cellular link and D2D link can be determined by the Shannon capacity [27].

$$R_{c,i} = B_{c,i} \log_2 \left(\text{SINR}_{c,i}\right), \qquad R_{d,i} = B_{d,i} \log_2 \left(\text{SINR}_{d,i}\right), \quad (4)$$

where $\text{SINR}_{d,i}$ and $\text{SINR}_{c,i}$ are the Signal-to-Noise Ratio (SINR) in D2D and cellular communication links and $B_{c,i}$ and $B_{d,i}$ are the allocated licensed band of resource for D2D and cellular communication. What is imperative to mention here is that we only consider the interference that occurred within a single cell and do not consider any influence from other microcells.

To describe reusing relationship of spectrum resource, we denote $x_{c,d} \in [0,1]$ as the indicator matrix of the D2D pairs; that is, $x_{c,d} = 1$ when the D2D pair d occupies the licensed band of resource of the cellular user c; otherwise $x_{c,d} = 0$. Thus, we can acquire the transmission rate of D2D pair multiplying the indicator $x_{c,d}$ by $R_{d,i}$ as $R_{d,i} \cdot x_{c,d}$. The system performance can be represented by the sum of $R_{c,i}$ and $R_{d,i}$.

$$R = \sum_{i=1}^{\mathcal{D}} \left(R_{c,i} + R_{d,i} \cdot x_{c,d}\right). \quad (5)$$

We can improve the system performance by maximizing the sum rate to judge whether our proposed optimal social-aware resource allocation scheme is effective:

$$\begin{aligned} \max \quad & \sum_{i=1}^{\mathscr{D}} R_{c,i} + R_{d,i} \cdot x_{c,d} \\ \text{s.t} \quad & \sum_{d^i \in \mathscr{D}} x_{d^i}^{n^c} \leq 1, \quad c \in \mathscr{C},\ n^c \in \mathscr{C} \\ & \sum_{n^c \in \mathscr{C}} x_{d^i}^{n^c} \leq 1, \quad c \in \mathscr{C},\ d^i \in \mathscr{D}. \end{aligned} \tag{6}$$

2.2. Problem Description

2.2.1. Power Interference. In D2D communication network, we assume the cellular users can share uplink resource with user equipment. During the D2D communication, it is inevitable that D2D transmitter interference will be introduced to others, especially to nearby CUs. And since we limit that each D2D pair can reuse the spectrum resource from at most one cellular user, by assuming there are D D2D pairs and C cellular users in the D2D underlaying communication cellular network, we can simplify the network as Figure 2.

In the simplified network we establish, besides the normal D2D communication, we only consider the effects of both the interference of a generic D2D transmitter introduced to others and all other interference caused to a D2D receiver. For instance, the base station (BS) introduces intratiers interference to the D2D receivers D2D_1^R as shown in Figure 2. Meanwhile, due to the full frequency reuse, D2D_1^T causes interference to CU_1. Considering the power interference caused by the transmitter of the D2D pairs to the nearby UE, we can give the definition that the interference introduced by D2D transmitter d to cellular users c is $I_{d\to c}$, $d \in \mathscr{D}$, $c \in \mathscr{C}$:

$$I_{d\to c} = g_{d,c} p_d, \tag{7}$$

where p_d denotes the transmission power of the corresponding D2D pairs $d, d \in \mathscr{D}$. $g_{d,c}$ denotes the gains of the channel between the transmitter of D2D pair d to cellular users c. Here, the terms c and $g_{d,c}$ are positive. Hence, all of the cellular users are assumed in the single cell and corresponding interference is introduced by prayer d, $d \in \mathscr{D}$, where the player d is called the generic D2D transmitter. Meanwhile, the transmission between player $c, c \in \mathscr{C}$, and the BS also introduces interference to D2D pair d, where we define the intratier interference from player c to player d as follows:

$$I_{c\to d} = g_{c,d} p_c, \tag{8}$$

where $g_{c,d}$ is the channel gain between the BS and the D2D pairs d. p_c is the transmission power of cellular user c. Here, we assume that orthogonal channels are used for different CUs, and we do not consider any power control policy at the macrocell layer. In our investigation, we pay attention to the power interference D2D transmitter introduced to the CUs, in other words, a new power control policy for the D2D transmitters.

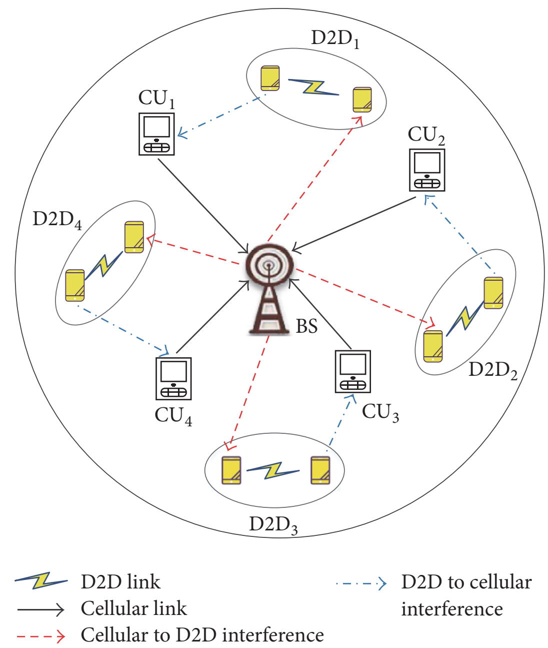

Figure 2: Interference model in the uplink.

2.2.2. Social Utilization. In this part, we use a visualized social-network graph to analyze the social relationship between the mobile users and depict the social characteristic of the network. In the virtual social network, social ties are defined to qualitatively measure the strength of social relationship between D2D users and report the communication demands between users. Besides, social centrality plays a very important role in D2D data transmission; users with high centrality are more likely to hold high capacity in terms of data transmission volume and frequency. In that case, for the purpose of obtaining a visualization of the social characteristics existing in user's daily activities, we adopt the proximity social network derived from a real-world mobility dataset—Karate club. The network contains the social data of 34 members within a Karate club, documenting 78 pairwise links between members who interact inside or outside the club [28]. By analyzing the realistic dataset and the interaction behaviors among these members, we plot the social network formed by users visualized by the trace in Figure 3, where the magnitude of the node indicates the centrality of the specified user, and the label of the node indicates the strength of the social ties of corresponding links.

In the virtual social network, active mobile users in close relationship form certain community. In order to weigh the influence from the social relationship between the mobile users within the same community to our resource allocation scheme, we define the utility of social relationship by quantifying the social characteristic. Since we suppose mobile users in different communities have no social trust between each other, when cellular users download some content from the BS, cellular users belonging to the same community can deliver the content to other interested users directly instead of forwarding by the BS. And the amount of the content is

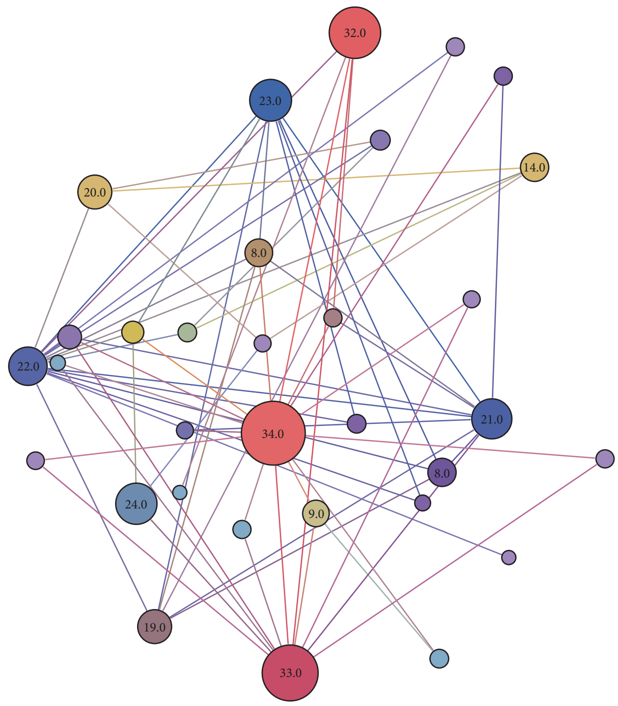

Figure 3: Social characteristics observed from social-network trace.

determined by the social closeness between the users. The more close social relationship the D2D users have, the more content they will exchange with each other [29].

Based on the analysis mentioned above, the social graph can be denoted by $G_s = (V_s, R_s)$. V_s and R_s stand for the set of all cellular users and D2D users and the set of relationships, respectively. To be mentioned, the matrix R_s demonstrates the strength of the relationship of V_s in the social network. Generally, we use the form of matrix described as $\omega_{d,r}$, $d, r = 1, 2, \ldots, D$, and $\xi_{d,c}$, $d = 1, 2, \ldots, D$, $c = 1, 2, \ldots, C$. $\omega_{d,r}$ denotes the intimacy coefficient between D2D users, and $\xi_{d,c}$ denotes the intimacy coefficient between the cellular users and D2D users. According to the definition in the dataset of Karate club, we plan to divide the closeness coefficient into two kinds: very close and a little close. The values of $\omega_{d,r}$ and $\xi_{d,c}$ follow the set of $[0, 1]$. For example, $\omega_{d,r} = 0$ implies a little close intimacy between the D2D users, and $\omega_{d,r} = 1$ naturally implies a very close intimacy. As illustrated in Figure 1, we construct a simple social network. In community 2, D2D users Jack and Alice have a very close intimacy, while Bob and Jack are unfamiliar with each other. Inspired by the analysis in Part A, the utility of D2D users can be represented as follows:

$$U_d = \log_2 \left(1 + \sum_{i=G_d^p \cap G_d^s} \text{SINR}_{d,i} \right), \quad \forall d \in \mathscr{D}. \qquad (9)$$

Approximately, the utility of cellular users can be represented as follows:

$$U_c = \log_2 \left(1 + \sum_{i=G_c^p \cap G_c^s} \text{SINR}_{c,i} \right), \quad \forall c \in \mathscr{C}. \qquad (10)$$

By the way, G^p and G^s denote the physical and social relationship of the system model mentioned above. Thus, G_c^p and G_c^s denote the set of cellular users that reuse the same frequency band of spectrum resource and maintain stable interaction with each other. G_d^p and G_d^s denotes the D2D users which reuse the same spectrum resource from cellular users and maintain stable interaction with the cellular users. U_d represents the influence of the social relationship to D2D communication and U_c represents the influence of the social relationship to cellular communication. To sum up, we can define the social-community utility function of D2D users d as follows:

$$U_d(X) = \sum_{r,d \in \mathscr{D}} \omega_{d,r} U_d + \sum_{c \in \mathscr{C}} \xi_{d,c} U_c. \qquad (11)$$

X denotes the correlation matrix of $x_{c,d}$, and, in general, the degree of social utility enhancement involves two aspects: the weighted sum of social utility enhancement by D2D pairs having social connections with each other as $\sum_{r \in \mathscr{D}} \omega_{d,r} U_d$ and the weighted sum of utility enhancement between familiar cellular users and D2D pairs as $\sum_{c \in \mathscr{C}} \xi_{d,c} U_c$. In this way, the element of social relationship is considered in the investigation of resource allocation in D2D communication underlaying cellular network.

3. Game Theory-Based Framework for Resource Allocation

In our investigation, we tend to maximize the sum transmission rate of the system. For example, if D2D transmitter brings about higher-than-sociality interference to cellular users, the operator would remove the D2D link. So, we model the resource allocation issue between D2D links and cellular links as the utility maximization game.

3.1. Problem Formulation. The resource allocation policy of each of the D2D pairs d depends on the power interference introduced by D2D communication and social relationships between the mobile users. Compared to the physical relationship between mobile users, the social relationship is relatively less changeable. Thus, we need to consider the joint influence from social enhancement and power interference to the D2D pairs dynamically. By that, we tend to define the utility of a D2D link as the profits which are contributed by cellular users and D2D users using spectrum resources and D2D users using social characteristics. In this case, the utility function of the dth D2D links is defined as follows:

$$\Gamma_d(X) = \alpha \cdot R + \beta \cdot U_d(X) - \gamma \cdot B_{d,i} - \varepsilon \cdot I_{d \to c} \quad \text{iff } U_d(X) \geq I_{d \to c}. \qquad (12)$$

α and β are the charging price of unit data rate supported by the spectrum resource and the social network. γ and ε are the cost function of a D2D occupied resource and power interference. With respect to γ, a pricing function from (12) is adopted, which can be expressed as follows:

$$\gamma = n + s \cdot (B_{d,1} + \cdots + B_{d,i})^{\tau}, \quad i = 1, 2, \ldots, m. \tag{13}$$

n, s, and τ denote nonnegative constants and $\tau \geq 1$ to guarantee that the cost function is convex. In order to improve the applicability, we suppose

$$[N_0 + g_d P_{d,r}] = \frac{p}{B_{d,i}}, \tag{14}$$

where p is a nonnegative constant [30]; then

$$\begin{aligned} \Gamma_d(X) = {} & \alpha \cdot B_{d,i} \log_2 (1 + \mathrm{SINR}_{d,i}) + \beta \cdot \sum_{j \in \mathscr{D}} \omega_{d,r} U_d \\ & + \sum_{c \in \mathscr{C}} \xi_{d,c} U_c - \left[n + s \cdot \sum_{i=1}^{m} B_{d,i} \right] B_{d,i} - \varepsilon \cdot I_{i \to u}, \\ & \text{iff } U_d(X) \geq I_{d \to c}. \end{aligned} \tag{15}$$

In the proposed problem in (15), each D2D pair is aimed at integrating every aspect of influence and then maximizing its own utility. As the distribution of mobile equipment is changing all the time, the features of the network are varying instantaneously. So, for the purpose of exact comparison, we should implement some effective method to eliminate this kind of dilemma.

Dynamic game with complete information can model certain dynamic situation under the premise that the participant knows the type of the action it will take and the information needed for every decision of the action. It can be applied into our proposed model as every D2D pair can get to know the social utility and power interference and get the real-time $\Gamma_d(X)$ when D2D communication is in progress. So, the problem above can be regarded as a dynamic game with complete social information as well as sophisticated interference information. In this way, we can propose a dynamic game based scheme to optimize the overall performance of the D2D communication network due to the two-sides' competition.

3.2. UFM Game Formulation. From the analysis above, we derive the information from two-sides' action needed in our game theory. And, for the optimization problem, we usually utilize the game theory to solve it. Firstly, we define corresponding strategy adopted by each D2D user d in a certain point of history as $a_d, a_d \in A_d$, where A_d is the set of all available strategies of the D2D pair d. The choice of strategies of all the other participants, that is, all the other D2D pairs in our work, can be defined as $a_{-d} = \{a_1, \ldots, a_{d-1}, a_{d+1}, \ldots, a_D\}$. If the above assumption for the UFM game theory is perfect, there must exist a strategy $a_d \in A_d$ to maximize its own utility function:

$$\max_{a_d \in A_d} \quad \Gamma_d(a_d, a_{-d}), \quad \forall d \in \mathscr{D}. \tag{16}$$

The UFM game for the resource allocation thinking from the perspective of utility function is defined by quadruple $\Phi = \{\mathscr{D}, \{A_d\}_{d \in \mathscr{D}}, \{\Gamma_d\}_{d \in \mathscr{D}}, \{I_{d \to c}\}_{d \in \mathscr{D}, c \in \mathscr{C}}\}$, where $\mathscr{D}$ denotes the D2D pairs. X_d denotes all of the resource allocation strategies D2D pairs set $\mathscr{D}$ can take. Γ_d denotes the utility function of each of the D2D pairs d, and $I_{d \to c}$ denotes the interference introduced by D2D pairs d to cellular user c.

3.3. Nash Equilibrium. Nash Equilibrium is a very important terminology in game theory [31, 32]. It represents a set of strategies which are combined by all optimal choices taken by each participant which reflect the optimal reaction each participant adopts against the other participant's strategies. According to this, if the choices chosen by all the D2D pairs are optimal, the system sum rate of the D2D communication underlaying cellular network will reach the extreme one. The following part will discuss the existence of Nash Equilibrium in UFM game theory and provide proof for it.

Generally, the UFM game $\Phi = \{\mathscr{D}, \{A_d\}_{d \in \mathscr{D}}, \{\Gamma_d\}_{d \in \mathscr{D}}, \{I_{d \to c}\}_{d \in \mathscr{D}, c \in \mathscr{C}}\}$ can reach the Nash Equilibrium if each of the D2D pairs has the only optimal response to the other D2D pair's strategy:

$$a_d^* = \arg\max_{a_d \in A_d} \quad \Gamma_d(a_{-d}, a_d), \quad \forall d \in \mathscr{D} \tag{17}$$

and $a^* = \{a_1^*, a_2^*, \ldots, a_D^*\}$ denotes the Nash Equilibrium.

Because of the same incentive of changing their strategy for all the D2D pair, we refer to the potential game theory to demonstrate the existence of NE for the UFM game. In [33], Monderer and Shapley propose the definition of potential game and elaborate the idea in detail, too. In the field of wireless resource allocation games, game theory has been applied in a few of authors' papers, for example, [34–36]. In potential game theory, the change in individual player's gain can be mapped to the global function, which is called the potential function. By this way, we can conclude if there is any change that occurred on individual player, the potential function will change equally in the strict potential game. Γ denotes an exact potential function if and only if $\exists F(I) : I \to U$, $\forall i, j$, $\forall I_i, I_j$, $U_i \in I_i$, and $U_j \in I_j$.

$$\Gamma_i(I_i, U_{-i}) - \Gamma_j(I_j, U_{-j}) = F(I_i, U_{-i}) - F(I_j, U_{-j}). \tag{18}$$

In the D2D communication system we have modeled, the change of power interference and social utility caused by D2D links would change the utility function of the game, which is consistent with the principle of potential function. On the other hand, potential game has the following inherent properties, which are described in [33]: (1) There must exist a pure-strategy NE and a solution for it. (2) The Nash Equilibrium corresponds to the maxima of the potential function Γ. (3) Generally, the convergence to Nash Equilibrium would be reached in finite improvement or searching path according to sequential best-response dynamics.

For the condition of a single band frequency channel, the potential game is formulated by utilizing the following utility-maximizing function:

$$\begin{aligned} \Gamma_i = -(& \text{Total utility function generated by } i \\ & + \text{Total utility function experienced by } i). \end{aligned} \tag{19}$$

Based on the potential game theory, we can demonstrate the existence of the Nash Equilibrium of our proposed UFM game. For Γ for every $d \in \mathscr{D}$ and for every $a_{-d} \in A_{-d}$

$$P(d) = \Gamma_d(a_{-d}, a_d) - \Gamma_d(a_{-d}, a'_d). \tag{20}$$

Theorem 1. *In certain history point t, function $P(d)$ derived from UFM game is subgame perfect.*

Proof. We suppose strategy a_d denotes occupying the spectrum resource of cellular user c which is taken by D2D pairs d initially. Therefore, the initial indicator is $x_{c,d}$. Once D2D pair d change its strategy and make a request for the spectrum resource of cellular user c', the indicator changes to $x'_{c,d}$. Then, we can obtain

$$\begin{aligned}\Gamma_d - \Gamma'_d &= \alpha \cdot R + \beta \cdot U_d(X) - \varepsilon \cdot I_{d\to c} - \alpha \cdot R' - \beta \\ &\quad \cdot U_d(X) - \varepsilon \cdot I'_{d\to c} \\ &= \alpha \cdot (R - R') - \varepsilon \cdot (I_{d\to c} - I'_{d\to c}).\end{aligned} \tag{21}$$

We denote $\Delta_1 = R - R'$ and $\Delta_2 = I_{d\to c} - I'_{d\to c}$. As we can see, $\Delta_1 \gg \Delta_2$. Finally, we conclude that

$$\Gamma_d - \Gamma'_d > 0. \tag{22}$$

It means that no D2D pair can acquire performance enhancement by changing its strategy, so we prove that our proposed game is subgame perfect. As subgame is the restriction from the perspective of history circumstances, it can lead to the Nash Equilibrium of the game directly. □

4. Resource Allocation Scheme for UFM Game Theory

4.1. Priority Searching Based Solution. The value of the utility function Γ_d varies when D2D pair chooses to reuse spectrum resource from different cellular user, and the final aim of the UFM game is to determine the order of the utility function by the size of value. According to analysis in Sections 3.2 and 3.3, the resource allocation strategy a^* has a Nash Equilibrium. It means that we can finally achieve an optimal strategy by substituting the other strategies one by one in finite times. It is similar to the establishment of preference list and iterates until acquiring the best selection among different alternatives [10]. Inspired by the one-to-one matching theory, we will show the main idea of the proposed resource allocation algorithm in detail.

Definition 2. For any D2D pairs, we define the binary priority relation set $\succ_i$ to represent the entire set of resource allocation strategies that each D2D pair i would possibly take. In our UFM game, D2D pairs can choose to reuse the resource occupied by the associated cellular users or not according to the priority set. For any D2D pairs, $a_i \succ_i a'_i$ means D2D pairs i prefer choosing c as the target resource source instead of c'. Since the priority set is determined by the utility function, we can define the priority as follows:

$$\begin{gathered} a'_i \succ_i a_i \Longleftrightarrow \\ \Gamma_i(a'_i) > \Gamma_i(a_i), \\ \forall i \in \mathscr{D}. \end{gathered} \tag{23}$$

This definition demonstrates that D2D users i are likely to reuse the spectrum resource of cellular users c as no more options can bring additional performance gains. We can set the highest priority for cellular user c in the set belonging to D2D user i. By this, a complete priority set can be obtained by repeating searching operation. For every D2D pair, we can also design an optimization resource allocation scheme based on the priority set. In this scheme, every D2D pair urges finding its own highest priority and reusing the spectrum resource shared by the corresponding cellular users.

Let us present Algorithm 1.

Based on the definitions and priority searching operation, we can obtain a final Nash-stable resource scheme a_{fin} for D2D users to solve the utility maximization problem, which is given in Algorithm 1. From the whole knowledge given above, we can see that D2D users make switching iteration following a logically standard based on an arbitrarily chosen initial resource allocation strategy a_{ini}. At the beginning of each iteration, D2D user $i \in \mathscr{D}$ is randomly chosen by the system in step (13). And, then, the selected D2D user replaces its resource allocation strategy with a_{ini} by random choosing a occupied cellular users and determine its strategies a_i and uniformly selects another social-trust cellular user $c' \in \mathscr{C}$. Then, the D2D pair will request the base station for the channel state information once establishing communication link with these two cellular users c and c'. After acquiring specified information, the BS will computes the utility function of the resource allocation strategies of a and a' and broadcast to the participant of the game model. Meanwhile, making the decision that whether to carried out the switch operation for D2D link. If $a_i \succ_i a'_i$, the switch operation will not be executed. Otherwise, the switch operation will be executed. The iteration will continue until all of the priority searching operations for each D2D pair are traversed and reach a final Nash Equilibrium scheme a_{fin}.

Different from those conventional D2D resource allocation schemes, our proposed scheme needs to select suitable community detection dataset and analyze the social-community information inside. And a priority based potential game theory is applied in our scheme. This important information is taken into consideration in our proposed scheme fully.

4.2. Uniqueness and Boundedness. According to Theorem 1, for a given history point t, the combination of strategy $a_i, a_i \in A_i$, can reach a status of being subgame perfect as reaction to the combination of strategy a_{-i}. To prove the uniqueness and boundedness of our proposed game, it is necessary to confirm that if there exist any participant $\forall \hat{i} \in \mathscr{D}$ and its

(01) **Input**: Number of mobile users N and random resource allocation strategy a_{ini}.
(02) **Output**: A priority based resource allocation scheme a_{fin}.
(03) Utilize the dataset of Karate Club network
(04) Calculate the transmission rate of the D2D links and cellular links.
(05) Obtain $U_d(X)$ and $I_{d\to c}$
(06) **if** $U_d(X) \le I_{d\to c}$, remove the D2D links
(07) **else** keep the D2D links
(08) Define the matrix of indicator $x_{c,d} \in [0,1]$
(09) $I = \text{find } x_{c,d} \ne 0$ && $I = 1$
(10) There is just one c cellular users qualified to share resources to D2D user, $r = r_{c,d}$
(11) **else if**, uniformly randomly choose one cellular users c and a possible cellular users c', and denote its associate resource sharing as $a_i \in a_{\text{ini}}$
(12) Calculate $\Gamma(a_i')$ and $\Gamma(a_i)$, priority = 0;
(13) **if** $a_i' \succ_i a_i$; **then** Priority = 1;
(14) **else** repeat (15)~(16);
(15) **if** Priority == 1; **then**
(16) D2D pairs quit current resource occupying strategy of c, and turn to adapt the new resource allocation strategy of c'
(17) substitute the current resource occupying strategy a for strategy a', and add it to a_{cur}
(18) **Until** all of the D2D pairs complete the priority searching operation, resource occupying strategy switching operation and reach Nash Equilibrium a_{fin}

Algorithm 1: The utility function maximization D2D links redistribution algorithm.

corresponding strategy $\widehat{a}_i$ can give better reaction to the strategy combination a_{-i} than a_i and make $\widehat{a}_i \succ_i a_i$ available. So we provide the following proof relative to the uniqueness and boundedness of our proposed UFM game.

Theorem 3. *For all of the D2D pairs whose $x_{c,d} = 1$, the proposed priority searching based scheme can only obtain a unique resource allocation scheme a_{fin}.*

Proof. Based on the description in Algorithm 1, we suppose reversely that the combination of strategy a_i is not subgame perfect. And, then, there must exist certain participant i that has strategy $\forall\widehat{i} \in \mathscr{D}$ and outperforms a_i. Now, we investigate another strategy $\widetilde{a}_i$, and when $t < \widehat{t}$, $\widehat{a}_i$ is equal to $\widetilde{a}_i$, but, after $\widehat{t}$, it is equal to a_i. Then, in any subgame after the history point $\widehat{t}$, strategy $\forall\widehat{i} \in \mathscr{D}$ is at least as well as $\widetilde{a}_i$ for the reason that $\forall\widehat{i} \in \mathscr{D}$ has deviated from a_i once. We can also conclude that strategy $\forall\widehat{i} \in \mathscr{D}$ is at least as well as $\widetilde{a}_i$ after the history point t, which is contrary to the assumption that strategy $\forall\widehat{i} \in \mathscr{D}$ improves the strategy a_i. And so on, we can investigate other $\widetilde{a}_i$ to prove its equal benefit with $\forall\widehat{i} \in \mathscr{D}$ until reaching the unique resource allocation scheme a_{fin}.

Through the above analysis, we prove the uniqueness of the UFM game by Reduction to Absurdity. In each iteration in Algorithm 1, it may lead to a new resource allocation strategy. As there is only $\mathscr{C}$ in the physical domain and limited $\mathscr{D}$ D2D pairs due to the limited social relationship in the social domain, each of the D2D pairs is corresponding to $\mathscr{C}$ types of resource allocation scheme. So the priority searching operation will eventually end in limited steps. This fact assures the boundedness of our proposed UFM game based scheme. □

5. Simulation Results and Discussions

In this section, we implement the simulation results from different perspective to verify the performance of our proposed UFM algorithm and elaborate some necessary explanation for the results. Main simulation parameters have been given in Table 1. Simulations are executed in a single cell, which are within an isolated community circumstance. Path loss models are considered for cellular and D2D links, along with shadow fading model. According to the dataset of Karate club, we conduct the simulation within a 500 m × 500 m area to guarantee most of the club member's activities are within this area, and 34 members of the club are randomly distributed within the BS coverage area. Meanwhile, the bandwidth of allocated resource is assigned arbitrarily within the range limitation. We compare our proposed UFM algorithm with the following resource allocation schemes: (a) distributed resource allocation (DRA), which allocates the D2D communication resource by thinking in a distributed way [37], and (b) optimal social-community aware resource allocation (OSRA), which allocates the D2D communication resource to reduce the total transmission time [38]. All the results are averaged over 10 times' trial.

Without loss of generality, on one hand, we prescribe the pathloss model between the base station and all the mobile users as COST (European Cooperation in Science and Technology) 231 Hata model [39].

$$\mathrm{PL}_{\mathrm{CU}} = 36.7 + 35 \times \lg(d). \quad (24)$$

Meanwhile, we prescribe the pathloss model between different cellular users and D2D users as Xia model [40], given as follows:

TABLE 1: System simulated parameters in the performance evaluation.

Parameter	Value
Coverage radius of BS	500 m
Distance of D2D	20 m~50 m
Noise figure	9 dB at device
Transmission power	BS: 46 dBm; device: 23 dBm
Maximum D2D transmitter power	23 dBm
Range of bandwidth	10 MHz~20 MHz
Communication demand	50 W
Interference threshold	5.6×10^{-6} W
n, s, z, τ	1
α, β	20

$$\mathrm{PL} = \begin{cases} 66.5 + 40 \times \log(d), & d > 50 \\ 100.7 + 20 \times \lg(d), & d < 50. \end{cases} \quad (25)$$

Since we assume the inner distance of D2D pair remains in close standards and relatively close, the free space model can be given by

$$\mathrm{PL} = 38.4 + 20 \times \lg(d). \quad (26)$$

Moreover, we consider the case of fast fading model for Rayleigh fading. In different situation, we adopt a different fading model to investigate. In this way, the evaluation of the average performance is objective. We also set a great number of criterions for our simulation: the maximum power state of D2D users is set at 23 dBm, and the maximum interference which mobile users can tolerate is assumed to be 5.0×10^{-6}. Before investigating the system performance based on our proposed UFM game, we tend to show the joint influence of the power interference caused by spectrum sharing and social characteristics in each social community illustrated in Figure 4.

In this section, we analyze the sum power interference and sum social utility, respectively, as the number of cellular users varies. The case of 10 cellular users means the situation of system whose spectrum resource is in short supply. In this situation, D2D users possibly have to share the spectrum resource of the same users, while the case of 30 cellular users means D2D pairs have many resource-occupying choices. The results indicate that the sum power interference decreases with the trend of the number of cellular users increasing as the sum social utility stay in quite a stable level. And when the number of cellular users in the system exceeds 18, the influence from social utility will surpass the influence from power interference. And then we evaluate the system sum rate and sum time with different number of cellular users using the proposed UFM algorithm and the other two advanced schemes which is illustrated in Figures 5 and 6.

Figure 5 compares the sum rate of the three algorithms under the isolated scenarios, in which we set the number of cellular users varied in the range of [10, 30]. From Figure 5, we observe that, by removing some interference-intolerable D2D links, significant performance enhancement can be

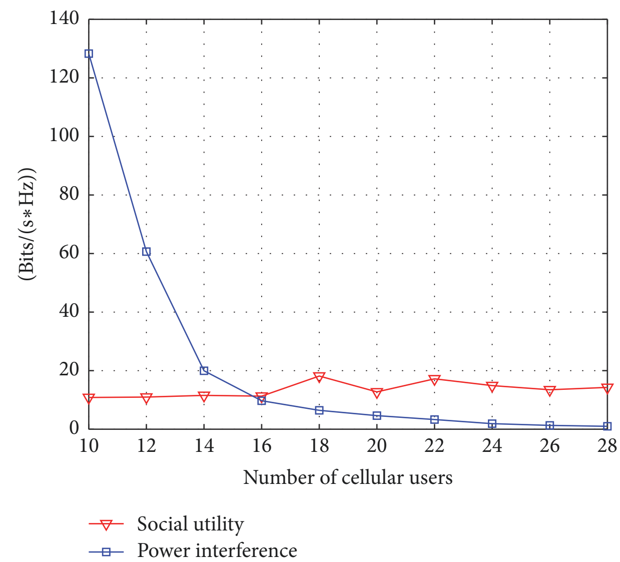

FIGURE 4: Comparison of the joint interference.

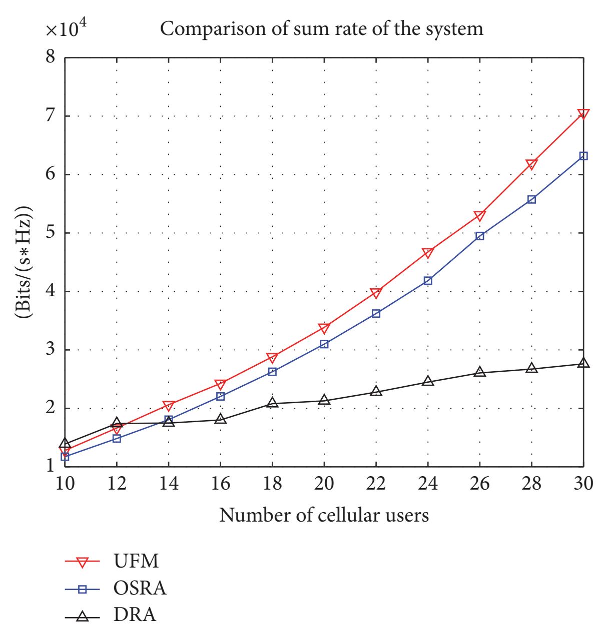

FIGURE 5: Transmission rate comparison of different resource allocation algorithms with different number of cellular users.

achieved when the cellular users are relatively sufficient. But, in the situation that cellular users are not sufficient, performances of the two are roughly equal. The reason is that the excessive reuse relationships of frequency with the same cellular user will cause unbearable interference to the cellular users. According to our algorithm, the D2D link will be removed automatically in both schemes.

Figure 6 compares the sum transmission time of the three algorithms under the isolated scenarios. From Figure 6, we can observe that, in the case that some unnecessary D2D links has been removed, the UFM algorithm still provides quite a considerable reduction of transmission time. That is, because

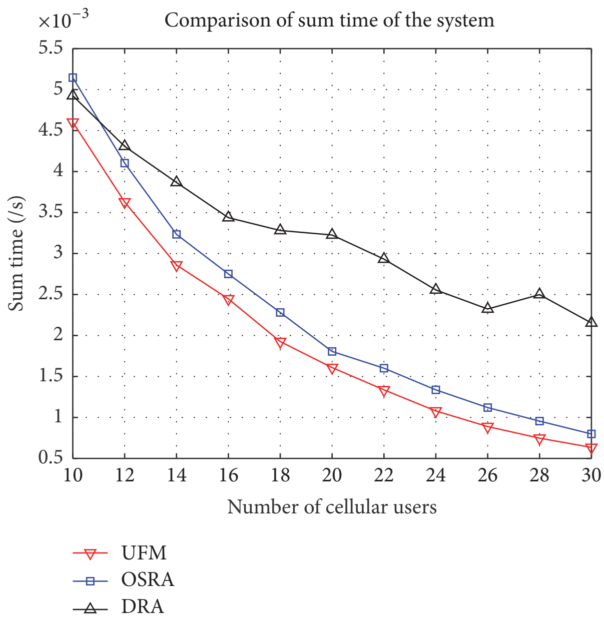

FIGURE 6: Transmission time comparison of different resource allocation algorithms with different number of cellular users.

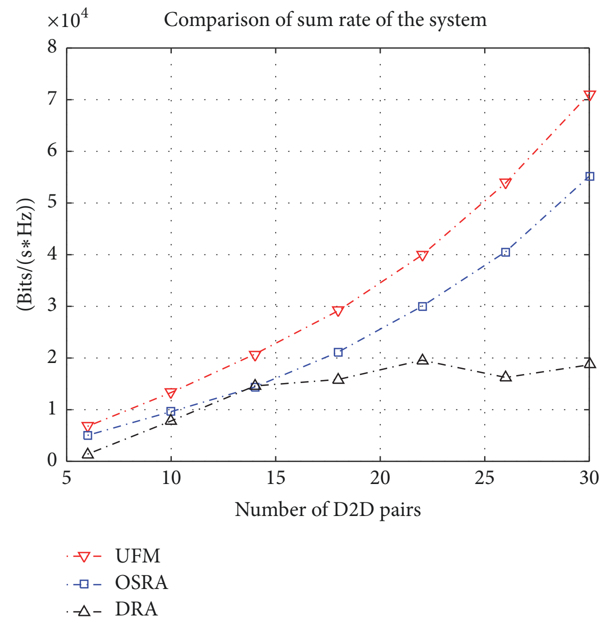

FIGURE 7: Transmission rate comparison of different resource allocation algorithms with different number of D2D pairs.

we allow D2D users to continue to acquire content via cellular communication when D2D communication comes across link interruption. So, the sum transmission time will not be affected greatly.

For the purpose of evaluating the system performance while the number of D2D users varies within a certain range, we set geographical scope as 300 m × 300 m around the BS and suppose the number of cellular users is 10. As illustrated in Figures 7 and 8, the variation range of number of D2D pairs is [5, 30]; the result demonstrates that our proposed UFM game always attains the best performance with the increase of D2D users, compared to the OSRA and DRA. This is because, in the algorithm of DRA or OSRA, there exist little coordination measures to restrict D2D pairs to select their resource and it is inevitable to establish some high-interference links between D2D pairs and cellular users. In our proposed algorithm, UFM game effectively coordinates both social relationship and power interference and then decides whether to access the spectrum resource of certain cellular users, not in a random way. In these circumstances, we can avoid many high-risk links and attain a better system performance in terms of the evaluation of the sum transmission rate. At this point, we can summarize that our proposed scheme precedes the other two schemes in a relatively comprehensive scale.

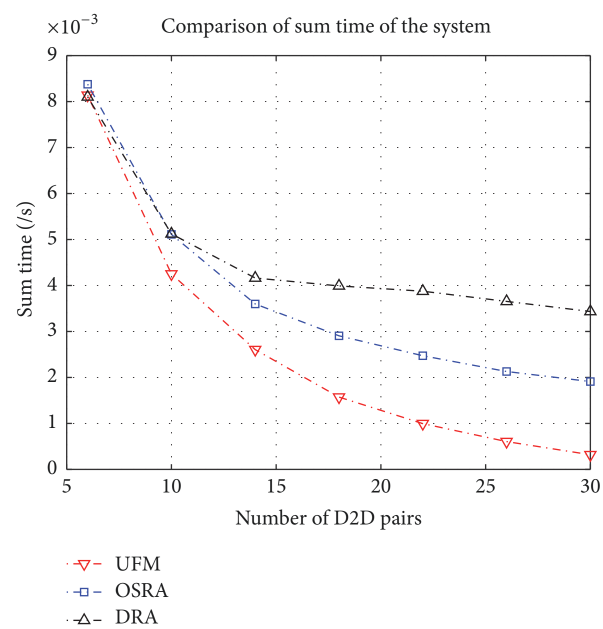

FIGURE 8: Transmission time comparison of different resource allocation algorithms with different number of D2D pairs.

6. Conclusion and Future Work

This paper studies game-theory based social-aware resource allocation in the D2D communication underlaying cellular network based on the realistic social network. By considering the power interference and social utility in the physical and social domain, respectively, a game-theoretic based utility function maximization scheme has been proposed. Also, to demonstrate the optimality of our proposed scheme, this paper provides evidence for the existence of Nash Equilibrium theoretically. Meanwhile, a priority searching operation based resource allocation scheme is designed to implement the Nash Equilibrium of the proposed UFM game. The proposed UFM scheme is numerically shown having superiority over traditional DRA and OSRA scheme: the performances of sum rate and total transmission time are better than the OSRA and DRA algorithm through massive simulation result, suggesting that the proposed scheme is more ideal for joint social-aware resource scenarios considering the social characteristics. Nevertheless, some issues related to further system optimization remain to be addressed, such as power allocation of mobile nodes and cluster formation of social community.

Notations

$\mathcal{N}$: Set of mobile users
$\mathcal{C}$: Set of cellular users
$\mathcal{D}$: Set of D2D pairs
Φ: The UFM game
$\succ_i$: Set of utility priority
$I_{d\to c}$: Interference from dth D2D to cth cellular signal
$I_{c\to d}$: Interference from cth cellular signal to dth D2D
$U_d(X)$: Social utility of dth D2D pairs
$\Gamma_d(X)$: Utility function of dth D2D pairs
$x_{c,d}$: Indicator of resource reusing relations
x_d^*: The Nash Equilibrium of dth D2D pair
X_d: Set of all feasible strategies in UFM game.

Conflicts of Interest

The authors declare no conflicts of interest related to the publication of this paper.

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References

[1] Y. Cao, T. Jiang, and C. Wang, "Cooperative device-to-device communications in cellular networks," *IEEE Wireless Communications Magazine*, vol. 22, no. 3, pp. 124–129, 2015.

[2] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: a survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 4, pp. 1923–1940, Fourthquarter 2015.

[3] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 1801–1819, 2014.

[4] H. Nishiyama, M. Ito, and N. Kato, "Relay-by-smartphone: realizing multihop device-to-device communications," *IEEE Communications Magazine*, vol. 52, no. 4, pp. 56–65, 2014.

[5] M. Zhou, Y. Tang, Z. Tian, L. Xie, and W. Nie, "Robust neighborhood graphing for semi-supervised indoor localization with light-loaded location fingerprinting," *IEEE Internet of Things Journal*, vol. PP, no. 99, pp. 1-1.

[6] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hug, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, 2009.

[7] J. Liu, H. Nishiyama, N. Kato, and J. Guo, "On the outage probability of device-to-device-communication-enabled multichannel cellular networks: an RSS-threshold-based perspective," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 1, pp. 163–175, 2016.

[8] M. Zhou, Y. Tang, W. Nie, L. Xie, and X. Yang, "GrassMA: graph-based semi-supervised manifold alignment for indoor WLAN localization," *IEEE Sensors Journal*, vol. 17, no. 21, pp. 7086–7095, 2017.

[9] J. Liu, S. Zhang, N. Kato, H. Ujikawa, and K. Suzuki, "Device-to-device communications for enhancing quality of experience in software defined multi-tier LTE-A networks," *IEEE Network*, vol. 29, no. 4, pp. 46–52, 2015.

[10] C. Xu, L. Song, Z. Han et al., "Efficiency resource allocation for device-to-device underlay communication systems: a reverse iterative combinatorial auction based approach," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 9, pp. 348–358, 2013.

[11] L. Ferdouse, W. Ejaz, K. Raahemifar, A. Anpalagan, and M. Markandaier, "Interference and throughput aware resource allocation for multi-class D2D in 5G networks," *IET Communications*, vol. 11, no. 8, pp. 1241–1250, 2017.

[12] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Cooperative device-to-device communications in cellular networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 10, pp. 7099–7113, 2016.

[13] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing quality of service over a shared wireless link," *IEEE Communications Magazine*, vol. 39, no. 2, pp. 150–154, 2001.

[14] L. Wang, L. Liu, X. Cao, X. Tian, and Y. Cheng, "Sociality-aware resource allocation for device-to-device communications in cellular networks," *IET Communications*, vol. 9, no. 3, pp. 342–349, 2015.

[15] V. Shah and A. O. Fapojuwo, "Socially aware resource allocation for device-to-device communication in downlink OFDMA networks," in *Proceedings of the 2014 IEEE Wireless Communications and Networking Conference, WCNC 2014*, pp. 1673–1678, Istanbul, Turkey, April 2014.

[16] Y. Li, T. Wu, P. Hui, D. Jin, and S. Chen, "Social-aware D2D communications: qualitative insights and quantitative analysis," *IEEE Communications Magazine*, vol. 52, no. 6, pp. 150–158, 2014.

[17] F. Wang, L. Song, Z. Han, Q. Zhao, and X. Wang, "Joint scheduling and resource allocation for device-to-device underlay communication," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '13)*, pp. 134–139, IEEE, Shanghai, China, April 2013.

[18] F. Tang, Z. M. Fadlullah, N. Kato, F. One, and R. Miura, "AC-POCA: anti-coordination game based partially overlapping channels assignment in combined UAV and D2D based

networks," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1-1.

[19] S. M. Azimi, M. H. Manshaei, and F. Hendessi, "Hybrid cellular and device-to-device communication power control: Nash bargaining game," in *Proceedings of the 2014 7th International Symposium on Telecommunications, IST 2014*, pp. 1077–1081, Tehran, Iran, September 2014.

[20] Z. Zhou, K. Ota, M. Dong, and C. Xu, "Energy-efficient matching for resource allocation in D2D enabled cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 6, pp. 5256–5268, 2017.

[21] C. Xu, C. Gao, Z. Zhou, Z. Chang, and Y. Jia, "Social network-based content delivery in device-to-device underlay cellular networks using matching theory," *IEEE Access*, vol. 5, pp. 924–937, 2017.

[22] X. Feng, G. Sun, X. Gan et al., "Cooperative spectrum sharing in cognitive radio networks: a distributed matching approach," *IEEE Transactions on Communications*, vol. 62, no. 8, pp. 2651–2664, 2014.

[23] J. Zhang, "The interdisciplinary research of big data and wireless channel: a cluster-nuclei based channel model," *China Communications*, vol. 13, no. supplement 2, Article ID 7833457, pp. 14–26, 2016.

[24] S. Mumtaz, K. M. Saidul Huq, J. Rodriguez, and V. Frascolla, "Energy-efficient interference management in LTE-D2D communication," *IET Signal Processing*, vol. 10, no. 3, pp. 197–202, 2016.

[25] N. Kayastha, D. Niyato, P. Wang, and E. Hossain, "Applications, architectures, and protocol design issues for mobile social networks: a survey," *Proceedings of the IEEE*, vol. 99, no. 12, pp. 2130–2158, 2011.

[26] J. Zhang, L. Tian, Y. Wang, and M. Liu, "Selection transmitting/maximum ratio combining for timing synchronization of MIMO-OFDM systems," *IEEE Transactions on Broadcasting*, vol. 60, no. 4, pp. 626–636, 2014.

[27] M. Zhou, Y. Wei, Z. Tian, X. Yang, and L. Li, "Achieving cost-efficient indoor fingerprint localization on wlan platform: a hypothetical test approach," *IEEE Access*, vol. 5, pp. 15865–15874, 2017.

[28] "Zachary's karate club," https://en.wikipedia.org/wiki/Zachary%27s_karate_club.

[29] D. Wu, L. Zhou, and Y. Cai, "Social-aware rate based content sharing mode selection for D2D content sharing scenarios," *IEEE Transactions on Multimedia*, vol. 19, no. 11, pp. 2571–2582, 2017.

[30] J. Huang, Y. Yin, Y. Sun, Y. Zhao, C.-C. Xing, and Q. Duan, "Game theoretic resource allocation for multicell D2D communications with incomplete information," in *Proceedings of the IEEE International Conference on Communications, ICC 2015*, pp. 3039–3044, London, UK, June 2015.

[31] Y. Xiao, K.-C. Chen, C. Yuen, and L. A. DaSilva, "Spectrum sharing for device-to-device communications in cellular networks: a game theoretic approach," in *Proceedings of the IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN '14)*, pp. 60–71, IEEE, McLean, Va, USA, April 2014.

[32] D. Niyato and E. Hossain, "A game-theoretic approach to competitive spectrum sharing in cognitive radio networks," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '07)*, pp. 16–20, Kowloon, China, March 2007.

[33] D. Monderer and L. S. Shapley, "Potential games," *Games and Economic Behavior*, vol. 14, no. 1, pp. 124–143, 1996.

[34] N. Nie and C. Comaniciu, "Adaptive channel allocation spectrum etiquette for cognitive radio networks," in *Proceedings of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN '05)*, pp. 269–278, Baltimore, Md, USA, November 2005.

[35] Y. Xing, C. N. Mathur, M. A. Haleem, R. Chandramouli, and K. P. Subbalakshmi, "Dynamic spectrum access with QoS and interference temperature constraints," *IEEE Transactions on Mobile Computing*, vol. 6, no. 4, pp. 423–433, 2007.

[36] T. Heikkinen, "A potential game approach to distributed power control and scheduling," *Computer Networks*, vol. 50, no. 13, pp. 2295–2311, 2006.

[37] Y. Li, D. Jin, J. Yuan, and Z. Han, "Coalitional games for resource allocation in the device-to-device uplink underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 7, pp. 3965–3977, 2014.

[38] H. Ryu and S.-H. Park, "Performance comparison of resource allocation schemes for D2D communications," in *Proceedings of the 2014 IEEE Wireless Communications and Networking Conference Workshops, WCNCW 2014*, pp. 266–270, Istanbul, Turkey, April 2014.

[39] Y. Li, S. Su, and S. Chen, "Social-aware resource allocation for device-to-device communications underlaying cellular networks," *IEEE Wireless Communications Letters*, vol. 4, no. 3, pp. 293–296, 2015.

[40] D. I. Laurenson, D. G. M. Cruickshank, and G. J. R. Povey, "Computationally efficient multipath channel simulator for the COST 207 models," in *Proceedings of the IEE Colloquium on Computer Modelling of Communication Systems*, pp. 8/1–8/6, London, UK, May 1994.