Social-Aware Resource Allocation for Device-to-Device Communications Underlaying Cellular Networks

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***Abstract*—Device-to-device (D2D) communication is a vital component for the next generation cellular network to bring hop gains, improve spectral reuse, and enhance system capacity. These benefits depend on efficiently solving several technical problems, among which resource allocation that shares spectrum resources between cellular users and D2D pairs is critically challenging. We propose a social-aware D2D resource sharing scheme that exploits social network properties of community and centrality for the new system design paradigm. Extensive simulations with realistic network settings demonstrate the effectiveness of our proposed scheme, which significantly improves the system performance compared to the existing schemes.**

***Index Terms*—Device-to-device communications, social networks, community, centrality, resource allocation.**

I. INTRODUCTION

To meet the emerging demands for local area services, the next-generation cellular network has adopted device-to-device (D2D) communication as a vital component [1]–[3] to improve spectral reuse, bring hop gains, and enhance system capacity. In D2D communications, under the control of base stations (BSs), user equipments (UEs) transmit data to each other directly using the cellular resources. Most of context-aware applications that involve discovering and communicating with nearby devices, including the popular content downloading, can benefit from the D2D communication since it enables physical-proximity communication, which saves communication power while improving the spectral efficiency.

Resource allocation is one of the most critical issues in D2D communications, as cellular users and D2D pairs share the same spectrum resources, and how to allocate these resources has important impact on the efficiency of the whole system. The relationships between the cellular users and D2D pairs are dynamical, changing in time and space. Existing methods for resource allocation include enabling D2D pairs to join or leave a coalition based on the well-defined preferences [4], modeling the allocation mechanism as a reverse iterative combinatorial auction [5], and using the social centrality to assist peer discovery [6]. Problems related with the resource allocation in communities with unstable D2D conditions, i.e., some D2D pairs may not be able to use the resources of other cellular users, however, have not been considered [7], [8].

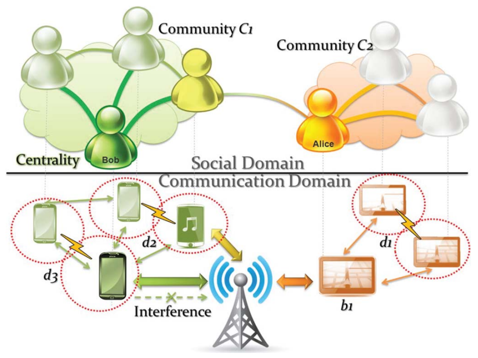

Fig. 1. System overview: a social-aware D2D system is projected onto the two domains.

In a D2D communication system, the devices are carried by human beings, who form social networks exhibiting certain social structures and phenomenons. A natural question is how to exploit human behaviors to assist solving the D2D resource allocation problem. We aim to leverage the social information to assist resource allocation by establishing a social-aware resource allocation approach for D2D communications. Specifically, we utilize the social characteristics of community and centrality to aid resource allocation. We address the resource allocation problem for multiple D2D pairs and cellular users by forming a model in which the D2D pairs are stimulated to share the resources of the cellular users in the same or outside the community. Then we develop an optimal social-community-aware resource allocation (OSRA) algorithm to solve this problem. We conduct extensive simulations under realistic network settings to evaluate the performance of our proposed scheme. The results show that our OSRA significantly enhances system performance, in terms of reducing the D2D transmission time, compared to the schemes that do not consider or only coarsely use the social-domain information.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Overview

We focus on the scenario of one cell involving all the cellular UEs under its coverage. From the communication viewpoint, among these UEs, there are some pairs of D2D users that are physical in close proximity and want to communicate with each other, while others are in the cellular communication mode. As illustrated in the bottom half of Fig. 1, there are one cellular user b_1, and the three D2D pairs $\{d_1, d_2, d_3\}$. The resource allocation problem investigate how to assign appropriate resource blocks shared by the cellular users to D2D pairs to enhance system performance.

These UEs are organized as a social network with stable social characteristics of community and centrality. Communities in a mobile network may present real social groupings, by location, interests, or background. The centrality on the other hand measures the importance of nodes in a community, e.g.

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TABLE I
PARAMETERS OF THE SOCIAL-AWARE D2D COMMUNICATION SYSTEM

Notations	Meanings
$\mathcal{N}$ and N	The set and the number of nodes
$\mathcal{C}$ and C	The set and the number of communities
$\mathcal{N}_c$ and N_c	The set and the number of nodes in community c
$\mathcal{G}_c^p \triangleq (\mathcal{M}_c, \mathcal{E}_c^p)$	D2D communication graph $\triangleq$ (vertex set, edge set)
$\mathcal{G}_c^s \triangleq (\mathcal{M}_c, \mathcal{E}_c^s)$	Social graph $\triangleq$ (vertex set, edge set)
$\mathcal{G}_c^{ps} \triangleq (\mathcal{M}_c, \mathcal{E}_c^{ps})$	Physical-social graph $\triangleq$(vertex set, edge set)
e_{ab}^s	Communication demand of node a and node b
e_{ab}^p	Indicator weather nodes a and b form a D2D link
e_{ab}^{ps}	Communication demands of D2D pair (a, b)

some people are more popular, and interact with more people than others. As shown in the top half of Fig. 1, the UEs form two communities of C_1 and C_2, with *Bob* and *Alice* as the central nodes in the two communities, respectively.

Thus the social-aware D2D system projects itself onto the two domains: in the communication domain, devices establish D2D communication links utilizing the cellular resource subject to the physical and communication constraints; while in the social domain, these devices form a mobile social network regulated by the stable social relationships of community and centrality. Thus, leveraging the properties of social community and centrality is a new paradigm for achieving a reliable and efficient D2D resource allocation.

B. System Model

The system contains a set of N nodes, denoted by $\mathcal{N} = \{1, 2, \cdots, N\}$. Each node $n \in \mathcal{N}$ is a mobile user that can communicate with the BS or with other users directly via D2D communication. These mobile users form C communities, denoted by the set $\mathcal{C} = \{1, 2, \cdots, C\}$, which are detected for example by the community detection algorithm [6]. Since a community is formed by kinship, friendship, or colleague relationship between nodes, we may use it to model the social trust among the nodes by assuming that the users in the same community have trust in each other, while inter-community nodes have no social trust. Users can exploit the social trust to improve the security and quality of D2D communication, e.g., by utilizing the resource of the trustworthy users in the same community to establish D2D links.

For community $c \in \mathcal{C}$, there are N_c active cellular users, denoted by the set $\mathcal{N}_c = \{1, 2, \cdots, N_c\}$, which communicate with the BS and will also share their uplink resources of $\{B_1, B_2, \cdots, B_{N_c}\}$ with the D2D pairs. The other M_c users, denoted by the set $\mathcal{M}_c = \{1, 2, \cdots, M_c\}$, may form D2D communication pairs. However, due to the physical constraints, only some of them are sufficiently close to form D2D pairs. To take such physical constraints into account, we introduce the D2D communication graph $\mathcal{G}_c^p \triangleq (\mathcal{M}_c, \mathcal{E}_c^p)$ in which the set of nodes $\mathcal{M}_c$ is the vertex set and $\mathcal{E}_c^p \triangleq \{(a, b) : e_{ab}^p = 1, \forall a, b \in \mathcal{M}_c\}$ is the edge set, where $e_{ab}^p = 1$ if and only if (iff) nodes a and b are in proximity to each other to form a D2D link. Naturally, these D2D pairs can choose to use the resource of any active cellular user $n \in \mathcal{N}_c$ in the same community. Since social ties influence the communication demands of different D2D pairs, we introduce the social graph $\mathcal{G}_c^s \triangleq (\mathcal{M}_c, \mathcal{E}_c^s)$ to model the service demands among the nodes, in which $\mathcal{E}_c^s \triangleq \{(a, b) : e_{ab}^s \in \mathbb{R}^+, \forall a, b \in \mathcal{M}_c\}$ is the edge set where e_{ab}^s is the communication demand of nodes a and b, and e_{ab}^s reflects the closeness of nodes a and b in the social network. Table I summarizes the key parameters of our model.

C. Problem Analysis

By combining the physical graph and social graph for every community, we obtain the D2D pairs and the corresponding communication demands. This is achieved by defining, for any community $c \in \mathcal{C}$, the physical-social graph $\mathcal{G}_c^{ps} \triangleq (\mathcal{M}_c, \mathcal{E}_c^{ps})$ in which $\mathcal{E}_c^{ps} \triangleq \{(a, b) : e_{ab}^{ps} = e_{ab}^p \cdot e_{ab}^s, \forall a, b \in \mathcal{M}_c\}$ is the edge set, where e_{ab}^{ps} is the communication demand of D2D pair (a, b), and $e_{ab}^{ps} > 0$ iff nodes a and b are in close proximity to form a D2D link and there is communication demand between them. In this way, we combine the physical and social information together to consider the transmission rate and communication demands. We further denote these D2D pairs by the set $\mathcal{D}_c = \{d_1^c, d_2^c, \cdots, d_{D_c}^c\}$ where D_c is the total number of pairs, and the corresponding communication demands e_{ab}^{ps} are denoted by $\{W_{d_1^c}, W_{d_2^c}, \cdots, W_{d_{D_c}^c}\}$.

We model the channel as the Rayleigh fading channel. Let the distance between the two UEs of D2D pair $d_i^c \in \mathcal{D}_c$ be $\zeta_{d_i^c}$, while the distance between cellular user $n^c \in \mathcal{N}_c$ and the receiver of D2D pair d_i^c is denoted by ζ_{n^c, d_i^c}. Further denote the path loss exponents of the two corresponding channels by $\ell_{d_i^c}$ and ℓ_{n^c, d_i^c}, respectively. Then, under the propagation path-loss model [5], if D2D pair d_i^c reuses the resource of cellular user n^c, the transmission rate of this D2D pair, denoted by $r_{d_i^c, n^c}$, can be expressed as

$$r_{d_i^c, n^c} = B_{n^c} \log_2 \left(1 + \frac{P_{d_i^c} \zeta_{d_i^c}^{-\ell_{d_i^c}} \left| h_{0(d_i^c)} \right|^2}{P_{n^c} \zeta_{n^c, d_i^c}^{-\ell_{n^c, d_i^c}} \left| h_{0(n^c, d_i^c)} \right|^2 + N_0} \right), \quad (1)$$

where $P_{d_i^c}$ is the transmit power of D2D pair d_i^c, P_{n^c} is the transmit power of cellular user n^c, and N_0 is the receiver noise power, while $|h_{0(d_i^c)}|^2$ and $|h_{0(n^c, d_i^c)}|^2$ denote the second-order statistics of the Rayleigh fading channel between the two UEs of D2D pair d_i^c and the channel from cellular user n^c to the receiver of D2D pair d_i^c, respectively. Combining all the $r_{d_i^c, n^c}$ together, we obtain all the possible transmission rates of d_i^c with the different choices of cellular users.

To describe the spectrum resource usage relationship, we define $x_{d_i^c, n^c} \in \{0, 1\}$ as the indicator, indicating whether the resource block of UE n^c is allocated to D2D pair $d_i^c, \forall\, n^c \in \mathcal{N}_c$, $\forall\, d_i^c \in \mathcal{D}_c$. Specifically, $x_{d_i^c, n^c} = 1$ when D2D pair d_i^c uses the resource block of UE n^c; otherwise $x_{d_i^c, n^c} = 0$. Thus, we can obtain the transmission rate of D2D pair d_i^c as $x_{d_i^c, n^c} \cdot r_{d_i^c, n^c}$, and the transmission time for D2D pair d_i^c to complete its service demand is then given by

$$t_{d_i^c, n^c} = \begin{cases} W_{d_i^c} / \left(x_{d_i^c, n^c} \cdot r_{d_i^c, n^c} \right), & x_{d_i^c, n^c} = 1; \\ \infty, & x_{d_i^c, n^c} = 0 \end{cases} \quad (2)$$

where $W_{d_i^c}$ represents the total amount of bits required to be transferred between the two UEs of D2D pair d_i^c. Let the matrix $\mathbf{X}$ contain all the decision variables $x_{d_i^c, n^c}$, in which $\mathbf{X}(d_i^c, n^c) = x_{d_i^c, n^c}$. We can maximize the system throughput by minimizing the overall transmission time. This leads to our optimal social community-aware resource allocation problem for the D2D underlaying system:

$$\begin{aligned} &\min \max_{c \in \mathcal{C}, d_i^c \in \mathcal{D}_c} t_{d_i^c, n^c}, \\ &\text{s.t.} \begin{cases} \sum\limits_{d_i^c \in \mathcal{D}_c} x_{d_i^c, n^c} \leq 1, \forall\, c \in \mathcal{C}, n^c \in \mathcal{N}_c; \\ \sum\limits_{n^c \in \mathcal{N}_c} x_{d_i^c, n^c} \leq 1, \forall\, c \in \mathcal{C}, d_i^c \in \mathcal{D}_c. \end{cases} \end{aligned} \quad (3)$$

Since we limit that a D2D pair can use the spectrum resource from only one cellular user, we have the constraint $\sum_{d_i^c \in \mathcal{D}_c} x_{d_i^c, n^c} \leq 1, \forall\, c \in \mathcal{C}$. As the problem (3) is a transformation of the 0-1 knapsack problem, it is NP-hard.

III. OSRA ALGORITHM

We use the notion "Qualified" to describe weather a cellular user is able to provide resource to a given D2D pair:

Definition 1 (Qualified): A cellular user n^c is qualified to provide resource to a D2D pair d_i^c iff it is able to offer such service, and the cooperation between them has not been removed which is denoted by $Con(i, n^c) = 1$.

We use "Settled and Locked" to describe the conditions that a D2D pair can only use the resource of one cellular user:

Definition 2 (Settled and Locked): We call a D2D pair d_i^c Settled iff there exists a cellular user qualified to provide resource to it, that is, $\sum_{k=1}^{N_c} Con(i, k) = 1$. This cellular user is regarded as Locked to d_i^c.

We use the terminology "Removable" to describe whether a possible cooperation between a cellar user and a D2D pair is sufficiently optimal to remain in the final scheme.

Definition 3 (Removable): We call a cooperation between $n' \in \mathcal{N}_c$ and d_i^c Removable iff after removing it

1) Each D2D pair d_i^c has at least one cellular user who is Qualified to provide the required resource for it, i.e. $\sum_{k \in \mathcal{N}_c \setminus n'} Con(i, k) \geq 1$.
2) There are at least D_c cellular users Qualified to provide resources for all the D_c D2D pairs, i.e. the number of cellular users $n \in \mathcal{N}_c$ with $\sum_{j=1}^{D_c} Con(j, n) \geq 1$ is no less than D_c.
3) The Locked cellular users are different from each other, i.e. $\forall\, j, k, p, q, \quad j \neq i$, if $(Con(j, k) = 1$ and $\sum_{l=1}^{D_c} Con(l, k) = 1$ and $Con(p, q) = 1$ and $\sum_{l=1}^{D_c} Con(l, q) = 1)$, then $k \neq q$.
4) The remaining cellular users who are Qualified to provide resources for d_i^c are all not the Locked ones, i.e. $\exists k$, $Con(i, k) = 1$ and $\sum_{l=1}^{D_c} Con(l, k) \neq 1$.

Algorithm 1 Social community-aware resource allocation.

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1: Utilize the community detection algorithm [6] to form $C$ communities;
2: Obtain the communication graph $\mathcal{G}_c^p$ and social graph $\mathcal{G}_c^s$;
3: Combine the two graphs to obtain the communication demand $W_{d_i^c}$ and transmission rate $r_{d_i^c, n^c}$, for all $c \in \mathcal{C}$, $d_i^c \in \mathcal{D}_c$;
4: Con$=\mathbf{X}$, Compute all the $t_{d_i^c, n^c}$ for $\forall\, n^c \in \mathcal{N}_c, \forall\, d_i^c \in \mathcal{D}_c$;
5: Find out the largest finite $t_{d_i^c, n^c}$;
6: while $\forall\, d_i^c, \sum_{k=1}^{N_c} Con(i, k) = 1; \forall\, n, \sum_{j=1}^{D_c} Con(j, n) = 1$ do
7:   if The cooperation between $d_i^c$ and $n$ is Removable then
8:     Remove it: Con$(i, n) = 0, t_{d_i^c, n} = \infty$
9:   else
10:    Keep it, remove all the other cooperations which include $d_i^c$ or $n$: if $((j = i$ and $k \neq n)$ or $(j \neq i$ and $k = n))$, Con$(j, k) = 0, t_{d_j^c, k} = \infty$;
11:  end if
12: end while
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TABLE II
SYSTEM SIMULATED PARAMETERS IN THE PERFORMANCE EVALUATION

Parameter	Value
Coverage radius of BS	500m ~ 1000m
Distance of D2D	20m ~ 55m
Noise figure at device	7dB
Communication demands of D2D pair	50W
Uplink resources of cellular users	10^7 Hz
Transmission power of D2D	24dBm
Transmission power to BS	46dBm

Based on the above definitions, we obtain the OSRA algorithm to solve the optimization problem (3), which is given in Algorithm 1. Different from the conventional D2D resource allocation scheme [7], [8], our proposed social-aware scheme needs to first collect and analysis the social community information and communication demands. These important information are then fully considered in the resource allocation.

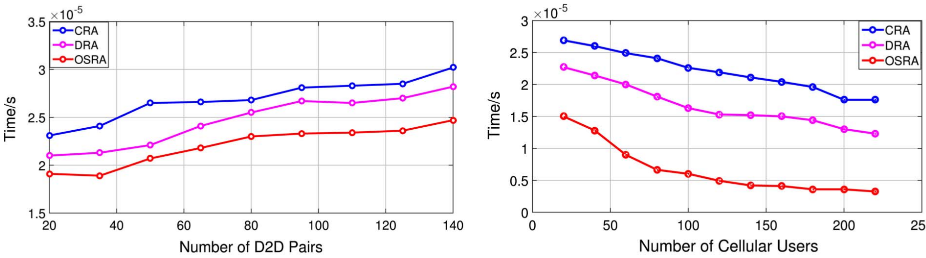
Theorem 1: Algorithm 1 obtains the optimal solution of the optimization problem (3).

Proof: We prove it by using Reduction to Absurdity. Assume that the solution obtained by Algorithm 1, which has the longest communication time of $t_{d_j^c, k^c}$, is not the optimal one. Then there must exist a solution whose longest communication time $t_{max} < t_{d_j^c, k^c}$, which means that all cooperations associated with $t_{d_i^c, n^c}$, including $t_{d_j^c, k^c}$, that are larger than or equal to t_{max} have been removed, see Algorithm 1, lines 5 to 12, and Definition 3 for Removable. However, the cooperation between d_j^c and k^c is kept by Algorithm 1, that is, the cooperation between d_j^c and k^c is not Removable. Thus, such a solution with $t_{max} < t_{d_j^c, k^c}$ does not possibly exist at all. ■

The optimal solution for the NP-hard problem (3) is normally obtained by the enumeration method. Since in the worst case each D2D pair can be allocated with the N_c possible results, the complexity of sucah an optimal algorithm is on the order of $\mathsf{O}(N_c^{D_c})$, where D_c is the number of the D2D pairs and N_c is the number of the cellular users. Our proposed OSRA scheme remove the time-consuming exhausting possible cooperations one by one, and it achieves a complexity on the order of $\mathsf{O}(N_c \cdot D_c)$, which is significantly lower than $\mathsf{O}(N_c^{D_c})$, while still attaining the optimal solution.

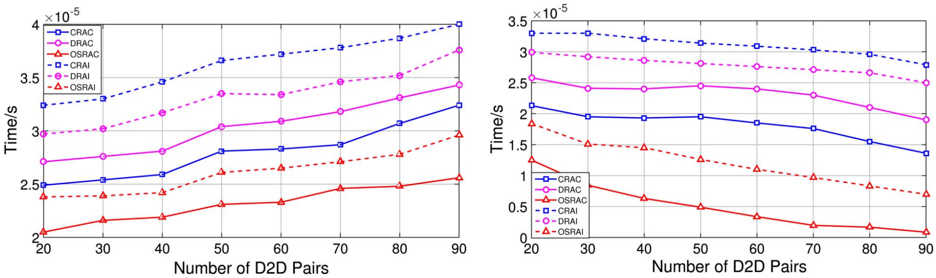
IV. PERFORMANCE EVALUATION

The simulations were carried both in an isolated community scenario, i.e., the D2D pairs in one community could only use their own resources in the same community, and in a connected community scenario, i.e., D2D pairs were able to use the resources of other communities by establishing social trust stimulated by some incentives [6]. The D2D communication channel was based on the scenario that two communicating UEs were physically in close proximity, while the cellular communication channel was simulated according to the urban microcell scenario [9]. Based on the system parameters listed in Table II, which were chosen according to the ITU-R guidelines [9], we simulated the system within a 500 m × 500 m area with the BS located in the center, and uniform randomly distributed the cellular users and D2D pairs within the BS coverage area. All the results were averaged over 10 random trials. We compared our OSRA scheme with the following two D2D resource allocation schemes: a) centralized resource allocation (CRA), where the system allocates the resources of cellular users to the D2D pairs based on the centralized scheme of [10], and b) distributed resource allocation (DRA) which allocates the D2D communication resources based on the distributed scheme of [10]. To the best of our knowledge, these two schemes are the latest resource allocation schemes under the same scenario of our proposal.



(a) (b)

Fig. 2. Transmission time comparison of different resource allocation algorithms in the isolated community scenario. (a) Varying D2D pairs. (b) Varying cellular users.



(a) (b)

Fig. 3. Transmission time comparison of different resource allocation algorithms in both the connected and isolated community scenarios. (a) Varying D2D pairs. (b) Varying cellular users.

We first evaluated the achievable performance of the OSRA, CRA and DRA schemes under the isolated community scenario, in which we set the number of cellular users (D2D pairs) to 140 (20) and varied the number of D2D pairs (cellular users) in the range of [20, 140] ([20, 220]), respectively. The results of the data transmission time obtained are plotted in Fig. 2(a) and (b), respectively. From Fig. 2(a), we observe that the transmission time increases with the number of D2D pairs. The reason is obvious as the more D2D pairs we have, the more time we need to complete the transmission. From Fig. 2(b), it can be seen that the transmission time decreases as the number of cellular users increases, since with more cellular users, more resources are available to enhance the system performance. Compared to the CRA and DRA schemes, our OSRA scheme achieves the best performance. Specifically, it outperforms the CRA and DRA by about 20% to 50% averagely.

We next evaluated the system performance under the connected community scenario, in comparison to the results obtained under the isolated community scenario. Thus, we denoted the three isolated community based schemes as the OSRAI, CRAI and DRAI, while we used the OSRAC, CRAC and DRAC to denote the three corresponding connected community based schemes. Again, we varied the numbers of D2D pairs and cellular users in Fig. 3(a) and (b), respectively. From the results obtained, we observe that in both the isolated and connected community cases, our OSRA always attains the best performance, compared to the CRA and DRA. Furthermore, all the three connected community based schemes outperform their corresponding isolated community based counterparts, demonstrating that when the D2D users are allowed to use the resources of other communities, the system performance is enhanced. For example, the OSRAC reduces the transmission time by about 36% to 82% on average, compared to the OSRAI. The results of Fig. 3 confirm the potential benefits of resource-sharing among the communities. This indicates that in the social-aware D2D communication system, the resource should be shared among different communities by the utilization of social incentives.

V. CONCLUSION

Based on a fundamental understanding of social-aware D2D communication systems in both communication and social domains, we have designed a social-aware resource allocation algorithm to obtain the optimal allocation scheme, and we have carried out extensive simulations to evaluate its performance. The results have demonstrated that our solution has a significant advantage over the two state-of-the-art schemes, in terms of reducing D2D data transmission time.

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