Exploiting Social Ties for Cooperative D2D Communications: A Mobile Social Networking Case

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***Abstract*—Thanks to the convergence of pervasive mobile communications and fast-growing online social networking, mobile social networking is penetrating into our everyday life. Aiming to develop a systematic understanding of mobile social networks, in this paper we exploit social ties in human social networks to enhance cooperative device-to-device (D2D) communications. Specifically, as handheld devices are carried by human beings, we leverage two key social phenomena, namely social trust and social reciprocity, to promote efficient cooperation among devices. With this insight, we develop a coalitional game-theoretic framework to devise social-tie-based cooperation strategies for D2D communications. We also develop a network-assisted relay selection mechanism to implement the coalitional game solution, and show that the mechanism is immune to group deviations, individually rational, truthful, and computationally efficient. We evaluate the performance of the mechanism by using real social data traces. Simulation results corroborate that the proposed mechanism can achieve significant performance gain over the case without D2D cooperation.**

***Index Terms*—Cooperative networking, device-to-device (D2D), game theory, mobile social networking, social reciprocity, social trust.**

I. Introduction

MOBILE data traffic is predicted to grow further by over 100 times in the next 10 years [2], which poses a significant challenge for future cellular networks. One promising approach to increase network capacity is to promote direct communications between handheld devices. Such device-to-device (D2D) communications can offer a variety of advantages over traditional cellular communications, such as higher user throughput, improved spectral efficiency, and extended network coverage [3]. For example, a device can share the video content with neighboring devices who have the similar watching interest, which can help to reduce the data traffic from the network operator.

Cooperative communication is an efficient D2D communication paradigm where devices can serve as relays for each other.[1] As illustrated in Fig. 1, cooperative D2D communication can help to: 1) improve the quality of D2D communication for direct data offloading between devices; and 2) enhance the performance of cellular communications between the base station and the devices as well. Hence, cooperative D2D communication can be a critical building block for efficient cooperative networking for future wireless networks, wherein individual users cooperate to substantially boost the network capacity and cost-effectively provide rich multimedia services and applications, such as video conferencing and interactive media, anytime, anywhere. Nevertheless, a key challenge here is how to stimulate effective cooperation among devices for cooperative D2D communications. As different devices are usually owned by different individuals and they may pursue different interests, there is no good reason to assume that all devices would cooperate with each other.

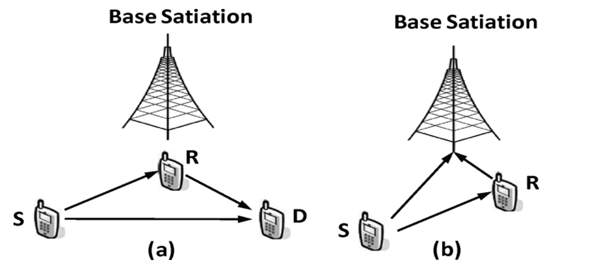

Fig. 1. Cooperative D2D communication for cooperative networking. (a) Device R serves as the relay for the D2D communication between devices S and D. (b) Device R serves as the relay for the cellular communication between device S and the base station. In both cases, the D2D communication between devices S and R is part of cooperative networking.

A. Key Motivation

Since the handheld devices are carried by human beings, a natural question to ask is, "Is it possible to leverage human social relationship to enhance D2D communications for cooperative networking?" Indeed, with the explosive growth of online social networks such as Facebook and Twitter, more and more people are actively involved in online social interactions, and social relationships among people are hence extensively broadened and significantly enhanced [4]. This has opened up a new avenue for cooperative D2D communication system design—we believe that it has potential to propel significant advances in mobile social networking.

[1]There are many approaches for cooperative communications, and for ease of exposition, this study assumes cooperative relaying.

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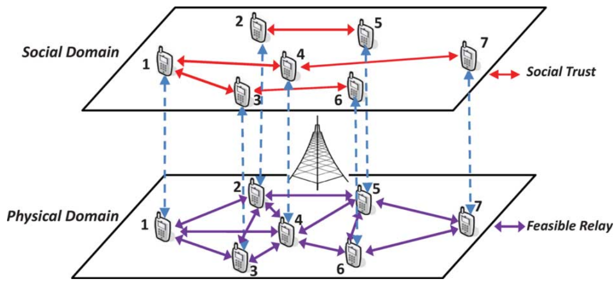

Fig. 2. Social trust model for cooperative D2D communications. In the physical domain, different devices have different feasible cooperation relationships subject to physical constraints. In the social domain, different devices have different assistance relationships based on social trust among the devices.

One primary goal of this study is to establish a new D2D cooperation paradigm by leveraging two key social phenomena: social trust and social reciprocity. Social trust can be built up among humans such as kinship, friendship, colleague relationship, and altruistic behaviors are observed in many human activities [5]. For example, when a device user is at home or work, typically family members, neighbors, colleagues, or friends are nearby. The device user can then exploit the social trust from these neighboring users to improve the quality of D2D communication, e.g., by asking the best trustworthy device to serve as the relay. Another key social phenomenon, social reciprocity, is also widely observed in human society [6]. Social reciprocity is a powerful social paradigm to promote cooperation so that a group of individuals without social trust can exchange mutually beneficial actions, making all of them better off. For example, when a device user does not have any trusted friends in the vicinity, he (she) may cooperate with the nearby strangers by providing relay assistance for each other to improve the quality of D2D communications.

As illustrated in Fig. 2, cooperative D2D communications based on social trust and social reciprocity can be projected onto two domains: the physical domain and the social domain. In the physical domain, different devices have different feasible relay selection relationships subject to the physical constraints. In the social domain, different devices have different assistance relationships based on social trust among the devices. In this case, each device has two options for relay selection: 1) either seek relay assistance from another feasible device that has social trust toward him (her); or 2) participate in a group formed based on social reciprocity by exchanging mutually beneficial relay assistance. The main thrust of this study is devoted to tackling two key challenges for the social-trust- and social-reciprocity-based approach. The first is which option a device should adopt for relay selection: social trust or social reciprocity. The second is how to efficiently form groups among the devices that adopt the social-reciprocity-based relay selection. We will develop a coalitional game-theoretic framework to address these challenges.

B. Summary of Main Contributions

The main contributions of this paper are as follows.

- *Social-trust- and social-reciprocity-based cooperative D2D communications*: We propose a novel social-trust- and social-reciprocity-based framework to promote efficient cooperation among devices for cooperative D2D communications. By projecting D2D communications in a mobile social network onto both physical and social domains, we introduce the physical-social graphs to model the interplay therein while capturing the physical constraints for feasible D2D cooperation and the social relationships among devices for effective cooperation.
- *Coalitional game solutions*: We formulate the relay selection problem for social-trust- and social-reciprocity-based cooperative D2D communications as a coalitional game. We show that the coalitional game admits the top-coalition property based on which we devise a core relay selection algorithm for computing the core solution to the game.
- *Network-assisted relay selection mechanism*: We develop a network-assisted mechanism to implement the coalitional game-based solution. We show that the mechanism is immune to group deviations, individually rational, truthful, and computationally efficient. We further evaluate the performance of the mechanism by the real social data trace. Simulation results show that the proposed mechanism can achieve up to 122% performance gain over the case without D2D cooperation.

A primary goal of this paper is to build a theoretically sound and practically relevant framework to understand social-trust- and social-reciprocity-based cooperative D2D communications. This framework highlights the interplay between potential physical network performance gain through efficient D2D cooperation and the exploitation of social relationships among device users to stimulate effective cooperation. Besides the cooperative D2D communication scenario where devices serve as relays for each other, the proposed social-trust- and social-reciprocity-based framework can also be applied to many other D2D cooperation scenarios, such as cooperative multiple-input–multiple-output (MIMO) communications and mobile cloud computing. We believe that these initial steps presented here open a new avenue for mobile social networking and have great potential to enhance network capacity in future wireless networks.

The rest of this paper is organized as follows. We first discuss the related work and introduce the system model in Sections II and III, respectively. We then study cooperative D2D communications based on social trust and social reciprocity and develop the network-assisted relay selection mechanism in Sections IV and V, respectively. We evaluate the performance of the proposed mechanism by simulations in Section VI, and finally conclude in Section VII.

II. Related Work

D2D communications have recently drawn great attention from the wireless research community. Most existing literature has focused on the interference coordination issue between D2D communications and cellular communications. Authors in [7] and [8] studied the power control problem for restricting co-channel interference from D2D communications to cellular communications. Janis *et al.* in [9] utilized MIMO transmission schemes to mitigate interference from cellular downlink to D2D receivers sharing the same spectrum resources. Zulhasnine *et al.* in [10] proposed to lessen interference to cellular communications by properly pairing the cellular and D2D users. Currently, more and more research efforts are devoted to cooperative D2D communications, which can significantly enhance the performance of D2D communications. Raghothaman *et al.* in [11] proposed a system architecture that enables D2D communications with cooperative mobile relays. Ma *et al.* in [12] developed a distributed relay selection algorithm for cooperative D2D communications. Lee *et al.* in [13] studied the multihop decode-and-forward relaying assisted cooperative D2D communications. The common assumption of these previous studies for cooperative D2D communications is that all the device users are cooperative and they are willing to help any other users. However, since each handheld device has limited battery and providing relaying assistance for cooperative D2D communications would incur significant energy consumption, there is no good reason to assume that all device users would cooperate with each other.

Much effort has been made in the literature to stimulate, via incentive mechanisms, cooperation in wireless networks. Payment-based mechanisms have been widely considered to incentivize cooperation for wireless ad hoc networks [14]–[16]. Another widely adopted approach for cooperation stimulation is reputation-based mechanisms, where a centralized authority or the whole user population collectively keeps records of the cooperative behaviors and punishes noncooperating users [17]–[19]. However, it is yet clear whether these incentive mechanisms are feasible in practice since they require central authorities to monitor and regulate user behaviors and resolves disputes, which require extensive signaling overhead between users and central authorities, and can easily diminish the capacity gain of cooperative D2D communication. Moreover, incentive mechanisms typically assume that all users are fully rational and they act in the selfish manner. Such an assumption is not appropriate for D2D communications as handheld devices are carried by human beings and people typically act with bounded rationality and involve social interactions [20].

The social aspect is now becoming a new and important dimension for communication system design [4]. With the development of online and mobile social networks such as Facebook and Twitter, more and more real-world data and traces of human social interactions are being generated. This enables researchers and engineers to observe, analyze, and incorporate the social factors into engineering system design in a way never previously possible [21]. Authors in [22] and [23] exploited social structures such as social community to design efficient data forwarding and routing algorithms in delay-tolerant networks . Hui *et al.* in [24] used the social betweenness and centrality as the forwarding metric. Costa *et al.* in [25] proposed predictions based on metrics of social interaction to identify the best information carriers for content publish-subscribe. Authors in [26] and [27] utilized the social influence phenomenon to devise efficient data dissemination mechanisms for mobile networks. The common assumption among these works, however, is that all users are always willing to help others, e.g., for data forwarding and relaying. In this paper, we propose a novel framework to stimulate cooperation among device users while also taking the social aspect into account.

III. System Model

In this section, we present the system model of cooperative D2D communications based on social trust and social reciprocity—a new mobile social networking paradigm. As illustrated in Fig. 2, cooperative D2D communications can be projected onto two domains: the physical domain and the social domain. In the physical domain, different devices have different feasible cooperation relationships for cooperative D2D communications subject to the physical constraints. In the social domain, different device users have different assistance relationships based on social relationships among them. We next discuss both physical and social domains in detail.

A. Physical (Communication) Graph Model

We consider a set of nodes $\mathcal{N} = \{1, 2, \ldots, N\}$ where N is the total number of nodes. Each node $n \in \mathcal{N}$ is a wireless device that would like to conduct D2D communication to transmit data packets to its corresponding destination d_n. Notice that a destination d_n may also be a transmit node in the set $\mathcal{N}$ of another D2D communication link, and hence a D2D traffic flow may traverse one hop or multiple hops among the devices. Similar to many previous studies in D2D communications [7]–[13], to enable tractable analysis, we consider a scenario where the locations of the nodes remain unchanged during a D2D communication scheduling period (e.g., several hundred milliseconds), while they may change across different periods due to users' mobility.[2]

The D2D communication is underlaid beneath a cellular infrastructure wherein there exists a base station controlling the uplink/downlink communications of the cellular devices. To avoid generating severe interference to the incumbent cellular devices, each node $n \in \mathcal{N}$ will first send a D2D communication establishment request message to the base station. The base station then computes the allowable transmission power level p_n for the D2D communication of node n based on the system parameters and the protection requirement of the neighboring cellular devices. For example, the proper transmission power p_n of the D2D communication can be computed according to the power control algorithms proposed in [7] and [8]. Moreover, with the assistance by the base station, each node can detect a set of neighboring nodes, which can be potential relay candidates for cooperative D2D communications [3].

We consider a time-division multiple access (TDMA) mechanism in which the transmission time is slotted and one node $n \in \mathcal{N}$ is scheduled to carry out its D2D communication in a time-slot.[3] At the allotted time-slot, node n can choose either to transmit to the destination node d_n directly or to use cooperative communication by asking another node m in its vicinity to serve as a relay.

Due to the physical constraints such as signal attenuation, only a subset of nodes that are close enough (e.g., with a de-

[2]This assumption is valid for our case since the proposed mechanism in Section V has a very low computational complexity and, hence, the D2D communication scheduling can be carried out in a smaller time scale than that of users' mobility.

[3]Our methods are also applicable to other multiple access schemes.

tectable signal strength) can be feasible relay candidates for the node n. To take such physical constraints into account, we introduce the physical graph[4] $\mathcal{G}^{\rm P} \triangleq \{\mathcal{N}, \mathcal{E}^{\rm P}\}$ where the set of nodes $\mathcal{N}$ is the vertex set and $\mathcal{E}^{\rm P} \triangleq \{(n,m) : e^{\rm P}_{nm} = 1, \forall n, m \in \mathcal{N}\}$ is the edge set where $e^{\rm P}_{nm} = 1$ if and only if node m is a feasible relay for node n. An illustration of the physical graph is given in Fig. 2. We also denote the set of nodes that can serve as a feasible relay of node n as $\mathcal{N}^{\rm P}_n \triangleq \{m \in \mathcal{N} : e^{\rm P}_{nm} = 1\}$. A recent work in [28] shows that it is sufficient for a source node to choose the best relay node among multiple candidates to achieve full diversity. For ease of exposition, we hence consider the single relay selection scheme such that each node n selects at most one neighboring node $m \in \mathcal{N}^{\rm P}_n$ as the relay. Moreover, since multiple relay selection scheme typically requires the synchronization among the relays, the single relay selection scheme hence demands less signaling overhead and is easier to be implemented in practice.

For ease of exposition, we consider the full duplex decode-and-forward (DF) relaying scheme [29] for the cooperative D2D communication. Let $r_n \in \mathcal{N}^{\rm P}_n$ denote the relay node chosen by node $n \in \mathcal{N}$ for cooperative communication. The data rate achieved by node n is then given as [29]

$$Z^{\rm DF}_{n,r_n} = \frac{W}{N} \min\{\log(1+\mu_{nr_n}), \log(1+\mu_{nd_n}+\mu_{r_nd_n})\}$$

where W denotes the channel bandwidth and μ_{ij} denotes the signal-to-noise ratio (SNR) at device j when device i transmits a signal to device j. As an alternative, the node n can also choose to transmit directly without any relay assistance and achieve a data rate of

$$Z^{\rm Dir}_n = \frac{W}{N} \log(1+\mu_{nd_n}).$$

For simplicity, we define the data rate function of node n as $R_n : \mathcal{N}^{\rm P}_n \cup \{n\} \rightarrow \mathbb{R}_+$, which is given by

$$R_n(r_n) = \begin{cases} Z^{\rm DF}_{n,r_n}, & \text{if } r_n \neq n \\ Z^{\rm Dir}_n, & \text{if } r_n = n. \end{cases} \quad (1)$$

We will use the terminology that node n chooses itself as the relay for the situation in which node n transmits directly to its destination d_n.

B. Social Graph Model

We next introduce the social trust model for cooperative D2D communications. The underlying rationale of using social trust is that the handheld devices are carried by human beings and the knowledge of human social ties can be utilized to achieve effective and trustworthy relay assistance for cooperative D2D communications.

More specifically, we introduce the social graph $\mathcal{G}^{\rm S} = \{\mathcal{N}, \mathcal{E}^{\rm S}\}$ to model the social trust among the nodes. Here, the vertex set is the same as the node set $\mathcal{N}$, and the edge set is given as $\mathcal{E}^{\rm S} = \{(n,m) : e^{\rm S}_{nm} = 1, \forall n, m \in \mathcal{N}\}$, where $e^{\rm S}_{nm} = 1$ if and only if nodes n and m have social trust toward each other, which can be kinship, friendship, or colleague relationship between two nodes. We denote the set of nodes that have social trust toward node n as $\mathcal{N}^{\rm S}_n = \{m : e^{\rm S}_{nm} = 1, \forall m \in \mathcal{N}\}$, and we assume that the nodes in $\mathcal{N}^{\rm S}_n$ are willing to serve as the relay of node n for cooperative communication.

[4]The graphs (e.g., physical graph and social graph) in this paper can be directed.

One critical task here is to identify the social relationships among device users. To this end, we can adopt a network-assisted approach such that two device users carry out the identification process through the cellular communications. Two device users can detect their social relationship by carrying out the "matching" process to identify the common social features among them. For example, two users can match their mobile phones' contact books. If they have the phone numbers of each other or many of their phone numbers are the same, then it is very likely that they know each other. As another example, two device users can match their home and working addresses and identify whether they are neighbors or colleagues. Furthermore, two device users can detect the social relationship among them by accessing to the online social networks such as Facebook and Twitter. For example, Facebook has exposed access to their social graph including the objects of friends, events, groups, profile information, and photographs. Any authenticated Facebook user can have access to these information through the OpenGraph API [30]. To preserve the privacy of the device users, the private set intersection technique in [31]–[35] can be adopted to design a privacy-preserving social relationship identification mechanism such that the intersection of private social information of two device users can be obtained without leaking any additional private information. Interested readers can refer to [31]–[35] for the detailed discussion of the privacy-preserving social relationship identification mechanism design. To further protect device user's personal information such as identity and visited locations, we can adopt the privacy-preserving scheme in [36].

Based on the physical graph $\mathcal{G}^{\rm P}$ and social graph $\mathcal{G}^{\rm S}$ above, each node $n \in \mathcal{N}$ can classify the set of feasible relay nodes in $\mathcal{N}^{\rm P}_n$ into two types: nodes with social trust and nodes without social trust. A node n then has two options for relay selection. On the one hand, the node n can choose to seek relay assistance from another feasible device that has social trust toward him (her). On the other hand, the node n can choose to participate in a group formed based on social reciprocity by exchanging mutually beneficial relay assistance. In the following, we will study: 1) how to choose between social-trust- and social-reciprocity-based relay selections for each node; and 2) how to efficiently form reciprocal groups among the nodes without social trust.

IV. Social-Trust- and Social-Reciprocity-Based Cooperative D2D Communications

In this section, we study the cooperative D2D communications based on social trust and social reciprocity. As mentioned, each node $n \in \mathcal{N}$ has two options for relay selection: social trust versus social reciprocity. We next address the issues of choosing between social-trust- and social-reciprocity-based relay selections for each node and the reciprocal group forming among the nodes without social trust.

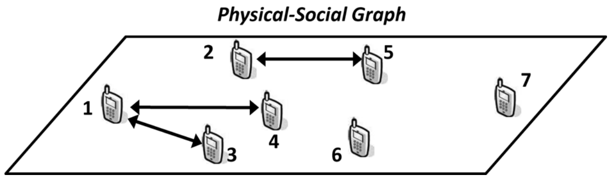

Fig. 3. Physical-social graph based on the physical graph and social graph in Fig. 2. For example, there exists an edge between nodes 1 and 3 in the physical-social graph since they can serve as the feasible relay for each other and also have social trust toward each other.

A. Social-Trust-Based Relay Selection

We first consider social-trust-based relay selection for D2D cooperation. The key motivation for using social trust is to utilize the knowledge of human social ties to achieve effective and trustworthy relay assistance among the devices for cooperative D2D communications. For example, when a device user is at home or a working place, he (she) typically has family members, neighbors, colleagues, or friends in the vicinity. The device user can then exploit the social trust from neighboring users to improve the quality of D2D communication by asking the best trustworthy device to serve as the relay.

To take both the physical and social constraints into account, we define the *physical-social graph* $\mathcal{G}^{\rm PS} \triangleq \{\mathcal{N}, \mathcal{E}^{\rm PS}\}$ where the vertex set is the node set $\mathcal{N}$ and the edge set $\mathcal{E}^{\rm PS} = \{(n,m) : e_{nm}^{\rm PS} \triangleq e_{nm}^{\rm P} \cdot e_{nm}^{\rm S} = 1, \forall n,m \in \mathcal{N}\}$ where $e_{nm}^{\rm PS} = 1$ if and only if node m is a feasible relay (i.e., $e_{nm}^{\rm P} = 1$) and has social trust toward node n (i.e., $e_{nm}^{\rm S} = 1$). An illustration of the physical-social graph is given in Fig. 3. We also denote the set of nodes that have social trust toward node n and are also feasible relay candidates for node n as $\mathcal{N}_n^{\rm PS} = \{m : e_{nm}^{\rm PS} = 1, \forall m \in \mathcal{N}\}$.

For cooperative D2D communications based on social trust, each node $n \in \mathcal{N}$ can choose the best relay $r_n^{\rm S} = \arg\max_{r_n \in \mathcal{N}_n^{\rm PS} \cup \{n\}} R_n(r_n)$ to maximize its data rate subject to both physical and social constraints.

B. Social-Reciprocity-Based Relay Selection

Next, we study the social-reciprocity-based relay selection. Different from D2D cooperation based on social trust that requires strong social ties among device users, social reciprocity is a powerful mechanism for promoting mutual beneficial cooperation among the nodes in the absence of social trust. For example, when a device user does not have any friends in the vicinity, he (she) may cooperate with the nearby strangers by providing relay assistance for each other to improve the quality of D2D communications. In general, there are two types of social reciprocity: direct reciprocity and indirect reciprocity[5] (see Fig. 4 for an illustration). Direct reciprocity is captured in the principle of "you help me, and I will help you." That is, two individuals exchange altruistic actions so that both obtain a net benefit. Indirect reciprocity is essentially the concept of "I help you, and someone else will help me." That is, a group of individuals exchange altruistic actions so that all of them can be better off.

[5]Reciprocity in this study refers to social reciprocity.

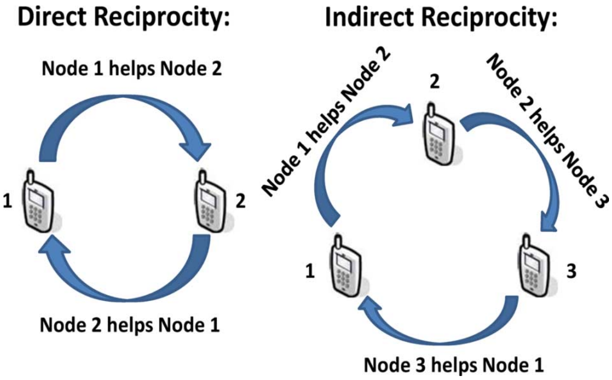

Fig. 4. Direct and indirect reciprocity.

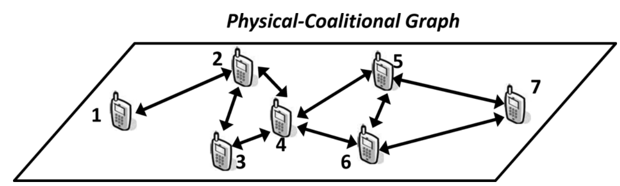

Fig. 5. Physical-coalitional graph based on the physical graph and social graph in Fig. 6. For example, there exists an edge between nodes 1 and 2 in the physical-coalitional graph since they can serve as the feasible relay for each other and have no social trust toward each other.

Note that, in this paper, we consider that the objective of each device user is to increase the throughput of its D2D communication, and hence a user is willing to participate in a reciprocal group if its communication performance can be improved. Our result can be extended to the case when the cost (e.g., energy consumption) of serving as a relay for other users is taken into account. In this case, each user will make the decision of participating a reciprocal group based on its net utility (i.e., the achieved throughput of getting relaying assistance minus the cost of serving as a relay for others). If the cost of a user is too high, then the user would not join any reciprocal relay groups and choose the direct communication without any relay.

To better describe the possible cooperation relationships among the set of nodes without social trust, we introduce the *physical-coalitional graph* $\mathcal{G}^{\rm PC} = \{\mathcal{N}, \mathcal{E}^{\rm PC}\}$. Here, the vertex set is the node set $\mathcal{N}$ and the edge set $\mathcal{E}^{\rm PC} = \{(n,m) : e_{nm}^{\rm PC} \triangleq e_{nm}^{\rm P} \cdot (1 - e_{nm}^{\rm S}) = 1, \forall n,m \in \mathcal{N}\}$ where $e_{nm}^{\rm PC} = 1$ if and only if node m is a feasible relay (i.e., $e_{nm}^{\rm P} = 1$) and has no social trust toward node n (i.e., $e_{nm}^{\rm S} = 0$). An illustration of physical-coalitional graph is given in Fig. 5. We also denote the set of nodes that have no social trust toward user n but are feasible relay candidates of node n as $\mathcal{N}_n^{\rm PC} \triangleq \{m : e_{nm}^{\rm PC} = 1, \forall m \in \mathcal{N}\}$. For social-reciprocity-based relay selection, a key challenge is how to efficiently divide the nodes into multiple groups such that the nodes can significantly improve their data rates by the reciprocal cooperation within the groups. We will propose a coalitional game framework to address this challenge.

1) Introduction to Coalitional Game: For the sake of completeness, we first give a brief introduction to the coalitional game [37]. Formally, a coalitional game consists of a tuple $\Omega = (\mathcal{N}, \mathcal{X}_{\mathcal{N}}, V, (\succ_n)_{n \in \mathcal{N}})$, where we have the following.

- $\mathcal{N}$ is a finite set of players.

- $\mathcal{X}_{\mathcal{N}}$ is the space of feasible cooperation strategies of all players.
- V is a characteristic function that maps from every nonempty subset of players $\mathcal{S} \subseteq \mathcal{N}$ (a coalition) to a subset of feasible cooperation strategies $V(\mathcal{S}) \subseteq \mathcal{X}_{\mathcal{N}}$. This represents the possible cooperation strategies among the players in the coalition $\mathcal{S}$ given that other players out of the coalition $\mathcal{S}$ do not participate in any cooperation.
- $\succ_n$ is a preference order (reflexive, complete, and transitive binary relation) on $\mathcal{X}_{\mathcal{N}}$ for each player $n \in \mathcal{N}$. This captures the idea that different players may have different preferences over different cooperation strategies.

In the same spirit as Nash equilibrium in a noncooperative game, the "core" plays a critical role in the coalitional game.

Definition 1: The core is the set of $\boldsymbol{x} \in V(\mathcal{N})$ for which there does not exist a coalition $\mathcal{S}$ and $\boldsymbol{y} \in V(\mathcal{S})$ such that $\boldsymbol{y} \succ_n \boldsymbol{x}$ for all $n \in \mathcal{S}$.

Intuitively, the core is a set of cooperation strategies such that no coalition can deviate and improve for all its members by cooperation within the coalition [37].

2) Coalitional Game Formulation: We then cast the social-reciprocity-based relay selection problem as a coalitional game $\Omega = (\mathcal{N}, \mathcal{X}_{\mathcal{N}}, V, (\succ_n)_{n\in\mathcal{N}})$ as follows.

- The set of players $\mathcal{N}$ is the set of nodes.
- The set of cooperation strategies $\mathcal{X}_{\mathcal{N}} = \{(r_n)_{n\in\mathcal{N}} : r_n \in \mathcal{N}_n^{\mathrm{PC}} \cup \{n\}, \forall n \in \mathcal{N}\}$, which describes the set of possible relay selections for all nodes based on the physical-coalitional graph $\mathcal{G}^{\mathrm{PC}}$.
- The characteristic function $V(\mathcal{S}) = \{(r_n)_{n\in\mathcal{N}} \in \mathcal{X}_{\mathcal{N}} : \{r_n\}_{n\in\mathcal{S}} = \{n\}_{n\in\mathcal{S}}$ and $r_m = m, \forall m \in \mathcal{N}\backslash\mathcal{S}\}$ for each coalition $\mathcal{S} \subseteq \mathcal{N}$. Here, the condition "$\{r_n\}_{n\in\mathcal{S}} = \{n\}_{n\in\mathcal{S}}$" represents the possible relay assistance exchange among the nodes in the coalition $\mathcal{S}$. The condition "$r_m = m, \forall m \in \mathcal{N}\backslash\mathcal{S}$" states that the nodes out of the coalition $\mathcal{S}$ will not participate in any cooperation and choose to transmit directly. For example, in Fig. 4, the coalition $\mathcal{S} = \{1, 2\}$ in the direct reciprocity case adopts the cooperation strategy $r_1 = 2$ and $r_2 = 1$ and the coalition $\mathcal{S} = \{1, 2, 3\}$ in the indirect reciprocity case adopts the cooperation strategy $r_1 = 3$, $r_2 = 1$, and $r_3 = 2$.
- The preference order $\succ_n$ is defined as $(r_m)_{m\in\mathcal{N}} \succ_n (r'_m)_{m\in\mathcal{N}}$ if and only if $r_n \succ_n r'_n$. That is, node n prefers the relay selection $(r_m)_{m\in\mathcal{N}}$ to another selection $(r'_m)_{m\in\mathcal{N}}$ if and only if its assigned relay r_n in the former selection $(r_m)_{m\in\mathcal{N}}$ is better than the assigned relay r'_n in the latter selection $(r'_m)_{m\in\mathcal{N}}$. In the following, we define that $r_n \succ_n r'_n$ when $R_n(r_n) > R_n(r'_n)$, and if $R_n(r_n) = R_n(r'_n)$, then ties are broken arbitrarily.

The core of this coalitional game is a set of $(r_n^*)_{n\in\mathcal{N}} \in V(\mathcal{N})$ for which there does not exist a coalition $\mathcal{S}$ and $(r_n)_{n\in\mathcal{N}} \in V(\mathcal{S})$ such that $(r_n)_{n\in\mathcal{N}} \succ_n (r_n^*)_{n\in\mathcal{N}}$ for all $n \in \mathcal{S}$. In other words, no coalition of nodes can deviate and improve their relay selection by cooperation in the coalition. We will refer the solution $(r_n^*)_{n\in\mathcal{N}}$ as the core relay selection in the sequel.

3) Core Relay Selection: We now study the existence of the core relay selection. To proceed, we first introduce the following key concepts of coalitional game.

Definition 2: Given a coalitional game $\Omega = (\mathcal{N}, \mathcal{X}_{\mathcal{N}}, V, (\succ_n)_{n\in\mathcal{N}})$, we call a coalitional game $\Phi = (\mathcal{M}, \mathcal{X}_{\mathcal{M}}, V, (\succ_m)_{m\in\mathcal{M}})$ a coalitional subgame of the game Ω if and only if $\mathcal{M} \subseteq \mathcal{N}$ and $\mathcal{M} \neq \varnothing$.

In other words, a coalitional subgame Φ is a coalitional game defined on a subset of the players of the original coalitional game Ω.

Definition 3: Given a coalitional subgame $\Phi = (\mathcal{M}, \mathcal{X}_{\mathcal{M}}, V, (\succ_m)_{m\in\mathcal{M}})$, a nonempty subset $\mathcal{S} \subseteq \mathcal{M}$ is a top coalition of the game Φ if and only if there exists a cooperation strategy $(\tilde{r}_m)_{m\in\mathcal{M}} \in V(\mathcal{S})$ such that for any $\mathcal{K} \subseteq \mathcal{M}$ and any cooperation strategy $(r_m)_{m\in\mathcal{M}} \in V(\mathcal{K})$ satisfying $\tilde{r}_m \neq r_m$ for any $m \in \mathcal{S}$, we have $\tilde{r}_m \succ_m r_m$ for any $m \in \mathcal{S}$.

That is, by adopting the cooperation strategy $(\tilde{r}_m)_{m\in\mathcal{S}}$, the coalition $\mathcal{S}$ is a group that is mutually best for all its members [38].

Definition 4: A coalitional game $\Omega = (\mathcal{N}, \mathcal{X}_{\mathcal{N}}, V, (\succ_n)_{n\in\mathcal{N}})$ satisfies the top-coalition property if and only if there exists a top-coalition for any its coalitional subgame Φ.

We then show the proposed coalitional game for social-reciprocity-based relay selection satisfies the top-coalition property. For simplicity, we denote $\tilde{\mathcal{N}}_n^{\mathrm{PC}} \triangleq \mathcal{N}_n^{\mathrm{PC}} \cup \{n\}$. For a coalitional subgame $\Phi = (\mathcal{M}, \mathcal{X}_{\mathcal{M}}, V, (\succ_m)_{m\in\mathcal{M}})$, we denote the mapping $\gamma(n, \mathcal{M})$ as the most preferable relay of node $n \in \mathcal{M}$ in the set of nodes $\mathcal{M} \cap \tilde{\mathcal{N}}_n^{\mathrm{PC}}$, i.e., $\gamma(n, \mathcal{M}) \succ_n i$ for any $i \neq \gamma(n, \mathcal{M})$ and $i \in \mathcal{M} \cap \tilde{\mathcal{N}}_n^{\mathrm{P}}$. Based on the mapping γ, we can define the concept of reciprocal relay selection cycle as follows.

Definition 5: Given a coalitional subgame $\Phi = (\mathcal{M}, \mathcal{X}_{\mathcal{M}}, V, (\succ_m)_{m\in\mathcal{M}})$, a node sequence $(n_1, \ldots, n_L)$ is called a reciprocal relay selection cycle of length L if and only if $\gamma(n_l, \mathcal{M}) = n_{l+1}$ for $l = 1, \ldots, L-1$ and $\gamma(n_L, \mathcal{M}) = n_1$.

Notice that when $L = 1$ (i.e., $\gamma(n, \mathcal{M}) = n$), the most preferable choice of node n is to choose to transmit directly. When $L = 2$, this corresponds to the direct reciprocity case; when $L \geq 3$, this corresponds to the indirect reciprocity case. Since the number of nodes (i.e., $|\mathcal{M}|$) is finite, there must exist at least one reciprocal relay selection cycle for the coalitional subgame Φ. This leads to the following result.

Lemma 1: Given a coalitional subgame Φ, there exists at least one reciprocal relay selection cycle. Any reciprocal relay selection cycle is a top-coalition of the coalitional subgame Φ.

Proof: For the first part of the lemma, we can choose any node $n \in \mathcal{M}$ as the starting node n_1. Then, we can find the second node $n_2 = \gamma(n_1, \mathcal{M})$ and continue in this manner. If no cycle exists, the node sequence $(n_1, n_2, \ldots.)$ can grow infinitely long, and any two nodes in the sequence are different. This obviously contradicts with the fact that the set of nodes $\mathcal{M}$ is finite.

For the second part of the lemma, given a reciprocal relay selection cycle $(n_1, \ldots, n_L)$, we denote the set of nodes in the cycle as $\mathcal{C}$. We can then adopt the cooperation strategy for the nodes in the cycle as $\tilde{r}_{n_l} = n_{l+1}$ for $l = 1, \ldots, L = 1$ and $\tilde{r}_{n_L} = n_1$. According to Definition 5, each node $n \in \mathcal{C}$ is allocated with its most preferable relay in the coalitional subgame Φ. Thus, for any other relays $r_n \neq \tilde{r}_n$, we have that $\tilde{r}_n \succ_n r_n$ for any $n \in \mathcal{C}$. ■

According to Lemma 1, we have the following result.

Lemma 2: The coalitional game Ω for cooperative D2D communications satisfies the top-coalition property.

Algorithm 1: Core Relay Selection Algorithm

```
initialization:
    set initial set of nodes M_1 = N.
    set iteration index t = 1.
end initialization

loop until M_t = ∅:
    find all the reciprocal relay selection cycles
        C_1^t, ..., C_{Z_t}^t.
    remove the set of nodes in the cycles from the current
        set of nodes M_t, i.e., M_{t+1} = M_t \ ∪_{i=1}^{Z_t} C_i^t.
    set t = t + 1.
end loop
```

Similar to the top trading cycle scheme for the housing market [39], based on the top-coalition property [38], we can then construct the core relay selection in an iterative manner. Let $\mathcal{M}_t$ denote the set of nodes of the coalitional subgame $\Phi_t = (\mathcal{M}_t, \mathcal{X}_{\mathcal{M}_t}, V, (\succ_m)_{m\in\mathcal{M}_t})$ in the tth iteration. Based on the mapping γ and the given set of nodes $\mathcal{M}_t$, we can then find all the reciprocal relay selection cycles as $\mathcal{C}_1^t, \ldots, \mathcal{C}_{Z_t}^t$ where each cycle $\mathcal{C}_z^t = (n_1^t, \ldots, n_{|\mathcal{C}_z^t|}^t)$ is a node sequence and Z_t denotes the number of cycles at the tth iteration. Abusing notation, we will also use $\mathcal{C}_z^t$ to denote the set of nodes in the cycle $\mathcal{C}_z^t$. We can then construct the core relay selection as follows. For the first iteration $t = 1$, we set $\mathcal{M}_1 = \mathcal{N}$ and find the reciprocal relay selection cycles as $\mathcal{C}_1^1, \ldots, \mathcal{C}_{Z_1}^1$ based on the set of nodes $\mathcal{M}_1$. For the second iteration $t = 2$, we can then set that $\mathcal{M}_2 = \mathcal{M}_1 \backslash \cup_{i=1}^{Z_1} \mathcal{C}_i^1$ (i.e., remove the nodes in the cycles in the previous iteration) and find the new reciprocal relay selection cycles as $\mathcal{C}_1^2, \ldots, \mathcal{C}_{Z_2}^2$ based on the set of nodes $\mathcal{M}_2$. This procedure repeats until the set of nodes $\mathcal{M}_t = \varnothing$ (i.e., no operation can be further carried out). We summarize the above procedure for constructing the core relay selection in Algorithm 1.

Suppose that the algorithm takes T iterations to converge. We can obtain the set of reciprocal relay selection cycles in all T iterations as $\{\mathcal{C}_i^t : \forall i = 1, \ldots, Z_t \text{ and } t = 1, \ldots, T\}$. Since the mapping $\gamma(n, \mathcal{M}_t)$ is unique for each node $n \in \mathcal{M}_t$, we must have that $\cup_{i=1,\ldots,Z_t}^{t=1,\ldots,T} \mathcal{C}_i^t = \mathcal{N}$ (i.e., all the nodes are in the cycles) and $\mathcal{C}_i^t \cap \mathcal{C}_j^{t'} = \varnothing$ for any $i \neq j$ and $t, t' = 1, \ldots, T$ (i.e., there do not exist any intersecting cycles). For each cycle $\mathcal{C}_i^t = (n_1^t, \ldots, n_{|\mathcal{C}_i^t|}^t)$, we can then define the relay selection as $r_{n_l^t}^* = n_{l+1}^t$ for any $l = 1, 2 \ldots, |\mathcal{C}_i^t| - 1$ and $r_{n_{|\mathcal{C}_i^t|}^t}^* = n_1^t$. We show that $(r_n^*)_{n\in\mathcal{N}}$ is a core relay selection of the coalitional game Ω for the social-reciprocity-based relay selection.

Theorem 1: The relay selection $(r_n^*)_{n\in\mathcal{N}}$ is a core solution to the coalitional game Ω for the social-reciprocity-based relay selection.

Proof: We prove the result by contradiction. We assume that there exists a nonempty coalition $\mathcal{S} \subseteq \mathcal{N}$ with another relay selection $(r_m)_{m\in\mathcal{N}} \in V(\mathcal{S})$ satisfying $(r_m)_{m\in\mathcal{N}} \succ_n (r_m^*)_{m\in\mathcal{N}}$ for any $n \in \mathcal{S}$. Let $\mathcal{C}^t = \cup_{i=1}^{Z_t} \mathcal{C}_i^t$ be the set of nodes in the reciprocal relay selection cycles obtained in the tth iteration. According to Lemma 1, we know that each cycle $\mathcal{C}_i^1$ is a top-coalition given the set of nodes $\mathcal{M}_1 = \mathcal{N}$. By the definition of top-coalition, we must have that $\mathcal{S} \cap \mathcal{C}^1 = \varnothing$. In this case, we have that $\mathcal{S} \subseteq \mathcal{M}_2 \triangleq \mathcal{M}_1 \backslash \mathcal{C}^1$. Similarly, each cycle $\mathcal{C}_i^2$ is a top-coalition given the set of nodes $\mathcal{M}_2$. We thus also have that $\mathcal{S} \cap \mathcal{C}^2 = \varnothing$. Repeating this argument, we can find that $\mathcal{S} \cap \mathcal{C}^t = \varnothing$ for any $t = 1, \ldots, T$. Since $\mathcal{N} = \cup_{t=1}^T \mathcal{C}^t$, we must have that $\mathcal{S} \cap \mathcal{N} = \varnothing$, which contradicts with the hypothesis that $\mathcal{S} \subseteq \mathcal{N}$ and $\mathcal{S} \neq \varnothing$. This completes the proof. ■

C. Social-Trust- and Social-Reciprocity-Based Relay Selection

According to the principles of social trust and social reciprocity above, each node $n \in \mathcal{M}$ has two options for relay selection. The first option is that node n can choose the best relay $r_n^{\mathrm{S}} = \arg\max_{r_n \in \mathcal{N}_n^{\mathrm{PS}} \cup \{n\}} R_n(r_n)$ from the set of nodes with social trust $\mathcal{N}_n^{\mathrm{PS}}$. Alternatively, node n can choose a relay $r_n \in \mathcal{N}_n^{\mathrm{PC}}$ from the set of nodes without social trust by participating in a directly or indirectly reciprocal cooperation group.

We next address the issue of choosing between social-trust- and social-reciprocity-based relay selections for each node by generalizing the core relay selection $(r_n^*)_{n\in\mathcal{N}}$ in Section IV-B.3. The key idea is to adopt the social-trust-based relay selection r_n^{S} as the benchmark for participating in the social-reciprocity-based relay selection. That is, a node n prefers social-reciprocity-based relay selection to social-trust-based relay selection if the social-reciprocity-based relay selection offers better performance. More specifically, we define that $r_n \succ_n n$ if and only if $r_n \succ_n r_n^{\mathrm{S}}$ and the selection "$r_n = n$" represents that node n will select the relay r_n^{S} based on social trust. Based on this, we can then compute the core relay selection $(r_n^*)_{n\in\mathcal{N}}$ according to Algorithm 1. In this case, if we have $r_m^* = m$ in the core relay selection $(r_n^*)_{n\in\mathcal{N}}$, then node m will select the relay r_n^{S} based on social trust. If we have $r_m^* \neq m$ in the core relay selection $(r_n^*)_{n\in\mathcal{N}}$, then node m will select the relay based on social reciprocity.

In a nutshell, we have studied the cooperative D2D communications based on social trust and social reciprocity. We have developed a coalitional game approach for efficiently forming the reciprocal groups among the nodes, and also addressed the issue of choosing between social-trust- and social-reciprocity-based relay selections for each node.

V. Network-Assisted Relay Selection Mechanism

In this section, we turn our attention to the implementation of the core relay selection for social-trust- and social-reciprocity-based cooperative D2D communications. A key challenge here is how to find the reciprocal relay selection cycles in the proposed core relay selection algorithm (see Algorithm 1). In the following, we will first propose a reciprocal relay selection cycle finding algorithm to address this issue, and then develop a network-assisted mechanism to implement the core relay selection solution in practical D2D communication systems.

A. Reciprocal Relay Selection Cycle Finding

We first consider the issue of reciprocal relay selection cycle finding in the core relay selection algorithm. We introduce a graphical approach to address this issue. More specifically, given the set of nodes $\mathcal{M}_t$ and the mapping γ, we can construct a graph $\mathcal{G}^{\mathcal{M}_t} = \{\mathcal{M}_t, \mathcal{E}^{\mathcal{M}_t}\}$. Here, the set of vertices is $\mathcal{M}_t$, and the set of edges $\mathcal{E}^{\mathcal{M}_t} = \{(nm) : e_{nm}^{\mathcal{M}_t} = 1, \forall n, m \in \mathcal{M}_t\}$ where there is an edge directed from node n to m (i.e., $e_{nm}^{\mathcal{M}_t} = 1$) if and only if $\gamma(n, \mathcal{M}_t) = m$. For the graph $\mathcal{G}^{\mathcal{M}_t}$, we have the following key observations.

Lemma 3: The out-degree of each node in the graph $\mathcal{G}^{\mathcal{M}_t}$ is one.

This is due to the fact that the node m generated by the mapping $\gamma(n, \mathcal{M}_t)$ is unique.

We next introduce the concept of path in graph theory. A path of length I on a graph is a sequence of nodes $(n_1, n_2, \ldots, n_I)$ where there is an edge directed from node n_i to n_{i+1} on the graph for any $i = 1, \ldots, I-1$. A cycle of the graph is a path in which the first and last nodes are identical. A reciprocal relay selection cycle of the coalitional game then corresponds to a cycle of the graph $\mathcal{G}^{\mathcal{M}_t}$. When $\gamma(n, \mathcal{M}_t) = n$, the cycle degenerates to a self-loop of node n. In the following, we say a path $(n_1, n_2, \ldots, n_I)$ induces a cycle if there exists a path beginning from node n_I that is a cycle. If two cycles are a cyclic permutation of each other, we will regard them as one cycle.

Lemma 4: Any sufficiently long path beginning from any node on the graph $\mathcal{G}^{\mathcal{M}_t}$ induces one and only one cycle.

Proof: We first show that a path beginning from a node n_1 induces a cycle. Since each node has an out-degree of one, this implies we can construct a path $(n_1, n_2, \ldots)$ of an infinitely large length if the path does not induce a cycle. This contradicts with the fact that the number of nodes on the graph is finite.

On the other hand, if the path induces multiple distinct cycles, there must exist a node with more than one outward directed edge. This contradicts Lemma 3. ■

Based on Lemmas 3 and 4, we propose an algorithm to find the reciprocal relay selection cycles in Algorithm 2. The key idea of the algorithm is to explore the paths beginning from each node. More specifically, if a path beginning from a node induces an unfound cycle, then we find a new cycle. We will set the nodes in both the path and cycle as visited nodes since any path beginning from these nodes would induce the same cycle. If a path beginning from a node leads to a visited node, the path would induce a cycle that has already been found if we continue to construct the path on the visited nodes. We will also set the nodes in the path as visited nodes. Since each node will be visited once in the algorithm, the computational complexity of the reciprocal relay selection cycles finding algorithm is $\mathcal{O}(|\mathcal{M}_t|)$.

Algorithm 2: Reciprocal Relay Selection Cycle Finding Algorithm

initialization:
  construct the graph $\mathcal{G}^{\mathcal{M}_t}$ based on the set of nodes $\mathcal{M}_t$ and the mappings $\{\gamma(n, \mathcal{M}_t)\}_{n \in \mathcal{M}_t}$.
  set the set of visited nodes $\mathcal{V} = \emptyset$ and the set of unvisited nodes $\mathcal{U} = \mathcal{M}_t \backslash \mathcal{V}$.
  set the set of identified cycles $\triangle = \emptyset$.
end initialization

loop until $\mathcal{U} = \emptyset$:
  select one node $n_a \in \mathcal{U}$ randomly.
  set the set of visited nodes in the current path $\mathcal{H} = \{n_a\}$.
  set the flag $F = 0$.
  loop until $F = 1$:
    generate the next node $n_b = \gamma(n_a, \mathcal{M}_t)$.
    if $n_b \in \mathcal{V}$ **then**
      set $\mathcal{V} = \mathcal{V} \cup \mathcal{H}$ and $\mathcal{U} = \mathcal{M}_t \backslash \mathcal{V}$.
      set $F = 1$.
    else if $n_b \in \mathcal{H}$ **then**
      set the identified cycle as $\mathcal{C} = (n_1 = n_b, \ldots, n_i = \gamma(n_{i-1}, \mathcal{M}_t), \ldots, n_I = n_a)$.
      set the set of identified cycles $\triangle = \triangle \cup \{\mathcal{C}\}$.
      set $\mathcal{V} = \mathcal{V} \cup \mathcal{H}$ and $\mathcal{U} = \mathcal{M}_t \backslash \mathcal{V}$.
      set $F = 1$.
    else
      set $\mathcal{H} = \mathcal{H} \cup \{n_b\}$.
      set $n_a = n_b$.
    end if
  end loop
end loop

B. NARS Mechanism

We now propose a network-assisted relay selection (NARS) mechanism to implement the core relay selection, which works as follows.

- Each node $n \in \mathcal{N}$ first determines its preference list $\mathcal{L}_n^{\mathrm{P}}$ for the set of feasible relay selections $\tilde{\mathcal{N}}_n^{\mathrm{P}} \triangleq \mathcal{N}_n^{\mathrm{P}} \cup \{n\}$ based on the physical graph $\mathcal{G}^{\mathrm{P}}$. Here, $\mathcal{L}_n = (r_n^1, \ldots, r_n^{|\tilde{\mathcal{N}}_n^{\mathrm{P}}|})$ is a permutation of all the feasible relays in $\tilde{\mathcal{N}}_n^{\mathrm{P}}$ satisfying that $r_n^i \succ_n r_n^{i+1}$ for any $i = 1, \ldots, |\tilde{\mathcal{N}}_n^{\mathrm{P}}| - 1$. This step can be done through the channel probing procedure to measure the achieved data rate resulting from choosing with different relays.
- Each node $n \in \mathcal{N}$ then computes the best social-trust-based relay selection $r_n^{\mathrm{S}} = \arg\max_{r_n \in \mathcal{N}_n^{\mathrm{PS}} \cup \{n\}} R_n(r_n)$ based on the physical-social graph $\mathcal{G}^{\mathrm{PS}}$ and the preference list $\mathcal{L}_n^{\mathrm{P}}$.
- Each node $n \in \mathcal{N}$ next determines its preference list $\mathcal{L}_n^{\mathrm{PC}}$ for the set of relay selections $\mathcal{N}_n^{\mathrm{PC}} \cup \{n\}$ based on the physical-coalitional graph $\mathcal{G}^{\mathrm{PC}}$. Notice that we have that $r_n \succ_n n$ in the preference list $\mathcal{L}_n^{\mathrm{PC}}$ if and only if $r_n \succ_n r_n^{\mathrm{S}}$ in the preference list $\mathcal{L}_n^{\mathrm{P}}$.
- Each node $n \in \mathcal{N}$ then reports its preference list $\mathcal{L}_n^{\mathrm{PC}}$ to the base station.
- Based on the preference lists $\mathcal{L}_n^{\mathrm{PC}}$ of all nodes, the base station computes the core relay selection $(r_n^*)_{n \in \mathcal{N}}$ according to Algorithm 1 and 2 and broadcasts the relay selection $(r_n^*)_{n \in \mathcal{N}}$ to all nodes.

As mentioned in Section IV-C, if $r_m^* = m$ in the core relay selection $(r_n^*)_{n \in \mathcal{N}}$, then node m will select the relay r_n^{S} based on social trust. If $r_m^* \neq m$ in the core relay selection $(r_n^*)_{n \in \mathcal{N}}$, then node m will select the relay based on social reciprocity.

We now use an example to illustrate how the NARS mechanism works. We consider the network of $N = 7$ nodes based on the physical graph $\mathcal{G}^{\mathrm{P}}$ and the social graph $\mathcal{G}^{\mathrm{S}}$ in Fig. 2. According to NARS mechanism, each node n first determines its preference list $\mathcal{L}_n$ for the set of feasible relay selections

TABLE I
PREFERENCE LISTS OF $N = 7$ NODES BASED ON THE PHYSICAL GRAPH $\mathcal{G}^{\mathrm{P}}$ AND SOCIAL GRAPH $\mathcal{G}^{\mathrm{S}}$ IN FIG. 2

Node n	Preference List $\mathcal{L}_n^P$	Relay r_n^S	Preference List $\mathcal{L}_n^{PC}$
1	(1,2,3,4)	1	(1,2)
2	(1,3,2,4,5)	2	(1,3,2,4)
3	(2,3,4,1)	3	(2,3,4)
4	(2,1,4,3,5,6)	1	(2,4,3,5,6)
5	(4,6,7,5,2)	5	(4,6,7,5)
6	(7,5,4,6)	6	(7,5,4,6)
7	(5,6,7)	7	(5,6,7)

$\mathcal{N}_n^{\mathrm{P}} \cup \{n\}$. We will use the preference lists $\mathcal{L}_n^{\mathrm{P}}$ in Table I. For example, in the table, the feasible relays for node 7 on the physical graph $\mathcal{G}^{\mathrm{P}}$ are $\{5, 6, 7\}$. The preference list $(5, 6, 7)$ represents that $5 \succ_7 6 \succ_7 \succ 7$, i.e., node 7 prefers choosing node 5 as the relay to choosing node 6 and transmitting directly offers the worst performance. Then, based on the physical-social graph $\mathcal{G}^{\mathrm{PS}}$ in Fig. 3 and the preference list $\mathcal{L}_n^{\mathrm{P}}$, each node n computes the best social-trust-based relay selection r_n^{S}. For example, node 4's best social-trust-based relay selection $r_n^{\mathrm{S}} = 1$ (i.e., node 1). Each node n next determines the preference list $\mathcal{L}_n^{\mathrm{PC}}$ based on the physical-social graph $\mathcal{G}^{\mathrm{PS}}$ in Fig. 5.

All the nodes then report the preference lists $\mathcal{L}_n^{\mathrm{PC}}$ to the base station. Based on the preference lists, the base station will compute the core relay selection $(r_n^*)_{n\in\mathcal{N}}$ according to the core relay selection algorithm in Algorithm 1. We illustrate the iterative procedure of the core relay selection algorithm in Fig. 6 by adopting the graphical representation $\mathcal{G}^{\mathcal{M}_t}$ introduced in Section V-A. Recall that there is an edge directed from node n to node m on graph $\mathcal{G}^{\mathcal{M}_t}$ if node m is the most preferable relay of node n given the set of nodes $\mathcal{M}_t$. At iteration $t = 1$, given that $\mathcal{M}_1 = \mathcal{N}$, the base station identifies one cycle, i.e., a self-loop formed by node 1. At iteration $t = 2$, given that $\mathcal{M}_2 = \mathcal{M}_1 \backslash \{1\}$, the base station then identifies one cycle formed by nodes 2 and 3. Notice that graph $\mathcal{G}^{\mathcal{M}_2}$ can be derived from graph $\mathcal{G}^{\mathcal{M}_1}$ by removing node 1 and any edges directed to node 1. For each node (e.g., node 2) from which there is a removed edge directed to node 1, we add a new edge directed from the node to its most preferable node among the set of nodes $\mathcal{M}_2$ (e.g., the edge $2 \rightarrow 3$). We continue in this manner until all the nodes have been removed from the graph. Fig. 7 shows all the reciprocal relay selection cycles identified by the core relay selection algorithm in Fig. 6. In this case, the core relay selection is: 1) since $r_1^{\mathrm{S}} = 1$, node 1 transmits directly; 2) nodes 2 and 3 serve as the relay of each other (i.e., direct reciprocity-based relay selection); 3) since $r_4^{\mathrm{S}} = 1$, node 4 seeks relay assistance from node 1 (i.e., social-trust-based relay selection); 4) node 5 serves as the relay of node 7, which in turn serves as the relay of node 6, and node 6 in turn is the relay of node 5 (i.e., indirect reciprocity-based relay selection).

C. Properties of NARS Mechanism

We next study the properties of the proposed NARS mechanism. First of all, according to the definition of the core solution of coalitional game, we know the following.

Lemma 5: The core relay selection $(r_n^*)_{n\in\mathcal{N}}$ by NARS mechanism is immune to group deviations, i.e., no group of nodes can deviate and improve by cooperation within the group.

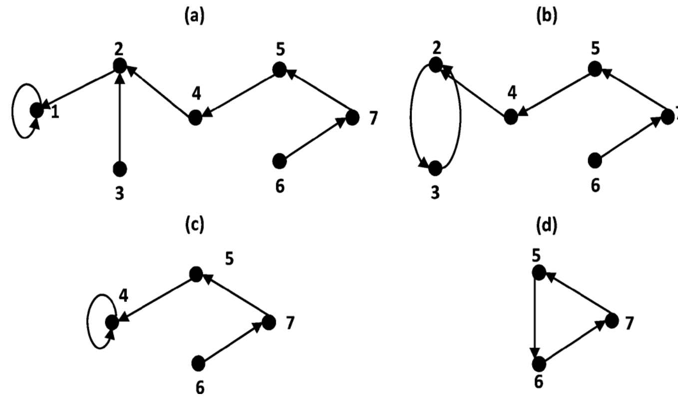

Fig. 6. Resulting graphs $\mathcal{G}^{\mathcal{M}_t}$ at each iteration t of the core relay selection algorithm. (a) $t = 1$. (b) $t = 2$. (c) $t = 3$. (d) $t = 4$.

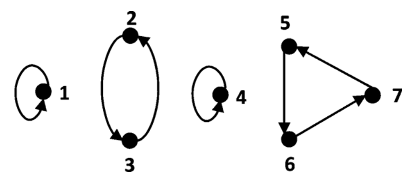

Fig. 7. Reciprocal relay selection cycles identified by the core relay selection algorithm in Fig. 6.

We can then show that the mechanism guarantees individual rationality, which means that each participating node will not achieve a lower data rate than that when the node does not participate (i.e., in this case the node will transmit directly).

Lemma 6: The core relay selection $(r_n^*)_{n\in\mathcal{N}}$ by NARS mechanism is individually rational, i.e., each node $n \in \mathcal{N}$ will be assigned a relay r_n^* that satisfies either $r_n^* \succ_n n$ or $r_n^* = n$.

Proof: If the assigned relay $r_n^* \prec_n n$ for some node $n \in \mathcal{N}$, then the node n can deviate from the current coalition and improve its data rate by transmitting directly (i.e., $r_n^* = n$). This contradicts with the fact that $(r_n^*)_{n\in\mathcal{N}}$ is a core relay selection. ■

We next explore the truthfulness of NARS mechanism. A mechanism is truthful if no node can improve by reporting a preference list different from its true preference list, given that other nodes report truthfully.

Lemma 7: NARS mechanism is individually truthful.

Proof: Let $\mathcal{C}^t$ be the set of nodes in the reciprocal relay selection cycles obtained in the tth iteration of core relay selection algorithm. Suppose that the node m reports another preference list that is different from its true preference list. Let τ be the index such that $m \in \mathcal{C}^\tau$. Given that the nodes in the set $\cup_{t=1}^{\tau-1}\mathcal{C}^t$ truthfully report, they will be assigned the relays in the core relay selection regardless of what the nodes out of the set $\cup_{t=1}^{\tau-1}\mathcal{C}^t$ report. In this case, given the set of remaining nodes $\mathcal{M}_\tau = \mathcal{N} \backslash \cup_{t=1}^{\tau-1} \mathcal{C}^t$, the most preferable relay of node m is the relay r_m^* in the core relay selection. This is exactly what the node m achieves by reporting truthfully. Thus, the node m can not improve by reporting another preference list. ■

We further show a stronger result of collectively truthfulness. A mechanism is collectively truthful if no group of nodes can improve by joint reporting their preference lists different from their true preference lists, given that other nodes report truthfully.

Lemma 8: NARS mechanism is collectively truthful.

Proof: Suppose that a group of nodes $\mathcal{S}$ report other preference lists that are different from their true preference lists. Let τ be the smallest index such that $\mathcal{S} \cap \mathcal{C}^\tau \neq \emptyset$. Given that the nodes in the set $\cup_{t=1}^{\tau-1}\mathcal{C}^t$ truthfully report, they will be assigned the relays in the core relay selection regardless of what the nodes out of the set $\cup_{t=1}^{\tau-1}\mathcal{C}^t$ report. Furthermore, given that nodes in the set $\mathcal{N}\backslash\mathcal{S}$ report truthfully, for any node $m \in \mathcal{S} \cap \mathcal{C}^\tau$, the most preferable relay of node m among the remaining nodes $\mathcal{M}_\tau = \mathcal{N}\backslash \cup_{t=1}^{\tau-1} \mathcal{C}^t$ is the relay r_m^* in the core relay selection. This is exactly what the node m achieves by reporting truthfully. Thus, a node $m \in \mathcal{S} \cap \mathcal{C}^\tau$ cannot improve by reporting another preference list. Similarly, we can show that for a node m in the set $\mathcal{S} \cap \mathcal{C}^{\tau+1}$, the most preferable relay of node m among the remaining nodes $\mathcal{M}_{\tau+1} = \mathcal{N}\backslash \cup_{t=1}^{\tau} \mathcal{C}^t$ is the relay r_m^* in the core relay selection. We can repeat the same augment for k times until that $\mathcal{S} \cap \mathcal{C}^{\tau+k} = \emptyset$, which completes the proof. ■

We finally consider the computational complexity of NARS mechanism. We say the mechanism is computationally efficient if the solution can be computed in polynomial time.

Lemma 9: NARS mechanism is computationally efficient.

Proof: Recall that the reciprocal relay selection cycle finding algorithm in Algorithm 2 has a complexity of $\mathcal{O}(|\mathcal{M}_t|)$. Since the reciprocal relay selection cycle finding algorithm is the dominating step in each iteration, the core relay selection algorithm hence has a complexity of $\mathcal{O}(\sum_{t=1}^{T} |\mathcal{M}_t|)$. As $\sum_{t=1}^{T} |\mathcal{M}_t| = N + \sum_{t=2}^{T}(N - \sum_{\tau=1}^{t-1} |\mathcal{C}^\tau|)$ and $\sum_{t=1}^{T} |\mathcal{C}^\tau| = N$, by setting $|\mathcal{C}^\tau| = 1$ for $\tau = 1, \ldots, T$, we have the worst case that $\sum_{t=1}^{T} |\mathcal{M}_t| = \sum_{i=1}^{N} i = \frac{N(N+1)}{2}$. Thus, the mechanism has a complexity of at most $\mathcal{O}(N^2)$. ■

Lemmas 5–9 together prove the following theorem.

Theorem 2: NARS mechanism is immune to group deviations, individually rational, individually and collectively truthful, and computationally efficient.

To summarize, in this section we have developed a graphical-based algorithm for finding the reciprocal relay selection cycles and have further devised an efficient NARS mechanism with nice property guarantee for implementing the social-trust- and social-reciprocity-based relay selection solution in practical D2D communication systems.

VI. Simulations

In this section we evaluate the performance of the proposed social-trust- and social-reciprocity-based relay selection for cooperative D2D communications through simulations.

We consider that multiple nodes are randomly scattered across a square area with a side length of 1000 m. Two nodes within a distance of 250 m are randomly matched into a source-destination D2D communication link. The motivation of randomly matching of source–destination pairs is as follows: 1) due to the mobility, a user may have opportunities to conduct D2D communications with different users at different time periods and different locations; 2) a user may have diverse interest to carry out D2D communications with different users for sharing different content. We compute the SNR value μ_{ij} according to the physical interference model, i.e., $\mu_{ij} = \frac{p_i}{\omega_0 \cdot ||i,j||^\alpha}$ with the transmission power $p_i = 1$ W, the background noise $\omega_0 = 10^{-10}$ W, and the path-loss factor $\alpha = 4$ [40]. Based

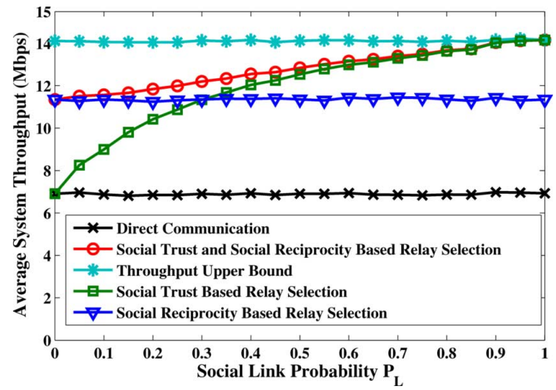

Fig. 8. System throughput with the number of nodes $N = 100$ and different social network density.

on the SNR μ_{ij}, we set the bandwidth $W = 10$ Mhz and then compute the data rate achieved by using different relays according to (1). We construct the physical graph $\mathcal{G}^{\mathrm{P}}$ by setting $e_{nm}^{\mathrm{P}} = 1$ (i.e., node m can be a relay candidate of node n) if and only if the distance between nodes n and m is not greater than a threshold $\delta = 500$ m (i.e., $||n, m|| \leq \delta$). We set a relatively large distance threshold due to the fact that, in the D2D communication, the detection of neighboring relay nodes can be significantly enhanced with the assistance by the base station [3]. For the social trust model, we will consider two types of social graphs: Erdos–Renyi social graph and real data-trace-based social graph.

A. Erdos–Renyi Social Graph

We first consider $N = 100$ nodes with the social graph $\mathcal{G}^{\mathrm{S}}$ represented by the Erdos–Renyi (ER) graph model [41] where a social link exists between any two nodes with a probability of P_L. To evaluate the impact of social link density of the social graph, we implement the simulations with different social link probabilities $P_L = 0, 0.05, 0.1, \ldots, 1.0$, respectively. For each given P_L, we average over 1000 runs. As the benchmark, we also implement the solution that each node transmits directly, the solution that each node selects the relay based on social trust only (i.e., $r_n = r_n^{\mathrm{S}}$), and the solution that each node selects the relay based on social reciprocity only by assuming that there is no social trust among the nodes. Furthermore, we also compute the throughput upper bound by letting each node select the best relay $\bar{r}_n = \arg\max_{r_n \in \mathcal{N}_n^{\mathrm{P}} \cup \{n\}} R_n(r_n)$ among all its feasible relays. Notice that the throughput upper bound can only be achieved when all the nodes are willing to help each other (i.e., all the nodes are cooperative).

We show the average system throughput in Fig. 8. We see that the performance of the social-trust-and-social-reciprocity-based relay selection dominates that of social-trust-only-based relay selection and social-reciprocity-only-based relay selection. When the social link probability P_L is small, the social-trust-and-social-reciprocity-based relay selection achieves up to 64.5% performance gain over the social-trust-only-based relay selection. When the social link probability P_L is large, the social-trust-and-social-reciprocity-based relay selection achieves up to 24% performance gain over the social-reciprocity-only-based relay selection. We also observe that

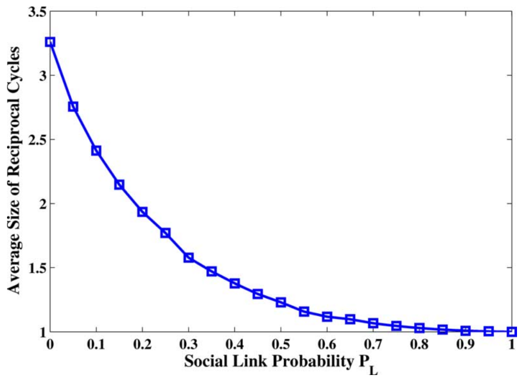

Fig. 9. Average size of the reciprocal relay selection cycles in the social-trust-and-social-reciprocity-based relay selection with $N = 100$ and different social network density.

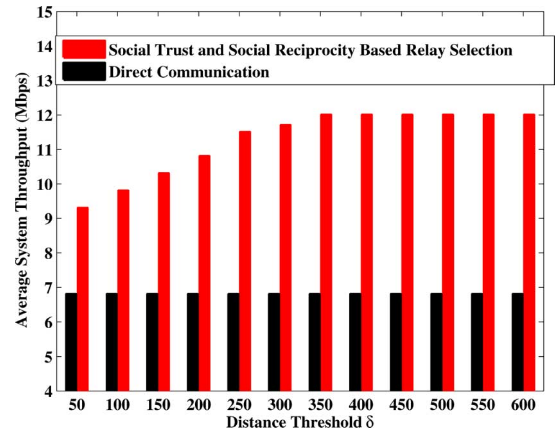

Fig. 10. System throughput of nodes $N = 100$ and different distance threshold δ for relay detection.

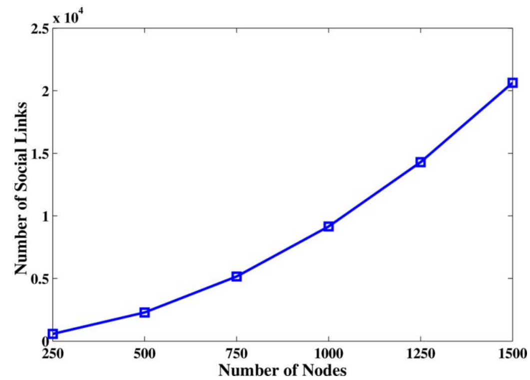

Fig. 11. Number of social links of the social graphs based on real trace Brightkite.

the social-trust-and-social-reciprocity-based relay selection achieves up to 100.4% performance gain over the case that all the nodes transmit directly. Compared to the throughput upper bound, the performance loss of the social-trust-and-social-reciprocity-based relay selection is at most 24%. As the social link probability P_L increases, the social-trust-and-social-reciprocity-based relay selection improves and approaches the throughput upper bound. This is due to the fact that when the social link probability P_L is large, each node will have a high probability of having social trust from any other node, and hence each node is likely to have social trust from its best relay node. This can be illustrated by Fig. 9, which shows the average size of the reciprocal relay selection cycles in the social-trust-and-social-reciprocity-based relay selection. We observe that as the social link probability P_L increases, the average size of the reciprocal relay selection cycles decreases. This is because as the social link probability P_L increases, more nodes are able to select their best relay nodes based on social trust. As a result, less nodes would select relay nodes based on social reciprocity and hence the average size of the reciprocal relay selection cycles decreases.

To investigate the impact of the distance threshold δ for relay detection, we implement the simulations with the number of nodes $N = 100$, the social link probability $P_L = 0.2$, and the distance threshold $\delta = 50, 100, \ldots, 600$ m, respectively. We see from Fig. 10 that initially the system performance of social-trust-and-social-reciprocity-based relay selection improves as the distance threshold δ increases. When the distance threshold δ is large, however, the performance of social-trust-and social-reciprocity-based relay selection levels off. This is because that initially as the distance threshold δ increases, more and more good relay nodes are available. Once the distance threshold δ is large enough, only those nodes that are within a relatively short distance can be good relays for cooperative D2D communications. For those nodes that have a long distance, they will not be chosen as relays since they would offer worse performance than that of the direct communication case.

B. Real Trace-Based Social Graph

We then evaluate the proposed social-trust-and-social-reciprocity-based relay selection using the real data trace Brightkite [42]. Brightkite is a data trace collected from a location-based social networking service platform where users share their location check-ins. Brightkite contains an explicit friendship network among the users. Different from the ER social graph, the friendship network of Brightkite is scale-free such that the node degree distribution follows a power law [43]. We implement simulations the number of nodes $N = 250, 500, \ldots, 1500$, respectively. We randomly select N nodes from Brightkite and construct the social graph based on the friendship relationship among these N nodes in the friendship network of Brightkite. For each given N, we average over 1000 runs. Fig. 11 shows the average number of social links among these nodes of the social graphs when using the real data trace Brightkite.

We show the average system throughput in Fig. 12. We see that the system throughput of the social-trust-and-social-reciprocity-based relay selection increases as the number of users N increases. This is because more cooperation opportunities among the nodes are present when the number of users N increases. Moreover, the social-trust-and-social-reciprocity-based relay selection achieves up to 122% performance gain over the solution that all users transmit directly. Compared to the throughput upper bound, the performance loss by the social-trust-and-social-reciprocity-based relay selection is at most 21%.

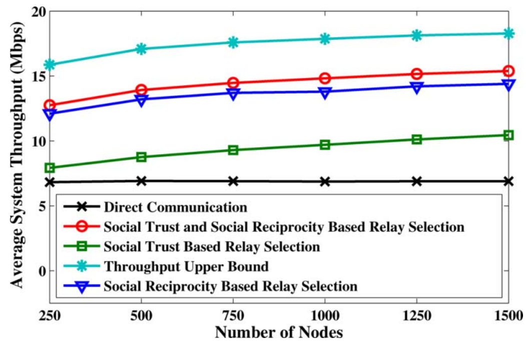

Fig. 12. Average system throughput with different number of nodes.

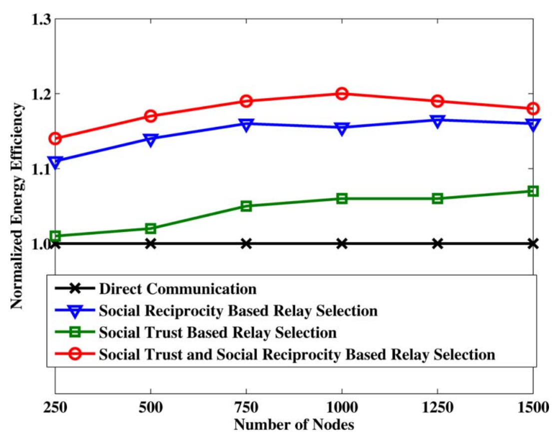

Fig. 13. Normalized energy efficiency with different number of nodes.

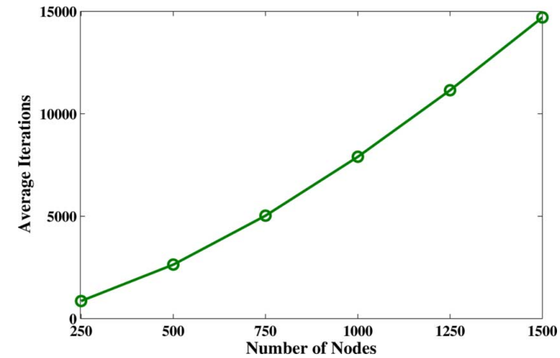

Fig. 14. Average number of iterations of the NARS mechanism.

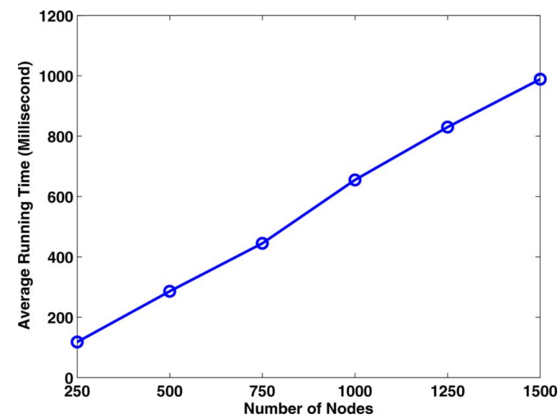

Fig. 15. Average running time of the NARS mechanism.

We then evaluate the energy efficiency of the proposed NARS mechanism. We adopt the common practice in literature [44] and compute the energy efficiency as the ratio between the system-wide throughput and the system-wide energy consumption. Fig. 13 shows the normalized energy efficiency of different relay selection schemes with respect to that of direct communication. It demonstrates that the proposed the social-trust-and-social-reciprocity-based relay selection scheme is energy efficient and achieves the highest energy efficiency among all the schemes.

We next show the computational complexity of the NARS mechanism for computing the social-trust-and-social-reciprocity-based relay selection solution in Fig. 14. We see that the average number of iterations of the mechanism grows linearly as the number of nodes N increases. We also measure the running time of the NARS mechanism on a 64-bit Windows PC with 2.5-GHz Quad-core CPU and 16 GB memory in Fig. 15. We observe that the running time of the mechanism increases linearly as the number of nodes N increases, and the running time is less than 1 s in all cases. Notice that when the NARS mechanism is implemented in practical D2D systems, the base station typically has a much stronger computational capability than a PC and the running time of the NARS mechanism can be further significantly reduced. This demonstrates that the proposed NARS mechanism is computationally efficient.

VII. Conclusion

In this paper, we studied cooperative D2D communications based on social trust and social reciprocity. We introduced the physical-social graphs to capture the physical constraints for feasible D2D cooperation and the social relationships among devices for effective cooperation. We proposed a coalitional game-theoretic approach to find the efficient D2D cooperation strategy and developed a network-assisted relay selection mechanism for implementing the coalitional game solution. We showed that the devised mechanism is immune to group deviations, individually rational, truthful, and computationally efficient. We further evaluated the performance of the mechanism based on Erdos–Renyi social graphs and real data-trace-based social graphs. Simulation results show that the proposed mechanism can achieve up to 122% performance gain over the case without D2D cooperation.

We are currently generalizing the notion of social trust from the current one-hop setting (e.g., friends) to the multihop setting (e.g., friend's friends). Intuitively, as the number of social hops between two nodes increases, the strength of social trust decreases. Mathematically, we can introduce a weighted social graph to model such features by defining the weight as the strength of social trust. It is of great interest to design efficient stimulation mechanisms for D2D cooperation by taking both generalized social trust and social reciprocity into account.

In this paper, we consider that the cooperative D2D communications between the relay node and the destination node use in-band communication (i.e., using cellular spectrum). To achieve better network connectivity and enhance the communication performance, both the in-band and out-band (i.e., using WiFi spectrum) D2D communications can be utilized. For instance, two users can adopt the WiFi-direct to conduct out-band

D2D communication; alternatively, the users can conduct the in-band D2D communication by using the cellular spectrum. We are currently building a prototype system on cooperative D2D communications using in-band (out-band) communications.

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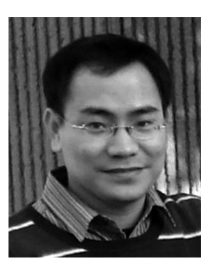

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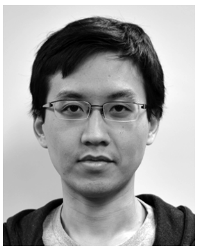

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