Impact of Selfishness in Device-to-Device Communication Underlaying Cellular Networks

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***Abstract*—In a device-to-device (D2D) communication underlaying cellular network, user equipment are required to operate cooperatively and unselfishly to transmit data as relays. However, most users more or less behave in a selfish way, which makes user selfishness a key factor that affects the performance of the whole communication system. We focus on the impact of user selfishness on D2D communications. By separating the user selfishness into two types in accordance with two D2D transmission modes, which are connected D2D transmission and opportunistic D2D transmission, we propose a time-varying graph model that characterizes the impacts of both individual and social selfishness on the D2D communications. Simulation results obtained under the realistic networking settings indicate that the interaction between connected and opportunistic selfishness worsens the impairment caused by individual selfishness. Additionally, when concerning social selfishness, inside-community selfishness can be ignored in some occasions, while otherwise its role is heavily influenced by community numbers.**

***Index Terms*—Device-to-device communication, user cooperation, user selfishness, community**

I. INTRODUCTION

With the increasing demand for content downloading by mobile devices in cellular network, cellular direct transmission may be unable to meet the downloading demand, especially when the network condition is poor with low signal-to-noise ratio [1]–[4]. Hence, Third Generation Partnership Project (3GPP) has integrated the device-to-device (D2D) communication as an underlay to the next generation cellular network known as Long Term Evolution-Advanced (LTE-A). Utilizing the physical proximity of mobile devices and local good channel conditions [1], [2], D2D communications require base stations (BSs) to distribute cellular resources to communicating user equipment (UE) pairs [5]. With the allocated cellular resources, an UE is able not only to help to forward data from a BS or another UE to other UE, but also to temporally store some data in its buffer and to wait for contact opportunities to send them out [6], which is composed of the two D2D transmission modes known as connected D2D transmission and opportunistic D2D transmission [7]. Note that the D2D connected mode relies on the usual relaying technique which requires the end-to-end path, while the D2D opportunistic mode utilizes the new paradigm of story-carry-forward which does not need the end-to-end path. Thus, a D2D communication underlaying cellular network by enabling direct data flows between communicating pairs improves the performance of cellular system in a cooperative way. In other words, in order to benefit the whole system, communicating devices are required to devote some of their own resources, such as power, CPU occupation and buffer, to D2D communications in an unselfish way [8]. For both these two types of D2D transmissions, we focus on the scenario of downlink transmission, where users are able to cooperate for content downloading through D2D transmissions.

On the other hand, in the real world, mobile devices are held and controlled by humans, who have the instinctive and indispensable nature – selfishness [9]. Unavoidable selfishness of UEs in D2D communications is the result of many practical factors, including finite energy, limited storage, valuable CPU resources, privacy and security considerations. A mobile phone user with dying battery may for example refuse to contribute the scarce battery resource to D2D communications just to improve the downloading speed of others, and many users may not be pleased to devote part of the limited buffer of their mobile devices to safeguarding the interests of strangers. Unfortunately, current researches have assumed that UEs are always willing to act in a cooperative way and fail to consider the inherent selfishness of UEs in the D2D communication systems [1], [3], [5], [10], [11], which may lead to overestimation of the system performance and misinterpretation of the relevant properties. Obviously, if most users are unwilling to participate in D2D transmission, the resources cannot be utilized sufficiently, and a D2D underlaying cellular system will not able to operate successfully. Consequently, user selfishness, which has not been studied by the existing works but is intrinsic and crucial to the operation of D2D systems, has to be understood in order to objectively evaluate the performance of D2D systems as well as to help to design better D2D underlaying systems.

However, it is difficult to quantify the impacts of this attribute of mobile users, who are different and have various motivations. As an individual, an UE tends to show unwillingness when required to selflessly forward or store data for other users. This type of selfishness may be referred to as *individual selfishness*. As a member of a community, an UE, although may be more willing to act as relay for the members of the

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same community, may be unwilling to do so for the users outside the community. This type of selfishness can be referred to as *social selfishness*. Both types of selfishness should be characterized and, moreover, their interplay in different D2D transmission modes should be considered. Against this background, our contributions are summarized as follows.

- We are the first to investigate the impacts of selfishness on D2D underlaying cellular networks, by defining two new selfishness modes, known as D2D connected selfishness and D2D opportunistic selfishness, in accordance with the two D2D transmission modes in D2D underlaying cellular networks, known as D2D connected transmission and D2D opportunistic transmission.
- We propose a time-varying graph model capable of revealing the impacts of both individual and social selfishness on the two D2D transmission modes. With this model, D2D connected selfishness and D2D opportunistic selfishness are studied both separately and jointly in terms of both individual selfishness and social selfishness.
- We implement extensive simulations with realistic human selfishness and network settings based on this model, and draw valuable conclusions regarding exasperated impairments caused by interactions between the two D2D selfishness modes. We also discuss the differences between the individual and social D2D selfishness.

The rest of the paper is organized as follows. We present an overview of the D2D communication underlaying cellular system and illustrate two types of D2D selfishness in Section II. In Section III, we establish the model that characterizes both types of selfishness, and then present the system constraints and solutions to this optimization framework. In Section IV, we analyze the simulation results and draw conclusions about individual and social selfishness. Section V summarizes the related works, and we conclude the paper and discuss our future works in Section VI.

II. SYSTEM OVERVIEW AND MOTIVATION

Fig. 1 depicts a typical D2D underlaying cellular network with selfish UEs. Since UEs are naturally mobile nodes with varying positions and fluctuating access states, we use "time frame" to loosely mark a system time period within which the access states and physical relationships of all the nodes remain nearly constant. For instance, Fig. 1 presents two different time frames – t_2 and t_4. The orange hexagons indicate the approximate coverage areas of BSs (B_1, B_2, B_3 and B_4) which have high-speed Internet access and can distribute cellular resources to their associated UEs for cellular direct transmissions or D2D transmissions. In content-downloading, there are two natural groups of UEs – subscribers and helpers. Subscribers are the UEs requesting and downloading data, such as S_1 in Fig. 1 whose D2D communication area is denoted by small purple circle, can benefit from D2D communications. The other group of the UEs who are not requesting data in the time period may act as helpers. For example, there are two helpers, H_1 and H_2, with green-circle D2D communication areas in Fig. 1. Although helpers may exhibit selfish behaviours, they can more or less participate in D2D transmissions by serving as "relays" via two possible D2D transmission modes introduced below.

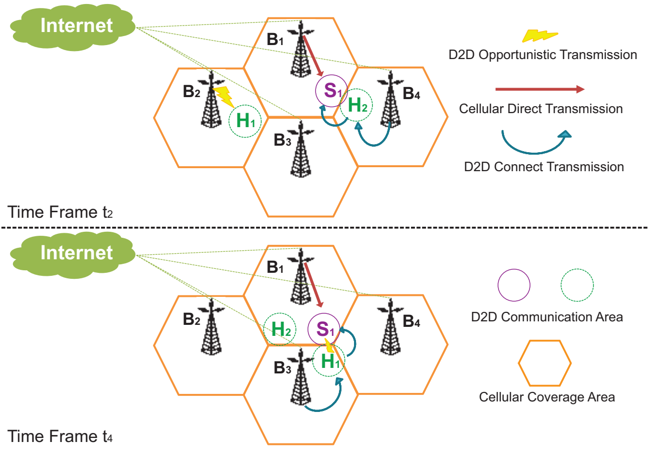


Fig. 1. Illustration of different transmission modes in D2D communication underlaying cellular network.

1) D2D connected transmission: By taking advantage of good local channel conditions and physical proximity of communicating UEs, a BS first transmits a data flow to a voluntary helper and then requires the helper to immediately forward the messages it just received to a subscriber or another helper via a D2D link. For instance, in Fig. 1, D2D communication contact has been established between S_1 and H_2, and H_2 is willing to participate in D2D connected transmission. Therefore, B_4 is transmitting data to S_1 with the aid of H_2 during time frame t_2. Similarly, H_1 serves as a relay in the data path from B_3 to S_1 during time frame t_2.

2) D2D opportunistic transmission: A D2D connected path is prone to break owing to the mobility of UEs. A helper who is willing to devote some buffer to D2D transmission can store and carry some data in its buffer and wait for an opportunistic communication contact to transmit the data to a subscriber or other helpers. This is known as store-carry-forwarding. Fig. 1 offers an example of D2D opportunistic transmission, where H_1 is willing to offer its buffer. In time frame t_2, B_2 is transmitting data flow to H_1 for potential D2D opportunistic transmission. Later, when H_1 establishes D2D connection with a subscriber under a satisfying channel condition, it can transmit the data from its buffer to this subscriber.

The concept of relay here is a physical layer one, rather than a MAC layer concept. Specifically, the purpose of relay in our system is to achieve cooperative data transmission in physical layer, instead of establishing routing in MAC or higher layer.

Note that both these two types of D2D transmissions (modes) involve individual selfishness and social selfishness at the same time. These two D2D modes are distinguished by their transmission modes, and the two types of selfishness are distinguished by the communities of users'. Both users' selfishness to its own community or other communities has impact on the performance of connected D2D transmission and opportunistic D2D transmission.

In Fig. 1, H_2 is unwilling to devote some buffer to the D2D opportunistic transmission although it is happy to help with the D2D connected transmission. For acting as a relay in D2D connected transmission, a user is required to contribute its battery resource, but to become a helper in D2D opportunistic transmission, a user must contribute both its battery and storage resources. Consequently, we should consider different selfishness metrics for the two D2D communication modes. Thus, we divide both individual selfishness and social selfishness into two components, termed as "**connected selfishness**" and "**opportunistic selfishness**", in accordance with the above-mentioned two D2D transmission types. Specifically, connected selfishness represents the degree of helpers' unwillingness to cooperate in connected D2D transmission, while opportunistic selfishness reflects helpers' unwillingness to participate in D2D opportunistic transmission. Clearly, a user's opportunistic selfishness is higher than its connected selfishness.

III. MODEL AND ANALYSIS FRAMEWORK

In order to model this sophisticated scenario and analyze the impacts of both social and individual selfishness on D2D underlaying cellular networks, we focus on the theoretical performance bound and propose an optimization framework that takes the two different D2D modes into consideration.

A. *Time-varying Graph Model*

There are five basic types of network events: start of cellular accessing, end of cellular accessing, start of D2D contact, end of D2D contact, and change in link quality [7]. Both access states and D2D contacts can only be affected by these five types of events, and a time frame denotes the time period between two successive network events during which the access states of all the network participating nodes remain unchanged. In other words, time frames divide the continuous time, and within a time frame both the access states and the D2D connections of the cellular network are static.

If there are b BSs labeled as $\mathcal{B} = \{B_1, B_2, \cdots, B_b\}$, h helpers labeled as $\mathcal{H} = \{H_1, H_2, \cdots, H_h\}$ and s subscribers labeled as $\mathcal{S} = \{S_1, S_2, \cdots, S_s\}$, a static graph similar to Fig. 1 with b BSs, h helpers and s subscribers can be drawn for every time frame. Each formed static graph includes all data-transmission behaviors, consisting of cellular direct transmissions and D2D communications, in the time frame. To simplify the graphs, let each BS or UE in a graph be represented by a node. Then there are $b + h + s$ nodes in the static graph model of each time frame. We can also use directed edges to represent the data flows between nodes in a time frame. Specifically, the edges of D2D connected transmissions are from BSs via some voluntary helpers to subscribers, and the edges of cellular direct transmissions are directly from BSs to subscribers, all within a same time frame.

However, for D2D opportunistic flows, a single graph for one time frame is unable to represent a whole process of D2D opportunistic communication because this communication mode covers multiple successive time frames. Specifically, helpers that are willing to help with D2D opportunistic transmissions store the content in their local buffer at certain time frame and then transmit them during some later time frame when the opportunities occur. Therefore, we need to integrate multiple static graphs into one graph that can cover some successive time frames in order to represent D2D opportunistic transmissions. Between the reception of the content and the transmission of them to a subscriber, a helper may carry the data in its buffer across several successive time frames. It is this "carrying" mechanism that enables data flow across time frames and hence makes it possible to model the time evolution of this time-varying system by linking the static graphs of different time frames to form a dynamic graph.

Formally, let the entire time period be divided into n time frames. We can first generate n static graphs, one for each time frame, and then link them with directed edges to represent data flows in buffers across time frames. In other words, with the buffer data flows across time frames (but only from a time frame to its successive time frames), the connectivity of this static graph is extended through successive time frames. Then, the edges of outgoing D2D opportunistic flows are from willing helpers to subscribers or other helpers in a time frame as well as to themselves in the successive time frame, which represent the contents stored in the helpers' buffers. For example, the dynamic graph depicted in Fig. 2 includes all the possible transmission modes, cellular direct transmissions, D2D connected transmissions and D2D opportunistic transmissions, where BSs and UEs are represented by vertices. Moreover, directed edges are added to link BS and UE vertices, which represent the data flows of cellular direct transmissions and/or D2D communications. In particular, we can observe from Fig. 2 that helper H_h receives the content in time frame 2 from h_1, and carries the data through the successive time frames until later at time frame n, it encounters subscriber S_1 and is able to transmit the content to it.

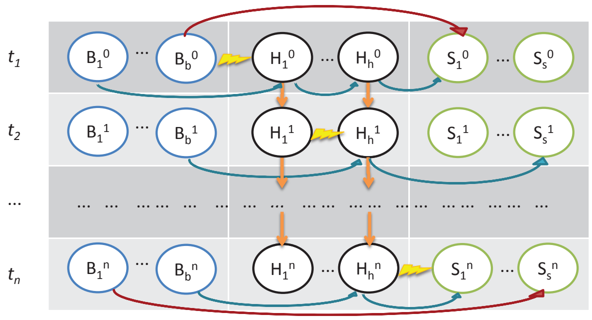


Fig. 2. A dynamic graph model which includes all possible data flows in the D2D underlaying cellular system. For graphic clarification, the weight associated with each directed edge is omitted.

Furthermore, we can attribute weights to directed edges to model the data flows in these "links". Thus, transmission forms and magnitudes of data flows are all included in this weighted connected digraph. For example, each directed edge in the same row (time frame) in Fig. 2 represents one of the following communication forms: crimson arrow for cellular direct transmission, blue arrow for D2D connected transmission, and yellow flash for D2D opportunistic transmission. Each edge in a same time frame is associated with a positive value representing the amount of data transmitted within this time frame, bound by the product of the time-frame duration and the temporal link transmission rate. A directed edge across time frames in Fig. 2 is bound by the buffer size that the particular helper is willing to contribute and, therefore, is linked to node selfishness. For the graphic conciseness, we omit the weights on all the directed edges in Fig. 2. It is worth emphasizing that this weighted connected dynamic graph explicitly takes into account user selfishness.

To quantitatively reveal the impacts of user selfishness in the two D2D modes, both incoming flow and outgoing flow of each node in each time frame are divided into two flows, one for connected D2D transmission and one for opportunistic D2D transmission.

- Connected incoming flow: is the part of incoming flow of a node for D2D connected mode, and if the node is a helper, it will be forwarded immediately after reception to another node and does not occupy the helper's buffer for inter-time frame transmission. A helper may receive this kind of incoming flow only if it has devoted some of its energy resource to participating in D2D connected transmission. The data amount of connected incoming flow of helper H_i in time frame l is denoted as $v_l(H_i)$.
- Opportunistic incoming flow: is the part of incoming flow of a node for D2D opportunistic mode, and if the node is a helper, it will be stored in the helper's buffer for opportunistic transmission at some later time frame. Only a helper who has devoted some of its energy resource and buffer to participating in D2D opportunistic transmission may receive this kind of incoming flow. The data amount of opportunistic incoming flow of helper H_i in time frame l is denoted as $w_l(H_i)$.
- Connected outgoing flow: is the part of outgoing flow that is just received and forwarded immediately by a helper. Connected outgoing flow, which is not from the helper's buffer, is equal to connected incoming flow for each node in the graph model. The data amount of connected outgoing flow from helper H_i to helper H_j or subscriber S_j in time frame l is denoted as $x_l(H_i, H_j)$ or $x_l(H_i, S_j)$
- Opportunistic outgoing flow: is the part of outgoing flow of a helper that is from the helper's buffer. The data in this kind of flow were received in a previous time frame and have been stored in the helper's buffer for one or more time frames. The data amount of opportunistic outgoing flow from helper H_i to helper H_j or subscriber S_j in time frame l is denoted as $y_l(H_i, H_j)$ or $y_l(H_i, S_j)$.

To sum up, in a D2D communication underlaying cellular system, the accessing relationships between BSs and UEs as well as between UEs are time-varying and the communication contacts are dynamic. However, each row in our graph model has a static topology for the duration of one time frame as the access states of all the participating nodes remain unchanged for the duration of each frame. The temporal and spatial distributions of the whole network topology are included in this weighted directed graph, which models the behaviors of all the participating BSs and UEs, including the selfishness of UEs. In addition, by characterizing the data flows according to different D2D modes for each helper, it is convenient to regulate the D2D underlaying cellular system with connected selfishness and opportunistic selfishness. Compared to existing SINR-based model, the key feature of our graph model is that it is able to include flows among nodes in different time frames, which allows us to analyze D2D selfishness in opportunistic transmissions.

B. D2D Selfishness Modes

In our graph model, whether a connected outgoing flow or a opportunistic outgoing flow is allowed to establish depends on two factors – the physical access states between node pairs and the selfishness of UE senders – a very selfish helper may for example refuse to participate in some possible transmissions.

Since the access states within each time frame remain constant, in each time frame, a Boolean matrix, referred to as Connection Matrix, can be used to describe the access states of UE pairs. In this matrix, the row number of an element specifies a helper, and the column number of an element specifies a helper or subscriber, while the Boolean value of an element represents whether a connection between this node pairs is allowed or not. Similarly, another Boolean matrix, referred to as Cover Matrix, can be used to store the access states between BSs and UEs. In this matrix, the row number of an element specifies a BS and the column number of an element specifies a helper or subscriber. If we denote Connection Matrix as N and Cover Matrix as V, then:

$$\begin{aligned} &\text{size}(N) = h \times (h+s), \\ &\text{size}(V) = b \times (h+s). \end{aligned} \tag{1}$$

Further denote the set of UEs as $\mathcal{UE} = \{UE_1, UE_2, \cdots, UE_{h+s}\} = \mathcal{H} + \mathcal{S}$. Then, for example, if the (i,j)-th element in N is $N_{i,j} = \textit{TRUE}$, the helper H_i is able to establish D2D connection with the UE UE_j, where $1 \leq i \leq h$ and $1 \leq j \leq h+s$. If the (i,j)-th element in V is $V_{i,j} = \textit{FALSE}$, on the other hand, the BS B_i is unable to transmit data to UE UE_j, where $1 \leq i \leq b$ and $1 \leq j \leq h+s$.

As mentioned previously, a helper may be unwilling to participate in D2D communication because of its connected selfishness and/or opportunistic selfishness. To model the UEs' unwillingness to participate in D2D communications, we enable helpers to randomly forbid any potential D2D connected or opportunistic transmission that it may establish. For possible D2D connected transmissions, the forbiddance occurs according to a probability p which we refer to as "connected selfishness probability", while for possible D2D opportunistic transmissions, the forbidding probability q is referred to as "opportunistic selfishness probability". Then, two random Boolean matrices, referred to as Connected Selfishness Matrix R and Opportunistic Selfishness Matrix G, respectively, can be generated for each time frame, which store the random forbiddance to the two respective D2D modes. Clearly,

$$\text{size}(R) = \text{size}(G) = h \times (h+s). \tag{2}$$

More specifically, let $p_{i,j}$ be the connected selfishness probability of helper h_i for UE UE_j. Then (i,j)-th element $R_{i,j}$ of R represents whether the connected D2D transmission mode from h_i to UE_j is allowed, namely,

$$\begin{cases} \Pr\big(R_{i,j} = FALSE\big) = p_{i,j}, \\ \Pr\big(R_{i,j} = TRUE\big) = 1 - p_{i,j}, \end{cases} 1 \leq i \leq h,\, 1 \leq j \leq h+s. \tag{3}$$

Similarly, let $q_{i,j}$ be the opportunistic selfishness probability of h_i for UE_j. Then (i,j)-th element $G_{i,j}$ of G represents whether the opportunistic D2D transmission mode from h_i to UE_j is allowed, namely,

$$\begin{cases} \Pr\big(G_{i,j} = FALSE\big) = q_{i,j}, \\ \Pr\big(G_{i,j} = TRUE\big) = 1 - q_{i,j}, \end{cases} \quad 1 \le i \le h,\ 1 \le j \le h+s. \tag{4}$$

By combining Connection Matrix with Connected Selfishness Matrix and Opportunistic Selfishness Matrix, respectively, we acquire two new matrices M and W according to

$$M_{i,j} = N_{i,j} \& R_{i,j},\ 1 \le i \le h,\ 1 \le j \le h+s, \tag{5}$$

$$W_{i,j} = N_{i,j} \& G_{i,j},\ 1 \le i \le h,\ 1 \le j \le h+s, \tag{6}$$

which explicitly model the selfishness in the D2D communication underlaying system. In our proposed graph model, whether a D2D connected connection is allowed to establish or not at a given time frame is determined by M matrix of this time frame, while the permission of D2D opportunistic connection depends on W matrix. Note that the constraints of Connection Matrix are imposed on output flows rather than input flows. Moreover, because of the randomness of R and G, the optimization simulation should be repeated a sufficiently large number of times for reducing the variance in order to obtain reliable results.

C. Optimization Formulation and Solution

1) Optimization Objective: Let the total amount of the data received by all the subscribers be D in the time period considered. We set maximizing D as the objective of our optimization framework, which is defined by

$$D = \sum_{l} \Big(\sum_{i,j} \big(x_l(H_i, S_j) + y_l(H_i, S_j)\big) + \sum_{k,j} c_l(B_k, S_j) \Big), \tag{7}$$

where $c_l(B_k, S_j)$ denotes the data amount transmitted through the flow via cellular direct transmission from BS B_k to subscriber S_j in time frame l.

2) Flow Conservation: In time frame l, the incoming flow of helper H_i via its own buffer from previous time frame $l-1$ is denoted as $a_l(H_i)$, while the outgoing flow of H_i via its own buffer to successive time frame $l+1$ is denoted as $b_l(H_i)$. Before the first time frame, namely, at time frame $l = 0$, the initial buffer of each helper is empty, i.e. $a_0(H_i) = 0,\ \forall i$. Owing to flow conservation, we have the following constraints

$$y_l(H_i, H_j) \le a_l(H_i),\ \forall i, j, l, \tag{8}$$

$$y_l(H_i, S_j) \le a_l(H_i),\ \forall i, j, l, \tag{9}$$

$$w_l(H_i) + a_l(H_i) \ge b_l(H_i),\ \forall i, l, \tag{10}$$

$$v_l(H_i) = \sum_{j} x_l(H_i, H_j) + \sum_{k} x_l(H_i, S_k),\ \forall i, l, \tag{11}$$

$$\sum_{j} \big(y_l(H_j, H_i) + x_l(H_j, H_i)\big) + \sum_{k} c_l(B_k, H_i) = w_l(H_i) + v_l(H_i),\ \forall i, l. \tag{12}$$

Therefore, the optimization problem can be formulated as follows:

$$\begin{array}{ll} \max & D, \\ \text{s.t.} & \text{constraints } (8) \text{ to } (12) \text{ hold.} \end{array} \tag{13}$$

3) Transmission Rate and Channel Access: Since the D2D communications in a cellular system rely on the allocated cellular resources, which are limited, the magnitude of each data flow, namely, the weight of each edge in the graph, is directly associated with the allocated resource. Specifically, the transmission rate between each node pair must meet the resource constraint, and the total transmitted data amount of each edge is constrained by the product of the transmission rate and the time-frame duration. Moreover, considering connection states and user selfishness, the transmitted content flows must be strictly circumscribed within the connected and willing UEs in each time frame, as defined by V, M and W.

4) Optimization Solution: By further adding all the constraints described in *3)* to the constrained optimization problem (13), we formulate the completed constrained maximization problem, whose decision variables include all the data flows, such as the weights of all the directed edges in Fig. 2. However, not all the associated constraints are linear constraints, indicating that this constrained optimization problem does not belong to the category of linear programming problems. Fortunately, we can use the reformulation linearization technique (RLT) [3] to transform those nonlinear constraints into linear expressions and, consequently, we can use the existing optimization tool kits, such as CPLEX [8] and YALMIP [12], to solve this constrained maximization problem. By solving this constrained maximization problem, we obtain the total amount of data that can be transmitted successfully, namely, the maximized objective value. Therefore, we can derive the total achievable transmission rate by dividing the data amount with the duration. The transmission rate in Section IV is obtained in this way.

The time-varying graph model and the formulated optimization framework allow us to understand the impact of user selfishness on the performance of D2D communications and to "quantify" the optimal system performance achievable under different levels of user selfishness, which are vital for aiding the current process of defining effective and workable D2D protocol standards for next-generation mobile networks.

Our proposed time-varying graph requires the information of all the possible links, including users mobility statistics and channel state information, and we assume that they can be obtained for each time frame and therefore are known. Note that in the planning and operating of any mobile network, these statistics are always required, in order to perform resource allocation, transmission scheduling and other operational tasks. Acquisition of these necessary statistics is an important but separate topic which is beyond the scope of this paper.

IV. SELFISHNESS ANALYSIS

A. Evaluation System Setup

We utilized the proposed optimization framework to analyze the impacts of selfishness on D2D communication underlaying cellular networks. We first implemented the evaluation system using *Cambridge* trace [9], [13], which was gathered by two groups of undergraduate students from University of Cambridge. We used the method of [14] to compute the individual contact rates of node pairs by averaging the statistics from the trace. We then averaged the contact rates of users in the same community as well as across communities to implement simulations. Additionally, we also implemented the simulation system using *SLAW* [15] and *INFOCOM05* dataset [16]. In each simulation scenario, there were 35 realistic human mobility traces, among which 12 UEs were randomly selected as helpers. The total bandwidth was 20 MHz, and 80% of the cellular resources were allocated to the BS for transmitting data to UEs, and the other 20% were used for D2D communications between UEs. In our simulation study, the path loss was assumed to follows the *Friis Transmission Equation* [17], and we adopted the standard Rayleigh fading. We calculated the total achievable transmission rate of the flows to evaluate the impact of user selfishness. All the results were averaged over hundreds of simulation trials. Further details about the user traces and simulated region can be founded in [9], [13], [15], [16].

B. *Interaction between Individual Connected and Opportunistic Selfishness*

In our dynamic graph model, we can represent the two types of individual selfishness by two probabilities, individual connected selfishness probability (ICSP) and individual opportunistic selfishness probability (IOSP), which reflect helpers' unwillingness to cooperate in the two D2D transmission modes, respectively. Let us denote the ICSP as c with $0 \leq c \leq 1$, and the IOSP as o with $0 \leq o \leq 1$. Then c is the probability of a helper's refusal to cooperate with a UE within its D2D communication range in D2D connected communication. In other words, we have the connected selfishness probability $p_{i,j} = c$ in this senario. Likewise, the opportunistic selfishness probability $q_{i,j} = o$ in this case.

With the *Cambridge* trace driven simulation system, Fig. 3 depicts the total data transmission rate obtained for all the subscribers as the function of two individual selfishness probabilities, ICSP and IOSP. The results clearly show that a slight decrease in IOSP leads to a large increase in the data transmission rate, while ICSP has less influence on the system performance. A possible explanation for this phenomenon is that re-usability is the key advantage of D2D opportunistic transmission over D2D connected transmission. A helper with popular contents in its storage may transmit them during every D2D contact. Consequently, it can take the advantage of physical proximity more efficiently. By contrast, D2D connected transmission participants have to rely on the data flows sent by the BS and the same contents may be downloaded frequently, although D2D connected transmission requires little buffer offered by helpers.

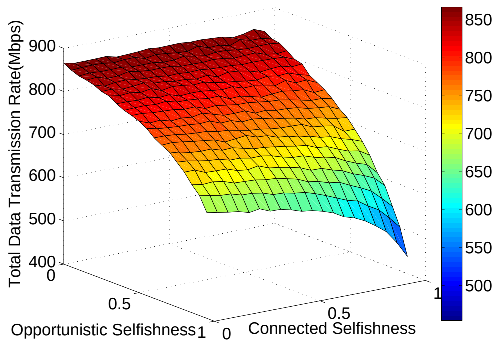
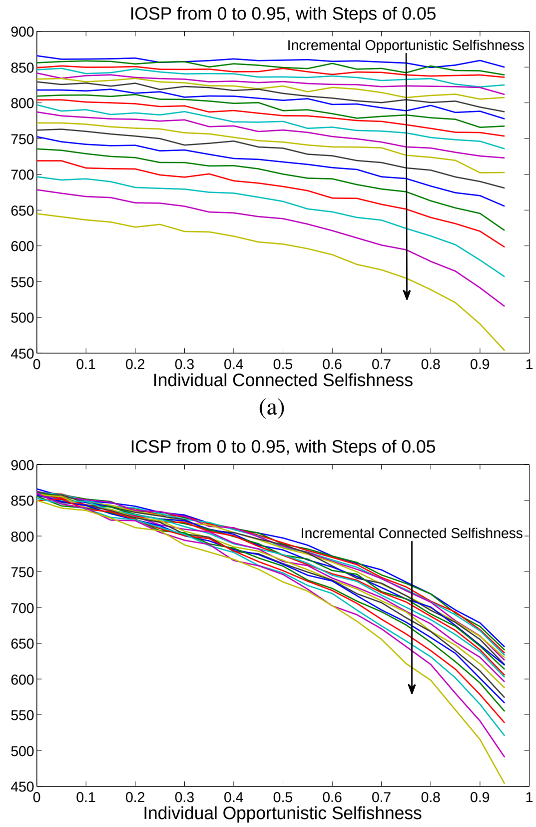


Fig. 3. The general trend of how total data transmission rate varies with two modes of individual selfishness. The simulation system is implemented based on *Cambridge* dataset.



(a)

(b)

Fig. 4. The total transmission rate indicates an obvious interaction between two individual selfishness modes. The simulation system is driven by *Cambridge* dataset.

Intuitively, when ICSP is relatively low and IOSP is relatively high, the unoccupied cellular resources as the result of users' refusal to participate in D2D opportunistic transmission can be redistributed to D2D connected communications. Similarly, when IOSP is relatively low and ICSP is relatively high, the resources may be switched from D2D connected mode to D2D opportunistic mode. We present the total data transmission rates under different selfishness metrics in Fig. 4, where there are 20 lines in both figures, with IOSP ranging from 0 to 0.95 with a step of 0.05 in Fig. 4 (a), while ICSP ranging from 0 to 0.95 with a step of 0.05 in Fig. 4 (b). Not surprisingly, Fig. 4 (a) and (b) indicate that the impacts of the D2D connected selfishness and D2D opportunistic selfishness are far from independent. Let us denote the total data transmission rate as $d = f(c, o)$, which is a function of c and o, and its partial derivatives with respect to c and o as $a = \frac{\partial f}{\partial c}(c, o)$ and $b = \frac{\partial f}{\partial o}(c, o)$, respectively. Observe from Fig. 4 that both a and b are approximately monotonically

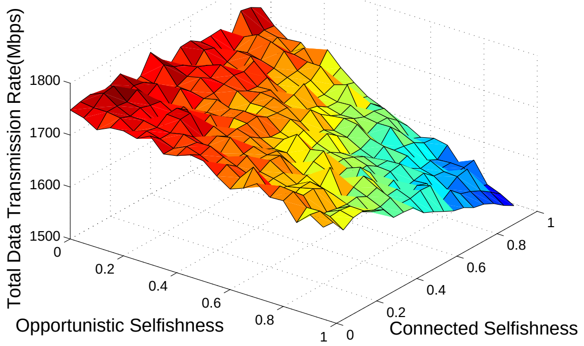


Fig. 5. Total data transmission rate as the function of two individual selfishness probabilities obtained by the *INFOCOM05* dataset based simulations.

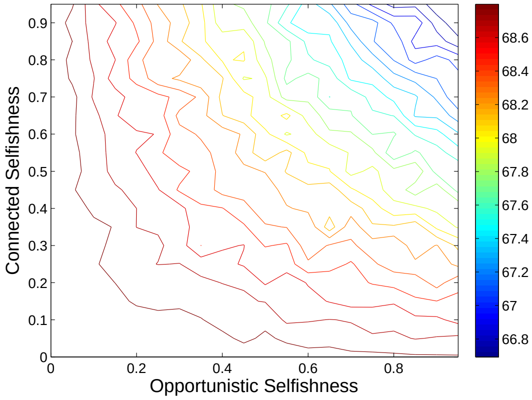


Fig. 6. Contours of the total data transmission rate as the function of two individual selfishness probabilities obtained by the *SLAW* dataset based simulations.

decreasing functions of c and o, defined on the unit square area $(c, o) \in [0,\ 1] \times [0,\ 1]$. Thus, we have

$$\begin{cases} a(c,o) = \frac{\partial f}{\partial c}(c,o) < 0, \\ b(c,o) = \frac{\partial f}{\partial o}(c,o) < 0, \end{cases} \quad (c,o) \in [0,\ 1] \times [0,\ 1].$$

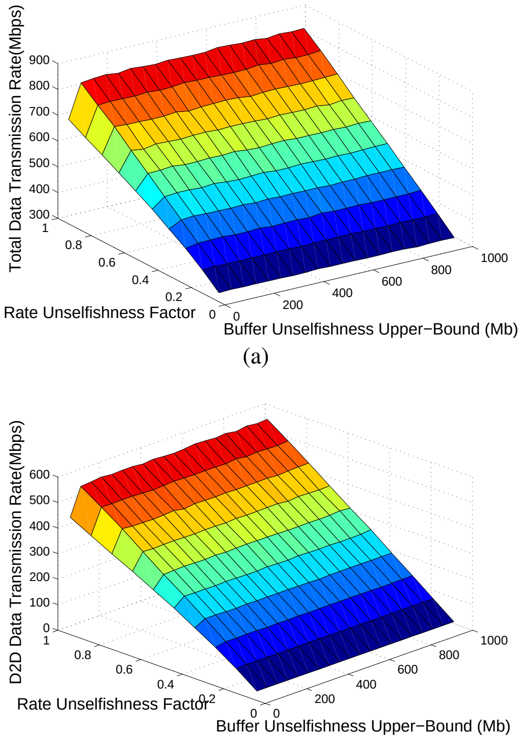
This indicates that with the increase of ICSP or IOSP, a same increment in IOSP or IOSP may result in a sharper reduction in the total data transmission rate achieved. The same observations can also acquired from Figs. 5 and 6, which were obtained from the *INFOCOM05* and *SLAW* based simulations, respectively. For example, it can be seen from Fig. 6 that when the IOSP is high, the direction of increasing ICSP the (y-axis) is closer to the radial direction of the contours, which means a sharper drop in the total data transmission rate.

In addition, according to Fig. 4 (a), when the IOSP is relatively small, the reduction in the total data transmission rate caused by increasing the ICSP is negligible. Unfortunately, this scenario is not likely to happen in the real world. This is because most users, left to their own will, are more likely to increase the IOSP than to increase the ICSP, due to the considerations of battery consumption and buffer occupation as well as potential hardware risks. Therefore, in terms of the impact of individual selfishness on D2D communications, if users are left freely to refuse D2D communication requests, the D2D communication underlaying system is likely to endure poor performance caused by high D2D opportunistic selfishness.

Fortunately, there are possible solutions to this problem. If D2D connected mode is compulsory in the protocol, the results will regress to the highest (blue) curve in Fig. 4 (b), which shows that the reduced data transmission rate can be regained to some extent from around 600 Mbps to around 700 Mbps at high IOSP. By ensuring alternative D2D connected communication choices in the case of high rejection of D2D opportunistic mode, this solution makes the D2D communication underlaying cellular network resilient to high D2D opportunistic selfishness, and it also avoids forcing users to devote their storage. Another possible solution is to set a minimum D2D-request-acceptance ratio and a reasonable buffer reservation, which constrains the system to the top left part (the crimson part) of Fig. 3, and therefore guarantees a satisfying performance. Although this solution is able to maintain a high system transmission rate, the drawback is unavoidable user buffer occupation.

C. *Rate and Buffer Limits in Individual Selfishness*

Apart from the above-mentioned ICSP and IOSP, individual selfishness also manifests in terms of power and buffer limits offered to D2D transmission. To quantitatively reveal the impacts of these two kinds of user selfishness, we use two parameters, rate unselfishness factor (RUSF) and buffer unselfishness upper-bound (BUSU), to measure how willing users to contribute power and storage for D2D communications. Specifically, RUSF is the ratio of the allowed D2D communication rate to the maximum available rate, which affects both D2D communication modes, while BUSU is the upper-bound of the allocated buffer by helpers, which only constrains D2D opportunistic transmission. Therefore, we can set $p_{i,j} = 0$ and $q_{i,j} = 0$, and instead use the RUSF and BUSU to represent the constraints imposed by



(a)

(b)

Fig. 7. System performance is severely influenced by rate selfishness, but shows a tendency of saturation with the decrease of buffer selfishness. The simulation system is driven by *Cambridge* dataset.

the individual selfishness. After performing the *Cambridge* trace driven simulation study under the same practical network settings, we acquire the empirical results of the total data and total D2D data received per second, depicted in Fig. 7 (a) and (b), respectively, as the functions of RUSF and BUSU.

From Fig. 7, it can be seen that as the RUSF decreases, the achievable system rate reduces significantly. Obviously, reducing power or uploading rate limit, which is a form of user selfishness, can severely decrease the data transmitted via D2D communications. On the other hand, enlarging buffer size also brings significant performance improvement when it is small but has little impact when it is already sufficiently large, i.e. the system performance shows a tendency of saturation with the increase of the buffer size. More specifically, for the simulated system, an increase in the buffer size of helpers has little influence on the achievable system performance when it is larger than 70 Mb. Therefore, the results of Fig. 7 suggest that to fully develop the potential of D2D underlaying cellular networks, service providers should discourage users to set the uploading rate limit for D2D communications.

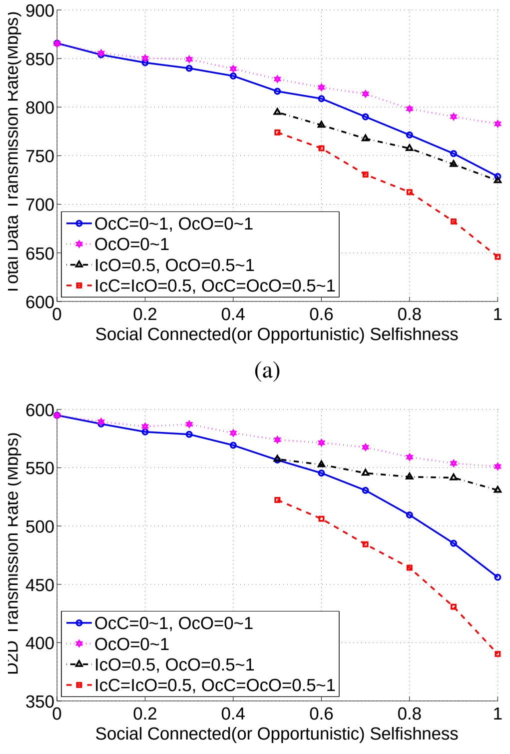
D. *Social Selfishness*

To reveal the impacts of social selfishness on D2D communications underlaying cellular networks, we use inside-community connected selfishness probability (IcC), outside-community connected selfishness probability (OcC), inside-community opportunistic selfishness probability (IcO) and outside-community opportunistic selfishness probability (OcO) to represent users' unwillingness to cooperate in the two D2D transmission modes with inside-community and outside-community users, respectively. Each probability represents the probability of forbidding the corresponding mode of inside-community or outside-community D2D transmission that is physically potential. In this case, these four probabilities define Connected Selfishness Matrix R and Opportunistic Selfishness Matrix G. More specifically, if UE_i and UE_j belong to a same community, we have $p_{i,j} =$ IcC and $q_{i,j} =$ IcO. Otherwise, $p_{i,j} =$ OcC and $q_{i,j} =$ OcO, since UE_i and UE_j belong to two different communities. In the real world, it is reasonable to assume that IcC $\leq$ OcC $\leq$ OcO and IcC $\leq$ IcO $\leq$ OcO.

TABLE I
THE SOCIAL SELFISHNESS PARAMETERS FOR THE SIMULATION RESULTS OF FIGS. 8 TO 10.

Curve	Hexagram	Circle	Triangle	Square
IcC	0	0	0	0.5
IcO	0	0	0.5	0.5
OcC	0	0 to 1	0	0.5 to 1
OcO	0 to 1	0 to 1	0.5 to 1	0.5 to 1

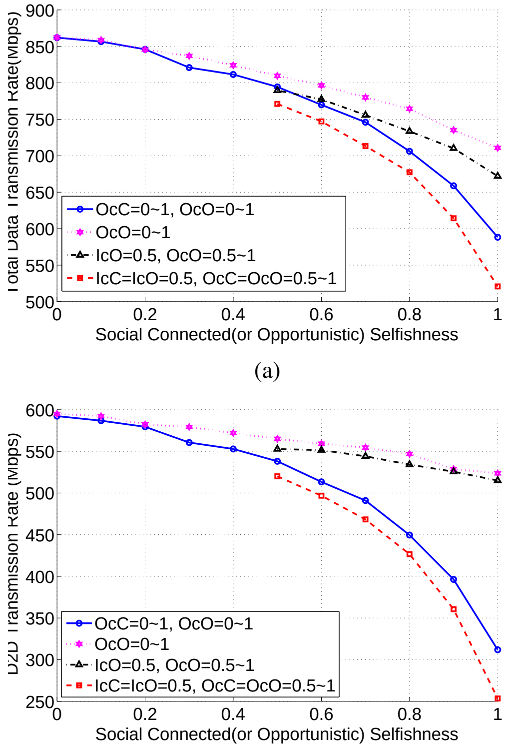
After dividing the helpers and subscribers into 2, 4 and 6 different social communities, respectively, we use the four different sets of IcC, OcC, IcO and OcO, as listed in Table I, to perform the *Cambridge* trace driven simulations, and the results obtained are shown in Figs. 8, 9 and 10, respectively. In each of these figures, the hexagram-marker curve models the inside-community-selfless users but who are unwilling to devote buffer to strangers, and the circle-marker curve models the users who are inside-community-selfless but very outside-community-selfish, while the triangle-marker curves represents the users who are mainly concerned with buffer occupation, and the square-marker curve is for the users who are rather



(a)

(b)

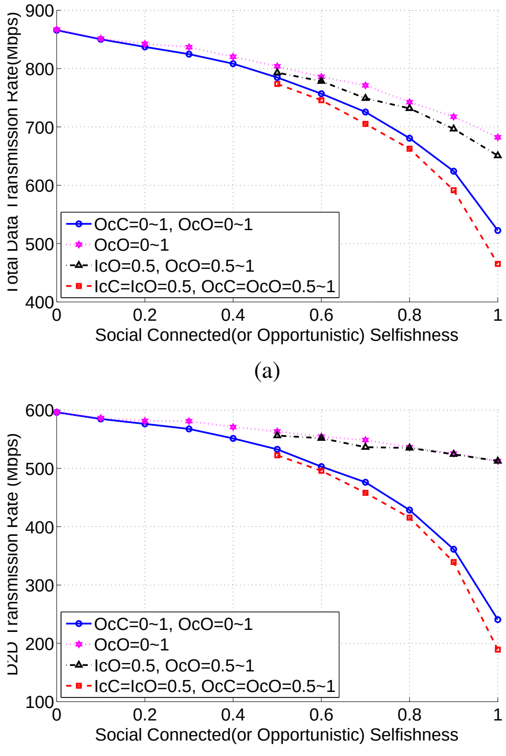
Fig. 8. System performance as a function of two-community social selfishness with the four sets of representative selfishness parameters described in Table I. The simulation system is driven by *Cambridge* dataset.



(a)

(b)

Fig. 9. System performance as a function of four-community social selfishness with the four sets of representative selfishness parameters described in Table I. The simulation system is driven by *Cambridge* dataset.



(a)

(b)

Fig. 10. System performance as a function of six-community social selfishness with the four sets of representative selfishness parameters described in Table I. The simulation system is driven by *Cambridge* dataset.

selfish. From the results of Figs. 8, 9 and 10, we can draw the following observations.

1) Inside-Community and Outside-Community Selfishness: A comparison between the circle-marker and square-marker curves in Fig. 8 (a) indicates that a system consisting of the selfish users who are not even very willing to cooperate inside community (the square-marker curve with IcC $= 0.5$ and IcO $= 0.5$) has a degraded theoretical up-bound performance, compared to an inside-community-selfless system (the circle-marker curve). Although this performance difference seems obvious in Fig. 8 (a), the absolute reduction in the range of $40\,$Mbps to $80\,$Mbps represents only the relative reduction of 5.2% to 11.4%. Moreover, with the increase in the number of communities, the gap becomes smaller. Specifically, Fig. 9 (a) shows that in the 4-community system, the performance gap between the square-marker and circle-marker curves is in the range of $23\,$Mbps to $68\,$Mbps, representing the relative reduction from 2.9% to 12.9%, while for the 6-community system shown in Fig. 10 (a), the performance gap is in the range of $11\,$Mbps to $58\,$Mbps, corresponding to the relative reduction from 1.4% to 10.9%. From the results of Figs. 8 to 10, it appears that when both the OcC and OcO are moderate (no more than 0.8), the degradations brought by moderate inside-community selfishness are very small, in terms of both absolute and relative sizes.

Since in a real-world D2D underlaying system, the number of communities is usually large, the impacts of inside-community selfishness on the whole system will become negligibly small, especially considering that the true IcC and IcO are not likely to surpass the value of 0.5 used in the simulation. Therefore, it is reasonable to assume low or even no inside-community selfishness when analyzing a real-world D2D communication underlaying cellular network.

2) Opportunistic and Connected Selfishness: From Fig. 8 (a), by focusing on the circle-marker curve with the OcC in the interval $[0.5,\ 1]$ and the triangle-marker curve of the IcO $= 0.5$, we observe that IcO $= 0.5$ is more devastating than a larger OcC. In other words, opportunistic selfishness causes larger degradation to the total data transmission rate than connected selfishness for this 2-community system. For this 2-community system, the numbers of UEs affected by inside-community selfishness and outside-community selfishness are the same, we can conclude that opportunistic selfishness has more serious adverse efforts than connected selfishness. But interestingly the reverse is true regarding the D2D data transmission rate, as can be seen by comparing the circle-marker and triangle-marker curves of Fig. 8 (b). An explanation is that for a system with high opportunistic selfishness and low connected selfishness (triangle-marker one), in order to optimize the total data transmission rate, the system has to rely more on D2D connected communications with the aid of the BS, which on one hand improves the D2D data transmission rate but on the other hand deprives the resource of cellular direct transmissions, leading to a higher D2D transmission rate but a lower total transmission rate in comparison to the circle-marker curve of higher connected selfishness.

Moreover, the comparisons between circle-marker and triangle-marker curves in Figs. 9 and 10 all indicate that the OcC, which affects more UEs, causes greater degradation than the IcO does. In other words, even if connected selfishness should be less influential than opportunistic selfishness, difference in the number of affected UEs is enough to reverse the outcome. Since the number of communities involved in a real-world D2D system is usually large, outside-community selfishness, whether in connected or opportunistic selfishness mode, should be seriously limited in order to maintain the high performance of the D2D communications underlaying system.

From the practical viewpoint, therefore, the results of Fig. 8 tell us that in systems with few communities, rather than forcing users to cooperate with strangers, cellular service providers should make effort to persuade users to devote some of their storage to their own community. On the other hand, according to Figs. 9 and 10, in systems with large number of communities, the most important task is to encourage outside-community cooperations.

3) Alleviated Interaction: If IcC $=$ OcC $=$ IcO $=$ OcO, social selfishness regresses to individual selfishness. Specifically, these conditions specify the curve at which the plane $c = o$ cuts the surface in Fig. 3. The results of individual selfishness presented in Subsection IV-B show that the interaction of the two individual selfishness, connected selfishness and opportunistic selfishness, significantly degrades the system performance. By contrast, the circle-marker and square-maker curves in Fig. 8 (a) indicate that the performance degradation caused by the interaction of the two social selfishness modes is less serious, especially when both social selfishness modes are high, in comparison to the results of individual selfishness. For example, in Fig. 8 (a), the lowest points of the circle-marker curve (inside-community selfless) and square-marker curve are approximately 730 Mbps and 645 Mbps, respectively, yielding the worst performance degradations of 135 Mbps and 220 Mbps, compared to the ideal upper-bound of about 865 Mbps achieved by the selfless system, while the worst performance degradation in Fig. 3 is approximately 865-450=415 Mbps. This indicates that a relatively low (square-marker curve) or no (circle-marker curve) inside-community selfishness will neutralize to some extent the high outside-community selfishness and, consequently, alleviates the performance degradation caused by the interaction of the two social selfishness modes. Intuitively, the alleviation will become less effective with the increase in the number of communities, which can be observed by comparing Figs. 8, 9 and 10.

The results of Figs. 8 to 10 therefore offer a potential solution to alleviate harmful interaction between the two selfishness modes in systems with several communities – encouraging users to consider joint communities and to cooperate within their communities, which will benefit the whole D2D underlaying cellular system. Although the solution becomes less effective when there exists a large number of communities, it is useful in many local scenarios, such as companies and neighbourhoods, when physical proximities within communities are taken into consideration.

4) Summary: To sum up, the results of Figs. 8 to 10 show that detrimental impacts of social selfishness to the D2D underlaying system's performance mainly come from high opportunistic selfishness and the interaction between connected and opportunistic selfishness, which are similar to those of individual selfishness. Nevertheless, a moderate inside-community selfishness will not heavily impair the system performance. With relatively low inside-community selfishness, the harmful interaction of high connected selfishness and high opportunistic selfishness can be alleviated to some extent, though the alleviation becomes less effective when the number of communities is large. In our simulation system where the communities are equally divided, the outside-community selfishness is much more influential because the probability of refusing connections is higher and it affects more UEs.

More detailed future works are obviously needed to evaluate the impacts of social selfishness to D2D communications underlaying cellular systems, in which the division of communities, in terms of number, sizes, and physical distributions, should be particularly investigated.

V. RELATED WORKS

The latest works that focus on D2D communications and/or selfishness analysis, including [8], [9], [18]–[22], can be partitioned into three types according to their main topics. First, considering the importance of D2D communications underlaying cellular networks, there are many works that study interference management and resource allocation. For instance, based on interference-suppression-area, Guo *et al.* propose a scheme to manage interference at cell edge [18], while Han *et al.* use a bipartite matching approach to allocate cellular resources in D2D underlaying cellular networks [19]. However, these works mainly focus on design mechanism and performance analysis, but they have not analyzed the impacts of selfishness on D2D communications. Second, many social network researches, such as [8], [20], [21], focus on design mechanisms based on social information and social properties, but they do not analyze the impacts of selfishness to the performance of D2D systems either. In our work, we explicitly study the modes and impacts of selfishness, and we suggest possible solutions to improve the performance of D2D underlaying systems with realistic user selfish behaviors. Third, the problems of selfishness, in terms of wireless forwarding and routing, are addressed in the existing works [9], [22]. However, we study selfishness from the perspective of the whole D2D communications underlaying cellular system. Furthermore, we classify selfishness modes according to D2D modes, and we focus on the impacts of various selfishness modes on the achievable performance of the D2D underlaying system.

VI. CONCLUSIONS

In this paper, we have defined selfishness metrics for D2D communications underlaying cellular networks, according to the two D2D communication modes. We have also proposed an optimization framework for analyzing the impacts of both individual and social selfishness on the performance of D2D communications underlaying systems. First, evaluations have been implemented under realistic system settings to investigate the impacts of individual selfishness, and the results obtained clearly indicate the interaction between the D2D connected selfishness and D2D social selfishness. Additionally, uploading rate limit and buffer size related to individual selfishness as well as solutions to alleviate the impacts of uploading rate and buffer size limits have been discussed. Second, we have studied the impacts of social selfishness to the system's achievable performance, and the results obtained under the same realistic network settings show that the harmful interaction between the two selfishness modes, connected selfishness and opportunistic selfishness, can be alleviated with low inside-community selfishness when considering the systems of few communities. But the alleviation becomes less effective for the systems with large number of communities.

The observations and insights drawn from this study will be beneficial to the current standardizing process of D2D protocols for next-generation mobile networks. Clearly, better network protocols can be designed by appropriately taking into the consideration of D2D selfishness. Specifically, in the design of new network protocols, suitable mechanisms can be adopted to encourage D2D users to be selfless. Our study also indicates that considerable future works are required to investigate how to balance users' unwillingness to cooperate and overall achievable D2D system performance as well as to study the potential profits to service providers. For example, our future work will investigate potential business model and effective solutions to resolve the conflicts between the selfishness of each UE and the interests of the whole community. Moreover, general surveys and trial operations are recommended to determine how much freedom users should have to block D2D requests or to change the related protocol parameters of the D2D underlaying cellular system.

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