Enhance Device-to-Device Communication with Social-Awareness: A Belief-based Stable Marriage Game Framework

Yong Xiao, Dusit Niyato, Kwang-Cheng Chen, and Zhu Han

Abstract

By allowing each user equipment (UE) or network service provider to access the information of social networks, social-aware D2D communication has been introduced recently as a new paradigm to improve the performance of D2D communication. One of the key technical challenges for social-aware D2D communication is to convert the social relationship among UEs into the information that is useful for the decision making processes of the corresponding physical D2D communication system. In this article, we propose a novel framework referred to as belief-based stable marriage game to analyze social-aware D2D communication. In this framework, each UE can establish a belief function about its social relationship with others and use this belief function to develop a social-aware preference over all the possible actions. We first review existing D2D communication strategies and discuss the issues and strategies that will be involved in the enhancement of D2D communication using social networks. We then introduce the concept of belief-based stable marriage game and consider the spectrum sharing problem for in-band social-aware D2D commination as an example to demonstrate how to apply the proposed framework to optimize the social-aware D2D communication system. We present numerical results to verify the performance improvement brought by our proposed framework. We also outline some potential research directions and extensions.

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I. INTRODUCTION

According to the recent release of Cisco's network index report, it is expected that the mobile data traffic will grow nine-fold reaching 367 Exabytes generated by over 5.5 billion global mobile users by 2020 compared to that of 2015 [1]. It is believed that the traditional cellular network architecture in which all communications have to go through the cellular infrastructure will become difficult to meet the demand for mobile services and applications in the near future. How to improve the network performance with physically limited spectrum resource and network infrastructure is still an open problem. Device-to-device (D2D) communication allows closely located user equipments (UEs) to directly communicate with each other without traversing their traffic through the network infrastructure. It has been introduced as an economical and efficient solution to improve system performance for the next generation wireless networks. Implementing D2D communication in the existing cellular network framework has the potential to significantly offload traffics from the cellular infrastructure, and increase the network capacity, reliability and spectrum utilization efficiency.

Recently, the popularity of social networks substantially increases the network traffics. The data traffic of social networks and peer-to-peer (P2P) transactions accounts for over 60% of total traffic in today's Internet [2]. Nonetheless, it is observed that the hidden relationship revealed by social networks can be further utilized to enhance the performance of the existing networks. For example, multiple UEs with similar social interests may have a high chance to broadcast similar contents (e.g., sharing the same video or audio clips) throughout the networks. The transmission efficiency of the communication network can be further improved by combining these similar contents shared among groups of UEs with the same social interests as shown in Figure 1. Allowing D2D communication to utilize the information revealed in social networks has great potential to further improve the resource utilization efficiency, reduce the network traffic and delay in social content dissemination, and enhance the security of data communication [3].

In this article, we focus on the technologies that can improve the performance of D2D communication using social network information, commonly referred to as the social-aware D2D communication. We first review the recent advances of D2D communication and then discuss the functional components and techniques that can enhance the existing D2D communication by exploiting the social relationship revealed in social networks. We also

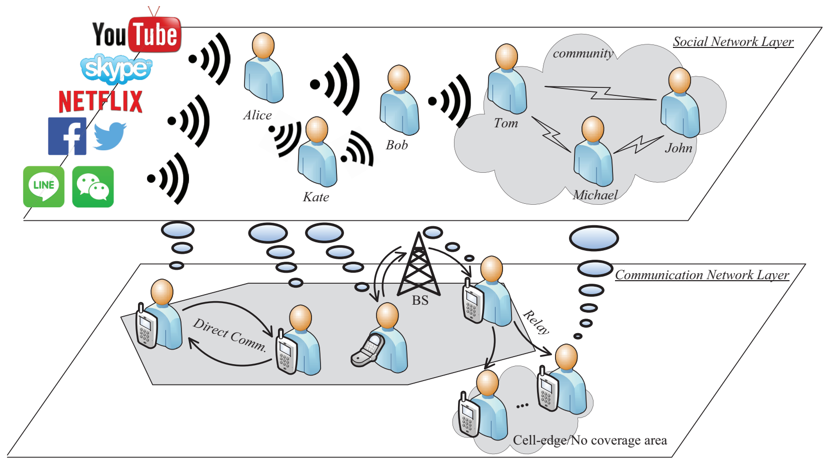

Fig. 1. Social network enhanced communication networks.

discuss the challenges and open problems for the social-aware D2D communication system. One of the main challenges for this system is how to find a simple and effective method to map the social relationship among UEs into the preference of physical connections and resource allocations for D2D links. We introduce a novel framework called *belief-based stable marriage game* to combine the social connections among UEs revealed in the social network with the physical preference specified by the physical condition of the environment and properties of the available resources. In this framework, each UE can establish and maintain a belief function characterizing its personal belief about the social relationship with others. By including this belief function into the decision making process, UEs are able to combine information revealed in the social network and that of the physical communication network to establish a social-aware preference over all the possible decisions. We consider the spectrum sharing problem between social-aware D2D communication and cellular network systems and use it as an example to describe how to apply belief-based stable marriage game to analyze and optimize the social-aware D2D communication system. Simulation results are presented to demonstrate the performance improvement that can be achieved by our proposed framework under different scenarios.

II. Overview of D2D Communication

In this section, we review key functional components and technical challenges of the existing D2D communication frameworks.

A. Peer Device Discovery

Before a direct communication link can be established, each UE must first discover other UEs in its proximity that have the potential to establish D2D links. This process has been commonly referred to as *peer device discovery*. UEs need to access specific resources and may require back-and-forth communication to discover each other which is resource consuming and may incur substantial communication overhead among UEs or between UEs and BSs. One of the main challenges is therefore to develop simple and efficient approaches for closely located UEs to quickly discover each other with minimized resource consumption. Most existing peer device discovery approaches can be classified into *network-assisted discovery* and *distributed discovery* depending on whether the peer device discovery process is helped by network infrastructure. In the network assisted discovery approach proposed in [4] for instance, the BSs can help each UE to determine whether there exist other UEs located within direct communication range by utilizing the location and identity information periodically collected from UEs. UEs can also discover each other using the distributed discovery approaches. For example, in the FlashQ protocol proposed in [5], the communication among UEs is synchronized, and a set of device discovery resource blocks can be autonomously obtained by the UEs to broadcast their identity information. Once a UE receives the device discovery signal broadcasted by other UEs, it can also send a link establishment signal through a link-establishment resource block to establish a D2D link with the requesting UE.

B. Resource Sharing and Allocation

One of the most challenging issues in D2D communication is to efficiently allocate sufficient resources for each D2D link. According to the types of resources that can be accessed by each UE, D2D communication can be classified into *in-band* and *out-of-band D2D communication*. In the in-band D2D communication, UEs can access the spectrum that has already been licensed to the cellular network operators. In this case, the transmission of D2D links should be carefully monitored and managed by the BS to limit the resulting interference to existing cellular network services within a tolerable level. In the out-of-band D2D communication, UEs can share the unlicensed spectrum that is publicly available with other communication systems including WiFi, ZigBee, Bluetooth, etc. D2D links in the out-of-band D2D communication have to compete with various unknown devices, and are therefore difficult to guarantee their performance during the communication process especially compared to the in-band D2D communication.

C. *Interference Control and Management*

In the in-band D2D communication, it is important for D2D links to control their interference to the existing cellular network service during the data transmission. One commonly adopted approach is to divide spectrum sharing schemes between D2D links and CSs into different modes including dedicated, reuse, relay and sharing modes [6]. Specifically, in the dedicated mode, D2D links can access dedicated sub-bands that are unoccupied by the CSs. Each D2D link, in the reuse mode, can share the same sub-band with a CS at the same time. If a D2D link operates in relay mode, its D2D communication traffic will be relayed through the BS. This mode is normally applied when direct communication cannot provide adequate performance for D2D links. In [7], a new spectrum sharing mode, referred to as the sharing mode, was proposed for in-band D2D communication. In this mode, two D2D links that have already been allocated with cellular spectrum for exclusive use can share their spectrum with each other to further improve their performance and the spectrum utilization efficiency.

III. From D2D Communication to Social-Aware D2D communication

A. *Discovery of Social Relationship*

In addition to discover each other based on their physical locations, UEs in social-aware D2D communication should also gather information about the social relationship with each other using offline or online social networks:

- *Offline Social Networks*: A central controller, e.g., a BS, can establish and maintain an offline social network for its local UEs using reported identities and location information. For example, a set of UEs connected to an access point that provides local communication service within a company or an office building can regard these UEs as co-workers within the same business community. Offline social networks can also be established by UEs in a distributed fashion. For example, each UE can broadcast its identities and desired social relationships to its neighboring UEs and wait for the responses. If the desired social relationships between two or more closely located UEs can be matched, the UEs can establish a local community and form D2D links according to the local social relationship.

- *Online Social Networks*: UEs can also obtain their social relationship from the online social network service providers such as Facebook and Twitter. Different from the offline social networks, the social relationship obtained from the online social networks can contain more detailed and more complex structural information. It is therefore important for UEs to decide on which specific information to collect from the online social network providers and how to use these information to improve their performance.

The discovered social relationship can be utilized by UEs to facilitate the peer device discovery process [8]. For example, UEs can discover the location information of each other using the location information registered in the social networks. In addition, the discovered social network can also help the digital content dissemination through D2D links. For example, UEs that have already obtained the data content to transmit can exploit the discovered social networks to search for nearby UEs that have the interest to receive the data. The social-network enhanced peer discovery process can also improve the security of the D2D communication by limiting the discovered devices within a specific community, e.g., a co-worker community, or a group of UEs with specific security features for data communication.

B. Social-Aware Resource Sharing and Interference Management

Apart from the physical location and local resource availability, each UE should also take into consideration of the social connection and relationship with other UEs. One of the main challenges for social-aware D2D communication is therefore to establish and maintain proper social-aware preference over the available physical resources that can be shared and allocated during D2D communication. Social-awareness can further enhance the following aspects of resource sharing and interference management for D2D communication:

- *Mode selection*: By taking into consideration of the discovered social relationship, the available resource can be properly allocated based on the social status and connections of UEs. For example, UEs with higher social status, e.g., managers or leaders of a business community, should be given higher priority to operate in the dedicated mode or relay mode instead of the reuse or sharing mode.

- *Traffic offloading and content dissemination*: Social networks can also reveal the correlation among the data content information of UEs which can be utilized to improve the efficiency of content dissemination and data traffic offloading from the cellular infrastructures [9]. For example, multiple UEs with similar social interests may want to send the same digital content to a common receiver. In this case, the transmission efficiency can be further improved by only letting one of the UEs to send its content to the receiver.
- *Relay selection and routing*: D2D communication can be used to relay information for the UEs that are located in the cell-edge or beyond the coverage area of the cellular networks as illustrated in Figure 1. In this case, UEs can optimize their selection of relay UEs and routings according to their social relationship. Social networks can also be utilized to enhance security of the data relaying and avoid congesting the relaying routes by combining the data traffic from different D2D links with high content similarity. Furthermore, social activities revealed in the online social networks can help predict the future mobility and locations of the UEs which can be further utilized to increase the network capacity [10].
- *Interference control and management*: D2D communication can utilize the information of social networks to control the interference to other network service subscribers. For example, if activity and event information revealed in the social networks suggests that the data traffic of cellular networks may significantly increase due to some upcoming social events (e.g., social gathering, festival, concerts, and exhibits), D2D links should limit their spectrum usage by choosing the reuse mode rather than the dedicated and relay modes to avoid network congestion.

C. Technical Challenges and Open Problems

Social networks consist of complex interactions among different persons, and hence are difficult to analyze. Integrating social networks into D2D communication introduces many technical challenges and open problems:

- *Information Extraction*: Social networks can involve rich information that can reflect complex social relationship among a large number of UEs with diverse personal interests and properties. In addition, a personal profile in an online social network may consists of many private personal information and activities. How to extract simple and useful social information that can improve the performance of D2D communication without violating the privacy of the users is still an open problem.

- *Mapping from Social Networks to D2D Communication*: Social networks cannot reflect the conditions of physical channels and environment among UEs. For example, if two UEs belong to two close friends in a social network, it does not necessarily mean that these two UEs are physically closely located to each other. There is still a lack of a simple and efficient framework that can seamlessly combine Ues' social relationship with their preferences over physical resources in D2D communication systems. In addition, both social networks and physical communication environments can change dynamically. It is therefore important for each UE to maintain and update information from the social network according to these changes.
- *Fairness and Rationality*: Social networks and physical wireless networks can be operated by different service providers with different objectives, constraints and rules. Optimization of a single network or service provider can result in unfairness and performance loss for other network systems. A general framework that can jointly optimize the interaction among UEs in different systems is important for social-aware D2D communication.
- *Incentive Mechanism Design*: It is generally impossible for each UE to know the global structure of a social network. Instead of relying on centralized approaches that require the global information, it is desirable to develop a distributed optimization framework that allows each UE to autonomously decide its action based on its own private information and previous observations. In addition, it is known that if all UEs are selfish and try to optimize their individual performance without considering the consequent damage to each other, it may result in unacceptable performance degradation. How to design efficient incentive mechanisms that can provide reasonable incentive for each UE to enforce the required fairness in the decision making processes is still an open problem.
- *Security*: Social networks consist of private personal information. Therefore, online social network providers should establish secure interfaces between their network infrastructure and D2D communication to avoid disclosure of private information to unintended UEs.

IV. Enhance Social-Aware D2D Communication with Belief-based Stable Marriage Game Framework

As mentioned previously, one of the main challenges for social-aware D2D communication is to extract the required information from social networks and efficiently utilize the extracted information to enhance the performance of D2D communication. In this section, we introduce a novel framework referred to as *belief-based stable marriage game* to demonstrate how to utilize social relationship among UEs to establish a social-aware preference for each UE to decide its optimal activities during D2D communication. We will first present the basic elements and concepts of belief-based stable marriage game and then discuss the methods to apply the proposed framework to improve the spectrum utilization efficiency for the social-aware D2D communication. We will also present numerical results to illustrate the performance of the proposed framework.

A. From Physical Preference to Social-aware Preference

A belief-based stable marriage game is extended from the stable marriage game originally motivated by the stable marriage problem focusing on the study of possible matching between a set of men and a set of women according to their preference over each other [11]. A stable marriage game consists of two finite and disjoint sets: a set of men $\mathcal{D}$ and a set of women $\mathcal{C}$. Each person from one set has preference that ranks persons of the other set in strict orders. The main objective for each man (or woman) is to propose to the most preferred woman (or man) that would like to accept its proposal. One of the main solutions of this game is the *stability*. A matching structure is said to be *stable* if there is no single player or pair of players who has the intention to deviate from it. The stable marriage problem has attracted significant interests in the past few decades and its solutions and algorithms such as the well-known deferred acceptance algorithm, also called Gale-Shapley algorithm, have been widely adopted into many areas including mathematics, economics, computer science, etc. It has been proved that if the preference list of each player is strict (i.e., each player from one set cannot have equal preference over two or more players in the other set) and complete (i.e., the preference list of each player in one set should consists of all the player in other set), a stable matching always exists and can be obtained using the deferred acceptance algorithm proposed in [11]. In this paper, we mainly

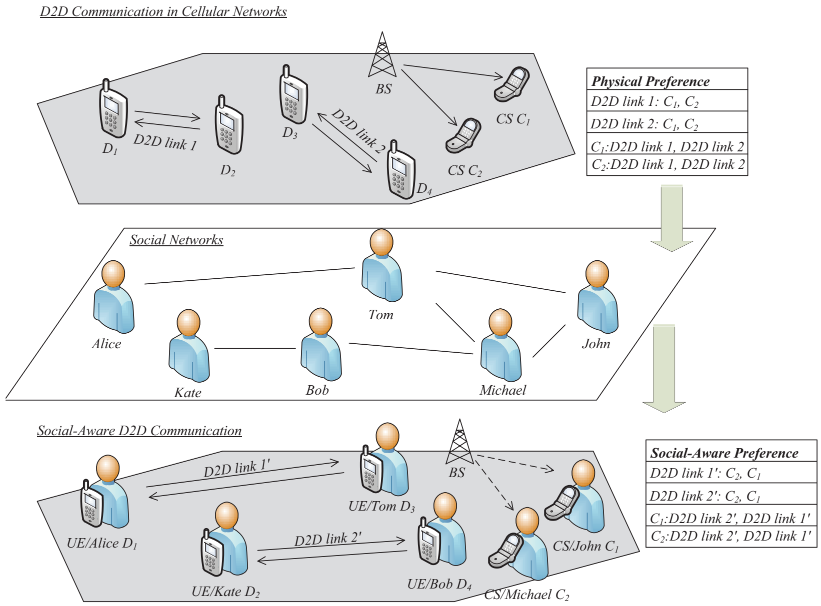

Fig. 2. Illustration of social-aware preference for D2D communication with social-awareness.

consider the traditional two-sided one-to-one stable marriage setting. However, our approach can be extended into more complex cases which will be discussed in Section IV-D.

Let us first discuss the concept of belief-based stable marriage game and then apply this framework to study the social-aware D2D communication. The main difference between the belief-based stable marriage and the traditional stable marriage games is that in the former game, each player can establish and maintain a belief function reflecting its personal belief of its social relationship with other UEs. A belief function is generally represented as a probability distribution over the possible social relationships with others. According to the information sharing mechanism among UEs, the belief functions can be classified into the following two types:

1) *Public belief function* can be known by all the UEs in the network systems. For example, in network-assisted D2D communication, the BS can establish the belief function for each UE using the information collected from the social network to jointly optimize the entire network system. A special case of the public belief function is to allow all UEs to have the same belief function. For instance, the BS can establish and maintain a common belief

function that reflects the social relationship among the UEs and periodically broadcast this belief function to all the UEs in its coverage area.

2) *Private belief function* is a private information that can only be known by each individual UE. For example, in some distributed network systems, each UE can access its personal portal in a social network to acquire the private information about its own social relationship with others.

Depending on the adaptation and learning abilities of the UEs, the belief function can either be stationary or dynamic:

1) *Stationary belief function* is a stationary probability distribution (e.g., prior beliefs) and cannot change with time.
2) *Dynamic belief function* for each UE can be periodically updated. For example, each UE can update its belief function according to the change of the environment, observation history and learning mechanism. In distributed D2D communication systems, A commonly used approach is for each UE to obtain a prior belief from social networks and sequentially update its belief function according to the previous observation history and dynamics of the environment using Bayesian inference [7].

Each UE can take advantage of its belief function to establish its preference. Let us consider a communication network system in Figure 2 for example. In this system, UEs can form D2D links and share spectrum with CSs according to the physical preference based on their relative physical locations. That is, each D2D link (e.g., D2D link 1 in Figure 2) formed by two closely located UEs (e.g., UEs D_1 and D_2) prefers to share the same spectrum with the CS (e.g., C_1 instead of C_2) that is located far from both UEs to avoid high cross-interference during spectrum sharing as shown in the top of Figure 2. However, it is possible that according to the belief functions of both UEs and CSs the digital content diffused through D2D links formed by some other UEs may have higher similarity with the digital content downloaded from the BS to a CS. In this case, it may be more efficient to establish a new D2D link (e.g., D2D link $1'$ in Figure 2) between these two UEs (e.g., UEs D_1 and D_3) and allow the newly formed D2D link to share the same spectrum with the nearby CS (e.g., CS C_2) with the highest content similarity as shown in the bottom of Figure 2. If the CS can receive the required digital content from the spectrum sharing D2D link with sufficient QoS, the downlink transmission from the BS to the CS can be saved to further improve the energy and communication efficiency of the network.

We refer to the preference which includes both physical location information and social relationships with others as the *social-aware preference*. Belief-based stable marriage game is suitable for analyzing social-aware D2D communication in the following scenarios:

1) In social networks, different people can have different views on their relationships with others. For example, person D_i believes that person D_j has the same social interests (or belong to the same community) does not mean that D_j also shares the same belief about D_i. Therefore, allowing each UE to establish an individual belief function that characterizes the belief about its social relationship is a reasonable setting for social-aware D2D communication. In addition, it can be observed that the social relationship between two UEs cannot be measured by deterministic values or functions. For example, two UEs cannot always generate high data traffic between each other even if they are close friends in a social network platform. The information revealed in social networks, however, can determine the statistic features of the communication contents of UEs. For example, if two UEs share similar interests in a social network, it means that these two UEs will have a high probability to broadcast or request the same digital contents.
2) Belief-based stable marriage game can improve the security of social networks and avoid the disclosure of private personal information to unintended third parties. More specifically, in belief-based stable marriage game, each UE can establish and maintain its private belief about its social relationship according to its previous interactions with others [7]. It is generally unnecessary for each UE to know the social relationship of other UEs.
3) Belief-based stable marriage algorithm can be more robust than traditional stable marriage algorithm. The belief of each UE about its relationship with others may not always accurate. In the belief-based stable marriage game, each UE can update its belief function according to its previous interactions with others. For example, in [12], each UE uses a Bayesian reinforcement learning approach to iteratively update its private belief function and sequentially improves its preference. It was proved that if the number of iterations is large enough, the effect of the initial error of the belief of each UE will diminish. In other words, even if the initial belief of some UEs cannot accurately reflect their true social relationship with others, these UEs can still adjust their belief functions according to the responses of others during the future interactions.

In the rest of this section, we will consider the spectrum sharing for in-band D2D communication with social awareness and use it as an example to illustrate how to take advantage of the information revealed by social networks to enhance D2D communication using belief-based stable marriage game.

B. Enhanced Spectrum Sharing for D2D Communication with Social-Awareness

It is known that the efficiency of spectrum utilization can be significantly improved by allowing D2D links and CSs to share the same spectrum. In traditional D2D communication, one of the main challenges is to find the spectrum sharing structure for which the cross-interference between each pair of spectrum sharing D2D link and CS is limited to a tolerable level. To achieve this, each pair of matched D2D link and CS should be far from each other [13]. However, it can be observed that, if there are similar contents in the information communicated in some D2D links and that in the uplink or downlink communication of CSs (e.g., a UE of a D2D link and a BS send the same video files or digital contents to their corresponding D2D receiver and CS, respectively), allowing each D2D link to share the same frequency band with the CS that shares the highest content similarity can further improve the spectrum utilization efficiency of cellular networks. In this case, each UE needs to establish a social-aware preference over CSs by jointly considering both physical locations and its content similarities with others. We model the above spectrum sharing problem as the belief-based stable marriage game in which two disjoint sets correspond to a set of D2D links, labeled as $\mathcal{D} = \{1, 2, \ldots\}$ and a set of CSs $\mathcal{C} = \{C_1, C_2, \ldots\}$. To simplify our description, we focus on the downlink transmission for cellular network and assume a portion α_{ij} of communication data sent in a D2D link i is the same as that sent through the downlink transmission from the BS to CS C_j. We also assume each CS C_j and both UEs in each D2D link i have a fixed belief function $b_{C_j} = b_i\left(\alpha_{ij}\right)$ about the probability distribution of α_{ij}. The main objective is to find a matching Γ between D2D links and CS which is a defined as a one-to-one correspondence from the set $\mathcal{D} \cup \mathcal{C}$ onto itself of order two such that if $\Gamma(i) \neq i$, then $\Gamma(i) \in \mathcal{C}$ and if $\Gamma(C_j) \neq C_j$ then $\Gamma(C_j) \in \mathcal{D}$.

In social-aware D2D communication, both D2D links and CSs try to improve their performance. We consider a general framework and the performance of each D2D link i and CS C_j can be measured by any function generated from its signal-to-interference-plus-noise ratio (SINR). For example, suppose both D2D link i and CS C_j try to improve their maximum transmission rates $R_i(\alpha_{ij})$ and $R_{C_j}(\alpha_{ji})$, respectively. We can write $R_i(\alpha_{ij}) = W \log\left(1 + \frac{h_i w_i + \alpha_{ij} g_{ji} w_{C_j}}{\sigma_i + (1-\alpha_{ij}) g_{ji} w_{C_j}}\right)$ and $R_{C_j}(\alpha_{ji}) = W \log\left(1 + \frac{g_j w_{C_j} + \alpha_{ji} h_{ij} w_i}{\sigma_{C_j} + (1-\alpha_{ij}) h_{ij} w_i}\right)$ where W is the transmission bandwidth, h_i is the channel gain of D2D link i, g_j is the channel gain from the BS to C_j, g_{ji} is the channel gain between the BS and the receiver of D2D link i, h_{ij} is the channel gain between the transmitter of D2D link i and CS C_j, w_i and w_{C_j} are the transmit power levels of the transmitter in D2D link i and the BS, respectively, and σ_i and σ_{C_j} are the additive noise levels received by the receiver of D2D link i and CS C_j, respectively. In this case, the expected transmission rates for D2D link D_i and the spectrum sharing CS C_j according to their belief functions can be written as

$$\varpi_i(\Gamma(i) = C_j) = \int_{\alpha_{ij}=0}^{1} R_i(\alpha_{ij})\, b_i(\alpha_{ij})\, d\alpha_{ij}, \quad (1)$$

$$\varpi_{C_j}(\Gamma(C_j) = i) = \int_{\alpha_{ij}=0}^{1} R_{C_j}(\alpha_{ji})\, b_{C_j}(\alpha_{ji})\, d\alpha_{ij}. \quad (2)$$

Each D2D link and CS can then establish a preference over each other by ranking the obtained utility from the highest to the lowest, e.g., D2D link i (or CS C_l) prefers to share spectrum with C_j (or D2D link m) instead of C_k (or D2D link n) if $\varpi_i(\Gamma(i) = C_j) > \varpi_i(\Gamma(i) = C_k)$ (or $\varpi_{C_l}(\Gamma(C_l) = m) > \varpi_{C_l}(\Gamma(C_l) = n)$). Once both D2D links and CSs have finished establishing their preference using (1) and (2), they can apply standard stable marriage algorithm (i.e., deferred acceptance algorithm) to establish a stable spectrum sharing structure. We present the detailed algorithm in Figure 3.

C. Numerical Results

We present numerical results to demonstrate the performance improvement that can be achieved by our proposed framework. We consider a network system consisting of 20 CSs and 20 D2D links uniformly randomly located in the coverage area of a BS. Each CS has already been allocated with a sub-band and D2D links can either share the sub-bands occupied by CSs or request for vacant sub-bands from the BS for exclusive use. We assume the portion of the shared content between any pair of D2D link and CS is the same, i.e., we have $\alpha_{ij} = \alpha$ $\forall i \in \mathcal{D}, j \in \mathcal{C}$ and α is a constant for $0 < \alpha \leq 1$. We also assume each D2D link i or CS C_j has the same belief function about the value of α_{ij} or α_{ji} and belief function b_i or b_{C_j} follows the Gaussian distribution with fixed mean $\mu = \alpha$ and variance δ, i.e., $b_i, b_{C_j} \sim \mathcal{N}(\alpha, \delta)$ $\forall i \in \mathcal{D}$ and $C_j \in \mathcal{C}$.

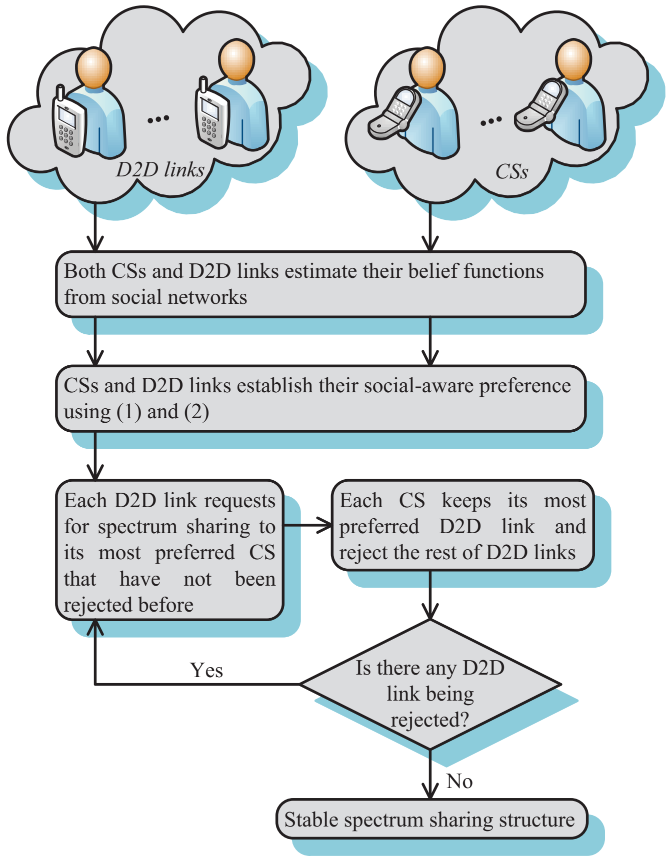

Fig. 3. Algorithm for spectrum sharing between D2D links and CSs with social-awareness.

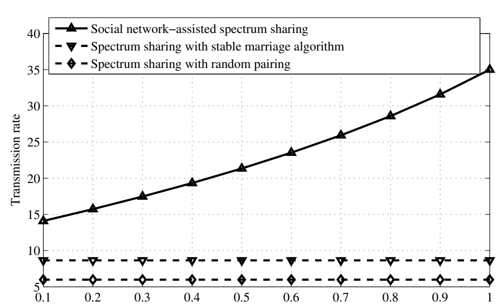

Fig. 4. Spectrum utilization efficiency for D2D communication with social-awareness.

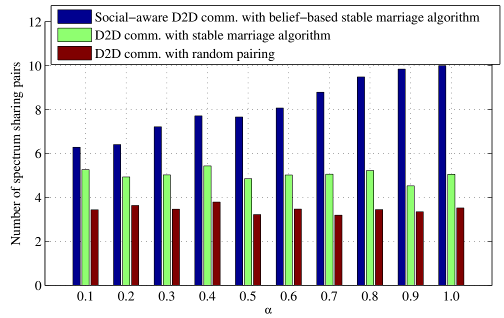

Fig. 5. Number of spectrum sharing pairs formed between D2D links and CSs with and without social-awareness.

Figure 4 compares the transmission rate of D2D communication under different values of α. We also consider the performance of the D2D communication when both D2D links and CSs cannot have any information about social similarity between each other. In this case, a pair of spectrum sharing D2D link and CS will treat each other's signals as interference. We can observe that the transmission rate of D2D communication can be significantly improved by utilizing the social similarity between D2D communication and cellular downlink transmission especially when α is large. In the case that each D2D link cannot obtain the social network information to establish the belief function but can only establish a physical preference over the CSs according to the relative distance, the performance of D2D communication can still be improved by allowing the spectrum sharing between D2D links and the CSs that are far from each other using the traditional stable marriage algorithm as discussed in [7].

In Figure 5, we assume a spectrum sharing pair can only be formed if the transmission rates of both spectrum sharing D2D link and CS exceed a threshold. We compare the number of spectrum sharing pairs between D2D links and CSs under different values of α. It is known that the more spectrum sharing pairs formed between D2D links and CSs, the higher the spectrum utilization efficiency can be achieved. We can observe that if both D2D links and CSs can know the content similarity of each other from the social networks, the number of spectrum sharing pairs can be significantly improved using the belief-based stable marriage algorithm especially when the value of α is large. Unfortunately, if D2D links and CSs cannot obtain any information from the social networks, each D2D link will always prefer to share the spectrum with the CS that is far to avoid intolerable cross-interference. In this case, the number of spectrum sharing pairs between D2D links and CSs will be independent with the value of α. Similar to Figure 4, compared to random pairing, the number of spectrum sharing pairs can still be increased if both D2D links and CSs can establish the physical preference of each other and use the stable marriage algorithm to form spectrum sharing pairs with each other.

D. Discussion and Extension

From the previous description, we can observe that the belief-based stable marriage framework is an effective approach to analyze and optimize social-aware D2D communication. However, there are many issues need to be further investigated.

For example, it is known that distributed multi-agent machine learning algorithms cannot always guarantee convergence and even if they converge it is generally difficult to develop a simple and effective algorithm that can always converge to the optimal solution. In [12], the belief function of each player was assume to follow a stationary Dirichlet distribution. A Bayesian reinforcement learning approach was then proposed for each player to sequentially update its belief function using its previous observation. It is interesting to investigate the performance of other potential belief updating approaches in social-aware D2D communication-enabled networks under different conditions.

In this article, we mainly focus on the standard stable marriage game also referred to as the two-sided one-to-one matching which involves two disjoint sets of players trying to be matched with each other. There are many variances of the stable marriage problems that have been also extensively studied in the literature. We briefly introduce the following major variants and their applications in social-aware D2D communication as follows. A detailed survey of the variances of stable marriage games is given in [14].

1) *College admission problem and its application in social-aware D2D communication*: College admission problem (also called hospitals/residents problem) is a many-to-one extension of the original stable marriage problem. Similar to the stable marriage problem, college admission problem also focuses on finding matchings between two disjoint sets of players: a set of students and a set of colleges. However, in this problem, each student can only apply for one college and each college can accept the applications of more than one student. In [13], we proposed a belief-based college admission framework to study the spectrum sharing between a set of D2D links and the spectrum resources owned by multiple cellular network

operators. In this framework, the spectrum of each operator can be accessed by multiple D2D links. Each D2D link can establish and maintain a belief function over its resulting performance that can be obtained by choosing each operator. This framework can be directly applied into social-aware D2D communication by including the information revealed from the social networks into the belief function of each D2D link.

2) *Stable roommates problem and its application in social-aware D2D communication*: Stable roommates problem is a nonbipartite extension of the stable marriage problem originated from the problem which focuses on assigning a set of $2N$ players into N twin-rooms according to their preference. In this problem, all players belong to a single set. Each player can have a preference over all the other players and its main objective is to match to another player (the roommate) to form a matching pair. In [7], we introduced a belief-based stable roommate framework to study the spectrum sharing between D2D links. In this framework, two D2D links can aggregate their spectrum and share the aggregated spectrum with each other. Each D2D link will then use its belief function to establish its preference over other D2D links and choose the preferred D2D link to share its spectrum. This framework can be extended into social-aware D2D communication by allowing each D2D link to also include its social relationship into its belief function and decide its spectrum sharing partner using the social-aware preference.
3) *Forest matching problem and its application in social-aware D2D communication*: Forest matching problem studies the matching between a set of players and a forest structure. A forest can consist of a set of trees with multiple branches. Each player will first match to a root of a tree and then sequentially match to the elements of different layers of the matched tree structure. In [15], we proposed a belief-based stable forest matching framework. In this framework, each operator and its spectrum resources was modeled as a tree structure where each operator is regarded as a root and its resources are the leaves. A network system consisting of multiple operators was modeled as a forest. Each UE can establish a belief function to decide the preferred operator as well as the spectrum resources that it will access after it has been matched to the operator. This framework can also be extended into social-aware D2D communication by modeling a cellular network system with multiple operators each of which has a set of wireless resources as a forest that can be matched to a set of D2D links with social-aware preference.

V. Conclusion

D2D communication is regarded as one of the key technologies for the next generation wireless networks. By utilizing the information revealed in the social networks, the performance of D2D communication can be further improved. In this article, we first described the functional components and technologies of existing D2D communication and then investigated the potential issues and strategies that can enhance the social-aware D2D communication. We introduced the belief-based stable marriage framework to analyze the D2D communication with social-awareness. We studied the spectrum sharing between social-aware D2D communication and cellular networks as an example to illustrate how to apply our proposed framework to optimize D2D communication with social-awareness. Numerical result was presented to verify the potential performance improvement that can be brought by our approach. Finally, discussions and possible future extensions were outlined.

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