Social-Aware D2D Communications: Qualitative Insights and Quantitative Analysis

Yong Li, Ting Wu, Pan Hui, Depeng Jin, and Sheng Chen

ABSTRACT

With emerging demands for local area services, device-to-device communication is conceived as a vital component for the next-generation cellular networks to improve spectral reuse, bring hop gains, and enhance system capacity. Ripening these benefits depends on efficiently solving several main technical problems, including mode selection, resource allocation, and interference management. Aiming to establish a new paradigm for solving these challenging problems in D2D communication, in this article we propose a social-aware enhanced D2D communication architecture that exploits social networking characteristics for system design. By developing a profound understanding of the interplay between social networks' properties and mobile communication problems, we qualitatively analyze how D2D communications can benefit from social features, and quantitatively assess the achievable gains in a social-aware D2D communication system.

INTRODUCTION

As one of the next-generation wireless communication systems, Long Term Evolution-Advanced (LTE-A) supports mobile content downloading [1]. To meet the increasing demands for local area services of popular content downloading, device-to-device (D2D) communication is proposed as a key component for LTE-A, which enables devices to communicate directly and is an underlay to the cellular network for improving spectral efficiency [2–4]. Under the control of base stations (BSs), user equipment devices (UEs) can transmit data to each other over direct links using cellular resources instead of through BSs. Most context-aware applications that involve discovering and communicating with nearby devices can benefit from D2D communication by reducing the communication cost, since it enables physical proximity communication, which saves power while improving spectral efficiency [3]. It is expected that D2D communication will be a key feature supported by the next generation cellular networks [4].

In this D2D communication underlaying cellular system, UEs can choose to communicate via their serving BSs, or transmit data to other devices over direct links using cellular resources. The choice of cellular communication or direct D2D communication defines the mode selection problem. Before mode selection, the devices need to find other nearby devices by a peer discovery procedure. After mode selection, the system needs to allocate spectrum resources to the cellular and D2D links accordingly, control the transmission power, and manage the interference between the D2D and cellular links. By acquiring the knowledge of instantaneous network load, channel conditions, and potential D2D pairs, the system is able to select the best mode, allocate the resources, and manage interference efficiently to realize the proximity, reuse, and hop gains brought by D2D communication [3, 4]. Thus, peer discovery, mode selection, resource allocation, and interference management are the key technical problems in promoting the D2D communication underlaying cellular system. In practice, these problems are challenging, since they are coupled with device-level behaviors, cell-level interference situations, and network-level loading and channel conditions.

Handheld communication devices are carried by human beings who form social networks that exhibit certain stable social structures and phenomena [5, 6]. A natural question to ask is "can we leverage the social behaviors to assist D2D communication in order to enhance the achievable system performance?" The answer is yes! Technological advances have facilitated digital interaction, global communication, and distant travel, and the social networks we inhabit — the connections of social ties among friends — have grown steadily and rapidly. Our technological and economic systems have also become critically dependent on the networked structure of information we consume. Consequently, it is increasingly important for us to understand and leverage the properties of social networks. Research on analyzing social network structures has been carried out in many areas (e.g., biology, physiology, mental care) and has revealed many intriguing features of social networks [6–8]. Although it is still in the early problem recogni-

Yong Li is with Tsinghua National Laboratory for Information Science and Technology, Tsinghua University.

Ting Wu and Pan Hui are with the Hong Kong University of Science and Technology. Pan Hui is also affiliated with Deutsche Telekom Laboratories and Aalto University

Depeng Jin is with Tsinghua University.

Sheng Chen is with the University of Southampton and King Abdulaziz University.

 0163-6804/14/$25.00 © 2014 IEEE

tion stage [9], coupling the properties of underlying social structures into D2D communication promises huge potential gains in solving the challenging technical problems of D2D communication and opens up a new avenue for D2D communication system design.

In this article we aim to establish a new paradigm for a D2D communication underlaying cellular system: social-aware D2D communication, which leverages social networking characteristics of the cellular system. Based on a profound understanding of the social networks' properties, we establish a framework to organize well recognized social relationships and characteristics, and further validate them by an example of real-life human mobility traces. For D2D communication system design, we illustrate the main technical problems. Based on this background, we make two main contributions to the proposed goal. First, by qualitative analysis, we investigate how the social features of social networks influence D2D communication, and how they can help solve the challenging technical problems of D2D communication. These qualitative results provide a profound understanding of and insight into the design of the social-aware D2D communication system. Second, by quantitative assessment, we target a realistic D2D communication underlaying cellular system, and design social-aware D2D communication solutions: centrality-aware peer discovery and community-aware resource allocation. The quantitative simulation results obtained demonstrate the efficiency of the proposed social-aware D2D communication scheme.

We structure the article as follows. We first discuss the key technical problems of the D2D communication underlaying system and summarize the main social characteristics existing in the social networks formed by mobile users. We then provide an overview statement to define the social-aware D2D communication system. After the problem statement, we investigate how social features impact D2D communication by qualitative analysis, and then analyze how much gain we can achieve by leveraging the social features through quantitative simulation.

Background and Problem Statement

Our primary goal is to establish the social-aware D2D communication paradigm by leveraging the properties of social networks on the design of the D2D communication underlaying cellular system. Such a system can naturally be projected onto two domains: the *communication domain* and the *social domain*. In the communication domain, devices gain access to the cellular network via BSs or establish D2D communication links, subject to physical and communication constraints. In the social domain, these devices form a social network regulated by some stable social relationships and phenomena. To gain a comprehensive understanding of the above system, we begin with individual descriptions of the key issues in the two domains, respectively, and then combine them to state the problem we need to investigate.

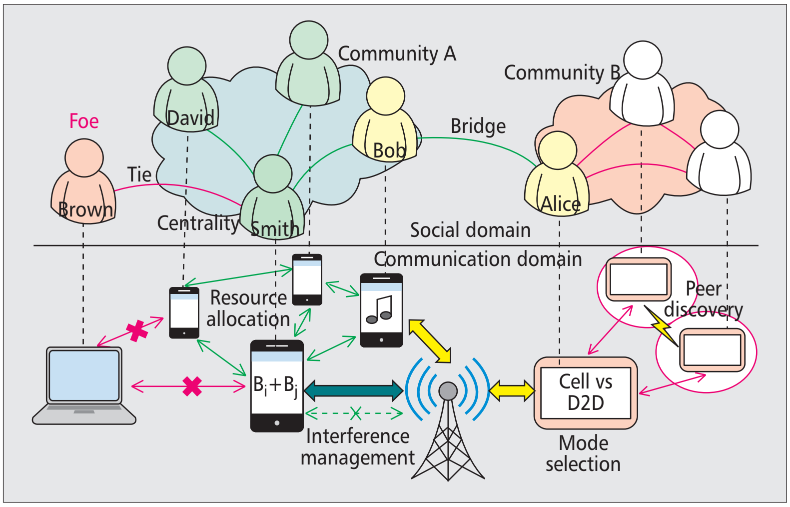

Figure 1. Illustration of social-aware D2D communication underlaying cellular system, where in the communication domain devices gain access to the cellular BSs or establish D2D communication subject to the physical and communication constraints, while in the social domain devices form a mobile social network regulated by stable social relationships and phenomena.

D2D Use Case and Key Technical Problems

The concept of D2D communication as an underlay to a cellular network, operating on the same spectrum resources, is illustrated in the bottom half of Fig. 1. The four key technical problems in designing the D2D communication underlaying cellular system are as follows.

Service and Peer Discovery — Before establishing D2D communications, the network and/or UEs need to discover the presence of their peer D2D candidates and identify whether the candidate D2D pairs need to communicate with each other [4]. Two techniques are usually used to identify the D2D candidates and required services. The first is the network-controlled approach, where the network uses paging or other signaling to mediate the discovery process by recognizing D2D candidates and potential services. The second is the ad hoc network approach, where the discovery is made by the devices themselves through transmitting a known synchronization or reference signal sequence. A beacon mechanism is usually adopted to achieve this kind of peer discovery. The fundamental problem here is that efficient discovery requires that the two peer devices be in the same space and time. If the devices are uncoordinated and have no other information, they can only perform randomized beaconing, which is time and energy consuming. Thus, prophetic information about the network and devices, such as mobility environment, is critical to the discovery performance.

Communication Mode Selection — In the D2D communication underlaying cellular system, a device can choose from the communication options of direct cellular transmission and D2D communications. Since D2D communication usually uses the same air interface as cellular communication, a UE can only operate in either the D2D mode or the cellular mode at the same time. Also, in the D2D mode, a decision must be made to choose connected or opportunistic transmission. Given all the possible transmission modes involving all the UEs, mode selection decides how to utilize them in order to maximize the data transmission capacity from all the BSs to all the UEs.

Spectrum Resource Allocation — D2D communications between devices use the same licensed band of cellular communication, and utilize the same air interface as the underlaying cellular network. Thus, D2D communications consume part of the cellular network's resources. Generally speaking, there are two resource allocation approaches, orthogonal sharing and non-orthogonal sharing. Orthogonal sharing between D2D and cellular communications can be achieved by allocating different frequency channels to D2D communication and cellular communication. However, to utilize network resources more efficiently, all the D2D communications may occur on the same frequency channel. Clearly, the interference between D2D communications will influence the achievable rate. Given the above resource sharing relations, the available network resource of frequency channels, and the D2D communication candidates, resource allocation decides how to share the spectrum between D2D communications and cellular communications in order to attain the maximum system throughput.

Interference Coordination and Management — The interference level in a D2D communication enabled system is more severe, compared to conventional cellular systems. Effective interference coordination and management for D2D communications is vital to realize the proximity, reuse, and hop gains. Interference coordination for D2D *connected* communications is relatively easy to handle as it can be managed "centrally" by BSs that have sufficient computing power and usually have all the information required to decide transmit powers. However, interference coordination for D2D *opportunistic* communications is much more difficult, since the D2D interference control may require distributed management by handsets, who have limited computing power and whose mobility further complicates the problem. Moreover, interference coordination can generally be divided into the intracell and intercell levels of interference coordination. The latter is much more challenging, since interference needs to be managed across multiple cells, and between the cellular and D2D layers.

SOCIAL CHARACTERISTICS

Social networks have gained much attention from researchers in various fields, since in the world all entities (e.g., people, devices, and systems) are related to each other in one way or another [10]. Social characteristics, existing in social networks, not only define the behaviors of these entities but also depict the structure of entities that are connected to each other through some relations, where these entities exhibit homophily by sharing common interests in contents and similar behaviors [11, 12]. Social networks can be considered as a system that provides communication services involving the social relationship among users, which is characterized by online social networks formed in the Internet platforms of Facebook, Twitter, and so on, and by the physically close social networks formed by human daily encounters. We review the social behaviors and structures of social networks, which are relevant to designing efficient D2D communication systems. As shown in the upper half of Fig. 1, we focus on the well recognized characteristics of social ties, community, centrality, and bridges.

Ties — The social tie is the most basic and fundamental notion characterizing the strength by which two individuals are related to each other. Social ties can be built up among humans through friendship, kinship, colleague relationships, and altruistic behaviors that are observed in human activities [13]. In mobile networks, social ties identify the weak or strong connections among individual mobile users.

Community — A social community is naturally formed according to social relations among people, and it defines clusters or groups of individuals sharing the same social interests or behaviors [5]. In mobile networks, communities may represent real social groupings by location, interests or background, and different communities are usually interested in different mobile contents. Thus, detecting this community information can help improve data transmission efficiency among distributed and intermittently connected mobile users.

Centrality — The term *centrality* in social network analysis is a quantification of the relative structural importance of a "node" within the network. A central user typically has a stronger capability of connecting other members in the network. There are several different ways to measure centrality; the most widely used are Freeman's degree, closeness, and betweenness measures [6, 10].

Bridge — The bridge structure manifests the connections between communities. A bridge acts as the interaction edge between two adjacent communities for information exchange. In general, each community has a group of nodes, and a bridge between two communities may provide the only path to connect the two communities, along which information or influence can flow between the nodes of these two groups.

To obtain a visualization of the social characteristics existing in daily human mobility and social activities, we take the proximity social networks derived from a real-world mobility dataset collected by the Reality Mining Project [14] as an example to illustrate them. In the experiment to collect a *Reality* mobility trace, about 100 smartphones were deployed to students and staff at the Massachusetts Institute of Technology over a period of nine months. The objective of this experiment was to study human social interactions and social dynamics by exploring the capabilities of smartphones. Through tracking a sufficient number of people with their personal mobile phones, this experiment resulted in the first and the most recognized mobile data set with rich human behaviors and interpersonal interactions, which include users' locations, communication behaviors, and device usage behaviors. By analyzing the nearby encounters and interaction behaviors of these traces, we plot the social network formed by the users recorded in the trace in Fig. 2, where the users are colored to identify different communities, and the size of the node indicates the centrality of the corresponding user, while the degree of nodes represent the strengths of social ties. We observe from Fig. 2 that the users form eight communities, and each user in a community has different centrality. Regarding the social ties, some user pairs have strong relations, while others have weak ones. When the strong relations happen across two communities, the social bridge phenomenon can be observed.

Problem Statement

From the viewpoint of the *communication domain*, D2D communication consumes some spectrum resources of the cellular network, but it may improve the resource utilization by the reuse of the spectrum for the devices that are physically in close proximity to communicate with each other at high rate and low power consumption. Thus, D2D communication performance depends on how often the devices can be in physical proximity communication with each other and how often they need to communicate online with each other or with content sources. In other words, the performance of the D2D underlaying cellular system critically depends on node mobility patterns and behaviors, and it is necessary to consider daily user mobility and social relations in order to observe the underlying D2D communication opportunities. On the other hand, mobile users naturally form social networks by online and proximity communications with inherent social structures and mobility patterns in the *social domain*. Moreover, altruistic tendencies are observed in many human social networks [5, 8]. Thus, the mobile user is able to exploit the existing social trust and relations from their neighbors to collaborate with each other to achieve efficient D2D communications. By utilizing this social domain knowledge, we are able to tackle the challenging problems of D2D communication more effectively.

We aim to develop a comprehensive understanding of the interplay between the social domain's characteristics and the communication domain's properties in the D2D communication underlaying cellular system. More specially, our objective is to utilize the social characteristics of community, centrality, bridge, and ties to aid peer discovery, mode selection, resource allocation, and interference management in order to maximize the gains of D2D communications. In the next two sections we answer the fundamental questions of what the benefits are and how much enhancement we can obtain by exploiting the social domain relationships and phenomena in the design of the D2D communication underlaying cellular system through qualitative analysis and quantitative simulation study.

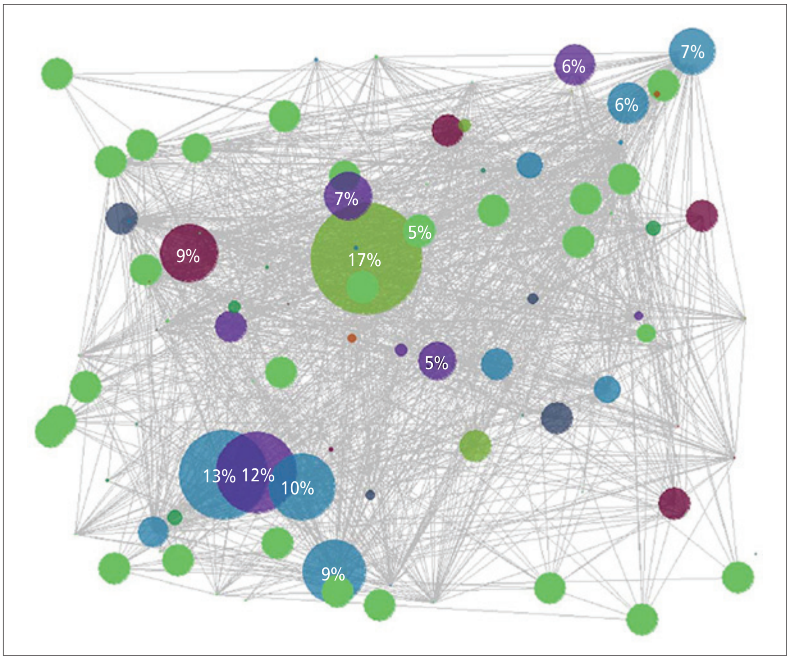

Figure 2. Social characteristics observed from a Reality trace.

Social Meets D2D: Qualitative Insight

In this section we qualitatively analyze how stable social characteristics can help solve D2D communication problems by identifying the key design issues, studying the main technical challenges, and providing some solution insights.

Social Ties

Social ties measure the strengths of users in D2D systems, and reflect to some degree the communication demands between users. The links correlated to strong ties may be expected to offer more communication contacts and have higher loads of data transmission than those with weak ties. Allocating more spectrum and energy resources to users with strong ties can increase the peer discovery ratio, help avoid congestion, improve spectral efficiency, and eventually increase the overall throughput and coverage of the D2D underlaying cellular network. As shown in Fig. 3a, users can adjust their beacon rates according to the strengths of the ties for peer discovery. Thus, how to optimally utilize the social tie information in peer discovery and resource allocation is a key issue in social-aware D2D system design.

In relay selection, the system often needs to consider privacy and security issues. Social tie information may be used as a measure to infer the trust between two nodes, since the strength of a tie may be correlated to the trustfulness between two peers. Thus, in the D2D communication system, leveraging the information of social ties in resource allocation can help not only attain higher throughput but also achieve better privacy and security compared to a non-social-aware architecture. In Fig. 1, *Smith* prefers to select *David* as the relay node even though Brown may offer higher throughput toward the BS, because forwarding data to Brown may bring

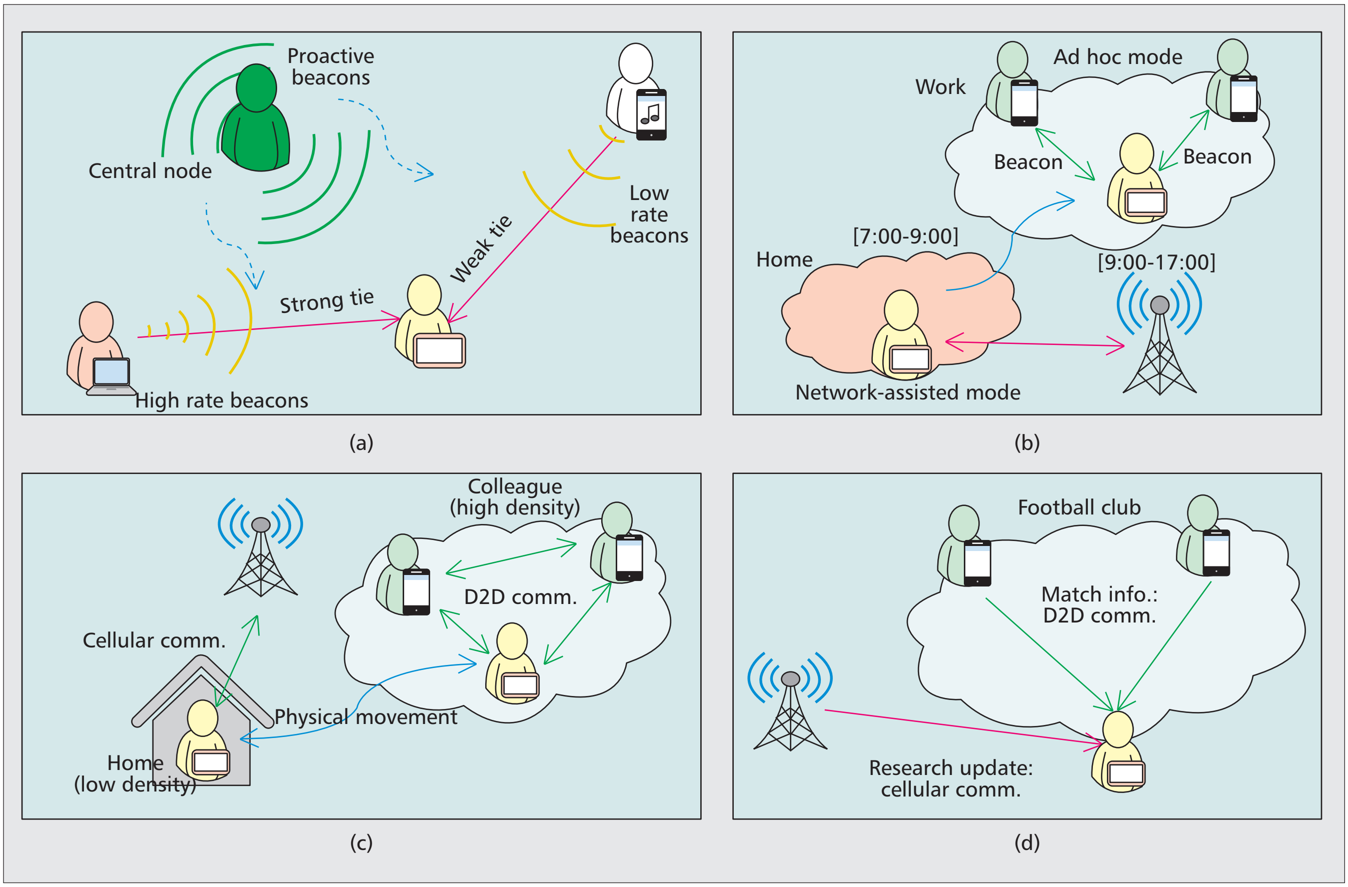

Figure 3. Qualitative analysis and insights for some key scenarios of social-aware enhanced D2D communications: a) social centrality and tie aware peer discovery; b) encounter pattern-assisted peer discovery; c) peer density-aware mode selection; d) community interest-enhanced mode selection.

data integrity and privacy leakage concerns. Here the issue is to design some security-enhancing mechanism to assist the social-ties-aware resource allocation and relay selection.

Social Community

Leveraging the properties of social community structure offers various advantages, including more efficient spectral usage, better resource allocation, and enhanced peer discovery.

An intuitive and intrinsic usage of the social community information is resource allocation. A user is expected to obtain information and content from the same community neighbors with less effort as they most likely will have similar interest in data. If a user is looking for some academic research materials, he/she can expect higher probability of data retrieval when requesting them from his/her research partners (community members). Therefore, allocating more resources in D2D communication for such links can help reduce the duplicated network load, which can increase the overall network throughput. In the D2D underlaying cellular network, radio resources are shared among different links. Similarly, leveraging community information can also help with designing efficient resource partitioning to avoid interference.

Peer discovery relying on the usual network assisted randomized searching/scanning for beacons is very time and energy consuming. Armed with the knowledge of community structure and encounter patterns, however, potential D2D candidates are able to autonomously conduct peer discovery by estimating their respective status within a community, and thereby optimize the energy efficiency and reduce the time duration in the communication pair discovery process. As shown in Fig. 3b, a user in a densely populated community (e.g., a workplace) can utilize the encounter patterns of the community to carry out the ad hoc peer discovery procedure, instead of relying on the network assisted procedure.

Mode selection relies on knowledge of the channel condition, intercell interference, and network load. Leveraging the community structure information can simplify the detection of these three physical parameters and therefore help the user make the mode selection decision quickly and accurately. In Fig. 3c *Alice* is at home and wants to contact a colleague in her university community. Selecting the direct cellular communication mode is a better choice than a D2D mode, because her neighbors are sparse, and the efforts of random beacons to find D2D communication pairs would mostly be wasted. Similarly, community interests are also helpful for mode selection. As shown in Fig. 3d, it is much more efficient for a student to obtain the match information from his/her football club community (e.g., roommates) by D2D communications while querying research updates by cellular communications.

Social Centrality

As stated before, a high degree of centrality indicates that the user may play a key role in data transmission. Consequently, users with high centrality should possess high capacity in terms of data transmission volume and frequency. Reference [7] suggested that a central node has higher demand for resources for data dissemination as multiple communication paths are built up based on it, while another study emphasized the responsibility of users occupying such positions for the maintenance of communication and their potential as coordinators of a group process [8]. Therefore, these central nodes should be allocated more resources in order to avoid congestion and increase spectrum efficiency. The mode selection module on a central node should also schedule more time for cellular communication since higher throughput on a central node means higher throughput for the whole community.

As mentioned previously, network-based centralized peer discovery suffers from the scalability problem. A central node tends to have high proximity-encounter possibility with nearby devices. Thus, these central devices may provide alternatives to relieve the synchronization and communication work load on BSs. For example, instead of simply relying on synchronizing via the cellular tower or randomized beaconing, the central node in Fig. 3a can proactively send beacons to other users to improve the peer discovery ratio, and Smith in Fig. 1 can help synchronize all the devices in his/her community to save resources for the BSs and reduce the energy consumption in peer discovery. Therefore, how to utilize the user centrality information to optimize the peer discovery process is another key technical challenge.

Social Bridges

Intuitively, a bridge undertakes the task to provide information and content exchange among communities, and it is prone to congestion under heavy network load conditions. To avoid congestion, the mode selection and resource allocation processes should be aware of the community bridges. Specifically, the resource allocation module needs to schedule more resources to bridge users, while the mode selection module needs to give higher preference for cellular communication to bridge nodes. For example, Fig. 1 illustrates an extreme example that the link between Alice and Bob is the only path to deliver information between communities A and B; therefore, Alice and Bob require more spectral resource and stable connectivity to satisfy the data transmission demand. It can be seen that bridge user detection algorithms, and bridge-aware resource allocation and mode selection schemes are challenging research problems that have the potential to improve the overall throughput and coverage of the D2D communication underlaying cellular network.

Based on the above analysis, we now summarize the insights and design aspects for the social-aware enhanced D2D communication underlaying cellular network in Table 1.

Social Meets D2D: Quantitative Evaluation

We use a realistic cellular network deployment to quantitatively evaluate the enhancement achieved by utilizing social-characteristics-enhanced D2D communication.

Targeted System

We used the Reality trace [12], which is the most recognized human social and mobility trace, introduced before, to simulate the social properties in the targeted system. In the area covered by the system, multiple BSs, each with a coverage radius of 400 m, were deployed to provide seamless coverage of the area. For D2D communication, we limited the maximum transmission range of a node to 50 m. The achievable link transmission rate between any two UEs was adjusted according to the distance between them, and related parameters were based on the wireless propagation settings given in [15]. The D2D communication channel was based on the scenario in which two communicating UEs were physically in close proximity, while the cellular communication channel was simulated according to the urban microcell scenario.

Based on the obtained social properties in the Reality trace, we designed a social-aware D2D system to demonstrate the huge potential of utilizing the social structure information of centrality and community. Specifically, we used the social centrality to assist peer discovery, and utilized the information of community and ties to aid resource allocation. In the design of these schemes, notice that instead of using transient information such as locations and dynamic traffic demands, we exploited the stable social relations and characteristics existing in the social domain.

To achieve scalable peer discovery, we focus on the ad hoc approach. Rather than performing randomized beaconing, however, we rely on the social centrality information extracted from the trace to decide the beaconing rate. Specifically, we adjust the beacon rates of users to be proportional to their centrality values in the network. In particular, we group users according to their centrality values, and then allocate the beacon rate to each group. In this way the users more likely involved in D2D communication pairs will beacon at a larger rate, and consequently improve the D2D peer discovery efficiency. In our system, cellular users share their uplink resources with D2D communication pairs. Consequently, at the uplink the cellular and D2D users sharing the same spectrum blocks interfere with each other. To maximize network capacity, we try to allocate the D2D pairs with the resources of cellular users in different communities since they are usually not in physical proximity. Within a community, we allocate spectrum resources considering the strengths of their social ties. Outside the different communities, we use their properties of social trust to stimulate them to share resources with each other, which achieves the optimal social-aware resource allocation.

	Ties	Community	Centrality	Bridge
Peer discovery	Beacon rate adjustment	Peer density Encounter patterns	Proactive beacons Communication demands	/
Mode selection	/	Community density Community interests	Cellular preferential Bottleneck detection	Inter-community demands
Resource allocation	Communication demands Security and privacy	Community-oriented sharing Communication demands	Resource demands Bottleneck prediction	Dissemination dominant Bottleneck prediction
Interference management	Relay selection Spectrum allocation	Resource partition Distributed coordination	/	/

Table 1. Qualitative analysis for the social-aware D2D communication underlaying cellular network.

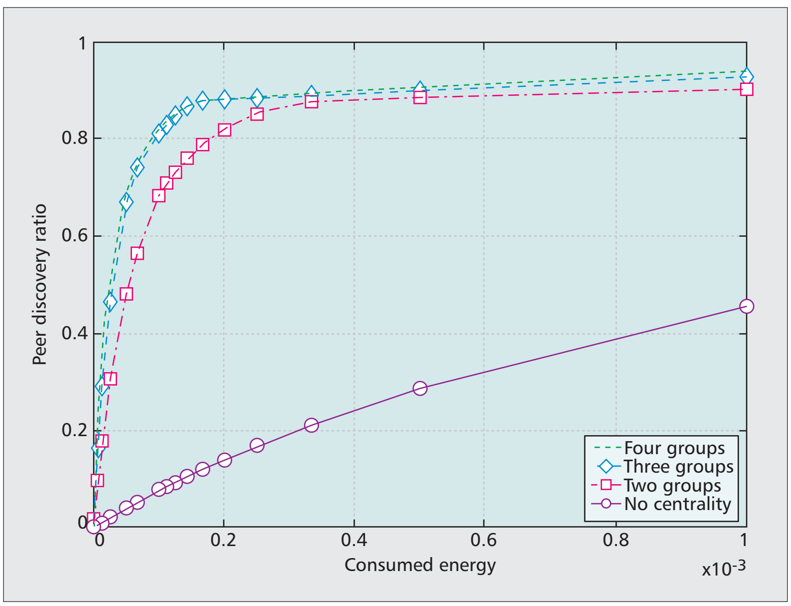

Figure 4. Comparison of the peer discovery performance as a function of the normalized energy consumed for the non-social-centrality-aware scheme and the social-centrality-aware scheme.

RESULTS ANALYSIS

Based on the results obtained by simulating the above social-aware D2D communication network, we analyze the gains brought by the social centrality, community, and ties defined in the previous section in terms of peer discovery efficiency, transmission rate, and system throughput.

Figure 4 compares the peer discovery ratios of the schemes with and without considering centrality, where we observe that by dividing the users into two groups according to their social centrality values, significant performance enhancement can be achieved in terms of a two to four times larger peer discovery ratio given the same consumed system energy compared to the non-social-centrality-aware scheme. Increasing the groups to three further enhances performance. This indicates the huge potential of utilizing social properties to save system energy and improve discovery efficiency. Here we only investigate a simple centrality-aware mechanism. For more complex systems, there is scope for investigating centrality-aware optimal beaconing mechanisms by adjusting the beacon rates of users according to their centrality variations in both the temporal and spatial dimensions.

Figure 5a compares the system transmission rate achieved by the four schemes in terms of the sum rate as a function of D2D pairs. The further first scheme, which allocates the D2D communication resources with the resources of the cellular users that are the furthest away from the D2D pairs, achieves a marginally better system sum rate compared to the random allocation, but it is inferior to the social-unaware optimization scheme without considering social information. However, our simple community guided resource allocation scheme achieves the best performance, because by carefully considering the social structures of D2D pairs, our scheme is capable of stimulating all users to share resources to deal with communication interference much better. This confirms the potential gains by utilizing social information in resource allocation.

The system throughputs achieved by our system are examined in Fig. 5b, where the system throughputs attained by the three different transmission modes are shown. In the simulation we assume a general content downloading system where mobile data are delivered from the corresponding content servers to the users either directly via cellular transmissions, or via D2D-based transmissions through other users, which is decided by the mode selections. From the results we observe that the largest amount of system throughput is obtained by the D2D mode, which accounts for about 70.4 percent of the total throughput when the content downloading latency is 1000 s. It is also clear that most of the D2D transmitted data are via the D2D opportunistic mode, and the importance of opportunistic transmission increases with the increase of the content downloading latency. These results demonstrate that D2D opportunistic communication plays an important role in data dissemination, and can significantly offload a large amount of data from traditional cellular transmission.

CONCLUSIONS

We have proposed a social-aware D2D communication architecture that exploits social network properties for better cellular system design. With the profound understanding and insight of the

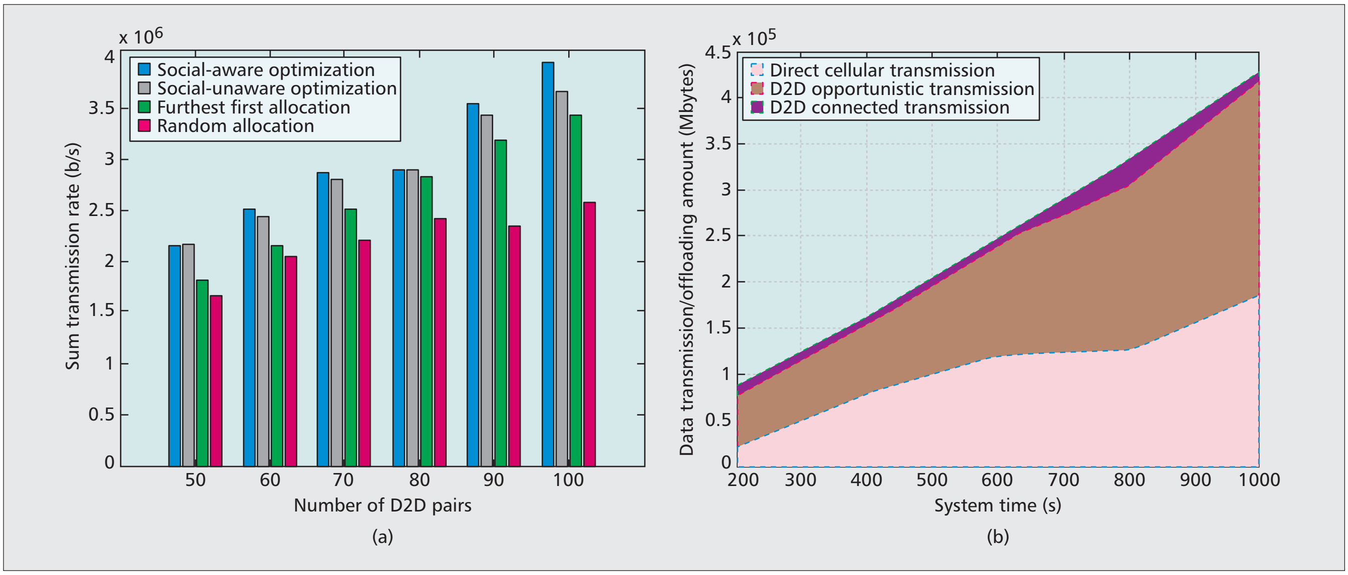

Figure 5. a) Comparison of the transmission efficiency in terms of sum rate achieved by the four resource allocation schemes; b) system throughput of the investigated D2D communication underlaying cellular network.

interplay between social networks and mobile communications, we have qualitatively analyzed how the D2D communication can benefit from social features, and quantitatively evaluated the huge potential gains attainable in a practical social-aware D2D communication system. Our study thus opens a new research direction for designing the next-generation social-aware D2D communication underlaying cellular system.

Acknowledgments

This work is supported by the National Basic Research Program of China (973 Program) (No. 2013CB329001), National Nature Science Foundation of China (No. 61301080, No. 61171065 and No. 61273214), National High Technology Research and Development Program (No. 2013AA013501 and No. 2013AA013505), Chinese National Major Scientific and Technological Specialized Project (No. 2013ZX03002001), and China's Next Generation Internet (No. CNGI-12-03-007).

References

[1] S. Sesia, I. Toufik, and M. Baker, Eds. *LTE — The UMTS Long Term Evolution: From Theory to Practice*, Wiley, 2009.
[2] K. Doppler *et al.*, "Device-to-Device Communication as an Underlay to LTE-Advanced Networks," *IEEE Commun. Mag.*, vol. 47, no. 12, Dec. 2009, pp. 42–49.
[3] G. Fodor *et al.*, "Design Aspects of Network Assisted Device-to-Device Communications," *IEEE Commun. Mag.*, vol. 50, no. 3, Mar. 2012, pp. 170–77.
[4] L. Lei *et al.*, "Operator Controlled Device-to-Device Communications in LTE-Advanced Networks," *IEEE Wireless Commun.*, vol. 19, no. 3, June 2012, pp. 96–104.
[5] D. J. Watts and S. H. Strogatz, "Collective Dynamics of 'Small-World' Networks," *Nature*, vol. 393, no. 6684, June 1998, pp. 440–42.
[6] R. M. Bond *et al.*, "A 61-Million-Person Experiment in Social Influence and Political Mobilization," *Nature*, vol. 489, no. 7415, Sept. 2012, pp. 295–8.
[7] P. Hui, J. Crowcroft, and E. Yoneki, "BUBBLE Rap: Social-Based Forwarding in Delay-Tolerant Networks," *IEEE Trans. Mobile Computing*, vol. 10, no. 11, Nov. 2011, pp. 1576–89.
[8] B. Han *et al.*, "Mobile Data Offloading through Opportunistic Communications and Social Participation," *IEEE Trans. Mobile Computing*, vol. 11, no. 5, May 2012, pp. 821–34.
[9] X. Chen *et al.*, "Social Trust and Social Reciprocity Based Cooperative D2D Communications," *Proc. MobiHoc '13*, Bangalore, India, July 29–Aug. 1, 2013, pp. 187–96.
[10] N. Kayastha *et al.*, "Applications, Architectures, and Protocol Design Issues for Mobile Social Networks: A Survey," *Proc. IEEE*, vol. 99, no. 12, Dec. 2011, pp. 2130–58.
[11] A. Anderson *et al.*, "Effects of User Similarity in Social Media," *Proc. 5th ACM Int'l. Conf. Web Search and Data Mining*, 2012, pp. 703–12.
[12] C. R. Shalizi and A. C. Thomas, "Homophily and Contagion are Generically Confounded in Observational Social Network Studies," *Sociological Methods & Research*, vol. 40, no. 2, 2011, pp. 211–39.
[13] S. Aral and D. Walker, "Identifying Influential and Susceptible Members of Social Networks," *Science*, vol. 337, no. 6092, July 2012, pp. 337–41.
[14] N. Eagle and A. Pentland, "Reality Mining: Sensing Complex Social Systems," *Personal and Ubiquitous Computing*, vol. 10, no. 4, May 2006, pp. 255–68.
[15] C. Xu *et al.*, "Efficiency Resource Allocation for Device-to-Device Underlay Communication Systems: A Reverse Iterative Combinatorial Auction Based Approach," *IEEE JSAC*, vol. 31, no. 6, Sept. 2013, pp. 348–58.

Biographies

Yong Li [M'09] (liyong07@tsinghua.edu.cn) received his B.S. degree in electronics and information engineering from Huazhong University of Science and Technology, Wuhan, China, in 2007, and his Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China, in 2012. During July to August in 2012 and 2013, he worked as a visiting research associate in Telekom Innovation Laboratories (T-labs) and the Hong Kong University of Science and Technology, respectively. From December 2013 to March 2014, he visited the University of Miami, Florida, as a visiting scientist. He is currently a faculty member of the Electronic Engineering Department at Tsinghua University. His research interests are in the areas of networking and communications, including mobile opportunistic networks, device-to-device communication, software-defined networks, network virtualization, future Internet, and others. He received the Outstanding Postdoctoral Researcher, Outstanding Ph.D. Graduates, and Outstanding Doctoral Thesis awards of Tsinghua University, and his research is granted by the Young Scientist Fund of Natural Science Foundation of China, Postdoctoral Special Fund of China, and industry companies such as Hitachi and ZET. He has published more than 100 research papers, and has 10 granted and pending Chinese and international patents. His Google Scholar Citation is about 440 with H-index of 11, as well as more than 120 total citations without self-citations in the Web of Science. He has served as Technical Program Committee (TPC) Chair for the Web Workshop of Simplex '13, and on the TPCs of several international workshops and conferences. He is also a Guest

Editor for *ACM/Springer Mobile Networks & Applications*, Special Issue on Software-Defined and Virtualized Future Wireless Networks. Currently, he is an Associate Editor of the *EURASIP Journal on Wireless Communications and Networking*.

TING WU is currently a Ph.D. candidate in the Department of Computer Science and Engineering at the Hong Kong University of Science and Technology (HKUST). She is also a member of the System and Media Lab, HKUST. She received her M.S. from the School of Computer Science, Carnegie Mellon University, and her B.E. from the University of Electronic Science and Technology of China. Her research interests include location-based social networks, spatio-temporal data mining, and web data management.

PAN HUI received his Ph.D. degree from the Computer Laboratory, University of Cambridge, and earned both his M.Phil. and B.Eng. from the Department of Electrical and Electronic Engineering, University of Hong Kong. He is currently a faculty member of the Department of Computer Science and Engineering at HKUST, where he directs the System and Media Lab. He also serves as a Distinguished Scientist of Telekom Innovation Laboratories (T-labs) Germany and an adjunct professor of social computing and networking at Aalto University Finland. Before returning to Hong Kong, he spent several years at T-labs and Intel Research Cambridge. He has published more than 100 research papers, and has several granted and pending European patents. He has founded and chaired several IEEE/ACM conferences/workshops, and served on the TPCs of numerous international conferences and workshops including IEEE INFOCOM, SECON, MASS, GLOBECOM, WCNC, and ITC.

DEPENG JIN received his B.S. and Ph.D. degrees from Tsinghua University in 1995 and 1999, respectively, both in electronics engineering. He is an associate professor at Tsinghua University and vice chair of the Department of Electronic Engineering. He was awarded the National Scientific and Technological Innovation Prize (Second Class) in 2002. His research fields include telecommunications, high-speed networks, ASIC design, and future Internet architecture.

SHENG CHEN [M'90, SM'97, F'08] obtained his B.Eng. degree from the East China Petroleum Institute, Dongying, in January 1982, and his Ph.D. degree from City University, London, in September 1986, both in control engineering. In 2005, he was awarded a higher doctorate degree, D.Sc., from the University of Southampton, United Kingdom. From 1986 to 1999, he held research and academic appointments at the Universities of Sheffield, Edinburgh, and Portsmouth, all in the United Kingdom. Since 1999, he has been with the Department of Electronics and Computer Science, University of Southampton, where he currently holds the post of professor in intelligent systems and signal processing. He is a Distinguished Adjunct Professor at King Abdulaziz University, Jeddah, Saudi Arabia. He is a Chartered Engineer and a Fellow of IET. His recent research interests include adaptive signal processing, wireless communications, modeling and identification of nonlinear systems, neural network and machine learning, intelligent control system design, and evolutionary computation methods and optimization. He has published over 470 research papers. He is an ISI highly cited researcher in the engineering category (March 2004).