Operator Controlled Device-to-Device Neighborhood Area Networks: The NSFC D2D-NAN Project

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Abstract

When research on the fifth generation mobile communications had just stepped into its startup period, a project called device-to-device neighborhood area networks (D2D-NAN) was launched in China supported by the National Science Foundation of China (NSFC). The core objective of the D2D-NAN project is to effectively combine cellular and mobile adhoc networks in license bands for designing architectures and protocols to meet the data traffic surge problems. D2D-NAN leverages recent advances in wireless communications and optimization theory, which can exhibit vast potential for achieving high spectrum efficiency and full exploitation of communication resources. In this article, the application requirements, the technological challenges, and some potential solutions are discussed. In particular, our recent results and key technologies employed in our demonstration system are presented.

I. Introduction

As more and more new multimedia rich services are becoming available to mobile users, there is an ever-increasing demand for higher data rate wireless access. As a consequence, the concept of device-to-device (D2D) communication has been recently introduced to allow local peer-to-peer transmissions among mobile devices bypassing the base stations (BSs) [1]. Specifically, besides cellular operation, where the mobile stations (MSs) can be served by the network via the BSs, some mobiles may communicate with each other directly over direct links. In particular, the BSs can control the radio resource allocation for the cellular and the D2D links. Also, the

BSs can set constraints on the transmission parameters of D2D users to limit the interference experienced by the cellular users and satisfy their quality-of-service (QoS) requirements [2].

In China, the D2D related research has attracted a great deal of attention from numerous researchers and wireless engineers in both academia and industries. In the universities, research topics regarding D2D communication cover a wide range from physical, MAC layer, to upper layer, etc. While for industries, researchers mainly look at the possibilities of standardization in 3GPP as well as real implementation and prototypes. These research work and projects on D2D systems typically focus on one-hop communication [3]. However, multihop communications for proximity-based services arise in many emerging applications, such as data communication in hotspots. The corresponding research are highly associated with specific applications such as mobile social networks for advertisement push [4], and community networks for fast data dissemination [5]. Most of these problems still remain open and are in need of extensive investigations [6].

To this end, the National Science Foundation of China (NSFC) recently granted a three-year (2013-2015) fundamental research project by the Outstanding Young Researcher Award Program, named Device-to-Device Local Area Networks (D2D-NAN). This project is coordinated by Prof. Lingyang Song from Peking University. The objective of D2D-NAN project is to enable seamless operation between cellular and mobile adhoc networks in a multi-cell level through the adoption of proper resource management [2], [7], [8]. Specifically, the D2D-NAN project focuses on practical multi-hop application scenarios, catering to the demands of high-efficiency cellular technology, and carries out researches from the two perspectives of basic theory and key technology, aiming to develop a new network structure that highly improving spectrum efficiency and system capacity.

One of the major challenges by enabling D2D-NAN communication is to realize efficient data spreading or data offloading in the D2D network without causing severe disturbance of the original cellular networks [9]. Other challenges to be extensively researched include identification of services for which D2D communication is useful, radio resource allocation and resource management for D2D links [10]–[12]. By now, the project has made innovative progress in various fields of research. The achievements have been published in international journals, conference proceedings, and applied for patents and proposals both in China and abroad. Moreover, the international and Chinese research institutions have given recognition and praise on the

work. The results obtained through intensive collaboration among the project partners are rather encouraging in comparison with relevant state-of-the-art approaches and thus pave the way to further study of more composite protocols in the future. The project has been further supported by the Ministry of Science and Technology of China to 2017.

The rest of this article is organized as follows: Section II introduces the basic information of D2D-NAN project. In Section III, we present the research challenges, possible solutions, and some recent results are provided in Section IV. In Section V, it draws some major conclusions.

II. Research Challenges and Key Technologies

The D2D-NAN project has many research issues that need to be addressed to guarantee the inter-operability with existing cellular networks. These are elaborated in the following work packages (WPs).

A. WP1: Network Architecture

Fig. 1 shows a typical heterogeneous network scenario, consisting of microcells, femtocells, conventional cellular communication, one-hop D2D direct transmission, and D2D-NAN for group communication. We primarily focus on a TDD system, where D2D users share the same uplink and downlink spectrum with cellular users. Specifically, the inter-networking between D2D and cellular networks will be carefully considered. Approaches for operators to control the whole network will be proposed [6].

B. WP2: Channel and Interference Modeling

Although D2D-NAN underlaying communication technologies are very promising, many research challenges need to be addressed before their wide development. Among them, one of the most important challenges is how to properly characterize D2D communication channels. Reliable knowledge of the propagation channel and a corresponding realistic channel model serve as the enabling foundation for flexible and practical design and testing of D2D-NAN systems. This underlines the importance of developing physically meaningful yet easy-to-use methods to mimic D2D channels [7]. In the channel modeling part, we consider D2D as any device-to-device communications, e.g., human-to-human (H2H), vehicle-to-vehicle (V2V), V2H, machine-to-machine. Unlike conventional cellular communication links, D2D links have the

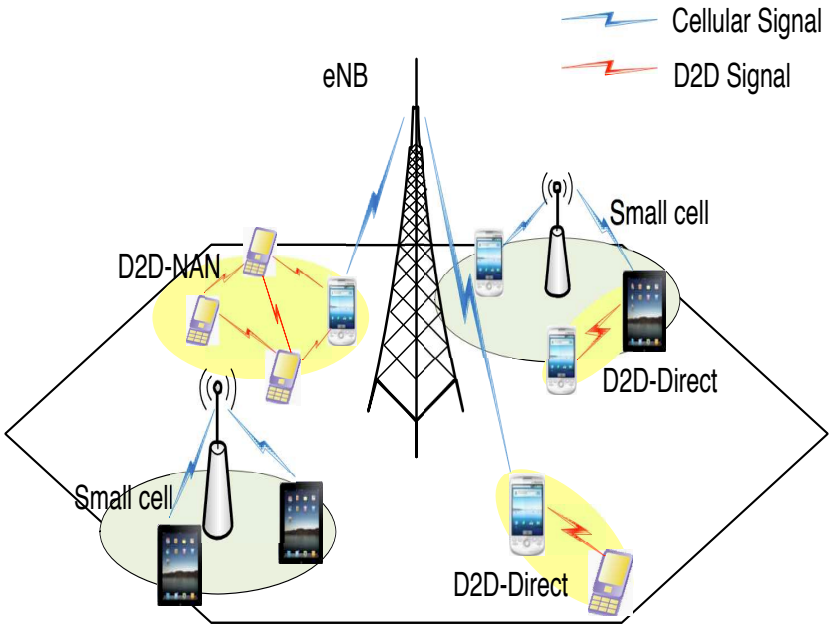

Fig. 1. D2D communication underlaying cellular networks including cellular communication, D2D direct, and D2D-NAN.

following features: 1) both ends of the link are typically at low heights; 2) both ends of the link can be moving (dual mobility); 3) both ends of the link are subject to shadowing by the user. This results in that modeling approaches and corresponding channel models for cellular systems cannot be directly used for D2D systems. Unlike a rich and fascinating history of the research in cellular channels, the investigation of D2D channel modelling is still in its infancy.

C. WP3: Interference-aware Transmission

Interference-ware transmission is of great importance to multi-hop D2D networks, especially for efficient and reliable data dissemination. D2D networks not only provide coverage at the customer premises, but also radiate toward neighboring mobile users, introducing interference. Given the fact that D2D communications typically happen within the coverage area of existing macro/mircrocells, they can cause strong performance degradation to the cellular networks. Furthermore, the occurrence of new D2D networks could also disturb the normal functioning of the already existing D2D communications. To overcome the effects of interference, cancelation techniques have been proposed but often disregarded due to errors in the cancelation process.

The use of multiple antennas beamforming at the mobile has also been suggested as a means of reducing interference by decreasing the number of interferers from the hardware based approach. On the other hand, strategies based on interference avoidance also represent efficient alternatives, (e.g., power and subchannel management). Power control algorithms and radio resource management are tools often used in cellular systems to mitigate interference [7].

Network coding (NC), as a new class of information processing and transmission techniques, is currently emerging in multi-hop multi-user wireless networks. In [13], an amplify-and-forward protocol based network coding scheme, referred to as the physical-layer network coding, was proposed. Currently, most of the existing cooperative communication protocols keep information of different users separate in different orthogonal channels (orthogonal in time, frequency or spreading codes). Hence, these schemes are actually physical-layer routing (detect, replicate and forward). As a new strategy for information transmission in networks, network coding allows messages from different sources (or to different sinks) to mix in the intermediate n-odes.Comparing to traditional routing techniques, PNC allows information processing in the intermediate nodes. Performance gains in e.g., energy-efficiency, fairness, robustness, or coverage are obtained. Application of network coding to wireless cellular networks in association with mobile adhoc network, especially for the D2D-NAN, is natural, for the intriguing connections.

D. WP4: Resource Management

The use of D2D communication can introduce another communication dimension, i.e. the handset freedom in a less strict way. Although D2D communication brings improvement in spectral efficiency and system capacity, it also causes interference to the cellular network and thus, proper resource management is in great need to reduce the interference. Thus, an efficient interference coordination must be formulated to guarantee a target performance level of communications. One of the benefits by using D2D communications is to reduce the transmit power of mobile handsets, and thus, to improve energy efficiency. Further, this problem can be investigated by joint radio resource and power allocation, and the objective is to improve the energy efficiency of the whole system. Unlike the radio resource allocation management which enable multiple D2D users and cellular user to maximally coexist, this energy efficiency problem mainly focus on the power interference and control, and thus, may not improve the system spectrum efficiency significantly [10]–[12].

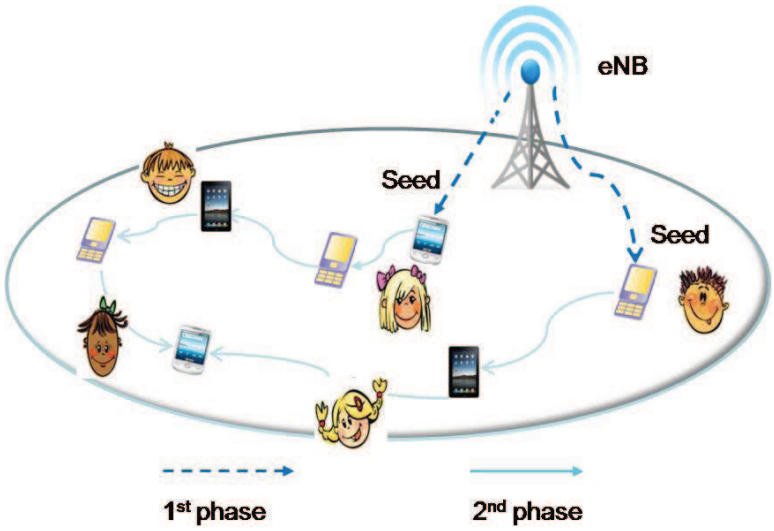

Fig. 2. Popular content downloading in hotspot areas, such as concert and stadium networks.

Besides, when a large number of similar requests are received by the eNB, the D2D-NAN can be used to efficiently offload data [9]. For example, in stadium or concert networks, when many mobile users request for the same content, some UEs as '*seeds*' can be first selected to obtain the complete information from the eNB, and then these seeds can share the data with the rest of the mobiles, as shown in Fig. 2. In Fig. 3, it shows the cumulative service curves of both coalition game-theoretic approach and noncooperative approach [6]. First, we can see that the proposed approach performs much better than the noncooperative approach. In the noncooperative approach, each mobile makes individual decisions, which may lead to severe data collisions. However, in the proposed approach, the mobiles cooperate with each other to maximize the utility function, and consequently, the proposed approach achieves a better performance in service rate.

III. Summary

The D2D-NAN project, supported by NSFC, aims to achieve performance improvement of combining cellular and mobile adhoc networks. The D2D-NAN project comprises of four major work packages in order to cover physical, MAC, networking, to system layers: dynamic heterogenous underlaying configuration, channel and interference modeling, spectrum efficient and

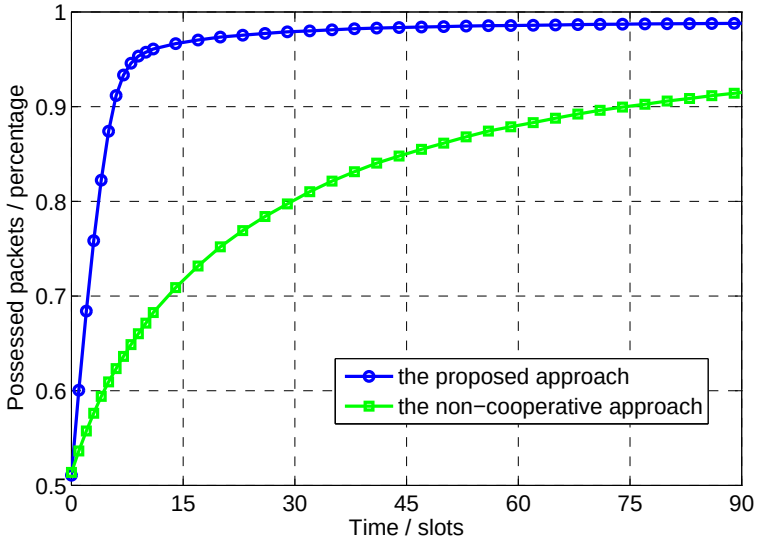

Fig. 3. Total possessed packets by the proposed coalition game-theoretic approach and the noncooperative approach.

interference-aware transmission, and cross-layer resource management. Major technical challenges as well as possible solutions are briefly presented in each work package. As interference is the main limitation in the deployment of underlaying networks, special attentions are given to those problems regarding spectrum allocation and interference avoidance. In particular, D2D-NAN uses recent advances in wireless communications, including the PNC, utility optimization, congestion and access control, game theory, etc, to promise network performance, and exhibites vast potential for achieving high capacity and full exploitation of communication resources. The results obtained so far through intensive collaboration among the project partners were rather encouraging in comparison with relevant state-of-the-art approaches and thus pave the way to further study of more composite protocols in the future.

Besides, there are still many potential future research directions in various D2D-NAN applications, for example,

- Billing and Incentive Mechanism: Billing is critical for D2D communications to the operators, which can be realized by monitoring the controlling information feedback from the D2D users, e.g. the communication time length. In addition, the amount of allocated radio resources can be another effective measurement for fully controlled D2D communication. Another important issue is to motivate mobile users working as the intermediate nodes to

relay the information. Game theory is expected to constitute a key tool to secure communication infrastructure of smart grid, which can guide both attacker and defender behaviors by linking state estimation, power dispatch, and electricity pricing. So far, this technique has been adopted in a wide number of disciplines ranging from economics, politics, to psychology. Very recently, game theory has been used to study the incentive problems in communication networks, and this implies that game theory can also naturally become a prominent tool to help build up the incentive mechanism for D2D-NAN [5], [14].

- Signaling Overhead Reduction: One of the difficulties using D2D communications is to reduce the signaling overhead, which depends very much on the access method. For network fully controlled scheme, it achieves the optimal performance in a centralized way, but requires too much signaling report from D2D communication links. Although self-organized scheme has flexible and easy operation, this distributed approach may cause disturbance to the cellular networks. Hence, by combining the merits of the above two methods, the network assisted method can be designed which allows the cellular to partially participate the communication and transfer some of the resource management functions to the D2D users.
- Mobility Management: In cellular networks, cell handoffs are triggered when users enter the coverage area of other cells. However, given the coverage size of D2D-NAN, this occurs more often than in the cellular case, hence increasing network signaling. Different handoff management procedures are thus needed to allow nonsubscribers to camp for longer periods on nearby D2D networks. Furthermore, a hierarchical cell structure, as shown in Fig. 1, where a mobile D2D-NAN layer is defined, can also be used to distinguish between cellular and D2D networks. In this way, the signaling across layers can be minimized as well as the neighboring cell and D2D-NAN list that users scan when performing a handoff, particularly for self-organized access D2D communications.
- Mobile Social Networks: The human behaviors and social tie can be associated with D2D-NAN communications for information spreading. Specifically, when a large number of similar requests are received by the BS, the D2D-NAN can be used to efficiently offload data. For example, in stadium or concert networks, when many mobile users request for the same content, some mobiles as '*seeds*' can be first selected to obtain the complete information from the BS, and then these seeds can share the data with the rest of the

mobiles [4].

- Security in the Physical-layer: In D2D-NAN, the issues of privacy and security have taken on an increasingly important role in wireless networks. The purpose of secure communications is to enable the legitimate destination to successfully obtain source information, while the eavesdroppers, untrusted or even malicious intermediate mobiles (wire-tappers) are not able to interpret this information. Additionally, physical-layer methods can be also adopted to improve the communication security. The basic idea of PHY layer security is to exploit the physical characteristics of the wireless channel in order to transmit messages securely. This line of work was pioneered by Wyner, who introduced the wire-tap channel and established the possibility of creating perfectly secure communication links without relying on private (secret) keys [15], [16].

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