

Fine-Grained Resource Allocation for Cooperative Device-to-Device Communication in Cellular Networks

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Abstract—Data traffic in cellular networks has dramatically surged in recent years due to the booming growth of various mobile applications. It is hence crucial to increase network capacity to accommodate new applications and services. In this paper, we propose a promising concept of cooperative device-to-device (D2D) communication to improve resource utilization in cellular networks. Based on a novel fine-grained resource allocation scheme, we study the problem of maximizing the minimum rate among multiple wireless links by jointly considering relay assignment, transmission scheduling, and channel allocation. Simulation results show that our proposed solutions can significantly increase resource utilization in cellular networks.

Index Terms—D2D, cooperative communication, multi-hop cellular networks, resource allocation.

I. INTRODUCTION

An explosion of data traffic has been observed in cellular networks in recent years due to the booming growth of mobile applications. For example, it has been reported that global mobile data traffic will increase nearly 11-fold between 2013 and 2018 [1], and NTT DoCoMo's mobile data traffic grew 60% each year in Japan. The growth has led to an immediate need of large network capacity for modern cellular networks to accommodate more users and new applications with satisfied service quality.

As a supporting technique for multi-hop cellular networks (MCN), device-to-device (D2D) communication [2] is a promising concept to improve resource utilization in cellular networks by letting two devices in proximity of each other establish a direct local link for data transmission. It can significantly improve spectral efficiency because multiple D2D links with reduced interference region may work simultaneously with other traditional cellular uplinks or downlinks in the same channel. The chances of D2D communication are highly dependent on the quality of D2D links. Unfortunately, without the support of a base station with powerful capability of information collection and signal processing, transmissions on D2D links are apt to be jeopardized by many factors like fading or environment noise, and the resulting low transmission rate would reduce the incentive of adopting D2D communication for both users and network operators.

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Cooperative communication (CC) [3] has shown its effectiveness in combating fading to achieve high channel capacity and reliability in a low-cost way, which is well suited to the context of D2D communication. Its basic idea is to let a relay node forward the signal received from a transmitter to its receiver such that diversity gain is obtained for the same signal traveling different paths from direct and relay transmissions. When D2D communication is reinforced by CC, which is referred to as cooperative D2D communication, new challenges, such as relay selection, channel allocation, and transmission scheduling, are raised for efficient resource allocation in cellular networks.

In this article, we study the efficient resource allocation for cooperative D2D communication in cellular networks. Instead of treating each communication link with its associated relay node as an indivisible unit as in most existing work [4], [5], we propose a fine-grained resource allocation scheme that divides each CC transmission into a broadcasting phase and a forwarding phase, which can be scheduled individually. Based on this idea, we present the fine-grained resource allocation under both single channel and multiple channels settings. Experimental results validate the effectiveness of our solutions.

II. NETWORK INFRASTRUCTURE AND CHALLENGES

A. Network Infrastructure

We consider a multi-cell multi-channel wireless network consisting of base stations (BSs), mobile stations (MSs), and relay stations (RSs) as shown in Fig. 1. Traditionally, all transmissions should go through base stations, which forms a centralized communication mode. When a user communicates with the base station, others on the same channel in the same cell should stay silent to avoid interference. When D2D communication is enabled, a direct link can be established between a pair of users in proximity of each other. For example, users MS_2 and MS_3 in Fig. 1 can bypass the base station BS_1 and communicate directly. Compared with the traditional centralized cellular mode, multiple D2D and cellular links can be active simultaneously if they cause negligible interference to each other, leading to a significantly increased channel utilization. D2D communications happen between a pair of nodes not only within a single cell, but also in different cells. The former is referred to as an intra-cell D2D pair, e.g., $MS_2 - MS_3$, while the latter is called an inter-cell D2D pair, such as $MS_4 - MS_5$ in Fig. 1.

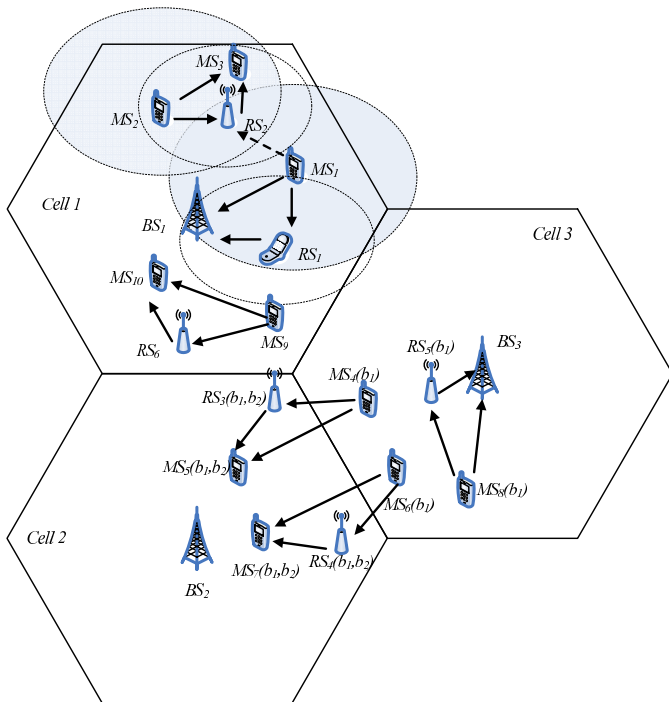


Fig. 1. Network infrastructure with D2D communications.

The network includes a number of relay stations, which may be deployed by network operators as dedicated ones, or contributed by third-party device providers, such as access points of local area networks or even mobile nodes that are willing to provide forwarding service. These relay stations can be employed by D2D and cellular users to improve their channel capacity. As an example shown in Fig. 1, relay RS_2 can assist the transmissions from node MS_2 to MS_3 , which forms a classical three-node model of cooperative communication. Typically, there are two cooperative communication modes, namely, amplify-and-forward (AF) and decode-and-forward (DF). The transmission processes under these two modes and direct transmission are presented as follows.

Amplify-and-forward (AF): When a source node transmits data to a destination node with the help of a relay node under AF mode, each time frame is divided into two time slots. In the first time slot, the source transmits a signal to the destination. Due to the broadcast nature of wireless communication, this transmission is also overheard by the relay. Then, the relay amplifies this received signal and forwards it to the destination in the second time slot. They are referred to as broadcast and relay transmissions. Finally, the destination decodes the original signal by combining the two received ones disseminated via different paths.

Decode-and-forward (DF): The transmissions under DF mode follow the similar process of AF mode except that the relay node decodes the signal received from the source in the first time slot and then transmits it to the destination in the second time slot.

Direct transmission (DT): Under DT, the transmission from source to destination takes up the whole time frame.

The achievable transmission rate in above three transmission

schemes can be found in [3].

B. Challenges

The main challenges in cooperative D2D communications are summarized as follows.

Relay assignment: When multiple relays are available in the network, it has been well recognized that relay assignment plays a critical role in determining the performance of CC under both AF and DF modes. Existing work [4], [5] has shown that selecting one relay is enough to achieve full diversity for a single source-destination pair. For example, Zhao et al. [5] have derived the closed-form expression of the outage probabilities when multiple relay and a single relay is employed, respectively, and shown that both probabilities are with the same order. When multiple CC sessions share a common set of relay nodes, the relay assignment should be globally optimized. For example, although RS_1 is the best relay node for both links $MS_9 - MS_{10}$ and $MS_1 - BS_1$ in Fig. 1, it cannot serve them simultaneously. An alternative for $MS_9 - MS_{10}$ is to choose RS_6 such that both links can achieve improved channel capacity on different channels.

Transmission scheduling: It is not practical to allocate a dedicated channel to each communication link because radio spectrum is a scarce resource that should be efficiently utilized. When multiple communication links share a common channel, they should be scheduled to guarantee a certain level of quality-of-service (QoS). When CC is applied, although channel capacity can be improved, wireless interference may become serious due to the participation of relay nodes, which can lead to a decreased throughput performance. Thus, the tradeoff between channel capacity improvement and wireless scheduling efficiency in CC should be studied.

Channel allocation: Channel allocation is also crucial for enhancing spectral efficiency. Under the traditional direct communication, two users can communicate when they tune to the same channel. Since a CC transmission involves three nodes, i.e., a source, a destination and a relay node, the channel allocation for cooperative D2D communication becomes more challenging as the two links use the same frequency channel in different time slots.

III. FINE-GRAINED RESOURCE ALLOCATION

A. System model

In the multi-cell wireless network, there are a number of base stations and a number of source-destination (S-D) pairs. Note that an S-D pair is in a cellular mode if a BS is involved, or in a D2D mode otherwise. A set of relay nodes are available in the network. Each node is equipped with a single antenna and works in a half-duplex mode that they cannot transmit and receive simultaneously. Following the discussions in [4], [5], we assign each source-destination at most one relay node in our model.

Different from the well-known model introduced in [6], where the radio resources are assumed to be always sufficient, we consider a more realistic one with a finite number of available channels. Note that the set of available channels at each node may be different under an arbitrary distribution of

all channels over the space of interest. Furthermore, different channels are allowed inside the basic frame for each cooperative communication pair.

To characterize the interference in the network, various interference models, e.g., the protocol and physical interference models [7], have been proposed in the literatures. Here, we consider the protocol interference model that has been widely used in the research of wireless networks. In this model, a transmission is successful if and only if the receiver is within the transmitting range of its intended transmitter, and outside the interference range of all other transmitters.

B. Improved space-division multiplexing

We first consider the fine-grained link scheduling for a single channel. To characterize the interference region of a cooperative communication session, we define (s, r, d) , consisting of an S-D pair (s, d) and a relay r , a cooperative link as a whole. In a frame-by-frame scheduling, each cooperative link is a basic scheduling unit and its interference region is the union of two circles with radius of interference range centered at relay r and destination d respectively. An interference-free scheduling should guarantee that no other transmitters are within the interference range of any cooperative link (s, r, d) during its assigned time frames.

By carefully examining the transmission process of CC, we find out that the interference region of a cooperative link (s, r, d) is different in the two time slots of a frame. The interference region in the first time slot is the union of two circles centered at relay r and destination d due to the broadcasting from source s to both r and d . In the second time slot, only destination d receives the forwarded signal from the relay node, which results in a reduced interference region defined by the circle centered at d . The above observation motivates us to investigate a fine-grained resource allocation scheme by distinguishing the interference regions in different slots of a CC frame such that the network performance can be improved. We use two cooperative links (MS_1, RS_1, BS_1) and (MS_2, RS_2, MS_3) in Fig. 1 as an example to show the benefits of slot-by-slot scheduling. As shown in Fig. 2, in a frame-by-frame scheduling, these two source-destination pairs cannot transmit simultaneously since the transmission of MS_1 will interfere with the reception at RS_2 as illustrated by a dotted arrow. However, if we schedule the broadcasting and forwarding links on a slot-by-slot basis, MS_2 and RS_1 can transmit signals at the same time because they cause no interference. A similar case is for MS_1 and RS_2 . In summary, our slot-by-slot scheduling achieves higher efficiency of space-division multiplexing.

C. Improved frequency-division multiplexing

The efficient resource allocation problem becomes more challenging in multiple channels. In many existing work, each source-destination pair with its associated relay node should be assigned a common channel. In other words, the relay has to forward the received signals on the same channel with the source. In this section, we show that the performance can be improved if direct and relay transmissions are allowed to be

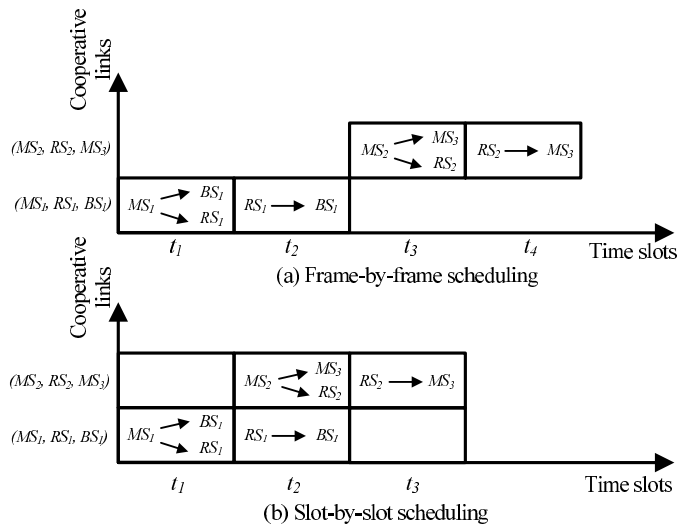


Fig. 2. The improved efficiency of space-division multiplexing by our fine-grained resource allocation scheme.

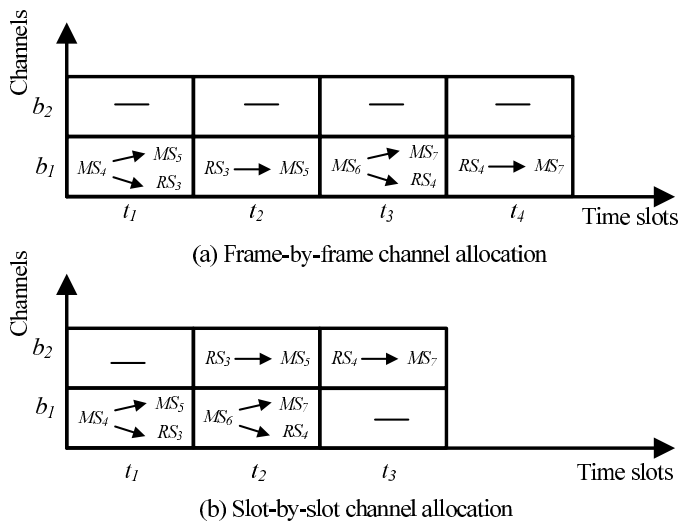


Fig. 3. The improved efficiency of frequency-division multiplexing by our fine-grained resource allocation scheme.

scheduled in different channels. Consider the cooperative links (MS_4, RS_3, MS_5) and (MS_6, RS_4, MS_7) in Fig. 1. Suppose that the accessible channels in cell 1 and cell 2 are $\{b_1\}$ and $\{b_1, b_2\}$, respectively. Under the traditional coarse-grained channel allocation, each group of nodes (MS_4, RS_3, MS_5) or (MS_6, RS_4, MS_7) involving in the CC mode should work at the same channel, leading to the channel allocation result with at least 4 slots as shown in Fig. 3(a). Under the same channel availability, when we allow the source and its selected relay to transmit on different channels, we obtain a new transmission scheme with only 3 slots as shown in Fig. 3(b), where the broadcast transmission (from MS_6 to MS_7 and RS_4) and the relay transmission (from RS_3 to MS_5) can work on different channels simultaneously. In summary, such fine-grained channel allocation scheme improves the efficiency of frequency-division multiplexing as well, and thus increases the throughput of each source-destination pair.

IV. ONLINE ALGORITHMS

The optimal fine-grained resource allocation in static networks with a single collision domain has been proven to be NP-hard [8]. In this section, we propose an online algorithm that can deal with multiple collision domains in a dynamic network where users may join and leave at any time. It makes relay assignment, transmission scheduling, and channel allocation on a slot-by-slot basis with the objective of maximizing the minimum average transmission throughput among all concurrent communication sessions. In the following, we first study the case with given relay assignment. Then, we extend it to handle a more challenging problem where relay assignment is unknown.

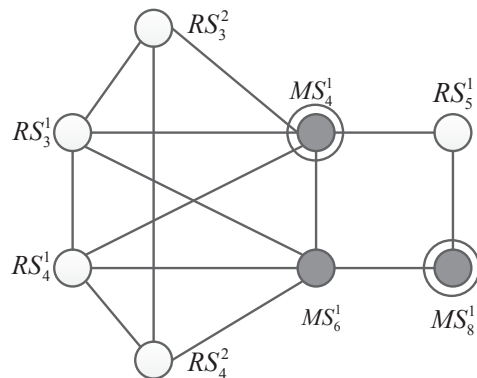
A. Algorithm with given relay assignment

The basic idea of our online algorithm is to iteratively make the transmission scheduling at each time-slot with higher priority to the sessions with lower average throughput achieved so far. In each iteration, the channel allocation and transmission scheduling will be made for each selected node such that its maximum transmission rate is achieved. In such a way, the minimum throughput of all sessions is expected to be maximized in a long run.

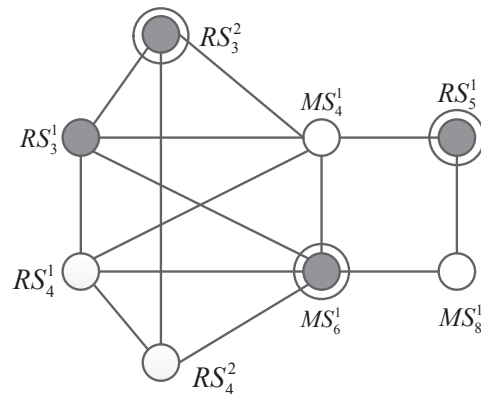
We construct conflict graph to describe the interference under all channel conditions. Recall that the interference region of a cooperative link is different in the two time slots within a frame. It motivates us to partition a cooperative link into a broadcasting link for the first time slot and a subsequent forwarding link for the second time slot. In our constructed conflict graph, we create two nodes representing the broadcasting and forwarding links, respectively, for each S-D pair. They should be connected in the conflict graph because they share the relay node that cannot be active simultaneously in our considered network model.

For a better understanding, we still use the topology in Fig. 1 as an example to show the corresponding conflict graph based on a slot-by-slot scheduling. Without loss of generality, we only consider communication pairs in cells 2 and 3 as our initial topology. As shown in Fig. 4(a), nodes MS_4^1 , MS_6^1 and MS_8^1 represent the broadcasting links of three S-D pairs, respectively, and other nodes represent the corresponding forwarding links. Note that we use superscript to denote the working channel. For example, nodes RS_3^1 and RS_3^2 represent the same forwarding link under channel b_1 and b_2 , respectively. Any two nodes in the conflict graph are connected if the corresponding cooperative links cannot be scheduled simultaneously. An interference-free scheduling should guarantee that no transmitters are within the interference range of each link during its assigned time slots. We define two states, pending and idle, for each node in the conflict graph. If a broadcasting or forwarding link is ready for transmission, its status is set to pending; otherwise, it is idle.

As the example shown in Fig. 4(a), nodes in pending status are black-marked, i.e., nodes MS_4^1 , MS_6^1 and MS_8^1 have data to transmit in the first time slot. Among these nodes, the selected ones, marked by double circles, will transmit



(a) The first time slot



(b) The second time slot

Fig. 4. Conflict graph in each time slot.

simultaneously. In other words, they are not connected with each other in the conflict graph. At the beginning, since the throughput of any pair is equal to zero, the selection can be made randomly, e.g., nodes MS_4^1 and MS_8^1 .

In the second time slot, both RS_3^1 and RS_3^2 are in pending status because relay RS_3 is ready to forward the data received in the first time slot. Node RS_5^1 is also in pending status because of the similar reason. Considering selecting either RS_3^1 or RS_3^2 is enough to complete the cooperative communication, we choose RS_3^2 because it will not conflict with MS_6^1 whose throughput is still zero. As a result, three links, represented by RS_3^2 , RS_5^1 and MS_6^1 , are scheduled for transmission in the second time slot.

In the following time slots, our algorithm proceeds in a similar way. Note that in addition to the updates of node status at each step, the conflict graph itself should be also updated if network topology or channel availability changes, e.g., due to node mobility.

B. Algorithm with joint resource allocation and relay assignment

Our basic idea of solving this problem with unknown relay assignment is to construct a conflict graph by taking all possible relay assignment schemes into consideration. Specifically, the direct transmission scheme will be considered as

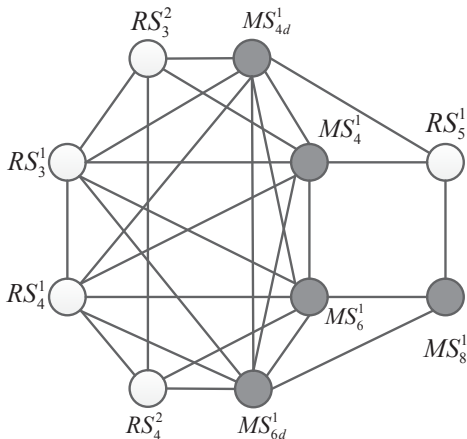


Fig. 5. Conflict graph taking relay assignment into consideration.

a special case, i.e., no relay is involved. For each scheme of any communication pair, we create a corresponding node in the conflict graph to represent different relay selection. For example, the resulting conflict graph of Fig. 4(a) is shown in Fig. 5, where an additional node MS_{4d}^1 represents the direct transmission for pair $MS_4 - MS_5$ under channel b_1 . Similarly, any pair of conflicting nodes in the graph should be connected. When multiple schemes are available for the same session in a pending status, the one leading to the highest throughput will be chosen.

Finally some implementation issues of our algorithm are discussed as follows. We consider a central controller that executes the online algorithm. When any communication pair joins the network, it will sense a set of accessible channels and report the results to the control node. Similarly, before any communication pair leaves the network, it also reports the departure event to the control node. With the global information, the control node determines the channel allocation and relay assignment.

V. PERFORMANCE EVALUATION

In this section, we study the performance of our proposed fine-grained resource allocation (FGA) in comparison with the direct transmission (DT) and the traditional coarse-grained resource allocation (CGA) with a frame-by-frame scheduling.

We consider random network instances within a 1500×1500 square region. All nodes in the network use the same transmission power with transmission distance of 500. The channel bandwidth is set to 22MHz. The SNR (Signal-to-Noise-Ratio) is calculated as $\frac{P|h_{uv}|^2}{\sigma^2}$, where the channel gain $|h_{uv}|^2$ between two nodes with a distance $\|u-v\|$ is calculated as $|h_{uv}|^2 = \|u-v\|^{-4}$, and the variance of background noise σ^2 is set to 10^{-10} W. The network instances initially contain 10 S-D pairs, and then 30-participation and 30-departure events happen subsequently according to a Poisson process. The inter-arriving and residence time of these dynamic nodes obey a negative exponential distribution with parameters $\lambda_a = 0.5$ and $\lambda_r = 0.05$, respectively. We study the average performance of 20 randomly generated network instances.

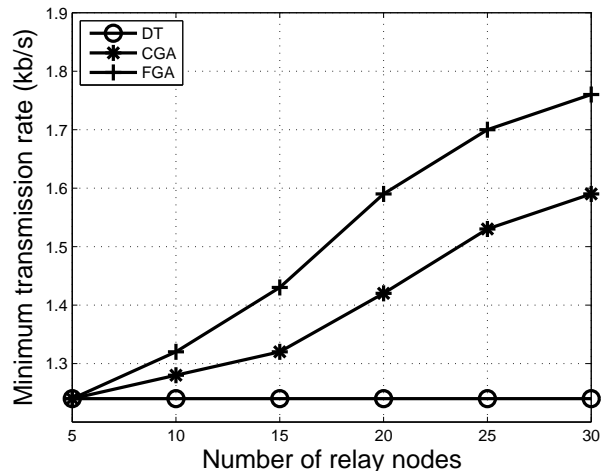


Fig. 6. The performance versus the number of relay nodes

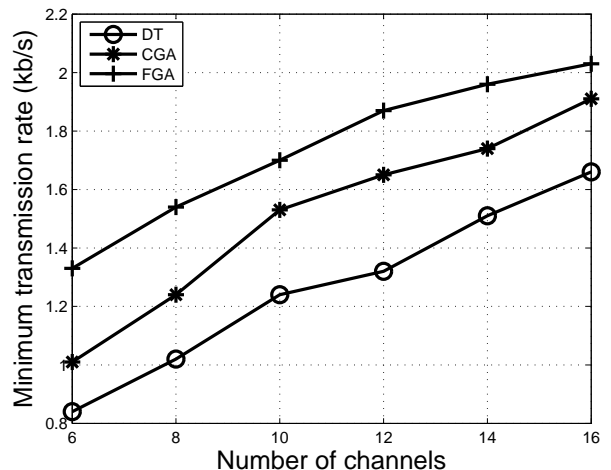


Fig. 7. The performance versus the number of channels

The minimum throughput as a function of the number of different number of relay nodes is shown in Fig. 6. The results of direct transmission show as a horizontal line because its performance does not depend on the number of relays. For FGA and CGA, their performance increases as the number of relay nodes grows. This is because more available relays lead to better relay assignment for each source-destination pair in the network.

Then, we investigate the effect of the available channels to the minimum throughput. As shown in Fig. 7, all results show as an increasing function of the channel number. We attribute the gain to the new transmission opportunities introduced by more channels. Moreover, the performance gap between FGA and CGA is larger when a less number of channels are available. When we further increase the available number of channels, the improved performance is very limited.

VI. CONCLUSION

In this paper, we study the fine-grained resource allocation for cooperative D2D communications in cellular networks. By

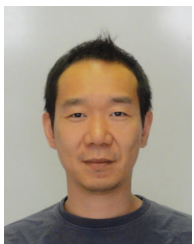
dividing each CC transmission into a broadcasting and a relay phases, which can be scheduled individually, we exploit the benefits of a slot-by-slot scheduling scheme by both space-division and frequency-division multiplexing. As the optimal resource allocation scheme is proved to be NP-hard, we propose an online algorithm to schedule packet transmissions. Simulation results show that our proposed solution can improve the performance significantly.

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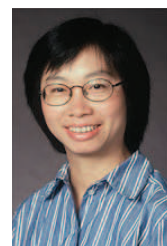


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