Subchannel and Transmission Mode Scheduling for D2D Communication in OFDMA Networks

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Abstract—**We study an opportunistic subchannel scheduling and transmission mode selection problem for the OFDMA system with device-to-device (D2D) communication. We allow D2D users to opportunistically select its transmission mode between two transmission modes: direct transmission between D2D users (direct one-hop transmission) and indirect transmission through the BS (indirect two-hop transmission). We develop a framework with which opportunistic transmission mode selection can be modeled as opportunistic subchannel scheduling, which enables our problem to be reduced to an opportunistic subchannel scheduling problem. We formulate a stochastic optimization problem that aims to maximize the average sum-rate of the system, while satisfying the quality-of-service (QoS) requirement of each user. By solving the problem, we develop an optimal opportunistic subchannel scheduling algorithm, which enables us to perform both subchannel scheduling and transmission mode selection opportunistically.**

Index Terms—**Device-to-device (D2D) communication; subchannel scheduling; transmission mode selection; OFDMA**

I. Introduction

In the conventional cellular network, mobile users always communicate only through a base-station (BS). However, when two users are close to each other with a good channel condition between them, by allowing direct communication between them rather than indirect communication through the BS, we may improve system performance significantly, while utilizing radio resources more efficiently. This direct communication between mobile users in the cellular network is called device-to-device (D2D) communication. D2D communication has several advantages over conventional communication through the BS [1]. First, D2D communication may increase transmission rate of communication to achieve a higher throughput between D2D users. Second, direct D2D communication may lower the transmission power level of D2D users to save their energy consumption and increase their battery lifetime, compared with conventional communication through the BS. Third, D2D communication would help to avoid congestion at the BS, allowing performance improvement of other users. Hence, D2D communication has received increasing attentions as a promising technique to improve spectral efficiency and performance of the cellular network.

In this paper, we study an opportunistic subchannel problem for the OFDMA cellular network with underlaying D2D communication, in which each subchannel is opportunistically scheduled to each user considering the channel condition and the QoS requirement of each user.

There are several works that consider a subchannel allocation problem in the OFDMA network with D2D communication. In [2], [3], and [4], the authors propose simple interference avoidance mechanisms, which commonly enable D2D users to reuse appropriate resource using resource allocation information of legacy users in control signaling. In [5], the proposed subchannel selection algorithm finds appropriate D2D users who will cause less interference to legacy users. In [6], the authors propose a subchannel allocation scheme that minimizes the maximum interference. The authors in [5] and [6] provide only suboptimal subchannel allocation algorithms that are based on heuristics.

In addition to subchannel scheduling, we also consider opportunistic transmission mode selection for D2D users by allowing D2D users to opportunistically switch between two transmission modes, i.e., direct one-hop transmission and indirect two-hop transmission. We first formulate a stochastic optimization problem that maximizes the average sum-rate of the system. By solving the optimization problem, we develop an optimal subchannel scheduling algorithm that provides not only opportunistic subchannel scheduling but also opportunistic transmission mode selection for D2D users considering the time-varying channel condition of each wireless link and the QoS requirement of each user.

This paper is organized as follows. Section II provides the system model that is considered in this paper. In Section III, we formulate an optimization problem and develop an opportunistic subchannel and transmission mode scheduling algorithm that solves the problem. We provide numerical results in Section IV and finally conclude in Section V.

II. System Model

We consider an OFDMA single cell that consists of one base station (BS), K pairs of D2D users and M legacy users, as in Fig. 1. Each D2D pair k consists of one D2D transmitting (Tx) user u_k^T and one D2D receiving (Rx) user u_k^R, and user u_k^T has data to transmit to user u_k^R. The sets of D2D Tx users and D2D Rx users are denoted as $U^T = \{u_k^T, k = 1, 2, ..., K\}$ and $U^R = \{u_k^R, k = 1, 2, ..., K\}$, respectively. The set of legacy users is denoted as $U^L = \{u_m^L, m = 1, 2, ..., M\}$. Legacy users communicate through the BS with their correspondent, which may or may not be in the same cell.

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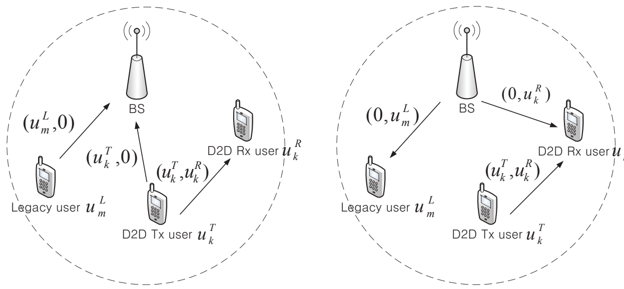


(a) Uplink phase. (b) Downlink phase.

Fig. 1. Cellular network with D2D communication.

We consider a time-slotted system and a TDD-based time-slot structure in which each time-slot is divided into two phases, i.e., uplink and downlink phases, with the same duration. As shown in Fig. 1, legacy users can transmit their data to the BS only at the uplink phase and receive their data from the BS only at the downlink phase, as in the conventional cellular network. For D2D pairs, we allow them to use either/both direct one-hop transmission or/and indirect two-hop transmission through the BS. We also allow users in D2D pairs to use both uplink and downlink phases for their direct one-hop transmission. However, for the indirect two-hop transmission through the BS, D2D Tx users can transmit their data to the BS only at the uplink phase and the BS can relay the received data to the corresponding D2D Rx users only at the downlink phase.

When node i transmits data to another node j, we denote the corresponding wireless link as (i,j). For instance, $(u_k^T,0)$ stands for a wireless link between the Tx user of D2D pair k and the BS whose index is denoted as 0. We now define sets of all wireless links for each of uplink and downlink phases as

$$\mathcal{L}^u = \{(i,j)|i \in U^T, j \in \{0\} \cup U^R\} \cup \{(i,0)|i \in U^L\}, \quad (1)$$

$$\mathcal{L}^d = \{(i,j)|i \in U^T \cup \{0\}, j \in U^R\} \cup \{(0,j)|j \in U^L\}, \quad (2)$$

where uplink and downlink phases are denoted by superscripts u and d, respectively.

The wireless channel is divided into N OFDMA subchannels, each of which consists of several numbers of subcarriers. The set of indices for the subchannels is denoted as $\mathcal{N} = \{1,2,...,N\}$. We assume that the wireless channel is time-varying and frequency-selective, but unchanged during a time slot and flat within a subchannel. In this paper, the channel state of each wireless link on each subchannel is modeled as a stationary stochastic process. To represent the stochastic channel states of all wireless links in the system in a simple way, we introduce the system state which is defined as a combination of the current channel states of all wireless link on all subchannels. Hence, the system state also can be modeled as a stationary stochastic process. The set of system states is denoted as $\mathcal{S} = \{1,2,...,S\}$. The system should be in one of finite system states in each time slot. We now denote the probability that system is in system state s in a time slot as π_s.

Each subchannel is allocated to a wireless link according to the current system state at the beginning of a time-slot by the BS. We now define subchannel assignment indicator $q_{(i,j)}^{n,\tau,s}$ as

$$q_{(i,j)}^{n,\tau,s} = \begin{cases} 1, & \text{if subchannel } n \text{ is assigned to link } (i,j) \\ & \text{at phase } \tau \text{ in a time-slot with system} \\ & \text{state } s \\ 0, & \text{otherwise} \end{cases}, \quad \forall n \in \mathcal{N}, \forall \tau \in \{u,d\}, \forall s \in \mathcal{S}, \forall (i,j) \in \mathcal{L}^\tau.$$

The vector $\bar{q}_s = [q_{(i,j)}^{n,\tau,s}]_{(i,j)\in\mathcal{L}^\tau}^{n\in\mathcal{N},\tau\in\{u,d\}}$ denotes the overall subchannel allocation in a time-slot with system state s. We assume that each subchannel can be assigned to at most one wireless link at each of uplink and downlink phases in a time-slot. Consequently, the subchannel allocation $\bar{q}_s$ should be in the following constraint set:

$$\mathcal{Q}_s = \left\{ \bar{q}_s \;\middle|\; \begin{array}{l} q_{(i,j)}^{n,\tau,s} \in \{0,1\}, \\ \qquad \forall n \in \mathcal{N}, \tau \in \{u,d\}, (i,j) \in \mathcal{L}^\tau \\ \sum_{(i,j)\in\mathcal{L}^\tau} q_{(i,j)}^{n,\tau,s} \le 1, \forall n \in \mathcal{N}, \tau \in \{u,d\} \end{array} \right\}, \quad \forall s \in \mathcal{S}. \quad (3)$$

We assume that each link (i,j) has a fixed Tx power P_i on a subchannel that depends on Tx node i, and the achievable instantaneous data rate of wireless link (i,j) on subchannel n at each phase τ in a time-slot with system state s is obtained based on the Shannon capacity formula as:

$$r_{(i,j)}^{n,\tau,s} \triangleq \log_2(1+\alpha_{(i,j)}^{n,\tau,s} P_i), \quad (4)$$

where $\alpha_{(i,j)}^{n,\tau,s}$ denotes the channel gain per unit transmission power for link (i,j) on subchannel n at phase τ in a time-slot with system state s. Without loss of generality, we assume that the values of channel bandwidth and AWGN noise power are normalized to one. Then, the actual aggregate instantaneous data rate on link (i,j) at phase τ in a time-slot with system state s is obtained as

$$R_{(i,j)}^{\tau,s}(\bar{q}_s) \triangleq \sum_{n\in\mathcal{N}} q_{(i,j)}^{n,\tau,s} r_{(i,j)}^{n,\tau,s}. \quad (5)$$

Since we assumed a fixed power allocation and $\alpha_{(i,j)}^{n,\tau,s}$'s are constants for given τ and s, the achievable instantaneous data rate in (4) is also a constant for given system state s. Hence, the aggregate data rate $R_{(i,j)}^{\tau,s}$ is a function of subchannel allocation $\bar{q}_s$ for given system state s.

From (5), we can obtain the average rate of each user. We then define the total average sum-rate of the system, which is the objective function of our problem that should be maximized, as

$$\sum_{s\in\mathcal{S}} \pi_s \sum_{k\in\mathcal{K}} \sum_{\tau\in\{u,d\}} R_{(u_k^T,u_k^R)}^{s,\tau} + \sum_{s\in\mathcal{S}} \pi_s \sum_{k\in\mathcal{K}} R_{(u_k^T,0)}^{s,u} + \sum_{s\in\mathcal{S}} \pi_s \sum_{m\in\mathcal{M}} \left(R_{(u_m^L,0)}^{s,u} + R_{(0,u_m^L)}^{s,d} \right), \quad (6)$$

where the first term represents the average sum rate of one-hop D2D communication from D2D Tx user to D2D Rx user at uplink and downlink phases, and the second term represents that of two-hop communication from the D2D Tx users to the BS at uplink phases. Finally, the last term represents the average sum-rate of legacy users at uplink and downlink phases.

We assume that each user has its QoS requirement, which is defined as the minimum average rate requirement as

$$\sum_{s\in\mathcal{S}}\pi_s\left(\sum_{\tau\in\{u,d\}}R^{s,\tau}_{(u_k^T,u_k^R)}+R^{s,u}_{(u_k^T,0)}\right)\geq\gamma_k,\quad\forall k\in\mathcal{K},\quad(7)$$

$$\sum_{s\in\mathcal{S}}\pi_s R^{s,u}_{(u_m^L,0)}\geq\gamma_m^{UL},\quad\forall m\in\mathcal{M},\quad(8)$$

$$\sum_{s\in\mathcal{S}}\pi_s R^{s,d}_{(0,u_m^L)}\geq\gamma_m^{DL},\quad\forall m\in\mathcal{M},\quad(9)$$

where γ_k is the minimum average rate requirement for D2D pair k, γ_m^{UL} and γ_m^{DL} are the minimum average rate requirements for legacy user m for its uplink and downlink communications, respectively.

In addition, in two-hop D2D transmission through the BS, to forward all the data transmitted from a D2D Tx user to the corresponding D2D Rx user, the average receiving rate at the BS from the D2D Tx user must be less than or equal to the average achievable transmission rate from the BS to the corresponding D2D Rx user, which is represented as

$$\sum_{s\in\mathcal{S}}\pi_s R^{s,u}_{(u_k^T,0)}\leq\sum_{s\in\mathcal{S}}\pi_s R^{s,d}_{(0,u_k^R)},\quad\forall k\in\mathcal{K}.\quad(10)$$

III. OPPORTUNISTIC SCHEDULING

In this section, we first formulate an optimization problem, and then develop an optimal algorithm that solves the problem. We formulate a stochastic optimization problem as

$$\begin{array}{lll}(\mathrm{P}) & \underset{\bar{q}}{\text{maximize}} & (6)\\ & \text{subject to} & (7),(8),(9),(10),\ \text{and}\ (3).\end{array}$$

Problem (P) is a mixed integer optimization problem which is hard to solve. We thus relax the integer subchannel assignment indicator $\bar{q}$ into a continuous valued vector such that it makes the problem easier to handle. A new constraint set is defined as

$$\mathcal{Q}'_s=\left\{\bar{q}_s\ \middle|\ \begin{array}{c}0\leq q^{n,\tau,s}_{(i,j)}\leq 1,\\ \forall n\in\mathcal{N},\tau\in\{u,d\},(i,j)\in\mathcal{L}^\tau\\ \sum_{(i,j)\in\mathcal{L}^\tau}q^{n,\tau,s}_{(i,j)}\leq 1,\forall n\in\mathcal{N},\tau\in\{u,d\}\end{array}\right\},\quad\forall s\in\mathcal{S}.\quad(11)$$

We now define a new optimization problem as:

$$\begin{array}{lll}(\mathrm{P}') & \underset{\bar{q}}{\text{maximize}} & (6)\\ & \text{subject to} & (7),(8),(9),(10),\ \text{and}\ (11).\end{array}$$

Although problem (P$'$) is different from problem (P), as we will show later, we can eventually obtain the optimal solution of problem (P) by solving problem (P$'$).

If we have information on system state S and the probability for each state s, i.e., $\pi_s,\forall s$, problem (P$'$) is a deterministic convex optimization problem that can be solved easily. However, in practice, it is difficult to obtain information about system states such as $\pi_s,\forall s$, a priori. Hence, we need to develop an algorithm that finds the optimal solution of the problem even without such information in advance. In this paper, we use a dual approach and a stochastic subgradient method to solve the problem without a priori knowledge on system states.

We now deal with the dual problem of problem (P$'$) and first define its Lagrangian function as

$$\begin{aligned}L(\bar{\lambda},\bar{q})&=\sum_{s\in\mathcal{S}}\pi_s\sum_{k\in\mathcal{K}}\sum_{\tau\in\{u,d\}}R^{s,\tau}_{(u_k^T,u_k^R)}+\sum_{s\in\mathcal{S}}\pi_s\sum_{k\in\mathcal{K}}R^{s,u}_{(u_k^T,0)}\\&+\sum_{s\in\mathcal{S}}\pi_s\sum_{m\in\mathcal{M}}\left(R^{s,u}_{(u_m^L,0)}+R^{s,d}_{(0,u_m^L)}\right)\\&+\sum_{k\in\mathcal{K}}\lambda_{A,k}\left(\sum_{s\in\mathcal{S}}\pi_s R^{s,d}_{(0,u_k^R)}-\sum_{s\in\mathcal{S}}\pi_s R^{s,u}_{(u_k^T,0)}\right)\\&+\sum_{k\in\mathcal{K}}\lambda_{B,k}\left(\sum_{s\in\mathcal{S}}\pi_s\left(\sum_{\tau\in\{u,d\}}R^{s,\tau}_{(u_k^T,u_k^R)}+R^{s,u}_{(u_k^T,0)}\right)-\gamma_k\right)\\&+\sum_{m\in\mathcal{M}}\lambda_{C,m}\left(\sum_{s\in\mathcal{S}}\pi_s R^{s,u}_{(u_m^L,0)}-\gamma_m^{UL}\right)\\&+\sum_{m\in\mathcal{M}}\lambda_{D,m}\left(\sum_{s\in\mathcal{S}}\pi_s R^{s,d}_{(0,u_m^L)}-\gamma_m^{DL}\right),\end{aligned}$$

where $\bar{\lambda}=[\lambda_{A,1},\lambda_{A,2},\ldots,\lambda_{D,m-1},\lambda_{D,m}]$. Then, the dual problem of problem (P$'$) is defined as

$$(D)\quad\min_{\bar{\lambda}\geq 0}F(\bar{\lambda}),$$

where

$$F(\bar{\lambda})=\max_{\bar{q}_s\in\mathcal{Q}'_s,\forall s\in S}\quad L(\bar{\lambda},\bar{q}).\quad(12)$$

In order to solve problem (12), we first rearrange the Lagrangian function in (12) as

$$\begin{aligned}L(\bar{\lambda},\bar{q})&=\sum_{s\in S}\pi_s L_s(\bar{\lambda},\bar{q}_s)\\&-\sum_{k\in\mathcal{K}}\lambda_{B,k}\gamma_k-\sum_{m\in\mathcal{M}}\lambda_{C,m}\gamma_m^{UL}-\sum_{m\in\mathcal{M}}\lambda_{D,m}\gamma_m^{DL},\end{aligned}\quad(13)$$

where

$$L_s(\bar{\lambda},\bar{q}_s)\quad=\quad\sum_{n\in N}\sum_{\tau\in\{u,d\}}\sum_{(i,j)\in\mathcal{L}^\tau}q^{n,\tau,s}_{(i,j)}g^\tau_{(i,j)}r^{n,\tau,s}_{(i,j)}\quad(14)$$

and

$$g^\tau_{(i,j)}=\left\{\begin{array}{lll}1-\lambda_{A,k}+\lambda_{B,k} & ,\text{if} & i=u_k^T,j=0\\ \lambda_{A,k} & ,\text{if} & i=0,j=u_k^R\\ 1+\lambda_{B,k} & ,\text{if} & i=u_k^T,j=u_k^R\\ 1+\lambda_{C,m} & ,\text{if} & i=u_m^L,j=0\\ 1+\lambda_{D,m} & ,\text{if} & i=0,j=u_m^L\end{array}\right\}.$$

For given $\bar{\lambda}$, $L(\bar{\lambda}, \bar{q})$ is now separable in each state of system s, as in (13). Moreover, each subchannel is not coupled with each other at each phase, thus $L_s(\bar{\lambda}, \bar{q}_s)$ in (13) can be further decomposed into $2N$ subproblems for each subchannel and each phase. Hence, we can easily carry out the maximization in (12) for the given Lagrangian multipliers $\bar{\lambda}$, by solving the following subproblem on subchannel n at phase τ in each time slot with system state s as

$$(\mathrm{D}_s^{n,\tau}) \quad \underset{\bar{q}_s^{n,\tau} \in \mathcal{Q}_s'^{n,\tau}}{\text{maximize}} \sum_{(i,j)\in\mathcal{L}^\tau} q_{(i,j)}^{n,\tau,s} g_{(i,j)}^{\tau} r_{(i,j)}^{n,\tau,s}, \qquad \forall n \in \mathcal{N}, \forall \tau \in \{u,d\}, \forall s \in \mathcal{S}.$$

where $\mathcal{Q}_s'^{n,\tau} = \left\{ \bar{q}_s^{n,\tau} \,\middle|\, 0 \le q_{(i,j)}^{n,\tau,s} \le 1, \sum_{(i,j)\in\mathcal{L}^\tau} q_{(i,j)}^{n,\tau,s} \le 1 \right\}$ and $\bar{q}_s^{n,\tau} = [q_{(i,j)}^{n,\tau,s}]_{(i,j)\in\mathcal{L}^\tau}$. Note that each problem $(\mathrm{D}_s^{n,\tau})$ does not require knowledge of π_s and can be solved without knowledge of π_s once the system state is known. In addition, since $g_{(i,j)}^{\tau}$ and $r_{(i,j)}^{n,\tau,s}$ are constants with given n, τ and s, we can obtain the maximizer of each subproblem separately by using the following strategy:

$$q_{(i,j)}^{n,\tau,s}(\bar{\lambda}) = \begin{cases} 1 & \text{, if } (i,j) = \underset{(i,j)'}{\operatorname{argmax}}\ g_{(i,j)'}^{\tau} r_{(i,j)'}^{n,\tau,s} \\ 0 & \text{, otherwise} \end{cases}, \qquad \forall (i,j) \in \mathcal{L}^\tau. \quad (15)$$

Note that the primal values in $\bar{q}_s(\bar{\lambda}) = [q_{(i,j)}^{n,\tau,s}(\bar{\lambda})]_{(i,j)\in\mathcal{L}^\tau}^{n\in\mathcal{N},\tau\in\{u,d\}}$ that are obtained by the above strategy satisfy the constraint (3) of problem (P) that we relaxed, since $q_{(i,j)}^{n,\tau,s}(\bar{\lambda})$ is always either 0 or 1. Hence, if we obtain the primal optimal solution of problem (P′), it would be also the optimal solution of original problem (P).

We now use the stochastic sub-gradient algorithm [7], [8] to solve the dual problem (D). The solution for this algorithm can be obtained by the following iterative updates in each time-slot.

$$\bar{\lambda}^{(t+1)} = [\bar{\lambda}^{(t)} - \alpha^{(t)} \bar{\upsilon}^{(t)}]^{+} \quad (16)$$

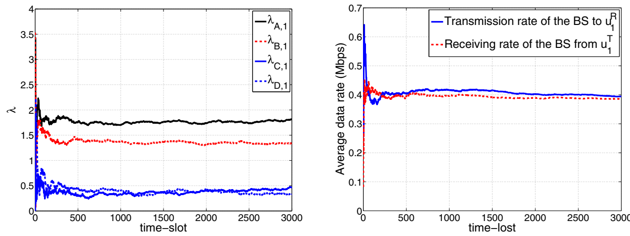
where $\alpha^{(t)}$ is a step-size at the t-th time-slot and $\bar{\upsilon}^{(t)} = [\upsilon_{A,1}^{(t)}, \upsilon_{A,2}^{(t)}, ..., \upsilon_{D,m-1}^{(t)}, \upsilon_{D,m}^{(t)}]$. In (16), $\bar{\upsilon}^{(t)}$ is a vector of random variables, each of which is an element of the stochastic subgradient of $F(\bar{\lambda})$ at $\bar{\lambda} = \bar{\lambda}^{(t)}$. By Danskin's Theorem [9], the stochastic subgradient of $F(\bar{\lambda}^{(t)})$ is obtained as

$$\upsilon_{A,k}^{(t)} = R_{(0,u_k^R)}^{s,d}(\bar{\lambda}^{(t)}) - R_{(u_k^T,0)}^{s,u}(\bar{\lambda}^{(t)}), \quad \forall k \in \mathcal{K}, \quad (17)$$

$$\upsilon_{B,k}^{(t)} = \left(\sum_{\tau\in\{u,d\}} R_{(u_k^T,u_k^R)}^{s,\tau}(\bar{\lambda}^{(t)}) + R_{(u_k^T,0)}^{s,u}(\bar{\lambda}^{(t)}) \right) - \gamma_k, \qquad \forall k \in \mathcal{K}, \quad (18)$$

$$\upsilon_{C,m}^{(t)} = R_{(u_m^L,0)}^{s,u}(\bar{\lambda}^{(t)}) - \gamma_m^{UL}, \quad \forall m \in \mathcal{M}, \quad (19)$$

$$\upsilon_{D,m}^{(t)} = R_{(0,u_m^L)}^{s,d}(\bar{\lambda}^{(t)}) - \gamma_m^{DL}, \quad \forall m \in \mathcal{M}, \quad (20)$$



(a) Convergence of Lagrangian multipliers.

(b) Convergence of indirect two-hop D2D transmissions.

Fig. 2. Convergence of our scheduling algorithm.

where $s^{(t)}$ is the system state at time-slot t.

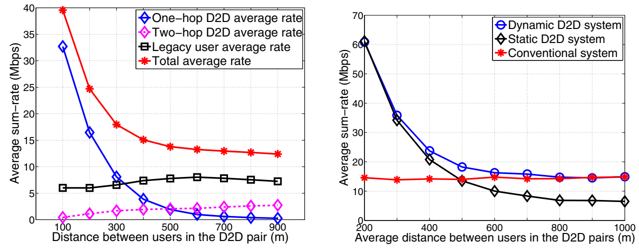
By this iterative algorithm, Lagrangian multiplier vector $\bar{\lambda}^{(t)}$ converges to the optimal solution of problem (D), $\bar{\lambda}^{*}$, with probability 1 as time-slot t goes to infinity if the step sizes satisfy some minor conditions [7]. Since the subchannel scheduling $\bar{q}(\bar{\lambda}^{*})$ satisfies the constraint (3) in problem (P), it is also the optimal subchannel allocation for the original problem.

IV. NUMERICAL RESULTS

In this section, simulation results are provided to evaluate the performance of the proposed subchannel and transmission mode scheduling algorithm. We consider a single cell OFDMA cellular network with a radius of R = 700 m. The time-varying frequency-selective channels are modeled by using path loss, shadow fading and fast Rayleigh fading, assuming that the channel condition of each subchannel independently vary with each other. The distance-dependent path loss of each wireless link is modeled as $128 + 37.6\log_{10}(d)$, where d is distance of the link. The whole bandwidth of the system is set to be 10MHz and is divided into 25 subchannels with equal bandwidth. The noise power spectral density is set to be -174dBm/Hz. The step size of the stochastic subgradient algorithm in (16) is set to be $\alpha^{(t)} = 1/t$, which guarantees the convergence of the algorithm.

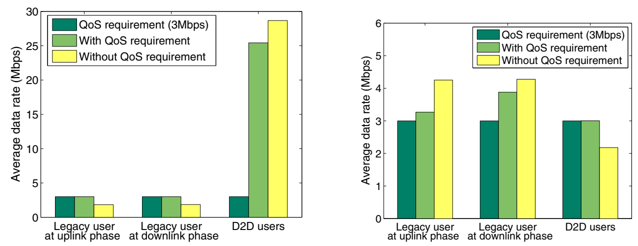
In Fig. 2, we first show the convergence of our algorithm. Five legacy users and five D2D pairs are uniformly distributed around the BS. The convergence of some of Lagrangian multipliers is shown in Fig. 2(a). The convergence of the average receiving and transmission rates at the BS for indirect two-hop transmission is shown in Fig. 2(b), which implies that our algorithm well satisfies constraint (10) of problem (P).

In Fig. 3(a), we provide the achieved average rate of each user, increasing the distance between a D2D Tx user and a Rx user. When the distance is small, the channel condition of the direct link between them will be the best. Hence, the graph shows that the D2D pair can achieve much higher average rate than the legacy user. This implies that in this case, our algorithm schedules subchannels to the direct one-hop transmission mostly to maximize the average sum-rate of the system. However, as the distance between users in the D2D pair is getting larger, the average rate of the D2D pair that is obtained by the direct one-hop transmission is decreasing,



(a) Achieved average rates of users in our system. (b) Average sum-rates of three different systems.

Fig. 3. Performance comparison varying the distance between D2D users.



(a) The distance between users in the D2D pair is 200m. (b) The distance between users in the D2D pair is 600m.

Fig. 4. Average achieved data rates for cases with and without QoS requirement.

since the channel condition of the direct link is getting worse. On the other hand, the average rate of the legacy user and the average rate of the D2D pair that is obtained by the indirect two-hop transmission are increasing. Hence, this figure clearly shows that our algorithm allocates more subchannels to links with a better channel condition than links with a worse channel condition to efficiently utilize subchannels to increase the average sum-rate of the system. In addition, it also shows that our algorithm can adaptively switch between direct one-hop transmission and indirect two-hop transmission of the D2D pair, appropriately comparing their efficiencies.

To show the effectiveness of the dynamic transmission mode switching between direct one-hop transmission and indirect two-hop transmission of the D2D pair, we compare the performance of our system with two other systems. In the conventional system, all users communicate only through the BS, and in the static D2D system, D2D users only communicate directly. We deploy five legacy users and five D2D pairs. In Fig. 3(b), we show the performances of three systems varying the average distance between users in the D2D pairs. When the average distance between users in D2D pairs is small, the conventional system provides the lowest performance, while the average distance between users in D2D pairs is large, the static D2D system provides the lowest performance. However, our dynamic system always provides the highest performance regardless of the change of system environments. This implies that the appropriate selection of the transmission mode of D2D pairs is important to improve the system performance and our algorithm can provide the appropriate transmission mode for D2D pairs adaptively considering system environments.

We now show the effect of the QoS requirement for each user in Fig. 4, comparing the performances of our algorithm for two cases, i.e., cases with and without considering the QoS requirement of each user. In the case without the QoS requirement, when the distance between users in the D2D pair is 200m (relatively small), the legacy user achieves very low average rate, i.e., the degree of unfairness among users is large, and when the distance between users in the D2D pair is 600m (relatively large), without the QoS requirement, the D2D pair achieves low average rate and the legacy user achieves high average rate and the QoS requirement of the D2D pair cannot be satisfied. However, as shown in the case with considering the QoS requirement of each user, the QoS requirement enables to control the degree of fairness among users and alleviates the unfairness problem of the basic opportunistic scheduling that does not consider the QoS requirement, while guaranteeing the minimum performance of each user.

V. CONCLUSION

In this paper, we developed an algorithm that can opportunistically schedule OFDMA subchannels and transmission mode for D2D communication based on dual approach and stochastic subgradient algorithm. In addition to develop the algorithm, through the simulation results, we have shown that in D2D communication, appropriate transmission mode selection for D2D communication between direct one-hop transmission and indirect two-hop transmission is important to improve system performance. The results also show that the optimal transmission mode depends on system environments that varies over time, and thus dynamic transmission mode selection, as in our algorithm, is required to improve system performance.

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