Enabling Green Wireless Networking With Device-to-Device Links: A Joint Optimization Approach

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***Abstract*—Device-to-device (D2D) communication has emerged as a promising technique for improving capacity and reducing power consumption in wireless networks. Most existing works on D2D communications either targeted CDMA-based single-channel networks or aimed at maximizing network throughput. In this paper, we, however, aim to enable green D2D communications in OFDMA-based wireless networks. We formally define an optimization problem based on a practical link data rate model, whose objective is to minimize total power consumption while meeting user data rate requirements. We propose solving it using a joint optimization approach by presenting two effective and efficient algorithms, which both jointly determines mode selection, channel allocation and power assignment. It has been shown by extensive simulation results that the proposed algorithms can achieve over 68% power savings, compared to several baseline methods.**

***Index Terms*—Green wireless networking, D2D, joint optimization, mode selection.**

I. INTRODUCTION

A. Background and Motivations

DUE TO RAPID growth of wireless terminals and their traffic demands, wireless networks have become one of the largest contributors to power usages. Recent studies [11] have shown that there were over 4 million Base Stations (BSs) and each of them consumes an average of 25 MWh per year. Such huge energy consumption has raised public concerns about electricity costs, and more importantly, greenhouse gas emissions that are known to have a negative impact on global climate.

Device-to-Device (D2D) communication commonly refers to the technique that enables wireless devices to communicate directly with each other without an infrastructure of access points or BSs, which has been considered as a key enabling technology for the next generation, (i.e., 5G) wireless communications. Basically, in such a network, two User Equipment (UE) units can communicate directly with each other over the *D2D link*. The BS only helps UE units set up connections without relaying any data traffic. With D2D communications, a UE unit can transmit packets to another UE unit nearby at a reduced power level such that power consumption can be reduced, moreover, interference to other traditional communications (via a BS) can be mitigated, which can improve network capacity. D2D communications can also offload the traffic of BS to improve network capacity further.

To take full advantage of D2D communications, channels need to be carefully allocated and transmit power (per channel) needs to be carefully assigned. However, resource allocation in a wireless network with D2D links is different from that in traditional wireless networks because of there exists an additional problem, mode selection (i.e., determining the mode, D2D or cellular, to be used for data transmissions), which is coupled with other resource allocation problems. Even though mode selection has been addressed by a few recent papers [9], [12], [15], [16], some of them [9], [12] were focused on 3G WCDMA-based cellular networks in which data transmissions were conducted on a single channel and the others [15], [16] aimed at maximizing the sum of data rates of mobile users (network throughput). In this paper, we study a new optimization problem for D2D communications in an OFDMA-based wireless network, whose objective is to minimize total power consumption while meeting user data rate requirements. We propose a joint optimization approach to solve it, which jointly determines mode selection, channel allocation and power assignment. In addition, the Shannon's equation has been widely adopted to model link data rate, which is not practical since it provides an upper bound, rather than the actual link data rate. Practically, by leveraging the Adaptive Modulation and Coding (AMC) technique, link data rate on a sub-channel becomes a discrete increasing step function $C(\cdot)$ of the SINR (at the receiver). We consider such a practical model here.

B. Related Work

Resource allocation has been addressed by quite a few research works in the context of D2D communications recently.

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In [2], the authors proposed a coalitional game based approach for mode selection of D2D links, with the objective of minimizing the total power while satisfying rate requirements. In [3], the authors aimed to maximize the number of admissible D2D pairs thereby minimizing the total uplink transmit power of cellular and D2D links by solving two subproblems separately. The authors of [4] formulated a joint optimization problem as a Mixed Integer Non-Linear Programming (MINLP) problem, where the mode to operate, radio resources to use, and power to transmit are to be optimally decided for a group of users. They also presented a heuristic algorithm with reduced complexity. The authors of [5] proposed novel mode selection algorithms that take into account the interference situation and the operational state of the cellular network in both single-cell and multi-cell scenarios. In [9], the authors derived means for obtaining optimal communication modes for all devices in the system in terms of system equations, which captured network states such as link gains, noise levels, SINR, etc. In [10], Han *et al.*, developed a stochastic framework for sub-channel and transmission mode scheduling, with the objective of maximizing the average sum-rate of the system, while satisfying the Quality-of-Service (QoS) requirement of each user. In [12], the authors proposed an exhaustive search based mode selection and power assignment scheme for D2D communication systems. In [13], the authors formulated the joint mode selection and resource allocation in D2D communications underlaying cellular networks as a flow maximization problem based on the transmission graph and then optimally solved it. In [14], the underlay and overlay mode selections were analyzed for D2D communications in the LTE-advanced single-cell scenario. In [15], [16], Xiang *et al.*, presented a distance-dependent algorithm and a cooperative mode selection mechanism respectively, both aiming at selecting optimal transmission modes with overall capacity maximized and QoS of mobile users satisfied. In [17], Yu *et al.* analyzed optimum resource allocation and power control, aiming to optimize throughput over shared resources while fulfilling prioritized cellular service constraints. In [18], the authors developed low-complexity heuristic algorithms for joint mode selection, channel assignment, and power control with the objective of throughput maximization. The authors of [20] proposed a dynamic stackelberg game framework in which the BS and potential D2D UEs act as the leader and the followers respectively to jointly address the problems of spectrum allocation and user-controlled mode selection. The authors of [19] studied the joint optimization problem of D2D mode selection, modulation and coding scheme assignment, resource block and power allocation with the objective of minimizing the overall power consumption under rate requirements. They decoupled the problem into two sub-problems, which are solved by Lagrangian relaxation and tabu search methods, respectively.

The differences between this work and these related papers are summarized as follows: 1) Unlike some related works studying D2D communications in a single-channel 3G CDMA-based cellular network [9], [12], we consider an OFDMA-based cellular network with multiple sub-channels and study channel allocation. 2) Unlike some related works that aimed to improve network capacity/throughput [4], [10], [13], [15]–[18], the main objective here is to minimize total power consumption to enable green wireless networking. 3) Unlike most related works [4], [5], [10], [12]–[18] that modeled link data rate using a continuous function based on Shannon's theorem, we consider a practical model in which link data rate is an increasing step function of SINR. 4) The problem studied here is mathematically different from those optimization problems formulated based on game theory in [2], [20], or the problems studied in [3], [19] (which have different objective functions and constraints).

TABLE I
MAJOR NOTATIONS

Notation	Description
$C(\cdot)$	The per-channel link data rate function
$G_{T(i),R(j),k}$	Channel gain between transmitter $T(i)$ of link i and receiver $R(j)$ of link j on sub-channel k
$I^{\text{legacy}}_{R(i),k}$	Interference to receiver of D2D link i on sub-channel k contributed by legacy users
K	The number of sub-channels
m_i	The mode of D2D link i
N	The number of D2D links
$p_{i,k}$	The transmit power of D2D link i on sub-channel k
$p_{i,m,k}$	The transmit power of D2D link i on sub-channel k with mode m
P^{legacy}	The maximal allowable interference power level from all D2D links on a sub-channel
Q^{legacy}	The set of sub-channels allocated to legacy links
$R_{i,0}/R_{i,1}$	The data rate of D2D link i in cellular or D2D mode
$R(\cdot)$	The receiver of a D2D link
$T(\cdot)$	The transmitter of a D2D link
Γ_i	The data rate requirement of D2D link i

C. Our Contributions

We summarize our contributions in the following:

- We formally defined an optimization problem for power-efficient D2D communications in OFDMA-based wireless networks based on a practical link data rate model.
- We present two effective and efficient algorithms to solve it in polynomial time, which both jointly determine mode selection, channel allocation and power assignment problem.
- It has also been shown by extensive simulation results that the proposed algorithms can achieve over 68% power savings, compared to several baseline methods.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this paper, we consider a single cell in an OFDMA cellular network, which consists of a BS, N pairs of D2D users (a.k.a D2D links), M legacy users (which only communicate with the BS), and K non-overlapping sub-channels. Since neighboring cells can be allocated sets of different channels, they can be operated independently in an interfere-free manner. Each D2D link i consists of a D2D transmitter $T(i)$ and a D2D receiver

$R(i)$. Similar to [4], [12], we focus on uplink communications since we aim to minimize power consumption of UE units by leveraging D2D communications. Each D2D link i can work in one of the two modes: 1) D2D mode: $T(i)$ directly communicates with $R(i)$; 2) cellular mode: $T(i)$ communicates with $R(i)$ via the BS (as relay). A subset of available sub-channels are assumed to be taken by legacy users for serving their own traffic, which can be re-used by D2D links as long as the total power contributed by D2D links does not exceed a given threshold P^{legacy} at the BS. A relatively conservative threshold can be set to guarantee that traditional communications are not affected by D2D communications.

$G_{T(i),R(i),k}$ denotes the gain of a link i on sub-channel k, which can be measured periodically using pilot signals. $p_{i,k}G_{T(i),R(i),k}$ gives power received at $R(i)$ on sub-channel k, and $p_{j,k}G_{T(j),R(i),k}(j \neq i)$ gives the interference contributed by $T(j)$ at $R(i)$ on sub-channel k, where $p_{i,k}$ is the transmit power at $T(i)$ on sub-channel k. In closely related works [4], [10], the well-known Shannon's equation is used to calculate link data rate. However, it is known that the Shannon's equation gives the capacity of a link, which may not be achievable in practice. Moreover, link data rate is usually not a continuous function of the Signal-to-Interference-Plus-Noise-Ratio (SINR). As mentioned above, we consider this practical model for link data rate. So if the SINR and spectrum bandwidth of a sub-channel k of link i are given, then we can obtain the data rate of link i on sub-channel k via the function $C(\text{SINR}_{i,k})$, which can be at several different *levels*. A data rate constraint needs to be enforced for each D2D link i, which requires its data rate to be no less than a given threshold Γ_i.

We present the problem formulation formally in the following, which is referred to as the *Green-D2D* problem. Mode selection variables $\mathbf{m} = \{m_i | m_i = \{0, 1\}, 1 \leq i \leq N\}$: $m_i = 1$ if D2D link works in the D2D mode; $m_i = 0$, otherwise.

Channel-power assignment variables $\mathbf{p} = \{p_{i,k} \geq 0 | 1 \leq i \leq N, 1 \leq k \leq K\}$: $p_{i,k}$ gives $T(i)$'s transmit power on sub-channel k. Note that $p_{i,k} = 0$ if sub-channel k is not allocated to D2D link i.

Green-D2D

$$\min_{\langle \mathbf{m},\mathbf{p}\rangle} \sum_{i=1}^{N}\sum_{k=1}^{K} p_{i,k} \tag{2.1}$$

Subject to:

$$m_i R_{i,1} + (1 - m_i) R_{i,0} \geq \Gamma_i, \forall i \in \{1, \cdots, N\}; \tag{2.2}$$

$$\sum_{i=1}^{N} m_i p_{i,k} G_{T(i),BS,k} \leq P^{\text{legacy}}, \forall k \in Q^{\text{legacy}}; \tag{2.3}$$

$$(1 - m_i) p_{i,k} \sum_{j \neq i} (1 - m_j) p_{j,k} = 0, \quad \forall i, j \in \{1, \cdots, N\}, \forall k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}; \tag{2.4}$$

$$(1 - m_i) p_{i,k} = 0, \forall i \in \{1, \cdots, N\}, \forall k \in Q^{\text{legacy}}; \tag{2.5}$$

$$\sum_{k=1}^{K} p_{i,k} \leq P^{\max}, \forall i \in \{1, \cdots, N\}; \tag{2.6}$$

where:

$$R_{i,0} = \sum_{k \in \{1,\cdots,K\} \backslash Q^{\text{legacy}}} C\left(\frac{p_{i,k} G_{T(i),BS,k}}{\sum_{j \neq i} p_{j,k} G_{T(j),BS,k} + N_0}\right), \quad \forall i \in \{1, \cdots, N\}; \tag{2.7}$$

$$R_{i,1} = \sum_{k \in \{1,\cdots,K\}} C\left(\frac{p_{i,k} G_{T(i),R(i),k}}{\sum_{j \neq i} p_{j,k} G_{T(j),R(i),k} + I^{\text{legacy}}_{R(i),k} + N_0}\right), \quad \forall i \in \{1, \cdots, N\}; \tag{2.8}$$

Note that in the formulation, we use $R_{i,0}$ (Equation (2.7)) to denote the rate of D2D link i working in the cellular mode; and $R_{i,1}$ (Equation (2.8)) to denote the rate of D2D link i working in the D2D mode. In Equation (2.8), $I^{\text{legacy}}_{R(i),k} = 0, k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}$. The objective (2.1) is to minimize the total power consumption of D2D links. The following constraints must be satisfied:

- *Link data rate constraints (2.2):* The data rate of each D2D link is no less than the given threshold Γ_i. As mentioned above, the per-channel link data rate is given by a discrete increasing step function $C(\cdot)$ of the SINR and sub-channel index.
- *Interference constraints (2.3):* On each sub-channel used by legacy users, the total interference power contributed by all links working in the D2D mode should not exceed the given threshold P^{legacy}.
- *Channel allocation constraints (2.4) and (2.5):* Sub-channels allocated to the legacy links cannot be used for D2D links working in the cellular mode. Moreover, two D2D links both working in the cellular mode can not share a common channel.
- *Power assignment constraints (2.6):* The transmitter of each D2D link distributes its power to the set of assigned sub-channels and the sum of the power assigned to these sub-channels cannot exceed the maximum power level $P^{\max}$.

This problem is a non-linear integer programming problem, which is usually very hard to solve. So we present effective and efficient heuristic algorithms to solve it in polynomial time.

III. JOINT OPTIMIZATION ALGORITHMS

The Green-D2D problem can be easily divided into 3 subproblems: *mode selection, channel allocation and power assignment*. A trivial solution is to solve the problem in three separate steps and then combine solutions to the three subproblems together. However, such a method usually does not work well, which has been validated by our simulation results. We present two algorithms, which solve these three subproblems jointly.

A. Joint Algorithm 1 (Joint-1)

In this algorithm (denoted as *Joint-1*), we use linear search to determine transmission modes (D2D or cellular) using power consumption as guidance first and then jointly compute the channel allocation and power assignment accordingly.

Algorithm 1. Joint Algorithm 1 (Joint-1)

```
   Input  : $\mathbf{\Gamma} =< \Gamma_i >, \mathbf{G} =< G_{T(i),R(j),k} >$
   Output: $\mathbf{m} =< m_i >, \mathbf{p} =< p_{i,k} >, P_{\min}$
1  Sort all D2D links in the ascending order of channel gain
   ratio $g_i$ (Eq. 3.1)
2  and store their indices in an array $A$;
3  $j := 0$;
4  while $j \le N$ do
5      $m_{A[i]} := 0, i \le j$ and $i \in [1, \ldots, N]$;
6      $m_{A[i]} := 1, j < i < N$ and $i \in [1, \ldots, N]$;
7      $< \mathbf{p}, P >:=$ Set-Channel-Power($\mathbf{m}, \mathbf{G}, \Gamma$);
8      If $j = 0$ or $P < P_{\min}$ then
9          $< \mathbf{m}_{\text{opt}}, \mathbf{p}_{\min}, P_{\min} >:=< \mathbf{m}, \mathbf{p}, P >$;
10     $j := j + 1$;
11 return $< \mathbf{m}_{opt}, \mathbf{p}_{\min}, P_{\min} >$;
```

The goal of the mode selection subproblem is to find a solution which can potentially lead to a low-power channel-power assignment. The mode selection is a combinatorial problem. It is not possible to examine all the combinations since the total number of such combinations increases exponentially with the number of D2D links (N). We certainly want a D2D link to work on a mode with low power consumption. However, it is hard to obtain its power consumption without knowing transmission modes, channel allocations and power assignments of other links. Our idea for mode selection is to sort all the D2D links based on a metric and then find a threshold to divide all the links into two subsets such that D2D links in one subset are set to work on the D2D mode while those in another subset will work on the cellular mode.

Intuitively, a D2D link i should work on a mode that can lead to relatively high channel gains, which hopefully can result in low power consumption. So we use the following channel gain ratio $g(i)$ as the metric to assist mode selection:

$$g(i) = \frac{\frac{\sum_{k=1}^{K} G_{T(i),R(i),k}}{K}}{\frac{\sum_{k\in\{1,\ldots,K\}\setminus Q^{\text{legacy}}} G_{T(i),BS,k}}{K-|Q^{\text{legacy}}|}}. \tag{3.1}$$

Basically, $g(i)$ is the ratio of the average channel gain in the D2D mode to that in the cellular mode. Note that $g(i)$ is the ratio between two channel gains, which is different from channel gain. The higher this ratio is, the more likely the link should work on the D2D mode. The hard part is to determine a threshold for this metric to split the D2D links into two modes. Our algorithm performs a linear search on the channel gain ratios of all D2D links and selects the one that leads to minimal total power consumption as the threshold (lines 4–10 in Algorithm 1). We formally present this algorithm as Algorithm 1.

This algorithm uses a subroutine to determine the channel-power assignment $\mathbf{p}$ based on given mode selection $\mathbf{m}$ (line 7 in Algorithm 1). The channel-power assignment subproblem is to determine the sub-channels allocated to each D2D link and the corresponding power assignment. The goal is to minimize total power consumption based on the given mode selection. P is the total power consumption for channel-power assignment $\mathbf{p}$. The channel-power assignment subroutine is formally presented as Algorithm 2.

Algorithm 2. Set-Channel-Power

```
   Input  : $\mathbf{m} =< m_i >, \mathbf{G} =< G_{T(i),R(j),k} >, \mathbf{\Gamma} =< \Gamma_i >$
   Output: $\mathbf{p} =< p_{i,k} >, P = \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k}$
1  $r_{i,k} := 0, \forall i \in [1, \ldots, N], \forall k \in [1, \ldots, K]$;
2  While 1 do
3      for each pair $(i, k)$ with $p_{i,k}$ not setting to 0 do
4          if Eq. (2.2) is not satisfied then
5              Increase $r_{i,k}$ one rate level up;
6              $r'_{i,k} := r_{i,k} + \Delta r_{i,k}$;
7              $P_{\mathbf{m},\mathbf{r}'} :=$ LP-Channel-Power($\mathbf{m}, \mathbf{r}'$);
8              $P_{\mathbf{m},\mathbf{r}} :=$ LP-Channel-Power($\mathbf{m}, \mathbf{r}$);
9              if LP-Channel-Power($\mathbf{m}, \mathbf{r}'$) infeasible then
10                 $W_{i,k} := -1$;
11             else
12                 Calculate $W_{i,k}$ using Eq. (3.8);
13         else
14             $W_{i,k} := 0$;
15     $W_{\max} := \max_{i\in[1,\ldots,N],k\in[1,\ldots,K]} W_{i,k}$;
16     $< \mathbf{r}_{\max}, \mathbf{p}_{\max} >:= \underset{<\mathbf{r},\mathbf{p}>}{\operatorname{argmax}} W_{i,k}$;
17     if $W_{\max} > 0$ then
18         $< \mathbf{r}, \mathbf{p} >:=< \mathbf{r}_{\max}, \mathbf{p}_{\max} >$;
19         Set some $p_{i,k} := 0$ according to Constraints (2.4);
20     else if $W_{\max} = 0$ then
21         break;
22     else
23         return $< null, -1 >$;
24 $P := \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k}$;
25 return $< \mathbf{p}, P >$;
```

Since equations (2.7) and (2.8) are step functions, the channel-power allocation problem still cannot be solved optimally after we are given the mode selection $\mathbf{m}$ for all D2D links. We propose a waterfilling-like algorithm (Algorithm 2), which increases only one D2D link's data rate by one level at each step, while minimizing total incremental power consumption (lines 3–18 in Algorithm 2).

We find that if mode selection $\mathbf{m}$ and channel rate assignment $\mathbf{r}$ are given, then the channel-power assignment $\mathbf{p}$ can be obtained by solving a Linear Programming (LP) problem, which can be done in polynomial time. We use $P_{\mathbf{m},\mathbf{r}}$ to denote the total power consumption, and use $\mathbf{p}_{\mathbf{m},\mathbf{r}}$ to denote the channel-power allocation solution when channel rate assignment is $\mathbf{r}$ and mode selection solution is $\mathbf{m}$. We formally present the LP for channel-power assignment in the following:

LP-Channel-Power ($\mathbf{m}, \mathbf{r}$)

$$P = \min_{<\mathbf{p}>} \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k} \tag{3.2}$$

Subject to:

$$\frac{p_{i,k}G_{T(i),R(i),k}}{\sum_{j\neq i} p_{j,k}G_{T(j),R(i),k} + I^{\text{legacy}}_{R(i),k} + N_0} \geq C^{-1}(r_{i,k}),$$

$$m_i = 1, \forall i \in \{1,\cdots,N\}, \forall k \in \{1,\cdots,K\}; \tag{3.3}$$

$$\frac{p_{i,k}G_{T(i),BS,k}}{\sum_{j\neq i} p_{j,k}G_{T(j),BS,k} + N_0} \geq C^{-1}(r_{i,k}),$$

$$m_i = 0, \forall i \in \{1,\cdots,N\}, \forall k \in \{1,\cdots,K\}\backslash Q^{\text{legacy}}; \tag{3.4}$$

$$\sum_{i=1}^{N} m_i p_{i,k} G_{T(i),BS,k} \leq P^{\text{legacy}}, \forall k \in Q^{\text{legacy}}; \tag{3.5}$$

$$(1-m_i)p_{i,k} = 0, \forall i \in \{1,\cdots,N\}, \forall k \in Q^{\text{legacy}}; \tag{3.6}$$

$$\sum_{k=1}^{K} p_{i,k} \leq P^{\max}, \forall i \in \{1,\cdots,N\}; \tag{3.7}$$

where $C^{-1}(r_{i,k})$ gives the SINR value corresponding to $r_{i,k}$ for link i and sub-channel k. This LP problem can be efficiently solved in polynomial time. In the simulation, we used the Gurobi Optimizer [8] to solve all LP problem instances.

Next, we explain the structure of Algorithm 2. Initially, the algorithm sets data rates of all link-channel pairs to 0 (line 1). In the while loop, the algorithm tries to find the most power-efficient upgrade in each iteration, which increases the data rate of a link-channel pair one level up (lines 3–18). In the for loop (lines 3–14), the algorithm examines all possible link-channel pairs to find the best one by solving a series of LP-Channel-Power. We use the following *rate-power ratio* to measure power efficiency:

$$W_{i,k} = \frac{\Delta r_{i,k}}{\Delta P_{\mathbf{m},\mathbf{r}}(\Delta r_{i,k})}, \tag{3.8}$$

where $\Delta r_{i,k}$ is the incremental data rate and $\Delta P_{\mathbf{m},\mathbf{r}}(\Delta r_{i,k})$ gives the corresponding incremental power consumption. The algorithm keeps selecting the most power-efficient link-channel pair (according to the rate-power ratio) to upgrade its rate in each iteration (lines 15–18) till the corresponding data rate requirement on each D2D link is satisfied (lines 20–21). To avoid violating constraints (2.4) after a link-channel rate ($r_{i,k}$) is upgraded (line 19), the algorithm disregards some link-channel pairs by setting their power assignments $p_{i,k} := 0$. Setting $p_{i,k} := 0$ ensures that the subchannel k cannot be used by D2D link i working in the cellular mode since some other link j working in the cellular mode has already used it.

The time complexity of Joint-1 (Algorithm 1) is dominated by the while loop, which takes $O(N \cdot T_2)$ time, where T_2 is the running time of Algorithm 2. Similarly, the running time of Algorithm 2 is also dominated by a while loop, which takes $O(N^2K^2L \cdot T_{\text{LP-Channel-Power}})$ time, where L is the number of SINR levels and $T_{\text{LP-Channel-Power}}$ is the time for solving the LP. So the overall time complexity of Joint-1 is $O(N^3K^2L \cdot T_{\text{LP-Channel-Power}})$. Note that in practice, the LP can be solved very quickly using a well-designed LP solver such as the Gurobi Optimizer [8].

Algorithm 3. Joint Algorithm 2 (Joint-2)

```
Input  : $\mathbf{\Gamma} =< \Gamma_i >, \mathbf{G} =< G_{T(i),R(j),k} >$
Output: $\mathbf{m} =< m_i >, \mathbf{p} =< p_{i,m,k} >, P_{\min}$
1  $r_{i,m,k} := 0, \forall m \in [0,1], \forall i \in [1,\ldots,N], \forall k \in [1,\ldots,K]$;
2  while 1 do
3      $W_{i,m,k} := -1, \forall m \in [0,1], \forall i \in [1,\ldots,N], \forall k \in [1,\ldots,K]$;
4      for each triplet $(i,m,k)$ with $p_{i,m,k}$ not set to 0 do
5          $\mathbf{m}' := \mathbf{m}$;
6          if Eq. (2.2) is not satisfied then
7              Push $r_{i,m,k}$ to $r_{\text{highest}}$ except that
8              lower rate level can satisfy $\Gamma_i$;
9              $m'_i := m$; $r'_{i,m,k} := r_{i,m,k} + \Delta r_{i,m,k}$;
10             while $r'_{i,m,k} \geq r_{\text{lowest}}$ do
11                 $P_{\mathbf{m}',\mathbf{r}'}$:=LP-Mode-Channel-Power($\mathbf{m}', \mathbf{r}'$);
12                 $P_{\mathbf{m}',\mathbf{r}}$:=LP-Mode-Channel-Power($\mathbf{m}', \mathbf{r}$);
13                 if LP-Mode-Channel-Power($\mathbf{m}', \mathbf{r}'$) infeasible
                   then
14                     Decrease $r'_{i,m,k}$ one rate level down;
15                 else
16                     Calculate $W_{i,m,k}$ using Eq. (3.15);
17                     break;
18         else
19             $W_{i,m,k} := 0$;
20     $W_{\max} := \max_{m\in[0,1],i\in[1,\ldots,N],k\in[1,\ldots,K]} W_{i,m,k}$;
21     $< \mathbf{m}_{\max}, \mathbf{r}_{\max}, \mathbf{p}_{\max} >:= \underset{<\mathbf{m},\mathbf{r},\mathbf{p}>}{\text{argmax}}\ W_{i,m,k}$;
22     if $W_{\max} > 0$ then
23         $< \mathbf{m}, \mathbf{r}, \mathbf{p} >:=< \mathbf{m}_{\max}, \mathbf{r}_{\max}, \mathbf{p}_{\max} >$;
24         Set some $p_{i,m,k} := 0$ according to Constraints
           (3.16)(3.17);
25     else if $W_{\max} = 0$ then
26         break;
27     else
28         return $< null, null, -1 >$;
29 $P := \sum_{i=1}^{N}\sum_{m=0}^{1}\sum_{k=1}^{K} p_{i,m,k}$;
30 return $< \mathbf{m}, \mathbf{p}, P >$;
```

B. Joint Algorithm 2 (Joint-2)

In this algorithm (denoted as *Joint-2*), we also jointly determine mode selection, channel allocation and power assignment but in a way different from above. Specifically, we enumerate all link-mode-channel triplets; then for each link-mode-channel triplet, we try to find the best power assignment, which, however, is hard to determine without knowing the data rate the corresponding triplet should work at. There are multiple levels for the data rate. Unlike in Joint-1, we employ a greedy approach by pushing the data rate of a link-mode-channel triplet to the highest possible level. Doing so leads to using relatively small number of subchannels over each link, which hopefully causes limited interference to other links, thereby resulting in less power for compensating interference. Joint-2 is formally presented as Algorithm 3.

As mentioned above, if mode selection and channel rate assignment are given, then the corresponding power assignment can be obtained by solving an LP problem, which can be done in polynomial time. Here, similar to LP-Channel-Power, we try to determine the power assignment by solving an LP problem. However, different from Joint-1, in which modes of all links are determined before solving LP-Channel-Power, Joint-2 tries to determine the power assignment for a triplet (instead of a link-channel pair) when some triplets have not yet been considered (i.e., modes/channels/rates of some links have not yet been determined). We formally present the LP for the power assignment in the following:

LP-Mode-Channel-Power (m, r)

$$P = \min_{<\mathbf{p}>} \sum_{i=1}^{N} \sum_{m=0}^{1} \sum_{k=1}^{K} p_{i,m,k} \tag{3.9}$$

Subject to:

$$\frac{p_{i,1,k} G_{T(i),R(i),k}}{\sum_{j \neq i} p_{j,1,k} G_{T(j),R(i),k} + I^{\text{legacy}}_{R(i),k} + N_0} \geq C^{-1}(r_{i,1,k}),$$
$$\forall i \in \{1, \cdots, N\}, \forall k \in \{1, \cdots, K\}; \tag{3.10}$$

$$\frac{p_{i,0,k} G_{T(i),BS,k}}{\sum_{j \neq i} p_{j,0,k} G_{T(j),BS,k} + N_0} \geq C^{-1}(r_{i,0,k}),$$
$$\forall i \in \{1, \cdots, N\}, \forall k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}; \tag{3.11}$$

$$\sum_{i=1}^{N} m_i p_{i,1,k} G_{T(i),BS,k} \leq P^{\text{legacy}}, \forall k \in Q^{\text{legacy}}; \tag{3.12}$$

$$(1 - m_i) p_{i,0,k} = 0, \forall i \in \{1, \cdots, N\}, \forall k \in Q^{\text{legacy}}; \tag{3.13}$$

$$\sum_{m=0}^{1} \sum_{k=1}^{K} p_{i,m,k} \leq P^{\max}, \forall i \in \{1, \cdots, N\}; \tag{3.14}$$

Similarly, in the above formulation, $\mathbf{p}_{\mathbf{m},\mathbf{r}}$ denotes the power assignment corresponding to mode selection **m** and channel rate assignment **r**. Equations (3.9)–(3.14) are similar to equations (3.2)–(3.7) respectively. The difference is that variables $< p_{i,k} >$ are replaced by $< p_{i,m,k} >$ since we consider link-mode-channel triplet in Joint-2 instead of link-channel pair in Joint-1. The objective is to minimize total power consumption. Note that this LP is solved iteratively. Every time when it is solved, for those triplets that have not yet be considered, the correspond rates ($r_{i,m,k}$) are set to 0, resulting in $C^{-1}(r_{i,m,k}) = 0$; while for those triplets that have been considered, their rates are set to the values determined in previous steps.

Next, we explain the structure of Algorithm 3. Initially, the algorithm sets the data rates of all link-mode-channel triplets to 0 (line 1). In the outer while loop, the algorithm tries to find the most power-efficient upgrade in each iteration, which increases the data rate of a link-mode-channel triplet to the highest possible level (lines 4–23). In the for loop (lines 3–19), the algorithm examines all possible link-mode-channel triplets to find the best one by solving a series of LP-Mode-Channel-Power. Similarly, we use the following *rate-power ratio* to measure power efficiency:

$$W_{i,m,k} = \frac{\Delta r_{i,m,k}}{\Delta P_{\mathbf{m},\mathbf{r}}(\Delta r_{i,m,k})}, \tag{3.15}$$

where $\Delta r_{i,m,k}$ is the incremental data rate and $\Delta P_{\mathbf{m},\mathbf{r}(\Delta r_{i,m,k})}$ gives the corresponding incremental power consumption. Joint-2 keeps selecting the most power-efficient triplet (i, m, k) (according to equations (3.15)), and pushes its rate to the highest possible level by checking if the above LP-Mode-Channel-Power can still return a feasible solution (lines 7–17). By doing so, the algorithm contributes to the rate requirement of the corresponding link in a greedy manner. This procedure stops when the rate requirement of every link is satisfied (lines 25–26).

After each rate upgrade for some link, the algorithm disregards those link-mode-channel triplets with conflicts to ensure feasibility by setting the corresponding $p_{i,m,k} := 0$. Specifically, the power assignment for some link-mode-channels ($p_{i,m,k}$) need to be set to 0 in order to avoid violating constraints (3.16) and (3.17) as listed below (line 24):

$$p_{i,0,k} p_{i,1,k} = 0, \forall i \in \{1, \cdots, N\}, \forall k \in \{1, \cdots, K\}; \tag{3.16}$$

$$(1 - m_i) p_{i,0,k} \sum_{j \neq i} (1 - m_j) p_{j,0,k} = 0,$$
$$\forall i, j \in \{1, \cdots, N\}, \forall k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}; \tag{3.17}$$

Constraints (3.16) ensure that each D2D link can work in only one mode, either cellular mode or D2D mode. Constraints (3.17) make sure that any two D2D links both working in cellular mode cannot share a common sub-channel.

The time complexity of Joint-2 (Algorithm 3) is dominated by the outer while loop. The running time of each iteration is dominated by the for loop, which takes $O(NKL \cdot T_{\text{LP-Mode-Channel-Power}})$ time, where L is the number of SINR levels and $T_{\text{LP-Mode-Channel-Power}}$ is the time for solving the LP. Thus, the overall time complexity of Joint-2 is $O(N^2K^2L \cdot T_{\text{LP-Mode-Channel-Power}}))$. Again, the LP can be solved very quickly in practice.

IV. PERFORMANCE EVALUATION

In the simulation, the coverage region of the cell was a disk with a radius of $R = 300$m. A BS was located at the center of the cell, and N^{legacy} legacy users were randomly distributed in the cell. $Q^{\text{legacy}} = 2 \times N^{\text{legacy}}$ sub-channels have been randomly assigned to legacy users. For each pair of D2D link $T(i)$, $R(i)$, the receiver $R(i)$ was randomly placed in the circle centered at the sender $T(i)$ with a radius of $D_{\max}$, which follows a 2D uniform distribution. For each D2D link i, the data rate requirement Γ_i was randomly chosen, which follows a uniform distribution between $\Gamma_{\min}$ and $\Gamma_{\max}$. In order to guarantee the QoS of legacy users, the aggregated interference on each legacy sub-channel from D2D links cannot exceed a threshold P_{legacy}. If a D2D link works in the cellular mode where data traffic is relayed by the BS, then it cannot use the legacy sub-channels reserved for legacy users. The sub-channel gains were set to follow the free space model [6]:

$$G = (20 \log_{10}(d) + 20 \log 10(f) + 92.45)(1 + \sigma), \tag{4.1}$$

TABLE II
COMMON SIMULATION SETTINGS

Parameter	Value
Radius of the cell	300m
Sub-channel bandwidth	0.4MHz
Background noise	−85dBm
Max transmit power ($P^{\max}$)	25mW
Gauss variance of σ	0.5
Min data rate requirement ($\Gamma_{\min}$)	0.4Mbps
P^{legacy}	−87.21dBm
No. of sub-channels for each legacy user	2
Frequency band (f)	1.92GHz

TABLE III
SINR THRESHOLDS AND THE CORRESPONDING PER-CHANNEL DATA RATES ACCORDING TO [1]

Modul.	Code Rate	Min SINR (dB)	Rates(Mb/s)
QPSK	1/2	10	0.4
16QAM	1/2	14.5	0.8
16QAM	3/4	17.25	1.2
64QAM	2/3	21.75	1.6
64QAM	3/4	23	1.8

where d is the distance between transmitter and receiver in the unit of km and f is the center frequency in the unit of GHz. σ is a zero mean random variable following standard distribution. We summarize common simulation settings in the Table II.

As mentioned above, the link data rate is an increasing step function of its SINR levels. According to the IEEE 802.16e standard [1], we show how we set per-channel link data rates using Table III. All the values presented here are calculated based on the settings that the sub-channel bandwidth is 0.4 MHz and the antenna gain is 2 dBi. Note that link data rate is a linear function of the sub-channel bandwidth, therefore we can easily obtain a similar step function if we are given a different sub-channel bandwidth.

In the simulation, we compared the proposed algorithm with the following baseline algorithms:

1) All D2D links in the cellular mode with random sub-channel allocation (*All-Cellular*): In this algorithm, all D2D links work in the cellular mode and sub-channels are randomly allocated to D2D links such that each D2D link gets the same number of sub-channels.
2) All D2D links in the D2D mode with random sub-channel allocation (*All-D2D*): In this algorithm, all D2D links work in the D2D mode and sub-channels are randomly allocated to D2D links such that each D2D link gets the same number of sub-channels.
3) Random mode selection and random sub-channel allocation algorithm (*Random*): Each D2D link's mode is randomly determined, with 50% probability for each mode. Channel allocation is the same as that of the other baseline algorithms.

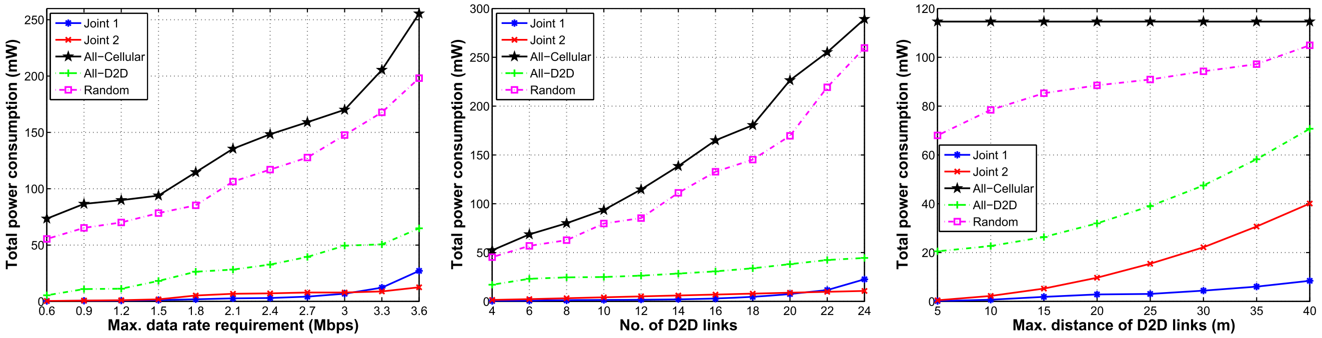
Note that in all these three baseline algorithms, after random channel allocation, they assign power to each sub-channel using a greedy subroutine: start channel-power assignment from certain level such that the link can have the highest possible SINR (that can lead to the highest data rate); lower channel-power assignment as long as the corresponding link data rate is large enough to meet the given requirement.

We compared the proposed joint algorithms against the three baseline algorithms in terms of total power consumption using the following 5 scenarios:

1) Scenario 1: We changed the maximum rate requirement $\Gamma_{\max}$ from 0.6 Mbps to 3.6 Mbps with a step size of 0.3 Mbps. The other parameters were set as follows: $N = 12$, $D_{\max} = 15$m, $K = 34$ and $N^{\text{legacy}} = 5$.
2) Scenario 2: We increased the number of D2D links N from 4 to 24 with a step size of 2. The other parameters were set as follows: $\Gamma_{\max} = 1.8$ Mbps, $D_{\max} = 15$m, $K = 34$ and $N^{\text{legacy}} = 5$.
3) Scenario 3: We varied the maximum distance of D2D links $D_{\max}$ from 5m to 40m with a step size of 5m. The other parameters were set as follows: $\Gamma_{\max} = 1.8$ Mbps, $N = 12$, $K = 34$ and $N^{\text{legacy}} = 5$.
4) Scenario 4: We increased the number of available sub-channels K from 22 to 50 with a step size of 4. The other parameters were set as follows: $\Gamma_{\max} = 1.8$ Mbps, $N = 12$, $D_{\max} = 15$m and $N^{\text{legacy}} = 5$.
5) Scenario 5: We increased the number of legacy users N^{legacy} from 2 to 10 with a step size of 1. The other parameters were set as follows: $\Gamma_{\max} = 1.8$ Mbps, $N = 12$, $D_{\max} = 15$m and $K = 34$.

The simulation results are presented in Figs. 1 and 2. We can make the following observations from these results:

1) In all scenarios, the proposed joint algorithms consistently outperform the baseline algorithms. On average, Joint-1 and Joint-2 achieve 88% and 84% power savings compared to All-Cellular, respectively. This shows that D2D communications can significantly reduce power consumption compared to the traditional communication approach. Moreover, compared to All-D2D, the proposed algorithms can lead to an average of 78% and 68% power savings, respectively. Compared to Random, the proposed algorithms result in an average of 86% and 82% power savings, respectively. This justifies our claim that mode selection, channel allocation and power assignment need to be carefully determined for D2D communications.
2) From Figs. 1(a) and 1(b), we can see that no matter which algorithm is used, the total power consumption increases monotonically with the data rate requirement and the number of D2D links. However, the proposed joint algorithms are superior to the baseline algorithms since unlike them, the corresponding power consumption grows very slowly with these two important parameters. This shows that compared to simple 3-step greedy methods, joint decision making along with LP-based optimization can lead to significant performance improvement.
3) From Fig. 1(c), we can see that a longer D2D link distance leads to more power consumption for both our joint algorithms and baseline algorithms except All-Cellular where all D2D links work in the cellular mode so that they have nothing to do with this parameter. Since all D2D links have to maintain their received SINR at certain levels in order to meet their data rate requirements, longer D2D link distances will result in higher transmit power for those D2D links working in the D2D mode. Power consumption of Joint-2 grows faster than that of Joint-1.

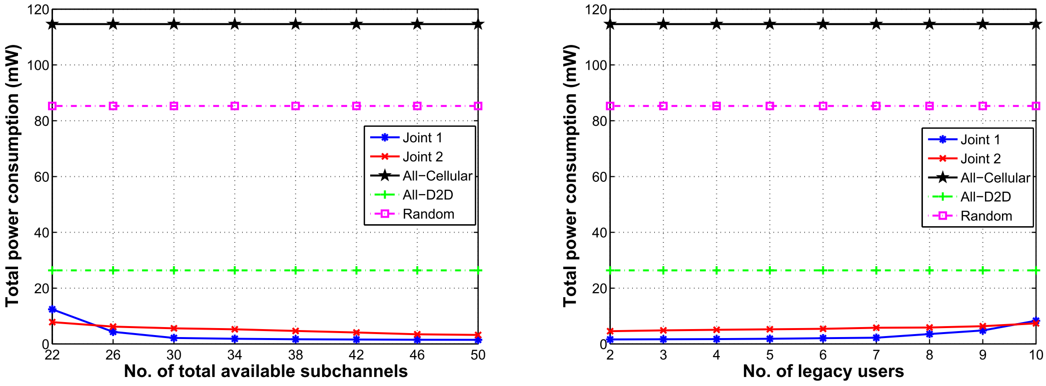


(a) Max. data rate requirement ($\Gamma_{\max}$)

(b) No. of D2D links (N)

(c) Max. distance of D2D links ($D_{\max}$)

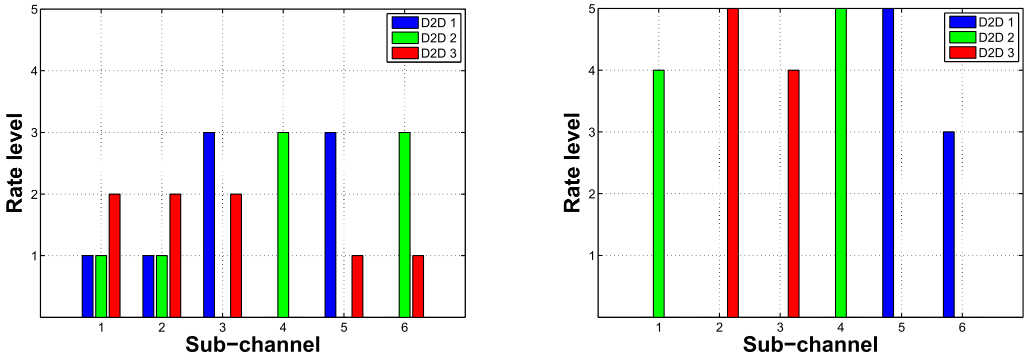
Fig. 1. Impact of $\Gamma_{\max}$, N and $D_{\max}$ on the total power consumption.



(a) No. of total available sub-channels (K)

(b) No. of legacy users (N^{legacy})

Fig. 2. Impact of K and N^{legacy} on the total power consumption.



(a) Rate level on each sub-channel by Joint-1

(b) Rate level on each sub-channel by Joint-2

Fig. 3. Channel-rate allocation given by Joint-1 and Joint-2.

This is because usually rate levels on active sub-channels obtained from Joint-2 are higher than those from Joint-1, thus, higher transmit power is necessary to achieve higher SINRs in Joint-2.

4) From Figs. 2(a) and 2(b), we can make two interesting findings. First, power consumption given by all the baseline algorithms remains the same even with more sub-channels. Power assignment in the baseline algorithms uses a simple greedy procedure. If a link's data rate requirement can be satisfied by certain number of sub-channels then the algorithms will not use more sub-channels. In other words, more sub-channels do not necessarily lead to better performance for those baseline algorithms. Second, the proposed joint algorithms result in less power consumption with more sub-channels. That is because our algorithms always select the most power-efficient sub-channel to use in each step. More available sub-channels means the algorithms has more options to choose from. If there are better sub-channels from the additional set of available sub-channels, total power given by our algorithms will be reduced. Otherwise they remain the same just like the baseline algorithms. This again shows that joint decision making with LP-based optimization outperforms simple greedy methods.

5) In some cases, power consumption of Joint-1 is less than that that of Joint-2. However, in some cases (e.g. $\Gamma_{\max} \geq 3.0$ Mbps, $N \geq 20$, $K \leq 26$, and $N^{\text{legacy}} \geq 9$ in Figs. 1 and 2), Joint-2 offers nearly the same or better performance. Usually, Joint-2 uses less sub-channels but higher rate levels, while Joint-2 uses more sub-channels but lower rate levels. Thus, in those cases with limited available sub-channels, Joint-2 may likely perform better than Joint-1. To further demonstrate this, we conducted simulation with a small case with $\Gamma_{\max} = 3.5$ Mbps, $N = 3$ and $K = 6$ and show the corresponding results in Fig. 3. We can clearly see that differences between Joint-1 and Joint-2 on sub-channel utilization.

V. CONCLUSIONS

In this paper, we studied green D2D communications in OFDMA-based wireless networks. We formally defined an optimization problem based on a practical model of link data rate, whose objective is to minimize total power consumption while ensuring link data rate requirements. We then presented two joint mode selection, power assignment and channel allocation algorithms, which both solve the problem effectively in polynomial time. Via extensive simulation results, we showed that the proposed algorithms can achieve over 68% power savings, compared to several baseline methods.

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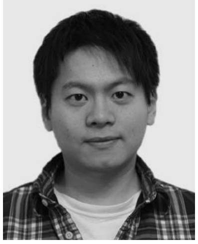

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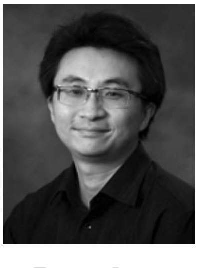

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