Joint Mode Selection, Channel Allocation and Power Assignment for Green Device-to-Device Communications

Chenfei Gao, Xiang Sheng, Jian Tang, Weiyi Zhang, Shihong Zou and Mohsen Guizani

***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 to maximize network throughput. In this paper, we, however, aim at enabling 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 power consumption while meeting user data rate requirements. We then present an effective algorithm to solve it in polynomial time, which jointly determines mode selection, channel allocation and power assignment. It has been shown by extensive simulation results that the proposed algorithm can achieve over 57% power savings, compared to several baseline methods.**

***Index Terms*–D2D communications, mode selection, channel allocation, power assignment, green wireless communications.**

I. Introduction

Fast growth of wireless users and their traffic demands have made wireless networks become one of the major contributors of power consumption. It has been shown by recent studies [10] that there are over 4 million Base Stations (BSs) and each of them consumes an average of 25MWh per year. And, the number of BSs is growing fast, especially in developing countries. Such huge energy consumption has raised public concerns about electricity costs, and greenhouse gas emissions that are known to have a significant impact on global climate. Therefore, substantial research attention has been paid to green wireless networking recently.

Device-to-Device (D2D) communication has emerged as a promising technique for reducing power consumption and improving capacity in wireless networks. We illustrate the concept of D2D communications as an underlay to a cellular network in Fig. 1. 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 likely transmit a signal in a reduced power level such that power consumption can be reduced and moreover, D2D communications can offload the BS's traffic load, which can improve network capacity.

Xiang Sheng, Chenfei Gao and Jian Tang are with the Department of Electrical Engineering and Computer Science at Syracuse University, Syracuse, NY, 13244, USA. Email: {xsheng, cgao03, jtang02}@syr.edu. Weiyi Zhang is with AT&T Labs Research, NJ, USA. Shihong Zhou is with the State Key Lab of Networking and Switching, Beijing University of Posts and Telecommunications, Beijing, China. Mohsen Guizani is with Qatar University, Qatar. This work was supported by an NSF grant CNS-1113398. The information reported here does not reflect the position or the policy of the federal government.

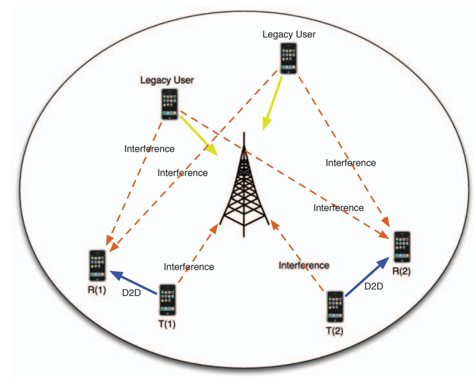


Fig. 1: D2D communications in a wireless network

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 an unique problem, mode selection, which determines the mode (D2D or cellular) to be used for data transmissions. Even though mode selection has been addressed by a few recent papers [8], [11], [14], [15], some of them [8], [11] were focused on 3G WCDMA-based cellular networks in which data transmissions were conducted on a single channel and the others [14], [15] aimed to maximize data rates of mobile users (network throughput). In this paper, we study an optimization problem for D2D communications in an OFDMA-based wireless network, whose objective is to minimize power consumption while meeting user data rate requirements. Our contributions are summarized in the following:

- We formally defined an optimization problem for power-efficient D2D communications in OFDMA-based wireless networks based on a practical model in which link data rate is an increasing step function of SINR at the receiver.
- We present an effective algorithm to solve it in polynomial time, which jointly determines mode selection, power assignment and channel allocation problem.
- It has also been shown by extensive simulation results that the proposed algorithm can achieve over 57% power savings, compared to several baseline methods.

To the best of our knowledge, we are the first to address such an optimization problem in the context of D2D communications and OFDMA-based wireless networks based on a practical link data rate model.

The rest of paper is organized as follows: We discuss related works in Section II. We formally present the problem formulation in Section III. We present the proposed joint algorithm in Section IV. The simulation results are presented in Section V and the paper is concluded in Section VI.

II. Related Work

Resource allocation has been addressed by quite a few research works in the context of D2D communications. In [2], the authors proposed a coalitional game based approach for D2D links' mode selection, with the objective of minimizing the total power while satisfying rate requirements. 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. In [8], 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. Furthermore, practical communication mode selection algorithms were presented to show their performance against the achievable bounds. In [9], 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 [11], the authors proposed an exhaustive search based mode selection and power assignment scheme for D2D communication systems. The proposed scheme searched all possible mode combinations which consist of mode indices for all devices in the system. In [13], the underlay and overlay mode selections were analyzed for D2D communications in the LTE-advanced single-cell scenario. Their results showed that the underlay mode was preferred when the cellular user was closer to the BS or relay node than the D2D user. In [14], [15], 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. General introduction to D2D communications, and related protocols and standards can be found in [5], [12]. Related resource allocation problems have also been studied in wireless sensor networks [3], [16].

The differences between this work and these related works are: 1) Unlike some related works studying D2D communications in a single-channel 3G CDMA-based cellular network [8], [11], we consider an OFDMA-based cellular network with multiple sub-channels and study sub-channel allocation. 2) Unlike some related works that aimed to improve network capacity/throughput [9], [14], [15], [17], the main objective here is to minimize total power consumption to enable green D2D communications. 3) Unlike most related works [4], [9], [11], [13]–[15], [17] 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 at the receiver. 4) We aim to present a practical algorithm with low time complexity, which is different from the exhaustive search based approach [11] with high time complexity. 5) The problem studied here is mathematically different from the optimization problem formulated based on game theory [2].

III. Problem Formulation

TABLE I: Major Notations

Notation	Description
$C(\cdot)$	The per-channel link data rate function;
$G_{T(i),R(j),k}$	Channel gain between $T(i)$ and $R(j)$ on sub-channel k
$I^{legacy}_{R(i),k}$	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^{legacy}	The maximal allowable interference power level from all D2D links on a 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.

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 communicates with the BS), and K non-overlapping sub-channels. Since neighboring cells can be allocated different sets of 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], [11], 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 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 certain threshold P^{legacy}. A relatively conservative threshold can be set to guarantee that traditional communications are not affected by D2D communications.

We use $G_{T(i),R(i),k}$ to denote 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], [9], 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 reality. Moreover, link data rate is usually not a continuous function of the Signal-to-Interference-Plus-Noise-Ratio (SINR) at receiver. 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 receiver). For example, 5 SINR thresholds are specified in the WiMAX standard [1], each of which corresponds to a different modulation index and data rate. In this work, 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 $C(SINR_{i,k})$. In the simulation, we adopted a discrete increasing step function based on the WiMAX standard, which will be described in greater details in Section V. A data rate constraint needs to be enforced for each D2D link i, which requires that its data rate is no smaller than a given threshold Γ_i. We present the problem formulation in the following.

- 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

$$\min_{\langle \mathbf{m}, \mathbf{p} \rangle} \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k} \tag{3.1}$$

Subject to:

$$m_i R_{i,1} + (1 - m_i) R_{i,0} \geq \Gamma_i, \quad 1 \leq i \leq N; \tag{3.2}$$

$$\sum_{i=1}^{N} m_i p_{i,k} G^k_{T(i),BS} \leq P^{\text{legacy}}, \quad \forall k \in Q^{\text{legacy}}; \tag{3.3}$$

$$(1 - m_i) p_{i,k} \sum_{j \neq i} (1 - m_j) p_{j,k} = 0, \quad 1 \leq i, j \leq N, \forall k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}; \tag{3.4}$$

$$(1 - m_i) p_{i,k} = 0, \quad 1 \leq i \leq N, \forall k \in Q^{\text{legacy}}; \tag{3.5}$$

$$\sum_{k=1}^{K} p_{i,k} \leq P^{\max}, \quad 1 \leq i \leq N. \tag{3.6}$$

where:

$$R_{i,0} = \sum_{k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}} C\left(\frac{p_{i,k} G_{T(i),BS,k}}{\sum_{j \neq i} p_{j,k} G_{T(j),BS,k} + N_0}\right), \quad 1 \leq i \leq N; \tag{3.7}$$

$$R_{i,1} = \sum_{k=1}^{K} C\left(\frac{p_{i,k} G_{T(i),R(i),k}}{\sum_{j \neq i} p_{j,k} G_{T(j),R(i),k} + I^{\text{legacy}}_{R(i),k} + N_0}\right), \quad 1 \leq i \leq N. \tag{3.8}$$

We refer to this problem as the *Green-D2D* problem in the following. The objective (3.1) is to minimize the total power consumption of D2D links. The following constraints must be satisfied:

- *Link data rate constraints (3.2):* The data rate of each D2D link is no less than a 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 channel index.
- *Interference constraints (3.3):* On each sub-channel, the total interference power contributed by all links working in the D2D mode should not exceed a given threshold P^{legacy}.
- *Channel allocation constraints (3.4) and (3.5):* 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 (3.6):* 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 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. We present an effective heuristic algorithm to solve it in polynomial time.

IV. Proposed Joint Algorithms

Essentially, 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. In this section, we present a polynomial-time heuristic algorithm that jointly solves these subproblems. In this algorithm, 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.

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 number of all 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:

$$g_i = \frac{\frac{\sum_{k=1}^{K} G_{T(i),R(i),k}}{K}}{\frac{\sum_{k \in \{1, \ldots, K\} \backslash Q^{\text{legacy}}} G_{T(i),BS,k}}{K - |Q^{\text{legacy}}|}}. \tag{4.1}$$

Basically, $g(i)$ is the ratio of the average channel gain in the D2D modes to that in the cellular mode. 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. We formally present this algorithm as Algorithm 1.

Algorithm 1 Joint Algorithm

Input: $\mathbf{\Gamma} =< \Gamma_i >$, $\mathbf{G} =< G_{T(i),R(j),k} >$

Output: $\mathbf{m} =< m_i >$, $\mathbf{p} =< p_{i,k} >$

Step 1 Sort all D2D links in the ascending order of channel gain ratio g_i (Eq. 4.1) and store their indices in an array A;

Step 2 $j := 0$;
  while $(j \leq N)$
    $m_{A[i]} := 0$, $i \leq j$ and $i \in [1, ..., N]$;
    $m_{A[i]} := 1$, $j < i < N$ and $i \in [1, ..., N]$;
    $< \mathbf{p}, P >:=$ Set-Channel-Power$(\mathbf{m}, \mathbf{G}, \mathbf{\Gamma})$;
    if $(j = 0)$ **or** $(P_{\min} < P_{\mathbf{m},\mathbf{r}})$
      $< \mathbf{m}_{\text{opt}}, \mathbf{p}_{\min}, P_{\min} >:=< \mathbf{m}, \mathbf{p}, P >$;
    endif
    $j := j + 1$;
  endwhile

Step 3 **return** $< \mathbf{m}_{\text{opt}}, \mathbf{p}_{\min}, P_{\min} >$.

This algorithm uses a subroutine to determine the channel-power assignment $\mathbf{p}$ based on given mode selection $\mathbf{m}$. 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.

Since equations (3.7) and (3.8) 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, which increases only one D2D link's date rate by one level at each step, while minimizing total incremental power consumption.

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 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 data 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

$$P = \min_{<\mathbf{p}>} \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k} \tag{4.2}$$

Subject to:

$$\begin{gathered} \frac{p_{i,k} G_{T(i),R(i),k}}{\sum_{j \neq i} p_{j,k} G_{T(j),R(i),k} + I^{\text{legacy}}_{R(i),k} + N_0} \geq C^{-1}(r_{i,k}) \\ m_i = 1, 1 \leq i \leq N, \forall k \in \{1, ..., K\} \end{gathered} \tag{4.3}$$

$$\begin{gathered} \frac{p_{i,k} G_{T(i),BS,k}}{\sum_{j \neq i} p_{j,k} G_{T(j),BS,k} + N_0} \geq C^{-1}(r_{i,k}) \\ m_i = 0, 1 \leq i \leq N, \forall k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}} \end{gathered} \tag{4.4}$$

$$\sum_{i=1}^{N} m_i p_{i,k} G^{k}_{T(i),BS} \leq P^{\text{legacy}}, \quad \forall k \in Q^{\text{legacy}}; \tag{4.5}$$

$$\begin{gathered} (1 - m_i) p_{i,k} \sum_{j \neq i} (1 - m_j) p_{j,k} = 0, \\ 1 \leq i, j \leq N, \forall k \in \{1, \cdots, K\} \backslash Q^{\text{legacy}}; \end{gathered} \tag{4.6}$$

$$(1 - m_i) p_{i,k} = 0, \quad 1 \leq i \leq N, \forall k \in Q^{\text{legacy}}; \tag{4.7}$$

$$\sum_{k=1}^{K} p_{i,k} \leq P^{\max}, \quad 1 \leq i \leq N; \tag{4.8}$$

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 [7] to solve all LP problem instances.

Initially, the data rates of all link-channel pairs are set to zero. The algorithm tries to find the most power-efficient upgrade at each step, which increases the data rate of a link-channel pair one level up. We use the following *rate-power ratio* to measure power efficiency.

$$W_{i,k} = \frac{\Delta r_{i,k}}{\Delta P_{\mathbf{m},\mathbf{r}}(\Delta r_{i,k})}, \tag{4.9}$$

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 at each step till the corresponding data rate requirement on each D2D link is satisfied.

V. Performance Evaluation

In this section, we present simulation results and the corresponding analysis.

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 $N^{\text{legacy}} = 5$ legacy users were randomly distributed in the cell. $Q^{\text{legacy}} = 10$ 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 $\Gamma_{\max}$. The channel gains were set to follow the free space model [6]:

$$G = (20 \log_{10}(d) + 20 \log 10(f) + 92.45)(1 + \sigma), \tag{5.1}$$

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 following table.

As mentioned above, the link data rate is an increasing step function of its SNR levels. According to the IEEE

Algorithm 2 Set-Channel-Power

Input: $\mathbf{m} =< m_i >$, $\mathbf{G} =< G_{T(i),R(j),k} >$, $\mathbf{\Gamma} =< \Gamma_i >$
Output: $\mathbf{p} =< p_{i,k} >$, $P = \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k}$

Step 1 $r_{i,k} := 0, \forall i \in [1, ..., N], \forall k \in [1, ..., K]$;
Step 2 **while** (TRUE)
    for each link-channel pair (i, k) **do**
        if (Eq. (3.2) is not satisfied)
            Increase $r_{i,k}$ one rate level up:
            $r'_{i,k} := r_{i,k} + \Delta r_{i,k}$;
            Solve LP-Channel-Power$(\mathbf{m}, \mathbf{r}')$
            and LP-Channel-Power$(\mathbf{m}, \mathbf{r})$
            to obtain $P_{\mathbf{m},\mathbf{r}'}$ and $P_{\mathbf{m},\mathbf{r}}$;
            if (LP-Channel-Power$(\mathbf{m}, \mathbf{r}')$ has no feasible solution)
                $W_{i,k} := -1$;
            else
                Calculate $W_{i,k}$ using Eq. (4.9);
            endif
        else
            $W_{i,k} := 0$;
        endif
    endfor
    $W_{\max} := \max_{i \in [1,...,N], k \in [1,...,K]} W_{i,k}$;
    $< \mathbf{r}_{\max}, \mathbf{p}_{\max} > := \underset{<\mathbf{r},\mathbf{p}>}{\operatorname{argmax}} W_{i,k}$;
    if $(W_{\max} > 0)$
        $< \mathbf{r}, \mathbf{p} > := < \mathbf{r}_{\max}, \mathbf{p}_{\max} >$;
    elseif $(W_{\max} = 0)$
        break;
    else
        Return $<$ null, $-1 >$;
endwhile
Step 3 $P := \sum_{i=1}^{N} \sum_{k=1}^{K} p_{i,k}$;
Step 4 **return** $< \mathbf{p}, P >$;

TABLE II: Common Simulation Settings

Parameter	Value
Radius of the cell	300m
Max distance of D2D links ($D_{\max}$)	15m
Subchannel 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 legacy users	5
Frequency band (f)	1.92GHz

802.16e standard [1], we show how we set per-channel link data rates using the following table. All the values presented here are calculated based on the settings that the sub-channel bandwidth is 0.4MHz and the antenna gain is 2dBi. Note that link data rate is a linear function of the channel bandwidth, therefore we can easily obtain a similar step function if we are given a different channel bandwidth.

Modulation	Min SNR (dB)	Rates(Mbps)
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

TABLE III: SNR thresholds and the corresponding per-channel data rates

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

1) All D2D links in the cellular mode with random 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 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 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.

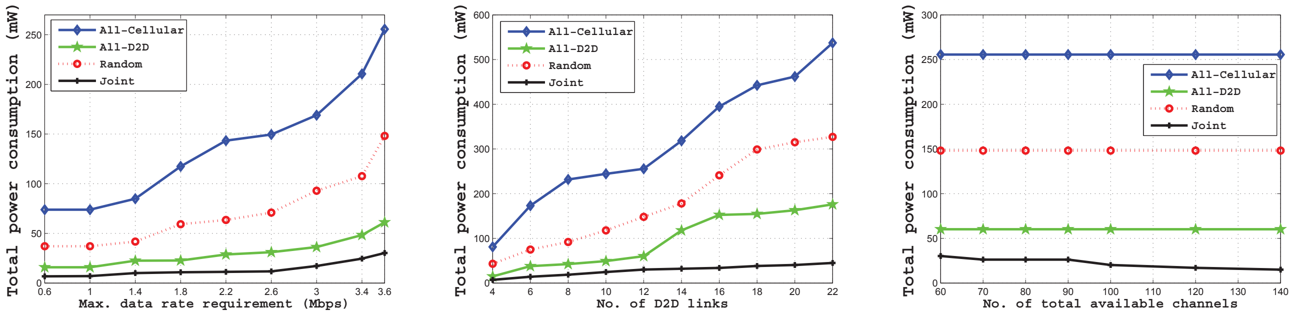
Note that in all these three baseline algorithms, after random channel allocation, they allocate power to each channel using a greedy subroutine: start channel-power assignment from certain level such that the link can have the highest possible SNR (that can lead to the highest data rate); lower channel-power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

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

1) Scenario 1: We changed the maximum rate requirement $\Gamma_{\max}$ from 0.6Mbps to 3.6Mbps with a step size of 0.4Mbps. The other parameters are set as follows: $N = 12$ and $K = 60$.
2) Scenario 2: We increased the number of D2D links N from 4 to 22 with a step size of 2. The other parameters are set as follows: $\Gamma_{\max} = 3.6$Mbps and $K = 60$.
3) Scenario 3: We increased the number of available channels K from 60 to 140 with a step size of 10. The other parameters are set as follows: $\Gamma_{\max} = 3.6$Mbps and $N = 12$.

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

1) In all scenarios, the proposed joint algorithm consistently outperforms the baseline algorithms. On average, it achieves 86% power savings compared to the All-Cellular algorithm. This shows that D2D communications can significantly reduce power consumption compared to the traditional communication approach. Moreover, compared to the All-D2D algorithm and the Random algorithm, the proposed algorithm can lead to an average of 57% and 78% power savings respectively. This justify our claim that when using D2D communications, mode selection, channel allocation and power assignment need to be carefully determined.



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

(b) No. of D2D links (N)

(c) No. of total available channels (K)

Fig. 2: Total power consumption in different scenarios

2) From Figs. 2(a) and 2(b), we can see that no matter which algorithm is used, the total power consumption increases monotonously with the maximum data rate requirement and the number of D2D links. However, the proposed joint algorithm is 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 greedy methods, joint decision making along with LP-based optimization can lead to significant performance improvement.

3) From Fig. 2(c), we made two interesting findings. First, power consumption given by all the baseline algorithms remains the same even with more channels. Power assignment in the baseline algorithms uses a simple greedy procedure. If an user's data rate requirement can be satisfied by certain number of channels then the algorithms will not use more channels. Thus, we can see that 60 channels are enough to meet all D2D user's data rate requirements. Hence, more channels do not necessarily lead to better performance. Second, the proposed joint algorithm results in less power consumption with more channels. That is because our algorithm always selects the most power-efficient sub-channel to use in each step. More available channels means the algorithm has more options to choose from. If there are better channels from the additional set of available channels, total power consumption given by our algorithm goes down. Otherwise it remains the same just like the baseline algorithms. This again shows that joint decision making with LP-based optimization outperforms simple greedy methods.

VI. 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 user data rate requirements. We then presented a joint mode selection, power assignment and channel allocation algorithm, which solves the problem effectively in polynomial time. Via extensive simulation results, we showed that the proposed algorithm can achieve over 57% power savings, compared to several baseline methods.

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