A QoS-Aware Power Optimization Scheme in OFDMA Systems with Integrated Device-to-Device (D2D) Communications

Xiaoming Tao, Xiao Xiao, Jianhua Lu

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A QoS-Aware Power Optimization Scheme in OFDMA Systems with Integrated Device-to-Device (D2D) Communications

Xiao Xiao, Xiaoming Tao, Jianhua Lu
State Key Laboratory on Microwave and Digital Communications
Tsinghua National Laboratory for Information Science and Technology
Department of Electronic Engineering Tsinghua University, Beijing 100084, P.R.China
E-mail: xiaoxxyue@gmail.com

***Abstract*—This paper proposes a power optimization scheme with joint resource allocation (i.e. subcarrier and bit allocation) and mode selection in an OFDMA system with integrated D2D communications. Through the proper control of the base station (BS), users can communicate with each other either directly or via the BSs as in traditional cellular networks. Particularly, an optimization problem is formulated to minimize total downlink transmission power constrained by users' QoS demands; while a heuristic scheme exploiting joint subcarrier allocation, adaptive modulation and mode selection is contrived to solve the problem. Simulation results show that our proposed scheme may not only conserve total downlink transmission power effectively, but also save overall power consumption of BSs significantly, compared with existing algorithms used in traditional OFDMA systems.**

I. Introduction

Energy consumption of information and communication technology (ICT) has become a sensitive issue and generated universal concerns throughout the research community and telecommunication operators. Currently, ICT responses for a fraction of the global energy consumption ranging from 2%-10% [1], which is still probable to increase. Many efforts have been made to increase energy efficiency or save energy cost for both wired and wireless networks. With respect to wireless networks, most attention should be paid on the access segment, mainly because it comprises the most elements and hence accounts for the most energy consumption of the whole networks. For a number of mobile operators, the energy needs of the access segment can achieve 70%+ of the total energy consumption [2]. Hence, it is quite necessary to save energy consumption from access nodes such as BSs, Node-Bs, etc.

As a strong candidate for the next generation wireless networks, Orthogonal Frequency Division Multiple Access (OFDMA) has been approved as the downlink multiple access technique for 3GPP LTE-Advanced, Wimax, etc. Thus, it is quite significant to deal with the energy consumption issue in OFDMA systems, and several contributions have been made to save the total downlink transmission power with QoS provisions [3, 4, 6, 7, 9]. Several algorithms have been proposed, and some conservations are achieved for the total downlink transmission power. However, these algorithms are all investigated in traditional OFDMA cellular systems where communications between different users can only take place relayed by BSs. When some users of these communication pairs stay far apart the BSs (e.g. near cell borders), extremely large power has to be emitted to guarantee their QoS and the total transmission power may exceed the upper bound of the BSs, resulting in these algorithms ineffective. Due to the emergence of high data rate local services [5] and their potential increasing demands, this issue of the communication pairs should be taken adequate account in wireless cellular systems. In such a case, D2D communications have been allowed by the IMT-Advanced systems as an underlay to cellular networks, and several studies have shown its potential of improving system capacity and saving transmission power [5, 8]. Hence it is quite promising to integrate D2D communications into OFDMA systems, which may further conserve downlink transmission power and even the overall power consumption of the BSs.

In this paper, we address the joint resource allocation and mode selection problem in a D2D communications integrated OFDMA system, aiming at optimizing downlink power consumption. Subcarrier allocation and adaptive modulation are adopted to allocate subcarriers and bits, while transmission mode is selected smartly for each D2D pair. Particularly, we further take a comprehensive consideration on the overall power consumption of BSs in simulations, and show our proposed scheme may not only save transmission power, but conserve the overall power consumption of access nodes.

The rest of this paper is organized as following. System model of the OFDMA system with integrated D2D communications is given in Section II. In Section III, the optimization problem is formulated to minimize total downlink transmission power. Heuristic schemes are proposed to address the problem in Section IV, while the numerical results are given in Section V. Finally, the conclusion is drawn in Section VI.

II. System Model for OFDMA System with Integrated D2D Communications

We consider the downlink scenario in one isolated cell with total M users denoted as $\mathcal{U} = \{1, 2, ..., K, K+1, ..., M\}$, sharing N subcarriers represented as $\mathcal{A} = \{1, 2, ..., N\}$. The total M users are divided into two types. The first type are called *cellular users* who apply services from system servers, and thus merely need communicating with the BS. The typical services of cellular users in downlink include download, surfing, etc. The other type are two users who need to exchange data with each other, and we call these two users one *D2D pair* whose typical services are video/audio calls, messages exchange, and those high data rate local services. In this downlink system, users 1 to K are assumed to be cellular users, while others are D2D pairs. We further assume downlink channel state information (CSI) between the users and the BS (*cellular links*) is perfectly known, and so is the CSI between the two terminals of each D2D pair (*direct links*). Since we discuss downlink scenarios, the cellular links for D2D pairs are between their receivers and the BS.

A. System Structure and Transmission Modes

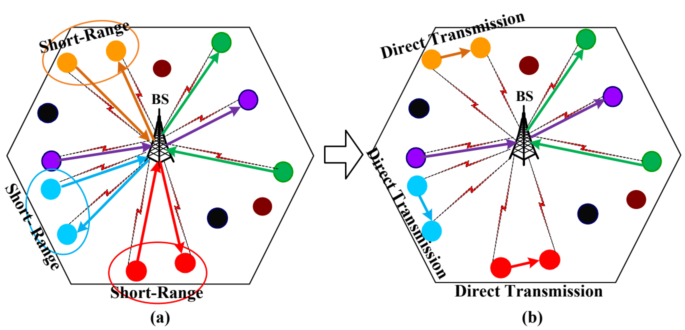

Fig. 1. System structure in one cell of (a) traditional OFDMA cellular system; (b) OFDMA system with integrated D2D communications.

The system structure in one cell for both traditional OFDMA cellular systems and the proposed OFDMA system with integrated D2D communications are given in Fig.1. In traditional OFDMA systems, any D2D pair can only communicate via the BS even if it stays far from the BS, and this transmission fashion is called *cellular mode*. In our D2D communications integrated OFDMA system, however, the two terminals of one D2D pair is allowed to communicate directly, if they are close to each other but stay far from the BS. This transmission mode is named *direct mode*. Since link quality degrades severely in an exponential fashion for large transmission distance, it is intuitive that transmission power can be effectively saved by the direct transmission for such D2D pairs far apart the BS, compared with the exclusive cellular mode used in traditional cellular systems.

For the cellular users, they just need communicating with the BS, and thus utilize cellular mode to transmit data; while for those D2D pairs, both modes are applicable.

B. CSI Matrices for Resource Allocation and Mode Selection

Fig.2 shows the CSI matrix for joint resource allocation and mode selection in one cell for the D2D communications integrated OFDMA system. It can be seen that after the subcarrier and bit allocation with the CSI matrix of cellular links for all the users, the transmission mode is selected and bits are rescheduled for each D2D pair using its CSI matrix with both cellular link and direct link CSI.

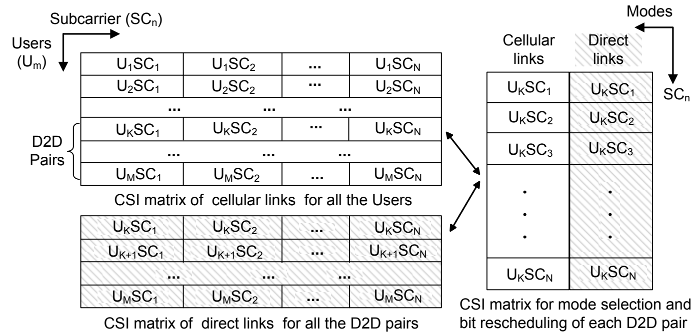

Fig. 2. CSI matrices for joint resource allocation and mode selection

III. Problem Formulation

Firstly, we discuss the downlink transmission power for the two transmission modes of D2D pairs. As for the cellular mode, let $P(r_{m,n})$ denote the downlink transmission power when $r_{m,n}$bit/symbol is required to transmit on the nth downlink subcarrier for the mth D2D pair. Since the transmission capacity between the two terminals of a D2D pair is given in [8] as the minimum of the uplink and downlink transmission rate with cellular mode, then the downlink transmission rate should be no less than $r_{m,n}$bit/symbol to warrant the QoS. Therefore, with the M-ary QAM modulation being applied in our system, $P(r_{m,n})$ is readily given as [6]

$$P(r_{m,n}) = \frac{N_0}{3|h_{m,n}|^2}\left[Q^{-1}\left(\frac{BER_m}{4}\right)\right]^2 \cdot (2^{r_{m,n}} - 1) \quad (1)$$

where $h_{m,n}$ is the CSI of cellular link for D2D pair m on the nth downlink subcarrier and N_0 stands for the power of additive white Gaussian noise.

For the direct mode, the transmission capacity for one subcarrier couple (i.e. an uplink subcarrier sending data from a D2D transmitter to the BS and the downlink one from the BS to the corresponding receiver), is defined in [8] as the sum of the uplink and downlink transmission rate on respective subcarrier. As we consider a system with the same subcarrier bandwidth for uplink and downlink, it is reasonable to assume an equal transmission rate of $0.5r_{m,n}$bit/symbol on either of the subcarrier couple to achieve capacity $r_{m,n}$. Let $g_{m,n}$ denote the CSI of direct link for the mth D2D pair, and the downlink transmission power $P(r_{m,n})$ for direct mode on downlink subcarrier n is

$$P(r_{m,n}) = \frac{N_0}{3|g_{m,n}|^2}\left[Q^{-1}\left(\frac{BER_m}{4}\right)\right]^2 \cdot \left(2^{\frac{r_{m,n}}{2}} - 1\right) \quad (2)$$

Here we introduce an integer variable $j \in \{0, 1\}$ to denote the 2 transmission modes, where $j = 0$ means cellular mode and $j = 1$ means direct mode. Then $P(r^{(0)}_{m,n})$ and $P(r^{(1)}_{m,n})$ are equivalent to (1) and (2) respectively. Then the optimization problem can be mathematically formulated as

$$\underset{r^{(j)}_{m,n}, x^{(j)}_{m,n}}{\text{Minimize}} \quad P_{\mathrm{T}} = \sum_{j=0}^{1}\sum_{n=1}^{N}\sum_{m=1}^{M} P(r^{(j)}_{m,n}) \cdot x^{(j)}_{m,n} \quad (3)$$

$$\text{s.t.} \quad \sum_{j=0}^{1}\sum_{n=1}^{N} r^{(j)}_{m,n} \cdot x^{(j)}_{m,n} \geq R_m, \quad \forall m \in \{1, 2, ..., M\} \quad (4)$$

$$\sum_{n=1}^{N} P(r_{m,n}^{(1)}) \cdot x_{m,n}^{(1)} \leq P_{\text{MS}},\ \forall m \in \{K+1, ..., M\} \quad (5)$$

$$\sum_{j=0}^{1} \sum_{m=1}^{M} x_{m,n}^{(j)} = 1, \quad \forall n \in \{1, 2, ..., N\} \quad (6)$$

$$x_{m,n}^{(j)} \in \{0, 1\}, \quad \forall n, \forall m, \forall j. \quad (7)$$

The QoS constraints are given in (4), where R_m is the required transmission capacity for user m and $r_{m,n}^{(j)}$ is its rate on subcarrier n using mode j. The transmission power upper bound of each D2D transmitter should be fully considered for the direct mode, and it is shown as P_{MS} in (5). The variable $x_{m,n}^{(j)}$ is binary, where $x_{m,n}^{(j)} = 1$ means the nth subcarrier serves user m with mode j and $x_{m,n}^{(j)} = 0$ otherwise. The combination of (6) and (7) means each subcarrier can be allocated to an exclusive user with only one transmission mode, avoiding co-channel interferences in the same cell. Because user m ($m \in \{1, 2, ..., K\}$) is a cellular user who gets services from the BS, it only has cellular transmission mode to transmit data and hence $r_{m,n}^{(1)} = x_{m,n}^{(1)} = 0$.

IV. Joint Subcarrier Allocation, Adaptive Modulation and Mode Selection

As the problem above is NP-complete with both integer and continuous variables, we propose a heuristic scheme with joint subcarrier allocation, adaptive modulation (bit allocation) and mode selection to solve it. Since being utilized in our proposed heuristic scheme, some existing subcarrier and bit allocation (referred as **ESBA**) algorithms in traditional OFDMA systems are firstly introduced concisely.

The algorithms in [6, 7] are proposed with obvious further power savings beyond [3, 4] respectively; while the so called "two phase" algorithms in [9] have too mild further savings (less than 0.5dB in most cases) compared with [6, 7], not worth the obvious increment on processing complexity . So the algorithms in [6, 7] are respectively utilized in our heuristic scheme as components with both effectiveness and efficiency, conducting subcarrier allocation and adaptive modulation.

A. ***ESBA***$_1$*: Zhang's Algorithm in [6]*

In [6], Zhang proposed an algorithm which firstly apply the Greedy water-filling to load bits for each user regardless the subcarrier allocation, and then coordinate the subcarriers owned by more than one users. The algorithm can be shortly described as following.

1) The Greedy water-filling algorithm is conducted for each user regardless of others, which leads to an bit loading strategy for each user;
2) As no subcarrier allocation is considered in 1), there must be some subcarriers allocated to more than one users. Find them and label them as "conflicting subcarriers (CSCs)";
3) Each time for the CSC with the largest sum power for bits loaded on it, the users who use this CSC reassign their bits on their exclusive subcarriers with Greedy water-filling. Choose the one with the largest power increment, allocate the CSC to this user exclusively, reassign the bits for others, and eliminate this subcarrier from CSC set;
4) Repeat step 3), until all the CSCs are coordinated successfully and reallocated as exclusive subcarriers.

B. ***ESBA***$_2$*: Gao's Algorithm in [7]*

Unlike ESBA$_1$, Gao al et. proposed an algorithm which predetermines the subcarrier allocation among users, and then carry out Greedy water-filling to do the bit allocation. The algorithm is given as following.

1) The average channel gain over all subcarriers is calculated for each user respectively, and the number of exclusive subcarriers allocated to each user is initialized to be 1;
2) The transmission power for each user is calculated with its average channel gain, using even bit allocation on its exclusive subcarrier number. Find the user with the largest power decrement if one more subcarrier is allocated, and plus the number of its exclusive subcarrier by 1. Repeat this process for $N - M$ times;
3) The number of exclusive subcarrier for user m is got from 2) denoted as N_m. Denote the transmission power of R_m/N_m bits on the unallocated subcarrier n as $P_{m,n}$. For all n unallocated, find the minimum P_{m^*,n^*}, allocate subcarrier n^* to user m^* , and mark subcarrier n^* as "allocated";
4) Reapeat 3) until all subcarriers are allocated. With the exclusive subcarrier set of each user, the Greedy water-filling is then conducted respectively.

C. Proposed Heuristic Scheme for Joint Subcarrier Allocation, Adaptive Modulation and Mode Selection

In this part, our heuristic algorithm is proposed to solve the problem in (3)-(7). Firstly, the existing subcarrier and bit allocation algorithm is utilized among all users with their cellular modes as in traditional OFDMA systems. By doing this, every user m is allocated with an exclusive subcarrier set $\mathbf{\Omega}_m$, and bit allocation set $\mathcal{R}_m^{(\text{C})} = \{r_{m,n}, n \in \mathcal{A}\}$. Clearly $r_{m,n} = 0$ if $n \notin \mathbf{\Omega}_m$. The total transmission power distributed to user m is $P_m^{(\text{C})}$ for corresponding $\mathcal{R}_m^{(\text{C})}$. The superscript (C) means "only **cellular** mode for existing algorithms".

Afterwards, the transmission mode is further selected for each D2D pair in its $\mathbf{\Omega}_m$ between the direct links and cellular links. As for the mode selection period, the Greedy water-filling is adopted to allocate each bit with the proper mode. Suppose we take the mth D2D pair into account, and $r_{m,n}^{(j)}$ bits have already allocated to mode j on subcarrier n (clearly $n \in \mathbf{\Omega}_m$). Then for the next bit to be allocated, the transmission power increment $\Delta P_{m,n}^{(j)}$ using mode j on the nth subcarrier can be readily given as

$$\Delta P_{m,n}^{(j)} = P(r_{m,n}^{(j)} + 1) - P(r_{m,n}^{(j)}). \quad (8)$$

If the total transmission power of the D2D transmitter is less than its upper bound P_{MS}, this bit is allocated to (j^*, n^*) with the minimum increment $\Delta P_{m,n^*}^{(j^*)} = \min_{j,n} P_{m,n}^{(j)}$, and subcarrier n^* is used by mode j^* exclusively. Otherwise direct mode is no more available and this bit can only be transmitted by cellular mode, so it is allocated to $(0, n^*) = \arg\min_n \Delta P_{m,n}^{(0)}$.

For D2D pair m, $\boldsymbol{\Omega}_m^{(j)}$ is the exclusive subcarrier set for mode j, and definitely $\boldsymbol{\Omega}_m^{(j)} \subset \boldsymbol{\Omega}_m$. $\mathcal{R}_m^{(j)}$ is the bit allocation set with elements $r_{m,n}^{(j)}$, and $P_m^{(j)}$ is the transmission power based on $\mathcal{R}_m^{(j)}$. $\mathcal{R}_m^{(\mathrm{D})}$ and $P_m^{(\mathrm{D})}$ are the bit allocation and transmission power respectively derived from the mode selection procedure. The superscript (D) means "mode selection with integrated **D2D** communications". The proposed algorithm is outlined as following.

Algorithm I Heuristic Algorithm for Joint Subcarrier Allocation, Adaptive Modulation and Mode Selection

1) Initialize $\mathcal{U} = \{1, ..., K, K+1, ..., M\}$, $\mathcal{A} = \{1, 2, ..., N\}$;

2) Run existing algorithms (e.g. ESBA_1 or ESBA_1) to get $\boldsymbol{\Omega}_m$, $\mathcal{R}_m^{(\mathrm{C})}$, and $P_m^{(\mathrm{C})}$ for all $m \in \mathcal{U}$;

3) ***For*** all $m = K+1$ to M,

a) Set $\mathcal{R}_m^{(j)} = \{r_{m,n}^{(j)} = 0, n \in \mathcal{A}\}$, $P_m^{(j)} = 0$ and $\boldsymbol{\Omega}_m^{(j)} = \boldsymbol{\Omega}_m, \forall j \in \{0, 1\}$;

b) ***While*** $\sum_n \sum_j r_{m,n}^{(j)} < R_m$, ***do***

$\Delta P_{m,n}^{(j)} = P(r_{m,n}^{(j)} + 1) - P(r_{m,n}^{(j)}), \forall j$ and $n \in \boldsymbol{\Omega}_m^{(j)}$;

if $\sum_n P(r_{m,n}^{(1)}) < P_{\mathrm{MS}}$, then $\forall j$ and $n \in \boldsymbol{\Omega}_m^{(j)}$

$(j^*, n^*) = \arg\min_{j,n}(\Delta P_{m,n}^{(j)})$, $r_{m,n^*}^{(j^*)} = r_{m,n^*}^{(j^*)} + 1$,

$P_m^{(j^*)} = P_m^{(j^*)} + \Delta P_{m,n^*}^{(j^*)}$, $\boldsymbol{\Omega}_m^{(j \oplus 1)} = \boldsymbol{\Omega}_m^{(j \oplus 1)} \backslash \{n^*\}$;

else direct mode is inapplicable, then $n \in \boldsymbol{\Omega}_m^{(0)}$

$(n^*) = \arg\min_n(\Delta P_{m,n}^{(0)})$, $r_{m,n^*}^{(0)} = r_{m,n^*}^{(0)} + 1$,

$P_m^{(0)} = P_m^{(0)} + \Delta P_{m,n^*}^{(0)}$;

c) $\mathcal{R}_m^{(\mathrm{D})} = \bigcup_j \mathcal{R}_m^{(j)}$, $P_m^{(\mathrm{D})} = \sum_n P_m^{(j)}$;

4) For all $m = K+1$ to M, set $P_m = \min\{P_m^{(\mathrm{C})}, P_m^{(\mathrm{C})}\}$, $\mathcal{R}_m = \arg\min(P^{(\mathrm{C})}, P^{(\mathrm{D})}) \in \{\mathcal{R}_m^{(\mathrm{C})}, \mathcal{R}_m^{(\mathrm{D})}\}$;

For a D2D pair with better direct links, bits are firstly allocated to direct mode with exclusive subcarriers. When the transmission power upper bound of the D2D transmitter is reached, however, the QoS may be not yet satisfied and several bits have to be piled on the very few subcarriers left for cellular mode. This may degrade the performance to some extent, which is caused by the transmission power upper bound of the D2D transmitter, leading the Greedy water-filling ineffective at times.

To tackle this problem, we compare the transmission power $P_m^{(\mathrm{C})}$ derived from **ESBA**s and $P_m^{(\mathrm{D})}$ got by mode selection procedure for each D2D pair as shown in step **4)**. Then the proper bit allocation strategy with the lower transmission power is chosen between $\mathcal{R}_m^{(\mathrm{C})}$ and $\mathcal{R}_m^{(\mathrm{D})}$.

V. Performance Evaluation

We evaluate the performance of our proposed heuristic scheme in one cell, adhering to LTE-Advanced based downlink OFDMA cellular systems. The total bandwidth is divided into 21 sub-bands. Each sub-band consists of 12 subcarriers which are allowed to be allocated either together or separately and each subcarrier is 15kHz. The QoS requirement of each user is set as $R_m = 40\mathrm{bits/symbol}$ and $BER_m = 10^{-3}$. Users are randomly located with uniform distribution in the cell whose radius is 750m. The upper bound for each D2D transmitter is $P_{\mathrm{MS}} = 200\mathrm{mW}$. 3GPP COST-WI propagation model is adopted as path loss, which is $L = 7.17 + 38\lg(R)$ dB (R is in meter) and the variance for shadowing is 8dB. The Rayleigh multipath channel in [11] is used to model frequency selective fading and we conduct 10^5 times of channel realization. To be more realistic, we set a peak instantaneous transmission power for the BS as 60W.

We also take a comprehensive consideration on the overall power consumption of the BS, which contains much more aspects besides transmission power such as the feeder losses, amplifier, etc., and the power offsets independent with transmission. The power consumption model is given in [12] as

$$P_{\mathrm{Total}} = a_{\mathrm{M}} \cdot P_{\mathrm{T}} + b_{\mathrm{M}}, \tag{9}$$

where $a_{\mathrm{M}} = 21.45$, $b_{\mathrm{M}} = 354.44\mathrm{W}$, and P_{T} is total transmission power of the BS.

Due to their advantages mentioned in Section IV, the ESBAs in [6, 7] are respectively utilized in our heuristic scheme to form two proposed algorithms. Each of the proposed algorithms is compared with the ESBA as its component. Via doing so, we try to illustrate that with any existing algorithm as its component, our proposed algorithm can outperforms this specific existing algorithm obviously.

A. Total Downlink Transmission Power

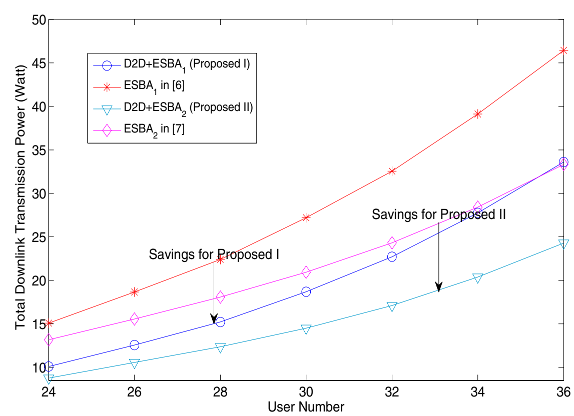

Fig. 3. Total downlink transmission power vs user number. The D2D pair's proportion is 50%.

Fig.3 shows the total downlink transmission power versus different user number. By integrating D2D communications into the OFDMA system, obvious conservations can be achieved by our proposed algorithms. In our simulation scenario, with ESBA_1 being utilized as the component of Proposed I, an average saving of nearly 35% is achieved; while almost the same conservation is obtained by the comparison between Proposed II and ESBA_2 as its component. This is intuitively correct, cause large transmission power originally emitted by the BS to cover the D2D pairs far apart, can be avoided by the smart mode selection in our proposed scheme.

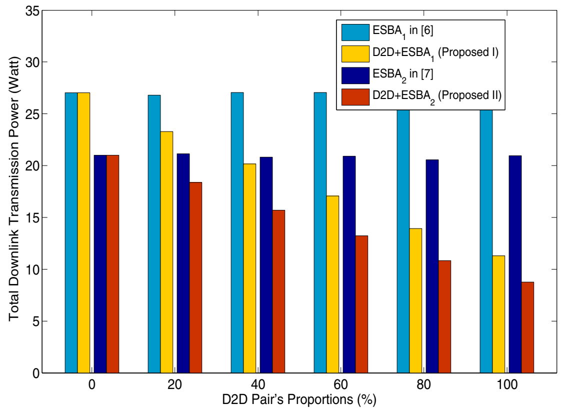

Fig. 4. Total downlink transmission power vs D2D pair's proportion. The total user number is 30.

Fig.4 demonstrates the total downlink transmission power versus various D2D pair's proportion among all users. No mode selection and bit rescheduling is available in traditional OFDMA systems and the direct link for D2D pairs are not exploited, so the D2D pairs are regarded the same as cellular users and the transmission power remains the same for ESBA_1 and ESBA_2. In contrast, as the D2D pair's proportion increases, there are more chances to conduct mode selection and bit rescheduling via our proposed algorithms. As a result, the direct links can be more fully used, making the power savings enlarged. Averagely, conservations around 34% can be both achieved by Proposed I and Proposed II, respectively based on ESBA_1 and ESBA_2. These results illustrate that via integrating whatever existing algorithm used in traditional OFDMA systems, our proposed algorithm can achieve significant further conservations beyond this specific existing algorithm.

B. Overall Power Consumption of the BS

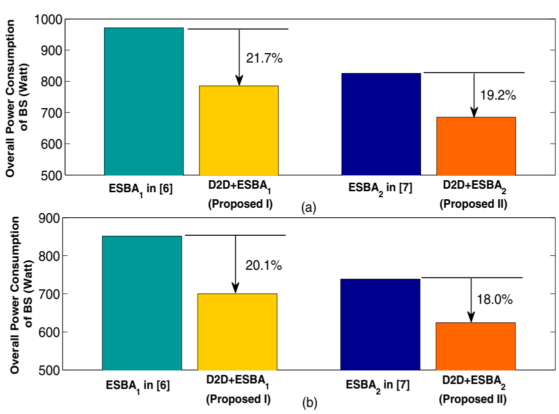

Fig. 5. Average overall power consumption over (a) user number from 24 to 36 (b) various D2D pair's proportion.

Fig.5 plots the overall power consumption of the BS. Fig.5 (a) shows the average value over user number from 24 to 36, while Fig.5 (b) is the average over different D2D pair proportions. The overall power consumption is reached by (9). It can be seen that via our proposed algorithms, an average saving of nearly 20% can be achieved over different user numbers and also for various D2D pair's proportions. We also discover from the simulation results that the total power spent by D2D transmitters is so small that it can be omitted compared with that of the BS. Therefore, these results well illustrate that our proposed scheme can not only save the transmission power but also effectively conserve the overall power consumption of the BS.

VI. Conclusion

In this paper, we propose a power optimization scheme with joint subcarrier allocation, adaptive modulation and mode selection in an OFDMA system with integrated D2D communications. After utilizing the existing algorithms to conduct subcarrier and bit allocation, the transmission modes of D2D pairs are further selected smartly and the advantages brought about by D2D pair's are fully exploited. Simulation results show that our proposed scheme can not only conserve downlink transmission power dramatically, but also save the overall power of the BS effectively; and these savings are particularly obvious for a system with high D2D pair's proportion.

Acknowledgement

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