JOURNAL OF INFORMATION SCIENCE AND ENGINEERING 34, 419-433 (2018)
DOI: 10.6688/JISE.201803_34(2).0007

Energy Efficiency Resource Allocation for Device-to-Device Communication Underlaying Cellular Networks

BAO-ZHOU YU AND QI ZHU
Key Wireless Laboratory of Jiangsu Province
School of Telecommunication and Information Engineering
Nanjing University of Posts and Telecommunications
Nanjing, 210003 P.R. China
Key Laboratory on Wideband Wireless Communications and Sensor Network Technology
Ministry of Education
Jiangsu Nanjing, 210003 P.R. China
E-mail: happyuzhou@163.com; Zhuqi@njupt.edu.cn

The energy efficiency (EE) of Device-to-Device (D2D) communication underlay cellular networks has become a significant issue because of increasing the resource utilization and extending the battery life of user equipment. However, the interference caused by sharing the same resources with the cellular users will descend the performance of the system. Therefore, D2D users should be allocated reasonable sub-carrier and suitable power to improve the performance of the cellular networks. In this paper, D2D communication can directly transmit information or transmit dates through an assisted relay based on the outage probability of D2D users. Meanwhile, we propose an algorithm to study the problem of EE of D2D communication under the condition of the required QoS (Quality of Services) of both cellular users and D2D users and the maximum transmission power threshold of D2D users. To solve the problem efficiency, we divide the algorithm into two stages to allocate sub-carrier and optimize power, respectively. By numerical simulation, we also prove the good performance of the proposed algorithm.

Keywords: energy efficiency, device-to-device communication, relay selection, outage probability, resource allocation

1. INTRODUCTION

Device-to-Device (D2D) communication [1, 2], where the users in close proximity transmit information with each other directly, has gained much attention because of its potential for improving the spectrum efficiency and reducing the power consumption of the cellular networks. These D2D users (DUEs) reuse the radio resources of cellular users (CUEs) under the careful control of the evolved NodeB (eNB) [3]. However, DUEs communication underlay cellular networks will cause the interference for sharing the resources of CUEs. Therefore, the reasonable resources occupied by the CUEs should be allocated to DUEs to decrease the interference and improve the performance.

To improve the performance of cellular networks, various techniques have been put forward to cope with the above mentioned problem. In LTE-A cellular networks, sub-carrier allocation and power control schemes are the two widely used interference management techniques [4, 5]. Furthermore, energy efficiency of D2D communication in cellular networks is an increasing concern [6-8] for its reducing power consumption of

Received September 2, 2016; revised February 1, 2017; accepted March 26, 2017.
Communicated by Meng Chang Chen.

the cellular networks. However, when D2D communication reuse the sub-carrier occupied by a CUE, the CUE will increase the transmission power to guarantee its QoS (Quality of Services). In [6], authors investigate a system model of multi-hop D2D communications where one UE may help other one potential D2D pair to exchange information. They also analyze the average energy efficiency and spectral efficiency of the multi-hop D2D communications and get close analytical approximations through Taylor-series expansion. In [7], energy-efficient resource allocation problem for D2D communication underlaying cellular networks is studied. Authors aim to maximize the minimum weighted energy efficiency of D2D links while guaranteeing minimum data rates for cellular links. Extensive numerical studies demonstrate that the proposed algorithm achieve superior performance and significantly outperform a conventional algorithm. A joint resource allocation and power control for energy-efficient D2D communications underlaying cellular networks are investigated in [8], which proposes an efficient iterative resource allocation and power control scheme to find the optimum at each iteration. Simulation results demonstrate the remarkable improvements in terms of energy-efficient by using the proposed scheme. However, the literature [6] assumes the situation of one cellular user or one D2D pair. And the papers [7, 8] do not consider joint optimization of energy efficiency and mode selection of users.

In this paper, we consider the situation of multiple D2D users sharing the multiple sub-carriers occupied by cellular users. And a selection communication mode [9] and resource assignment algorithm is proposed to optimize the energy efficiency of DUEs under the condition of guaranteeing the QoS of original CUEs and DUEs. And when DUEs intend to exchange information with each other, there are two different communication modes that can be considered: Mode A (Direct D2D communication) and Mode B (Two-hop D2D communication through idle CUE). Meanwhile, the main contributions of this paper are summarized as follows:

(1) We take the outage probability of CUEs and DUEs into consideration to manage the interference between CUEs and DUEs. And based on the outage probability, DUEs that intend to exchange information could select Mode A or Mode B. However, if one DUE can't meet the conditions of above communication modes, the DUE do not transmit information in the point.
(2) We construct an analysis model of EE of DUEs underlaying the cellular networks, where the advantages in spectrum utilization, the energy saving, the diverse QoS requirements of users, and both transmission power and the circuit power consumption are characterized quantitatively.
(3) We put forward a novel algorithm for solving the resource distribution problem. We design a two-stage scheme, the first stage copes with sub-carrier allocation, and the second stage copes with power control. Meanwhile, the properties of the proposed algorithm influenced by the system parameters are discussed.

The remainder of this paper is organized as follows. In Section 2, we briefly introduce the network model and energy efficiency analysis. In section 3, the sub-carrier allocation and power control problem as an optimal problem are formulated. We also propose a two-steps algorithm and analyze its important properties. In Section 4, simulation results are provided. Finally, we conclude this paper with a summary in Section 5.

2. SYSTEM MODEL AND OUTAGE PROBABILITY ANALYSIS

2.1 System Model

We consider a single cell that contains two types of users in Fig. 1, which are the cellular users (CUEs) and the D2D users (DUEs). And the CUEs only can communicate with the cellular communication mode, where CUEs communicate through the BS (base station). However, the DUEs have two different communication modes. One is the Mode A, where the DUE (one D2D pair) communicate with each other directly. The other is the Mode B, where D2D communication with relay selected from idle CUEs is used for the outage probability of DUE going beyond the threshold defined by the system. We only consider the intra-cell interference for a single cell system model. Meanwhile, in the system model, we also assume a fully loaded cellular network [10], where all the sub-carriers are allocated to CUEs. And M active CUEs occupy M orthogonal uplink sub-carriers and there is no additional uplink sub-carrier for N DUEs in the cell, where DUE communicates by reusing the uplink (UL) spectrum resources of an active CUE, which is called paired CUE. The sets $\Theta_a = \{CUE_i\}$, $i = 1, 2, \ldots, M$ and $\Omega = \{DUE_j\}$, $i = 1, 2, \ldots, N$ donate the M active CUEs and N DUEs in the cell, respectively. From Fig. 1, we assume that there are K idle CUEs as the candidate relay of DUEs with Mode B. Furthermore, we employ the set Θ_i to indicate the idle CUEs within the cell.

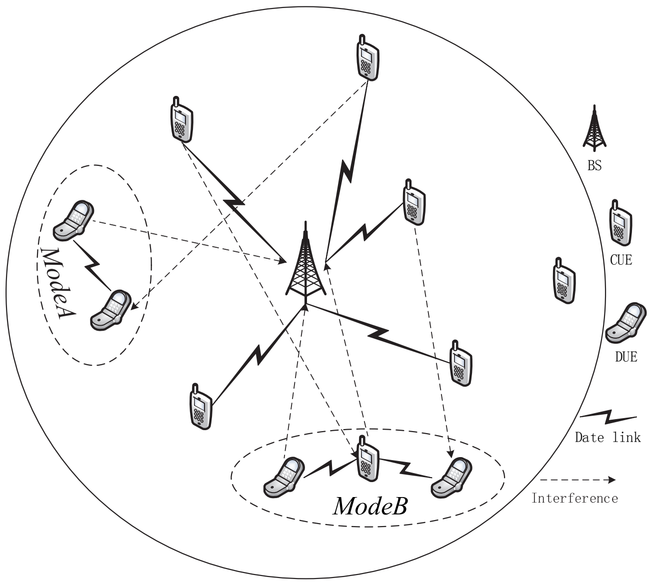

Fig. 1. Network model of DUE communication underlaying cellular network where one CUE and one DUE share UL resources.

In Mode A, the paired CUE causes interference to the receiver of DUE and the transmitter of DUE causes interference to BS. In Mode B, relay (RN) is selected from idle CUEs, which do not transmit information in this period. Besides, the transmitter of DUE communicates with RN directly, and it is the same as RN communicates with the receiver of DUE. The relay lies close to both the transmitter and the receiver of DUEs. The transmitter of DUEs exchanges information with the relay through reusing the sub-carrier of CUEs, which is the same as the relay and the receiver of DUEs. We also assume the system UL frequency resources have been allocated to the active CUEs uniformly, and the transmission power of CUEs is constant, which is denoted as P_C. We consider the extreme case that all of the DUEs communicate with Mode B. Thus, additional N idle CUEs at least are required to serve as the relay. Therefore, we assume there are K idle CUEs in the system and $K > N$.

2.2 Outage Probability Analysis

For Mode A, DUE will exchange information through direct one-hop communication. The paired CUE i transmits a signal x_1^i to BS, and a signal x_2^i is the transmission signal between DUE j. Thus, the received signal of BS and the receiver of DUE can be formulated as

$$y_{BS,i} = \sqrt{P_C} g_{i,B} x_1^i + \sqrt{P_{j,i}^d} g_{j,B} x_2^j + n_1, \tag{1}$$

$$y_{d,j} = \sqrt{P_{j,i}^d} g_j x_2^j + \sqrt{P_C} g_{i,j} x_1^i + n_2. \tag{2}$$

In above expressions, $P_{j,i}^d$ denotes the transmission power of DUE j reusing the channel of CUE i. The channel gain between BS and the CUE i can be written as $g_{i,B} = \kappa \cdot d_{i,B}^{-\alpha} \cdot |h_i|^2$, where $d_{i,B}$ is the distance between CUE i and BS, κ and α are the path loss constant and the path loss exponent, respectively. h_i represents the fading coefficients with CUE i. Similarly, the channel gain between the BS and DUE j is $g_{j,B}$, g_j is the channel gain between the transmitter and receiver of DUE j and $g_{i,j}$ is the channel gain between the active CUE i and DUE j. n_1 and n_2 indicate the additive white Gaussian noise (AWGN) for BS and the receiver of DUE, respectively. Without loss of generality, we assume that all communication links receive the same AWGN power N_0. We assume the DUE j reuse the subcarrier of CUE i to transmit the information. And then, the Signal-to-Interference-and-Noise-Ratio (SINR) of paired CUE i and DUE j can be formulated as

$$\Gamma_{i,j}^c = \frac{P_C \cdot g_{i,B}}{N_0 + P_{j,i}^d \cdot g_{j,B}}, \tag{3}$$

$$\Gamma_{j,i}^d = \frac{P_{j,i}^d \cdot g_j}{N_0 + P_C \cdot g_{i,j}}. \tag{4}$$

The rate of DUE j sharing the sub-carrier of CUE i can be formulated as Eq. (5), which can be got by Shannon capacity formula.

$$r_{j,i} = \log_2(1 + \Gamma_{j,i}^d) \tag{5}$$

The energy efficiency (EE) of DUE link can be defined as the ratio between throughput and total power of DUE. As mentioned in [11], transmission power and average circuit power are important of energy efficiency. Therefore, the EE of DUE j reusing the sub-carrier of CUE i can be expressed as

$$u_{j,i}^{ModeA} = \frac{r_{j,i}}{P_{j,i}^{d} + P_{cir}}. \tag{6}$$

Where $P_{j,i}^{d}$ and P_{cir} are the transmission power and the average circuit power, respectively.

Similar to [11, 12], the EE of the total DUEs underlay cellular network can be defined as

$$ee^{ModeA} = \sum_{j=1}^{N} u_{j,i}^{ModeA} \tag{7}$$

The outage probability of paired CUE i, which equals the Cumulative Distribution Function (CDF) of $\Gamma_{i,j}^{c}$, can be formulated as

$$P_{out}^{C} = \Pr\left\{\Gamma_{i,j}^{c} < \eta\right\} = \int_{0}^{\eta} f_{\Gamma_{i,j}^{c}}\left(\Gamma_{i,j}^{c}\right) d\Gamma_{i,j}^{c} = F_{\Gamma_{i,j}^{c}}(\eta). \tag{8}$$

Where η indicates the SINR threshold of paired CUE i, and $f_{\Gamma_{i,j}^{c}}(\Gamma_{i,j}^{c})$ is the Probability Density Function (PDF). We can get the expression of outage probability of CUE i according to the Lemma 1 in [11]

$$P_{out}^{c,i} = 1 - \frac{P_C g_{i,B}}{P_C g_{i,B} + \eta P_{j,i}^{d} g_{j,B}} \exp\left(-\frac{\eta N_0}{P_C g_{i,B}}\right). \tag{9}$$

Similarly, the outage probability expression of DUE j is written as

$$P_{out}^{d,j} = 1 - \frac{P_{j,i}^{d} g_j}{P_{j,i}^{d} g_j + \delta P_c g_{i,j}} \exp\left(-\frac{\delta N_0}{P_{j,i}^{d} g_j}\right). \tag{10}$$

Where δ is the SINR threshold of DUE j, and the proof of Eqs. (9) and (10) are presented in Appendix A.

Comparing with Mode A, Mode B is an extension of Mode A, *i.e.* two hops of Mode A. And we assume the idle CUE k as the relay of DUE j, where the transmitter of DUE j and the relay RN_k reuse the sub-carrier of paired CUE i in two time slots. In the first time slot, the transmitter of DUE j communicates with RN_k. In the second time slot, RN_k communicates with the receiver of DUE j. Therefore, the outage probabilities of DUE j with Mode B related to every hop are similar to Eqs. (9) and (10).

3. PROBLEM FORMULATION AND RESOURCE ALLOCATION ALGORITHM

3.1 Construction of Optimization Problem

The priority of CUE is high than the DUE, that is to say, the QoS of paired CUE should be guaranteed. Based on the section 2, when the outage probability of the paired CUE or the DUE oversteps the threshold defined by the system, Mode B intend to be used. Hence, we can divide the DUEs into different parts according to the following expression

$$\begin{cases} P_{out}^{c,i} \le \xi \\ P_{out}^{d,j} \le \zeta \end{cases}. \tag{11}$$

Where ξ and ζ are the outage probability thresholds of paired CUE and DUE, respectively.

The DUE j communicate with Mode A when it satisfies Eq. (11). Otherwise, the DUE j will communicate with Mode B. Hence, the DUE need a relay to realize the communication. For all idle CUE $k \in \Theta_i$, if there is any idle CUE as relay of DUE making both the DUE j and the relay meeting the condition (11), the DUE j transmit with Mode B. Otherwise, the DUE j can't transmit at this period. Therefore, the set Ω can be divided into Ω_A, Ω_B and Ω_O according to the following expression

$$\Omega = \begin{cases} \Omega_A, P_{out}^{c,i} \le \xi \,\&\, P_{out}^{d,j} \le \zeta, \exists i \in \Theta_a \\ \Omega_B, \left(P_{out}^{c,i} \le \xi \,\&\, P_{out}^{d,n} \le \zeta\right) \& \left(P_{out}^{c,i} \le \xi \,\&\, P_{out}^{d,j} \le \zeta\right), \exists i \in \Theta_a, \exists n \in \Theta_i \\ \Omega_O, \text{other} \end{cases}. \tag{12}$$

The DUEs in sets Ω_A, Ω_B and Ω_O correspond to the communication mode of Mode A, Mode B and Mode O, respectively. Where the DUE with Mode O donates the DUE can't transmit information since there is no more sub-carrier for the DUE communicating with original cellular mode. We also define $\pi_{i,j}$ to indicate the sub-carrier reuse exponent, where $\pi_{i,j} = 1$ expresses the DUE j reuse the sub-carrier of CUE i, and $\pi_{i,j} = 0$ indicates the DUE j can't reuse the sub-carrier of CUE i. We also assume that each DUE can reuse the only one sub-carrier of CUEs and each sub-carrier of CUEs can be reused by one DUE. Thus, the total EE of DUEs can be achieved as follows

$$\begin{aligned} ee &= ee^{ModeA} + ee^{ModeB} \\ &= \sum_{j \in \Omega_A} \sum_{i \in \Theta_a} \frac{\log_2\left(1+\Gamma_{j,i}^d\right)}{P_{j,i}^d + P_{cir}} \pi_{i,j} + \sum_{j \in \Omega_B} \sum_{i \in \Theta_a} \sum_{k \in \Theta_i} \frac{1}{2} \left(\frac{\log_2\left(1+\Gamma_{k,i}^d\right)}{P_{k,i}^d + P_{cir}} \pi_{i,k} + \frac{\log_2\left(1+\Gamma_{j,i}^d\right)}{P_{j,i}^d + P_{cir}} \pi_{i,j} \right). \end{aligned} \tag{13}$$

Where i is the CUE sharing the sub-carrier with the DUE and relay in two different time slots. And k donates the relay selected from the idle CUEs. The main work is selecting the reasonable paired CUE for DUE with Mode A and the reasonable paired CUE and relay for DUE with Mode B. Therefore, we establish the following optimal problem:

$$\max_{\left\{\pi_{i,j}, P_{j,k}^d\right\}} \sum_{j \in \Omega_A} \sum_{i \in \Theta_a} u_{j,i}^{ModeA} \pi_{i,j} + \sum_{j \in \Omega_B} \sum_{i \in \Theta_a} \sum_{k \in \Theta_i} \frac{1}{2} u_{(j,k),i}^{ModeB} \pi_{i,(j,k)} \tag{14}$$

Subject to

$$\sum_{i \in \Theta_a} \pi_{i,j} \le 1 \tag{15}$$

$$\sum_{j\in\Omega}\pi_{i,j}\le 1 \tag{16}$$

$$0\le P^d_{j,i}\le P_{\max} \tag{17}$$

Where $u^{ModeB}_{(j,k),i}=\frac{\log_2\left(1+\Gamma^d_{k,i}\right)}{P^d_{k,i}+P_{cir}}+\frac{\log_2\left(1+\Gamma^d_{j,i}\right)}{P^d_{j,i}+P_{cir}}$ and object function indicates maximizing the EE of total DUEs. Eqs. (15) and (16) guarantee each DUE can reuse the only one sub-carrier of DUE and each sub-carrier of active CUE can be reused by only one DUE. Eq. (17) restricts the transmission power of DUE to guarantee the QoS of paired CUE.

From the constraints, we find the optimal problem can be considered as an assignment problem, which contains one more constraint (17) compared to the standard assignment problem. Meanwhile, the above optimal problem is non-convex, which can't be solved by the general methods. Therefore, the original optimal problem is divided into two sub-problems. To begin with, we use the Hungarian algorithm to allocate the reasonable sub-carrier of CUEs to DUEs. And then, we optimize the transmission power of DUE to improve the EE of the total DUEs.

3.2 Sub-carrier Allocation for DUE

Fig. 2 illustrates the sub-carrier allocation problem in Eq. (14) with the constraints (15) and (16). In this figure, the set of DUEs with Mode A and Mode B and the reuse candidate sub-carrier set are the two groups of vertices in the bipartite graph. If the sub-carrier of CUE *i* is a reuse candidate for DUE *j*, and the vertex *j* connects to vertex *i* by an edge *i*, *j*. Meanwhile, $u^{ModeA}_{j,i}$ and $u^{ModeB}_{(j,k),i}$ is the weight of edge *i*, *j* of DUEs with Mode A and Mode B, respectively.

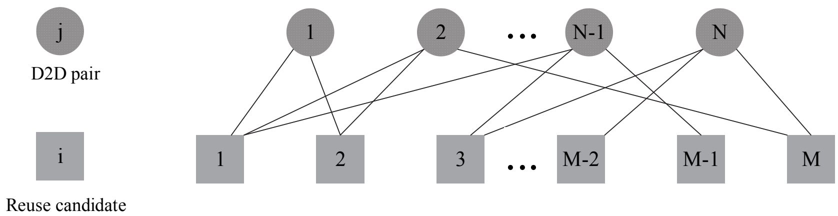

Fig. 2. Bipartite graph for DUEs and the reuse candidates matching problem.

We employ Hungarian algorithm [12] to solve this problem. The algorithm is an efficient bipartite allocation scheme. In general $N \le M$, but the Hungarian algorithm demands the bipartite graph to be perfectly symmetric. To meet this requirement, we add $M - N$ virtual vertices to the set of D2D pairs in the original graph. The object function of optimal problem maximizes the EE of total DUEs. However, the standard Hungarian algorithm is used to solve the minimum weighted matching problem on the transformed bipartite graph. Therefore, we transform the original object function to be minimizing the EE through using a sufficiently large constant subtract the EE of each DUE. And the transformed optimal problem is equivalent to the original problem. The detail steps are presented in Table 1.

Table 1. Optimal sub-carrier allocation algorithm.

Algorithm 1: Optimal Sub-carrier Allocation Algorithm

Input: The sets of active and idle CUEs in the cell Θ_a and Θ_i
The set of DUEs Ω, the distance between DUEs Rd
The set of DUEs with Mode A and Mode B $\Omega_A = \varnothing$ and $\Omega_B = \varnothing$
The set of relay candidates of DUEs $RN = \varnothing$
The set of distance between the CUEs and DUEs $Z = [dist_{i,jTx}, dist_{i,jRx}]$

Output: The set of sub-carrier reuse exponent $\pi = [\pi_{i,j}]$

Step 1
For all $i \in \Theta_a$ and $j \in \Omega$ do
  Calculate the outage probability $P_{out}^{c,i}$ and $P_{out}^{d,j}$ by Eqs. (9) and (10)
  If $P_{out}^{c,i} \le \xi$ && $P_{out}^{d,j} \le \zeta$
    Then put j into Ω_A : $\Omega_A = \Omega_A \cup \{j\}$
    Calculate $u_{j,i}^{ModeA}$ by Eq. (6)
  Else
    For all $i \in \Theta_i$ do
      Calculate $dist_{i,jTx}$, $dist_{i,jRx}$
        If $(dist_{i,jTx} + dist_{i,jRx}) \le 2Rd$
          Then $RN_j = \{k \mid k = i\}$ and $\Theta_i = \Theta_i / i$
          For all $i \in \Theta_a$ do
            If $P_{out}^{c,i} \le \xi, P_{out}^{d,j} \le \zeta$ && $P_{out}^{c,i} \le \xi, P_{out}^{d,k} \le \zeta$
            Then put j and k into Ω_B: $\Omega_B = \Omega_B \cup \{j, k\}$
              Calculate $u_{j,i}^{ModeA}$, $u_{k,i}^{ModeA}$ by Eq. (6) to get $u_{(j,k),i}^{ModeB}$
            Else $\Omega_0 = \Omega_0 \cup \{j\}$
            End if
          End for
        End if
      End for
    End if
  End for

Step 2
For all $i \in \Theta_a$ and $j \in \Omega$ do
  If $|\Omega_A| \ne 0$ or $|\Omega_B| \ne 0$
    Construct symmetric bipartite graph by $V_m - u_{j,i}$, which V_m is a enough large value
      Use the Hungarian algorithm to obtain $\pi_{i,j}$
  Else
      There is no sub-carrier for DUE and the algorithm ends
  End if
End for

3.3 Optimal Power Control for DUE

The sub-carrier occupied by the paired CUEs has been allocated to the DUEs, so we can simplify optimal problem (14) as the following optimal problem

$$\max_{P_{j,k}^{d}} \sum_{j\in\Omega_A}\sum_{i\in\Theta_a} u_{j,i}^{ModeA} + \sum_{k,j\in\Omega_B}\sum_{i\in\Theta_a}\frac{1}{2}u_{(j,k),i}^{ModeB} \tag{18}$$

Subject to $0 \le P_{j,i}^d \le P_{\max}$ (19)

For simplification, we donate $A_{j,i}$ as $A_{j,i} = \dfrac{g_j}{N_0 + P_C g_{i,j}}$. Thus, the EE of DUE j with Mode A and Mode B can be respectively donated as

$$u_{j,i}^{ModeA} = \frac{\log_2\left(1 + A_{j,i}P_j^d\right)}{P_j^d + P_{cir}}, \tag{20}$$

$$u_{(j,k),i}^{ModeB} = \frac{1}{2}\left(\frac{\log_2\left(1 + A_{j,i}P_j^d\right)}{P_j^d + P_{cir}} + \frac{\log_2\left(1 + A_{k,i}P_k^d\right)}{P_k^d + P_{cir}}\right) = \frac{1}{2}\left(u_{j,i}^{ModeA} + u_{k,i}^{ModeA}\right). \tag{21}$$

The form of Eqs. (20) and (21) are similar to the function of $f(a, x)$, which can be defined as $f(a,x) = \dfrac{\log_2(1+ax)}{x+b}$, where b is a constant. The sub-carriers reusing by DUEs are independent, the solutions of Eq. (18) is the same as the sum of maximum EE of each DUE. That is to say, if we achieve the maximum value of $f(a, x)$, we get the optimal solutions of Eq. (18). Therefore, we briefly analysis the characteristic of $f(a, x)$.

To begin with, seeking the derivative of $f(a, x)$ corresponding to the variable x.

$$\frac{\partial f(a,x)}{\partial x} = \frac{1}{(x+b)^2}\cdot\left(\frac{a(x+b)}{\ln 2(1+ax)} - \log_2(1+ax)\right) = \frac{1}{(x+b)^2}\cdot g(a,x) \tag{22}$$

And then, seeking the derivative of $g(a, x)$ corresponding to the variable x

$$\frac{\partial g(a.x)}{\partial x} = -\frac{a^2(x+b)}{\ln 2(1+ax)^2}. \tag{23}$$

According to Eq. (23), we know that $g(a, x)$ is a monotonically decreasing function in x and $g(a,0) = \dfrac{ab}{\ln 2} > 0$, $g(a,+\infty) = \lim\limits_{x\to+\infty}\left(\dfrac{a(x+b)}{\ln 2(1+ax)} - \log_2(1+ax)\right) = -\infty < 0$. Therefore, with the increasing of x, there is a x_0 making $g(a, x_0)$. And $g(a, x)$ is greater than zero on the interval $(0, x_0)$ and less than zero on the interval $(x_0, +\infty)$. So the function $f(a, x)$ is monotonically decreasing on the interval $(0, x_0^*)$ and monotonically ascending on the interval $(x_0^*, +\infty)$. That is to say, x_0^* is the maximum value point of function $f(a, x)$.

Bisection method is used to solve the maximum of function $f(a, x)$ with the constraint of maximum transmission power $P_{\max}$ and the detailed steps are illustrated in Table 2.

Table 2. Bisection method for optimal power of DUE.

Algorithm 2: Bisection method for optimal power of DUE

Input: given the maximum transmission power $P_{\max}$, the tolerance $\varepsilon > 0$ and sufficiently small value $l = 0$ and sufficiently large value $v = 10^8$.

Output: the optimal transmission power P^* of DUE.

1. for $j = 1$ to $j = N$
2. if $j \in \Omega_A$; then

3. while $|v_j - l_j| > \varepsilon$
4. $t_j = (l_j + v_j)/2$
5. $\Delta_j = \left.\dfrac{\partial u_j^{ModeA}}{\partial P_j}\right|_{P_j = t_j}$
6. if $\Delta_j > 0$, $l_j = t_j$; else $v_j = t_j$
7. end if
8. end while
9. $P_j^* = (l_j + v_j)/2$
10. if $P_j^* > P_{\max}$, $P_j^* = P_{\max}$; else end
11. else if $j \in \Omega_B$; then
12. for j and corresponding relay k, execute steps 3-10. And then getting the optimal power of D2D users $j(P_j^*)$ and $k(P_k^*)$
13. end if
14. end for

4. SIMULATION RESULTS

In this section, we present the simulation results of the proposed sub-carrier allocation and power control algorithm, and analyze the EE performance of DUEs with the different communication mode of the DUEs, the distance between DUEs, and the maximum transmission power of DUEs.

We consider a single isolated circular cell and the radius is fixed. The location of eNB is in the center of the cell, where CUEs are uniformly distributed and each transmitter and receiver of DUEs are located in a uniformly distributed within a radius Rd . In this section, we present extensive simulation of EE for DUEs of different transmission mode. Table 3 summarizes the list of simulation parameters and their default value.

Table 3. Simulation parameters.

Parameter	Values
Cell radius (R)	500m
AWGN power (N_0)	−114dBm
Path-loss constant (κ)	0.01
Path-loss exponent (α)	4
Active CUE transmit power (P^c)	24dBm
Max. DUE transmit power ($P_{\max}$)	21dBm
UE circuit power (P_{cir})	17dBm
Req. SINR of CUE (η)	3dB
Req. SINR of DUE (δ)	3dB
The distance between DUE (Rd)	20, 30, …, 100m
Number of active CUEs (M)	20, 40
Number of idle CUEs (K)	40
Number of DUEs (N)	10%, 20%, …, 100% of active CUEs
Outage probability threshold of CUE (ξ)	0.001
Outage probability threshold of DUE (ζ)	0.001

We will show the capacity of DUEs and CUEs, and the EE of DUEs in the following Fig. 3-6. As a comparison, we compare the performance of our proposed algorithm to the location-based algorithm (LBA) in [13]. The authors of [13] prove that the EE of the D2D link is mainly determined by the location of the CUE that shares sub-carrier with the DUE. On this basis, a LBA is proposed to maximize the sum EE of DUEs. Since the LBA gets the transmission power by conversion formula of SINR, the transmission power may not be the optimal. However, the proposed algorithm optimize the transmission power of DUEs. Specifically, when a DUE has been allocated sub-carrier occupied by CUE, the transmission power of DUEs on the sub-carrier is optimized using Bisection methods. We also investigate the performance of our algorithm with fixed transmission power at 17dBm.

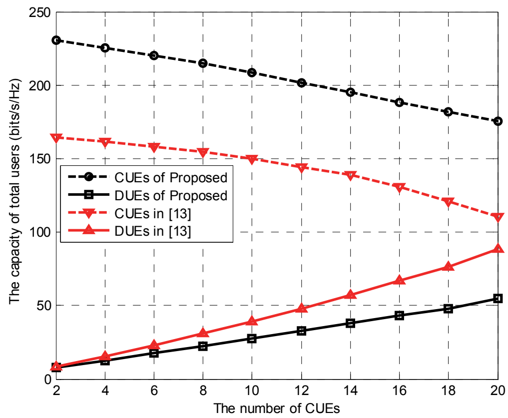

Fig. 3. The capacity of DUEs and CUEs with the increasing number of DUEs, where R=500m.

Fig. 3 shows the capacity of total DUEs and CUEs with the increasing number of DUEs. The number of active CUEs is 20. Note that we assume the number of CUEs equals the number of sub-carriers, since each sub-carrier is occupied by one CUE. With the increasing number of DUEs, the capacity of total DUEs increase, while the capacity of total CUEs descend. This is because the more DUEs will reuse the more sub-carriers of active CUEs and cause more interference to the active CUEs. From Fig. 3, we can see that the capacity of DUEs of our proposed algorithm is less than the LBA in [13], while the capacity of CUEs is much higher than the LBA in [13]. Since the LBA does not consider the QoS of the CUEs, which causes more interference to the CUEs and descends the capacity of total CUEs.

We present the EE of DUEs with the different number of DUEs in Fig. 4. We can see that EE improves with the increasing number of DUEs, which indicates that with joining of more DUEs, more DUEs can exchange information through sharing sub-carriers occupied by active CUEs. Therefore, the EE of total DUEs is increased. Meanwhile, our proposed algorithm behaves better than the algorithm in [13]. Since the algorithm in [13] achieves transmission power by conversion formula of SINR, which could not be the optimal. However, the transmission power of our proposed algorithm is optimal. The proposed algorithm with fixed power achieves a lower EE for it transmits more power.

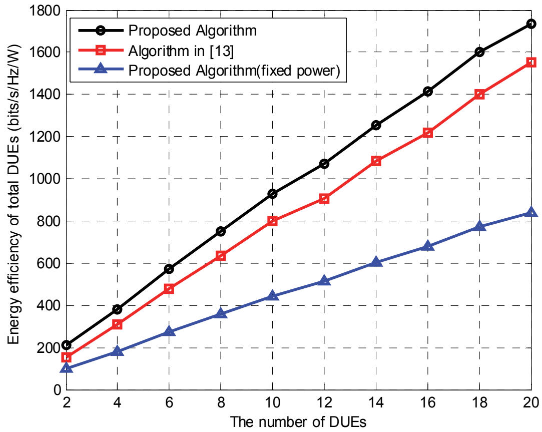

Fig. 4. Energy efficiency of total DUEs with the increasing number of DUEs, where R=500m, M=20.

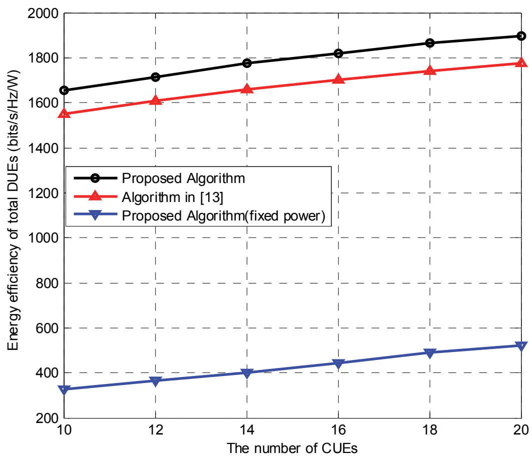

Fig. 5. Energy efficiency of total DUEs with the increasing number of CUEs, where R=500m.

In Fig. 5, we present the EE of DUEs with the number of active CUEs (sub-carriers). And the number of DUE is 10. We observe that with the increasing number of sub-carriers, the EE of DUEs increase slowly. With more sub-carriers, DUEs have more sub-carriers to choose from, and thus the performance is improved. However, the increase of EE of DUEs is slow, which implies that the DUE can reuse only one sub-carrier occupied by CUE and the CUEs do not have major impact on the performance of DUEs.

Fig. 6 shows the EE of total DUEs with the circuit power of the DUE. It can be seen that our proposed algorithm offers better performance than the other two algorithms. For small circuit power, the EE of the proposed algorithm is about 25% higher than the algorithm in [13] and about 400% higher than the proposed algorithm with fixed power, respectively. However, when circuit power increases, the performance gap between the proposed algorithm and the other two schemes is reduced since the total consumed power is dominated by the circuit power.

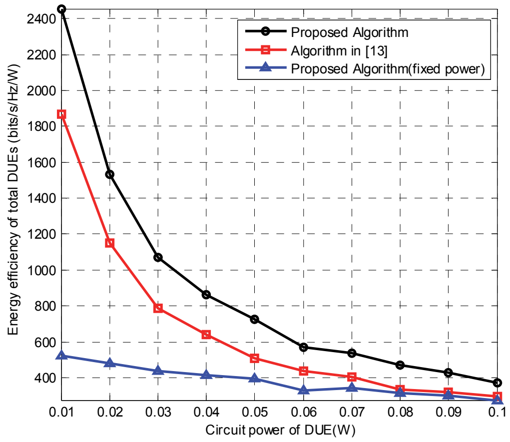

Fig. 6. Energy efficiency of total DUEs with circuit power of DUEs.

5. CONCLUSIONS

In this paper, we analyze the sub-carrier allocation and power control under the condition of maximum transmission power constraint of DUEs to optimize the EE of different communication mode of DUEs underlaying cellular networks. We apply the relay selected from the idle CUEs to D2D communication when the outage probabilities of CUE and DUE, which share the same sub-carrier, exceed the threshold defined by the system. Numerical simulations show the EE of different types of communication modes, and reveal the advantage of DUE with relay mode in average by comparing with directly D2D communication mode.

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation of China (61571234, 61631020), National Basic Research Program of China (973 program: 2013CB329005).

APPENDIX

With the help of [14, Eq. (5)-(18)], the PDFs of **x** and **y** are expressed as $f(x) = \frac{1}{\alpha}\exp\left(-\frac{x}{\alpha}\right)U(x)$ and $f_y(y) = \frac{1}{\beta}\exp\left(-\frac{y}{\beta}+\frac{1}{\beta\delta}\right)U\left(y-\frac{1}{\delta}\right)$, respectively. Next, the PDF of **z** = **x**/**y** can be evaluated as follows: [14, Eq. (6)-(59)]

$$f_z(z) = \int_{1/\delta}^{\infty} y f_{xy}(yz, y)\, dy = \left[\frac{1}{(\alpha+\beta z)\delta} + \frac{\alpha\beta}{(\alpha+\beta z)^2}\right]\exp\left(-\frac{z}{\alpha\delta}\right). \tag{24}$$

From Eq. (24), the CDF can be expressed as

$$F_z(z)=\int_0^z\left[\frac{e^{-\frac{x}{\alpha\delta}}}{(a+\beta x)\delta}+\frac{\alpha\beta e^{-\frac{x}{\alpha\delta}}}{(a+\beta x)^2}\right]dx \tag{25}$$

Using the integration by parts, the right term in Eq. (25) can be evaluated as

$$\begin{aligned}\int_0^z \frac{\alpha\beta e^{-\frac{x}{\alpha\delta}}}{(\alpha+\beta x)^2}dx &=\int_0^z\left(\alpha e^{-\frac{x}{\alpha\delta}}\right)d\left(\frac{-1}{\alpha+\beta x}\right)\\ &=\left.\frac{-\alpha e^{-\frac{x}{\alpha\delta}}}{\alpha+\beta x}\right|_0^z-\int_0^z\frac{e^{-\frac{x}{\alpha\delta}}}{(\alpha+\beta x)\delta}dx\\ &=1-\frac{\alpha e^{-\frac{z}{\alpha\delta}}}{\alpha+\beta z}-\int_0^z\frac{e^{-\frac{x}{\alpha\delta}}}{(\alpha+\beta x)\delta}dx\end{aligned} \tag{26}$$

We can get the following expression by substituting Eq. (26) into Eq. (25)

$$F_z(z)=1-\frac{\alpha}{\alpha+\beta z}\exp\left(-\frac{z}{\alpha\delta}\right). \tag{27}$$

Let $\mathbf{x} = P_C g_{i,B}$, $\mathbf{y} = N_0 + P^d_{j,i} \cdot g_{j,B}$ and $\delta=\frac{1}{N_0}$. The desired result in Eq. (9) can be obtained. Similarly, the desired Eq. (10) can be obtained.

REFERENCES

1. K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communication Magazine*, Vol. 47, 2009, pp. 42-49.
2. G. Fodor *et al.*, "Design aspects of network assisted device-to-device communications," *IEEE Communication Magazine*, Vol. 50, 2012, pp. 170-177.
3. X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE Communication Magazine*, Vol. 52, 2014, pp. 40-48.
4. B. Kaufman, J. Lilleberg, and B. Aazhang, "Spectrum sharing scheme between cellular users and ad-hoc device-to-device users," *IEEE Transactions on Wireless Communications*, Vol. 12, 2013, pp. 1038-1049.
5. H. Meshgi, D. Zhao, and R. Zheng, "Joint channel and power allocation in underlay multicast device-to-device communications," in *Proceedings of IEEE International Conference on Communications*, 2015, pp. 2937-2942.
6. W. Lili, Y. Qian, and G. Wu, "Energy-efficiency and spectrum-efficiency of multi-hop device-to-device communications underlaying cellular networks," *IEEE Transactions on Vehicular Technology*, Vol. 65, 2015, pp. 367-380.
7. H. Tuong Duc, L. Long Bao, and T. Le-Ngoc, "Energy-efficient resource allocation

for D2D communications in cellular networks," *IEEE Transactions on Vehicular Technology*, Vol. 65, 2016, pp. 6972-6986.
8. J. Yanxiang, L. Qiang, Z. Fuchun, and C. Xiqi, "Energy-efficient joint resource allocation and power control for D2D communications," *IEEE Transactions on Vehicular Technology*, Vol. 68, 2016, pp. 6119-6127.
9. H. Min, W. Seo, J. Lee, S. Park, and D. Hong, "Reliability improvement using receive mode selection in the device-to-device uplink period underlaying cellular networks," *IEEE Transactions on Wireless Communications*, Vol. 10, 2011, pp. 413-418.
10. S. Alamouti and A. Sharafat, "Resource allocation for energy-efficient device-to-device communication in 4G networks," in *Proceedings of International Symposium on Telecommunications*, 2014, pp. 1058-1063.
11. G. Miao, N. Himayat, G. Y. Li, and S. Talwar, "Distributed interference-aware energy-efficient power optimization," *IEEE Transactions on Wireless Communications*, Vol. 10, 2011, pp. 1323-1333.
12. D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-to-device communications underlaying cellular networks," *IEEE Transactions on Communications*, Vol. 61, 2013, pp. 3541-3551.
13. C. Yin, Y. Wang, L. Wenxuan, and X. Wang, "Energy-efficient channel reusing for device-to-device communications underlaying cellular networks," in *Proceedings of Vehicular Technology Conference*, 2014, pp. 1-5.
14. A. Papoulis and S. U. Pillai, *Probability, Random Variables and Stochastic Process*, 4th ed., McGraw-Hill, Singapore, 2002.

Bao-Zhou Yu (于宝舟) was born in Jiangsu Province, China, in 1991. He received the B.E. degree in Communication Engineering from Nantong University, Nantong, in 2014. He is now pursuing master's degree in the Department of Communication and Information Engineering. He researches on the area of resource management and power control of D2D communication underlaying cellular networks.

Qi Zhu (朱琦) was born in Suzhou, Jiangsu, China, in 1965. She received the M.S. degree in Radio Engineering from Nanjing University of Posts and Telecommunications in 1989. Now she is a Professor in the Department of Telecommunication and Information Engineering, Nanjing University of Posts and Telecommunications, Jiangsu, China. Her research interests focus on technology of next generation communication, broadband wireless access, OFDM, channel and source coding, dynamic allocation of radio resources.