Joint Spectrum and Power Allocation for Green D2D Communication with Physical Layer Security Consideration

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Abstract

In this paper, we consider cooperative D2D communications in cellular networks. More precisely, a cellular user leases part of its spectrum to facilitate the D2D communication with a goal of improving the energy efficiency of a D2D pair. However the D2D pair is untrusted to the cellular user, such resource sharing may result in the information of this cellular user unsecured. In order to motivate the cellular user's generosity, this D2D pair needs to help the cellular user maintain a target secrecy rate. To address this issue, we formulate a joint spectrum and power allocation problem to maximize the energy efficiency of the D2D communication while guaranteeing the physical layer security of the cellular user. Then, a theorem is proved to indicate the best resource allocation strategy, and accordingly, an algorithm is proposed to find the best solution to this resource allocation problem. Numerical results are finally presented to verify the validity and effectiveness of the proposed algorithm.

Keywords: Untrusted relay, physical layer security, device-to-device communication, energy efficiency

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1. Introduction

With the explosive growth of wireless traffic and service variety, wireless users increasingly need higher data rates, lower energy consumption and higher level of security. However, the limited spectrum and energy resources may well hinder to fulfill such needs.

Firstly, nowadays wireless users require much higher data rate to support various impending service requirement, such as video conversation, multimedia sharing and so on. On the other hand, to obtain high data rate using more spectrum resource is becoming more and more impractical. The wireless spectrum proper for cellular communications is becoming denser and denser due to the explosively growing wireless service subscribers and techniques. Secondly, battery powered wireless users are more sensitive to energy consumption, all the more so when the current wireless services is much easier to consume more energy compared to the traditional voice calls. As such, to effectively use the precious spectrum and energy resources is becoming more and more pressing. Researchers are racking their brains to think how to confront these challenges.

Among the numerous solutions, Device-to-Device (D2D) communications have drawn much attention from both academia and industry in the last few years [1-4]. D2D communication sanctions two cellular users in proximity the viable access of licensed cellular spectrum under the control of the cellular network infrastructure. Then, the two cellular users can directly transmit data while bypassing the base station (BS). Consequently, the network traffic can be offloaded. Besides, D2D communication may bring high data rate and low energy consumption due to the proximity between the wireless users. And the resource utilization efficiency may be boosted due to the possible resource reuse between the D2D communications and the traditional cellular communications.

Meanwhile, due to the openness of nowadays wireless systems, the security of wireless users' confidential information has been receiving much attention. Security problem becomes much more severe especially when spectrum sharing is permitted. From the perspective of the physical layer security for a D2D communication system, there may exist an eavesdropper who is trying to wiretap the confidential data information of cellular users via the D2D pairs. Fortunately, D2D communication may help to guarantee the transmission of the confidential data, and then the level of the security for the cellular user may be improved. In this context, effective resource allocation becomes vital to realize the benefits of D2D communications while insuring the secure of cellular communications.

Resource allocation problem in D2D communications has been widely discussed in related work [5-10]. The authors of Ref. [5] and Ref. [6] investigate the coalition formation based energy efficiency enhancement scheme in multiple-user D2D systems. Ref. [7] proposes a distributed power allocation algorithm to enhance the energy efficiencies of both cellular users and D2D pairs based on non-cooperative game, besides the authors also investigate the tradeoff between energy efficiency and spectrum efficiency. All these work does not consider the problem of security, which is necessitate to be discussed when spectrum sharing is sanctioned. Furthermore, they do not consider the possible cooperation between cellular communication and D2D communication.

Ref. [8] introduces D2D communication to the problem of secrecy capacity. It maximizes the achievable data rate of D2D communication through deriving the optimal transmission power and access control of D2D communication, while keeping the secrecy outage probability under a certain threshold. In order to enhance the sum secrecy rate of multiple cellular users, the authors of [9] utilize Stackelberg game to allocate the transmit power of a D2D pair on the multiple cellular channels. A matching problem of the radio resource allocation for physical layer security in D2D underlay communications is formulated in [10] by using a Kuhn-Munkres algorithm. The above studies consider the impact on system secrecy capacity with D2D communication reusing the cellular spectrum. They all assume there exists single or multiple malicious wiretapping nodes and neglect the odds of eavesdropping between wireless entities who share the same spectrum.

On the other hand, secure communications in cooperative systems are investigated in [11-15]. Still in [11] and [12], special eavesdropper is assumed. The relays are all deployed as friendly jammers or beamformers, completely helping to enhance the secrecy rate of the communication. Differently, untrusted relays are investigated in [13-15], which may act as an eavesdropper itself or be wiretapped by a malicious eavesdropper. Due to the openness of modern wireless communication systems and the thriving of the concept of user cooperation, it is of much value to investigate the untrusted relays. However, most of the works seldom consider the cooperation among different coequal users, who have their respective communication requirements. What is more, the energy efficient resource allocation analysis under secrecy constraints is lacking.

In this paper, joint spectrum and power allocation scheme for energy efficient cooperative D2D communication is considered. The spectrum of cellular communications is reused by D2D communications due to the spectrum scarcity. Because of the spectrum reuse, cellular user's confidential message is threatened to be wiretapped through or by the corresponding D2D user. This secure problem is considered from a physical layer security perspective. And the D2D user is asked to relay the cellular user's message in order to guarantee a target secrecy rate. The objective of this paper is to determine a joint spectrum and power allocation scheme which can induce the best energy efficiency for the D2D pair, while guaranteeing the cellular user a target secrecy rate. We propose a theorem to show where the optimal resource allocation scheme maximizing the energy efficiency of the D2D pair lies. According to this theorem, an algorithm of low complexity to determine the best joint resource allocation scheme is designed.

The remainder of this paper is outlined as follows. Section 2 gives the discussed system model and describes the optimization problem. After that, we propose a theorem and an algorithm to determine the optimal resource allocation scheme in Section 3. In Section 4, numerical results and discussions are provided to verify the theorem and the algorithm. A conclusion of this paper is given in Section 5.

2. System Model and Problem Description

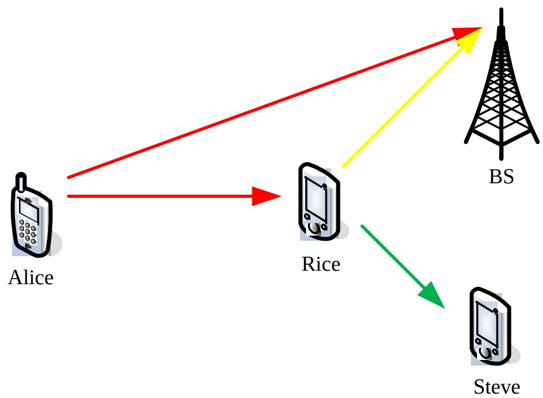

Fig. 1. System model

In this paper, a cooperative system consisting of a cellular user and a D2D pair is investigated as shown in **Fig. 1**. Here, we refer to two cellular users that can communicate with each other under the coordination by the network infrastructure as a D2D pair. The uplink cellular user Alice transmits confidential message to the base station (BS), while the D2D pair comprising Rice and Steve wants to reuse Alice's spectrum to communicate due to the spectrum scarcity in the cell.

A target secrecy rate of Alice must be firstly satisfied. After that, Alice is willing to cooperatively share his spectrum resource with Rice to help Rice to obtain high energy efficiency. On the other hand, Rice is asked to act as an amplify-and-forward (AF) relay for Alice to fulfill the secrecy rate requirement. Based on this configuration, Rice uses the spectrum of Alice to communicate with Steve through a device-to-device communication manner. Rice is assumed to be an untrusted relay to Alice, which means the confidential message of Alice is threatened to be eavesdropped through or by Rice.

Rice and Alice use Alice's spectrum resource through a temporally orthogonal manner. Assume that the holistic time duration is divided into two stages, i.e., the helping stage which persists for α and the self-transmitting stage with a duration of $1-\alpha$ $(0<\alpha<1)$. The transmit power level of Alice is p_0. And Rice's transmit power levels are p_1 and p_2 in the helping stage and in the self-transmitting stage, respectively. We further assume that $p_1 \le p_{\max}$ and $p_2 \le p_{\max}$, where $p_{\max}$ is the maximum transmit power of Rice. Denote the channel coefficient from terminal i to terminal j as h_{ij}, and then the corresponding channel gain can be written as $g_{ij} = \left|h_{ij}\right|^2$, where $i \in \{\text{A, R}\}$, $j \in \{\text{R, B, S}\}$ (A is short for Alice, R for Rice, B for BS, and S for Steve). g_{ij} is in direct proportion to d_{ij}^{-n}, where d_{ij} is the distance between i and j, and n is the path loss factor.

Base on amplify-and-forward (AF) cooperation mode, the achievable data rates of Rice (which is equivalent to the eavesdropping rate), the cellular communication and Steve are respectively

$$r_{\mathrm{E}} = \alpha \log_2 \left(1 + \mathrm{SNR}_{\mathrm{R}}\right) \tag{1}$$

$$r_{\mathrm{B}} = \alpha \log_2 \left(1 + \mathrm{SNR}_{\mathrm{B}}\right) \tag{2}$$

$$r_{\mathrm{S}} = (1-\alpha) \log_2 \left(1 + \mathrm{SNR}_{\mathrm{S}}\right) \tag{3}$$

where $\mathrm{SNR}_{\mathrm{R}} = \frac{p_0 g_{\mathrm{AR}}}{\sigma^2}$ is the received signal-to-noise ratio at Rice, $\mathrm{SNR}_{\mathrm{B}} = \frac{p_0 g_{\mathrm{AB}}}{\sigma^2} + \frac{p_0 g_{\mathrm{AR}} p_1 g_{\mathrm{RB}}}{\sigma^2 \left(\sigma^2 + p_0 g_{\mathrm{AR}} + p_1 g_{\mathrm{RB}}\right)}$ and $\mathrm{SNR}_{\mathrm{S}} = \frac{p_2 g_{\mathrm{RS}}}{\sigma^2}$ are those at BS and Steve in the two stages, respectively. And σ^2 is the variance of the thermal noise.

As a result, the achievable secrecy rate of Alice is given by

$$r_{\mathrm{sec}} = \left(r_{\mathrm{B}} - r_{\mathrm{E}}\right)^{+} \tag{4}$$

In this paper, we consider the practical case in which the system can be designed so that the secrecy rate is positive. Hence, the achievable secrecy rate can be rewritten as

$$\begin{aligned} r_{\mathrm{sec}} &= r_{\mathrm{B}} - r_{\mathrm{E}} \\ &= \alpha \log_2 \left(1 + \mathrm{SNR}_{\mathrm{B}}\right) - \alpha \log_2 \left(1 + \mathrm{SNR}_{\mathrm{R}}\right) \\ &= \alpha \log_2 \left(\frac{\sigma^2 + p_0 g_{\mathrm{AB}}}{\sigma^2 + p_0 g_{\mathrm{AR}}} + \frac{p_0 g_{\mathrm{AR}} p_1 g_{\mathrm{RB}}}{\left(\sigma^2 + p_0 g_{\mathrm{AR}} + p_1 g_{\mathrm{RB}}\right)\left(\sigma^2 + p_0 g_{\mathrm{AR}}\right)} \right) \end{aligned} \tag{5}$$

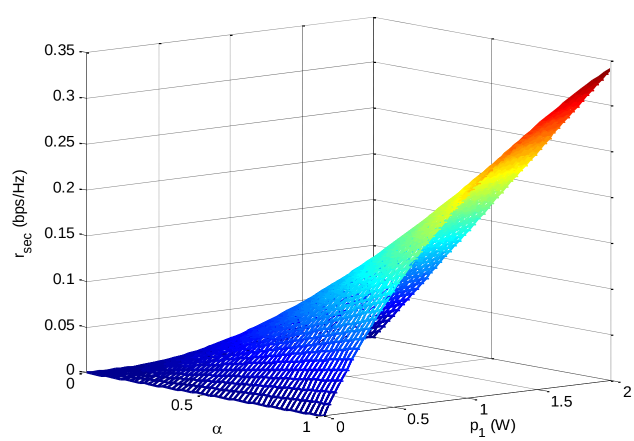

Fig. 2. The achievable secrecy rate r_{sec} with respect to p_1 and α .

Fig. 2 depicts $r_{\sec}=r_{\sec}(\alpha,p_1)$ in under a certain system setting with $\mathrm{SNR_B}>\mathrm{SNR_R}$. $r_{\sec}$ is monotonically increasing with respect to either p_1 or α, which tallies with the first derivatives of $r_{\sec}$ to p_1 and α: Eq. (6) and Eq. (7). When a target secrecy rate $r_{\sec}^{\mathrm{th}}$ is set, it will induce a region of α and p_1: $\left\{(\alpha,p_1):r_{\sec}(\alpha,p_1)\geq r_{\sec}^{\mathrm{th}}\right\}$, which is the feasible region of p_1 and α for the given target secrecy rate.

$$\frac{\partial r_{\sec}}{\partial\alpha}=\log_2\left(\frac{\sigma^2+p_0g_{\mathrm{AB}}}{\sigma^2+p_0g_{\mathrm{AR}}}+\frac{\sigma^2p_0g_{\mathrm{AR}}p_1g_{\mathrm{RB}}}{\left(\sigma^2+p_0g_{\mathrm{AR}}+p_1g_{\mathrm{RB}}\right)\left(\sigma^2+p_0g_{\mathrm{AR}}\right)}\right)>0 \tag{6}$$

$$\frac{\partial r_{\sec}}{\partial p_1}=\frac{\alpha\dfrac{\sigma^2p_0g_{\mathrm{AR}}g_{\mathrm{RB}}\left(\sigma^2+p_0g_{\mathrm{AR}}\right)\left(\sigma^2+p_0g_{\mathrm{AR}}\right)}{\left(\left(\sigma^2+p_0g_{\mathrm{AR}}+p_1g_{\mathrm{RB}}\right)\left(\sigma^2+p_0g_{\mathrm{AR}}\right)\right)^2}\log_2 e}{\dfrac{\sigma^2+p_0g_{\mathrm{AB}}}{\sigma^2+p_0g_{\mathrm{AR}}}+\dfrac{\sigma^2p_0g_{\mathrm{AR}}p_1g_{\mathrm{RB}}}{\left(\sigma^2+p_0g_{\mathrm{AR}}+p_1g_{\mathrm{RB}}\right)\left(\sigma^2+p_0g_{\mathrm{AR}}\right)}}>0 \tag{7}$$

This paper tries to maximize the energy efficiency of the D2D pair Rice and Steve with the fulfillment of a target secrecy rate $r_{\sec}^{\mathrm{th}}$ of Alice. Different from [16], wherein the authors investigate the energy optimization problem for wireless access networks as a whole, we focus on the energy consumption of individual wireless devices in this paper. And both the transmit power consumption and circuit power consumption are considered. The Rice's energy consumptions during the helping and self-transmitting stages are $\varepsilon_h=\alpha\left(p_{\mathrm{cr}}+p_1+p_{\mathrm{ct}}\right)$ and $\varepsilon_s=(1-\alpha)\left(p_2+p_{\mathrm{ct}}+p_{\mathrm{cr}}\right)$, respectively. Hence, the energy efficiency of the D2D pair can be given by

$$\zeta=\zeta(\alpha,p_1,p_2)=\frac{r_{\mathrm{S}}}{\varepsilon_h+\varepsilon_s}=\frac{r_{\mathrm{S}}}{\alpha p_1+(1-\alpha)p_2+p_{\mathrm{C}}} \tag{8}$$

where $p_{\mathrm{C}}=p_{\mathrm{ct}}+p_{\mathrm{cr}}$, p_{ct} and p_{cr} are the consumed power levels at the transmitter and the receiver, respectively.

Therefore, the optimization problem can be formulated as

$$\max_{\alpha,p_1,p_2}\quad \zeta=\zeta(\alpha,p_1,p_2) \tag{9}$$

$$s.t.\ \begin{cases} r_{\sec} \geq r_{\sec}^{\mathrm{th}} \\ 0 < \alpha \leq 1 \\ 0 \leq p_1 \leq p_{\max} \\ 0 \leq p_2 \leq p_{\max} \end{cases} \tag{10}$$

We only discuss the scenario that $r_{\sec}(1, p_{\max}) \geq r_{\sec}^{\mathrm{th}}$ holds.

Note that, the incentive mechanism for the cellular user is not considered in this paper. What is more, we only investigate a simple system with one cellular user and one D2D pair. When considering these two aspects, the joint resource allocation problem becomes a multi-objective problem. As such, game theory could be adapted to address this problem [5-6]; however, this is beyond the scope of our paper.

3. The Optimal Time and Power Allocation

In this section, we firstly propose a theorem to discuss the joint time and power allocation problem. After that, we propose an iterative algorithm to find the optimal solution resulting in the optimal energy efficiency of the D2D communication.

Theorem 1: The optimal energy efficiency of the D2D link ζ_{opt} can only be obtained when the equality in the first condition of Eq. (12) holds.

Proof: Given a target secrecy rate $r_{\sec}^{\mathrm{th}}$, according to **Fig. 2**, the contour line $r_{\sec} = r_{\sec}^{\mathrm{th}}$ represents a curve of the two dimension variable (α, p_1). Suppose that the joint optimal time division and power allocation strategy $(\tilde{\alpha}, \tilde{p}_1, \tilde{p}_2)$ maximizing the energy efficiency of the D2D link is not on the line $r_{\sec} = r_{\sec}^{\mathrm{th}}$, i.e., $r_{\sec}(\tilde{\alpha}, \tilde{p}_1) > r_{\sec}^{\mathrm{th}}$.

According to **Fig. 2**, there exist two points $(\tilde{\alpha}, p_1')$ and $(\alpha', \tilde{p}_1)$, which are on the line with $p' < \tilde{p}_1$ and $\alpha' < \tilde{\alpha}$. Given $(\tilde{\alpha}, p_1')$ and $(\alpha', \tilde{p}_1)$, the optimal transmit power levels from Rice to Steve are assumed to be p_2' and p_2'', respectively. Set

$$\frac{\partial \zeta}{\partial p_2} = \frac{\log_2 e}{\left(p_2 + \dfrac{\alpha p_1 + p_{\mathrm{C}}}{1-\alpha}\right)\left(p_2 + \dfrac{\sigma^2}{g_{\mathrm{RS}}}\right)} - \frac{\log_2\left(1 + \dfrac{p_2 g_{\mathrm{RS}}}{\sigma^2}\right)}{\left(p_2 + \dfrac{\alpha p_1 + p_{\mathrm{C}}}{1-\alpha}\right)^2} = 0 \tag{11}$$

We have,

$$\left(p_2 + \frac{\alpha p_1 + p_{\mathrm{C}}}{1-\alpha}\right)\log_2 e = \left(p_2 + \frac{\sigma^2}{g_{\mathrm{RS}}}\right)\log_2\left(1 + \frac{p_2 g_{\mathrm{RS}}}{\sigma^2}\right) \tag{12}$$

Denote $f\left(\alpha, p_1\right)=\dfrac{\alpha p_1+p_{\mathrm{C}}}{1-\alpha}$, $g\left(p_2\right)=\left(p_2+\dfrac{\sigma^2}{g_{\mathrm{RS}}}\right)\ln\left(1+\dfrac{p_2 g_{\mathrm{RS}}}{\sigma^2}\right)-p_2$, and then, the solution set of (12) contains the zero points of the following term

$$\Delta\left(p_2\right)=f\left(\alpha, p_1\right)-g\left(p_2\right) \tag{13}$$

Since $\Delta(0)=f\left(\alpha, p_1\right)>0$, $\lim\limits_{p_2\rightarrow+\infty}\Delta\left(p_2\right)<0$ and $\Delta'\left(p_2\right)=-\ln\left(1+\dfrac{p_2 g_{\mathrm{RS}}}{\sigma^2}\right)<0$, there exists only one zero point of $\Delta\left(p_2\right)$, which can be denoted as $\hat{p}_2=\hat{p}_2\left(\alpha, p_1\right)$. When $p_2<\hat{p}_2$, $\Delta\left(p_2\right)>0$, $\dfrac{\partial\zeta}{\partial p_2}>0$ holds, otherwise $\dfrac{\partial\zeta}{\partial p_2}<0$ holds. Consequently, the optimal transmit power levels that maximize the energy efficiency of the D2D link given $\left(\tilde{\alpha}, \tilde{p}_1\right)$, $\left(\tilde{\alpha}, p_1'\right)$ and $\left(\alpha', \tilde{p}_1\right)$ can be obtained by

$$\tilde{p}_2=\tilde{p}_2\left(\tilde{\alpha}, \tilde{p}_1\right)=\min\left(p_{\max}, \hat{p}_2\left(\tilde{\alpha}, \tilde{p}_1\right)\right) \tag{14}$$

$$p_2'=p_2'\left(\tilde{\alpha}, p_1'\right)=\min\left(p_{\max}, \hat{p}_2\left(\tilde{\alpha}, p_1'\right)\right) \tag{15}$$

$$p_2''=p_2''\left(\tilde{\alpha}, p_1'\right)=\min\left(p_{\max}, \hat{p}_2\left(\alpha', \tilde{p}_1\right)\right) \tag{16}$$

When the optimal transmit power equals to $p_{\max}$, the optimal energy efficiency of the D2D communication is

$$\zeta_{opt}=\zeta\left(\alpha, p_1, p_{\max}\right)=\frac{\log_2\left(1+\dfrac{p_{\max} g_{\mathrm{RS}}}{\sigma^2}\right)}{p_{\max}+f\left(\alpha, p_1\right)} \tag{17}$$

While if the optimal power equals to $\hat{p}_2\left(\alpha, p_1\right)$, the optimal energy efficiency yields,

$$\zeta_{opt}=\zeta\left(\alpha, p_1, \hat{p}_2\left(\alpha, p_1\right)\right)=\frac{\log_2\left(1+\dfrac{\hat{p}_2 g_{\mathrm{RS}}}{\sigma^2}\right)}{\hat{p}_2\left(\alpha, p_1\right)+f\left(\alpha, p_1\right)}=\frac{\log_2 e}{\hat{p}_2\left(\alpha, p_1\right)+\dfrac{\sigma^2}{g_{\mathrm{RS}}}} \tag{18}$$

Since we have $\frac{\partial f(\alpha, p_1)}{\partial \alpha} > 0$, $\frac{\partial f(\alpha, p_1)}{\partial p_1} > 0$ and $\frac{\mathrm{d}g(p_2)}{\mathrm{d}p_2} > 0$, $\hat{p}_2(\tilde{\alpha}, \tilde{p}_1) > \hat{p}_2(\tilde{\alpha}, p_1')$ and $\hat{p}_2(\tilde{\alpha}, \tilde{p}_1) > \hat{p}_2(\alpha', \tilde{p}_1)$ hold. Without loss of generality, let us compare the resultant energy efficiencies obtained by $(\tilde{\alpha}, \tilde{p}_1)$ and $(\tilde{\alpha}, p_1')$. Firstly, if $\hat{p}_2(\tilde{\alpha}, \tilde{p}_1) \le p_{\max}$, then the energy efficiencies corresponding to is $(\tilde{\alpha}, \tilde{p}_1)$ and $(\tilde{\alpha}, p_1')$ are respectively $\zeta(\tilde{\alpha}, \tilde{p}_1) = \frac{\log_2 e}{\hat{p}_2(\tilde{\alpha}, \tilde{p}_1) + \frac{\sigma^2}{g_{\mathrm{RS}}}}$ and $\zeta(\tilde{\alpha}, p_1') = \frac{\log_2 e}{\hat{p}_2(\tilde{\alpha}, p_1') + \frac{\sigma^2}{g_{\mathrm{RS}}}}$, so $\zeta(\tilde{\alpha}, \tilde{p}_1) < \zeta(\tilde{\alpha}, p_1')$.

Secondly, if $\hat{p}_2(\alpha', \tilde{p}_1) \ge p_{\max}$, then $\zeta(\tilde{\alpha}, \tilde{p}_1)$ and $\zeta(\tilde{\alpha}, p_1')$ are respectively $\zeta(\tilde{\alpha}, \tilde{p}_1) = \frac{\log_2\left(1 + \frac{p_{\max} g_{\mathrm{RS}}}{\sigma^2}\right)}{p_{\max} + f(\tilde{\alpha}, \tilde{p}_1)}$ and $\zeta(\tilde{\alpha}, p_1') = \frac{\log_2\left(1 + \frac{p_{\max} g_{\mathrm{RS}}}{\sigma^2}\right)}{p_{\max} + f(\tilde{\alpha}, \tilde{p}_1)}$. As $\frac{\partial f(\alpha, p_1)}{\partial p_1} > 0$ and $\tilde{p}_1 > p_1'$, we have $\zeta(\tilde{\alpha}, \tilde{p}_1) < \zeta(\tilde{\alpha}, p_1')$. Lastly, if $\hat{p}_2(\tilde{\alpha}, \tilde{p}_1) > p_{\max} \ge \hat{p}_2(\tilde{\alpha}, p_1')$, then the energy efficiencies corresponding to $(\tilde{\alpha}, \tilde{p}_1)$ and $(\tilde{\alpha}, p_1')$ are $\zeta(\tilde{\alpha}, \tilde{p}_1) = \frac{\log_2\left(1 + \frac{p_{\max} g_{\mathrm{RS}}}{\sigma^2}\right)}{p_{\max} + f(\tilde{\alpha}, \tilde{p}_1)}$ and $\zeta(\tilde{\alpha}, p_1') = \frac{\log_2\left(1 + \frac{\hat{p}_2(\tilde{\alpha}, p_1') g_{\mathrm{RS}}}{\sigma^2}\right)}{\hat{p}_2(\tilde{\alpha}, p_1') + f(\tilde{\alpha}, p_1')} > \frac{\log_2\left(1 + \frac{p_{\max} g_{\mathrm{RS}}}{\sigma^2}\right)}{p_{\max} + f(\tilde{\alpha}, p_1')}$, consequently, $\zeta(\tilde{\alpha}, \tilde{p}_1) < \zeta(\tilde{\alpha}, p_1')$.

To sum up, we will always have $\zeta(\tilde{\alpha}, \tilde{p}_1) < \zeta(\tilde{\alpha}, p_1')$. Following the same steps, we can also prove that $\zeta(\tilde{\alpha}, \tilde{p}_1) < \zeta(\alpha', \tilde{p}_1)$. These results all contradicts with the optimality of the point $(\tilde{\alpha}, \tilde{p}_1, \tilde{p}_2)$. In other words, $(\tilde{\alpha}, \tilde{p}_1, \tilde{p}_2)$ cannot be the optimal point if it is not on line $r_{\sec} = r_{\sec}^{\mathrm{th}}$. The Theorem is proven. ■

Based on the theorem, we give the following algorithm to find the optimal joint spectrum and power allocation scheme in **Table 1**.

Table 1. Algorithm to the optimal resource allocation

Step 1: Ascertain the minimum p_1 by $r_{\sec}(1, p_{\min}) = r_{\sec}^{\mathrm{th}}$. Set the search density as N, and then the search granularity is $\delta = (p_{\max} - p_{\min})/N$. Set $\tau = 1$.

Step 2: Set $p_1^0 = p_{\max}$, derive α^0 from $r_{\sec}(\alpha^0, p_1^0) = r_{\sec}^{\mathrm{th}}$. Find the optimal transmit power of the self-transmitting stage: if $\Delta(p_{\max}) \ge 0$, set $p_2^0 = p_{\max}$; otherwise, set $p_2^0 = \hat{p}_2^0$, where $\hat{p}_2^0$ enables $\Delta(\hat{p}_2^0) = 0$ and can be found by Newton method.

Obtain $\zeta^0 = \zeta\left(\alpha^0, p_1^0, p_2^0\right)$. Set $\zeta_{\text{opt}} = \zeta^0$.

Step 3: Set $p_1^\tau = p_1^0 - \tau\delta$, derive $\left(\alpha^\tau, p_1^\tau, p_2^\tau\right)$ following the procedures in Step 2, and then drive ζ^τ. If $\zeta^\tau \geq \zeta_{\text{opt}}$, set $\zeta_{\text{opt}} = \zeta^\tau$, set $\tau_{\text{opt}} = \tau$. If $\tau \leq N-1$, let $\tau = \tau + 1$, repeat Step 3.

Step 4: Output $\left(\alpha^{\tau_{\text{opt}}}, p_1^{\tau_{\text{opt}}}, p_2^{\tau_{\text{opt}}}\right)$ and the corresponding ζ_{opt} as the optimal resource allocation scheme and the D2D link's optimal energy efficiency.

Firstly, given a target secrecy rate $r_{\text{sec}}^{\text{th}}$, for some pair of (α, p_1), the proposed algorithm utilizes Newton method to find out the optimal transmit power p_2 in the self-transmitting stage based on Eq. (14). Secondly, by a density of N, we search on the line $r_{\text{sec}} = r_{\text{sec}}^{\text{th}}$ to find the optimal pair of $\left(\alpha^{\tau_{\text{opt}}}, p_1^{\tau_{\text{opt}}}\right)$ and then the joint resource allocation scheme $\left(\alpha^{\tau_{\text{opt}}}, p_1^{\tau_{\text{opt}}}, p_2^{\tau_{\text{opt}}}\right)$ which maximizes the energy efficiency of the D2D link.

4. Numeric Results and Discussion

In this section, we present some numerical results to evaluate the theorem and the algorithm. During our simulation, we assume the normalized transmit power of Alice is $p_0 = 2$ W, the maximal normalized transmit power of Rice is $p_{\max} = 2$ W, and the normalized variance of the thermal noise is $\sigma^2 = 1$. As to the circuit power consumption, we assume $p_{ct} = p_{cr} = 0.2$ W. The path loss factor is assumed to be $n = 3$. The values of these simulation parameters are mainly inspired by [15].

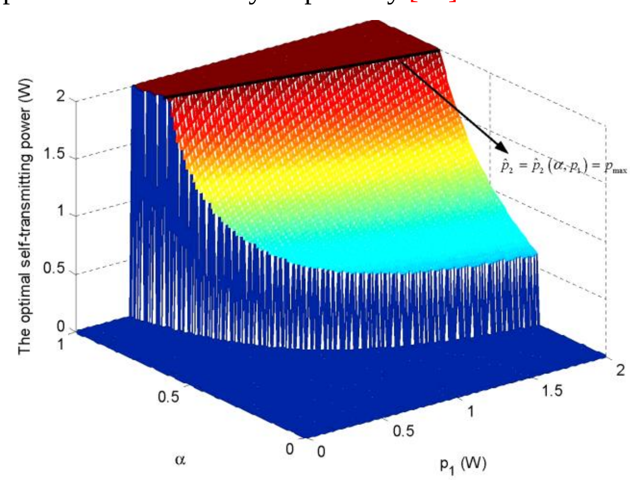

Fig. 3. The optimal self-transmitting power versus (α, p_1)

Fig. 3 depicts the optimal self-transmitting power $\tilde{p}_2$ of Rice corresponding to the helping transmit power p_1 and the time division factor α. The target secrecy rate is $r_{\mathrm{sec}}^{\mathrm{th}} = 0.1\mathrm{bps/Hz}$. $\tilde{p}_2$ is set to be zero and coloured in blue for those (α, p_1) that can not guarantee $r_{\mathrm{sec}}(\alpha, p_1) \geq r_{\mathrm{sec}}^{\mathrm{th}}$. This figure verifies some results in the proposed theorem. As discussed in the theorem, when (α, p_1) satisfies $\Delta(p_{\max}) \geq 0$ ($\Delta(\cdot)$ is given by Eq. (13)), the energy efficiency monotonously increases with the self-transmitting power, and as a result, $\tilde{p}_2 = p_{\max}$ is the desired solution optimizing the energy efficiency of the D2D pair. While if $\Delta(p_{\max}) < 0$, the optimal self-transmitting power $\tilde{p}_2$ can be derived by $\Delta(p_2) = 0$, which is denoted as $\hat{p}_2 = \hat{p}_2(\alpha, p_1)$. Besides, when $\tilde{p}_2 = \hat{p}_2$, the optimalself-transmitting power increases with both α and p_1, which can be also identified in the theorem.

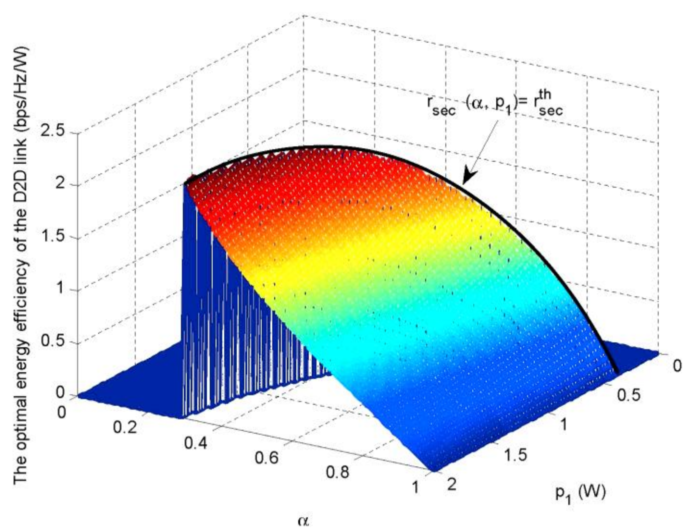

Fig. 4. The optimal energy efficiency of the D2D link versus (α, p_1)

Fig. 4 gives the optimal energy efficiency ζ_{opt} of the D2D link with respect to p_1 and α, where the target secrecy rate is also set to $r_{\mathrm{sec}}^{\mathrm{th}} = 0.1\mathrm{bps/Hz}$. The optimal selt-transmitting power $\tilde{p}_2$ is firstly obtained according to **Fig. 3**. Then ζ_{opt} is determined by Eq. (8). It indicates that ζ_{opt} is monotonously decreases with both α and p_1. According to the Theorem, the resource allocation scheme inducing the optimal energy efficiency lies on the black line $r_{\mathrm{sec}}(\alpha, p_1) = r_{\mathrm{sec}}^{\mathrm{th}} = 0.1\mathrm{bps/Hz}$. Our proposed algorithm is to search on this line for the global optimal energy efficiency.

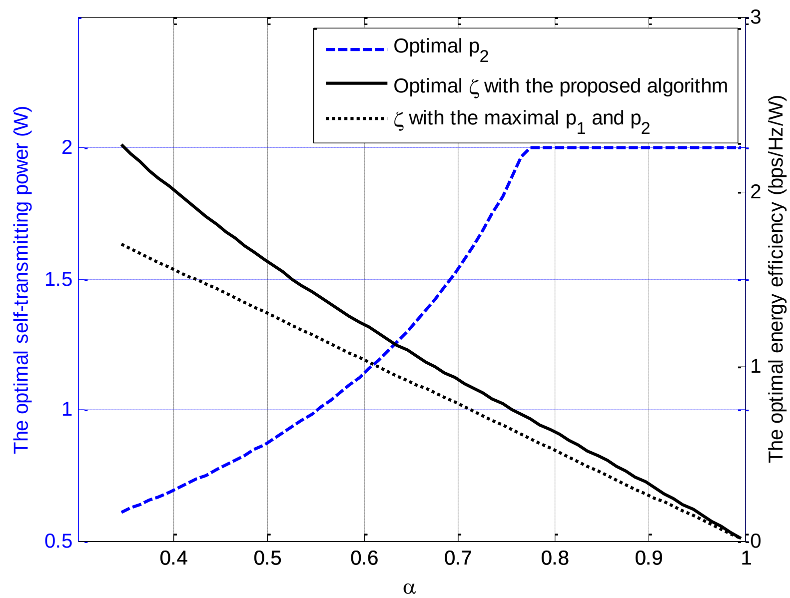

Fig. 5. The optimal self-transmitting power and energy efficiency versus α

Fig. 5 compares the energy efficiencies obtained by the proposed algorithm and the maximal transmit power scheme given $p_1 = 1.5\,\mathrm{W}$ and $r_{\sec}^{\mathrm{th}} = 0.1\,\mathrm{bps/Hz}$. It also shows the optimal self-transmitting power $\tilde{p}_2$ by the blue dashed line. From $r_{\sec}\left(\alpha_{\min}, p_1\right) = r_{\sec}^{\mathrm{th}}$, we can obtain the minimal $\alpha_{\min} \approx 0.35$. The required secrecy rate for the cellular user can be guaranteed only when $\alpha \geq \alpha_{\min}$. The optimal self-transmitting power rises to $\tilde{p}_2 = p_{\max}$ when $\alpha = 0.77$, and $\left(\alpha, p_1\right) = \left(0.77,\ 1.5\right)$ lies on the line $\hat{p}_2 = \hat{p}_2\left(\alpha, p_1\right) = p_{\max}$ shown in **Fig. 3**. When $\alpha_{\min} \leq \alpha \leq 0.77$, $\Delta\left(p_{\max}\right) \leq 0$ and $\tilde{p}_2$ is the solution of $\Delta\left(p_2\right) = 0$, which increases with α. Once $\alpha \geq 0.77$, we have $\Delta\left(p_{\max}\right) \geq 0$ and $\tilde{p}_2 = p_{\max}$. On the other hand, the energy efficiency with maximal $p_1 = p_{\max}$ and $p_2 = p_{\max}$ is also depicted by the black dotted line in this figure. Obviously, the proposed algorithm can yield higher energy efficiency compared to the scheme with the maximal transmit power. In addition, ζ_{opt} is monotonously decreasing versus α, which is consistent with the results in Eq. (18), Eq. (19), **Fig. 3** and **Fig. 4**.

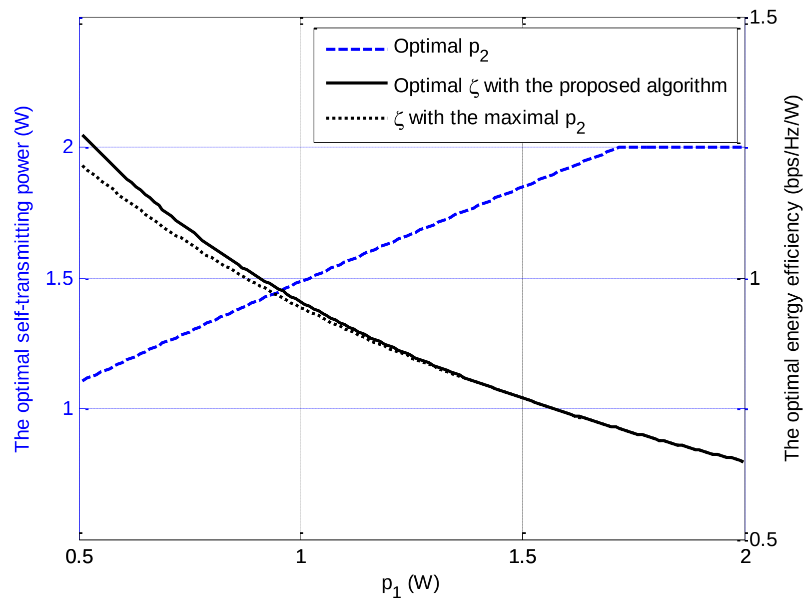

Fig. 6. The optimal self-transmitting power and energy efficiency versus p_1

Fig. 6 compares the energy efficiencies obtained by the proposed algorithm and the maximal transmit power scheme given $\alpha = 0.75$ and $r_{\text{sec}}^{\text{th}} = 0.1\,\text{bps/Hz}$. It also depicts the optimal self-transmitting power $\tilde{p}_2$ with respect to helping power p_1. From $r_{\text{sec}}(\alpha, p_{1\min}) = r_{\text{sec}}^{\text{th}}$, the minimal helping transmit power is $p_{1\min} = 0.51$ (W). Only when $p_1 \geq p_{1\min}$, can the secrecy rate requirement of the cellular user be satisfied. The optimal self-transmitting power rises to $\tilde{p}_2 = p_{\max}$ when $p = 1.7$, and $(\alpha, p_1) = (0.75,\ 1.7)$ lies on the line $\hat{p}_2 = \hat{p}_2(\alpha, p_1) = p_{\max}$ shown in **Fig. 3**. When $p_{1\min} \leq p_1 \leq 1.7$, $\Delta(p_{\max}) \leq 0$ and $\tilde{p}_2$ equals to $\hat{p}_2 = \hat{p}_2(\alpha, p_1)$, which increases with p_1. Once $p_1 \geq 1.7$, we have $\tilde{p}_2 = p_{\max}$. In addition, we also focus on the energy efficiency with maximal p_2. The proposed algorithm obtains higher energy efficiency compared to the scheme with the maximal p_2. ζ_{opt} decreases with p_1, which is consistent with Eq. (18), Eq. (19), **Fig. 3** and **Fig. 4**.

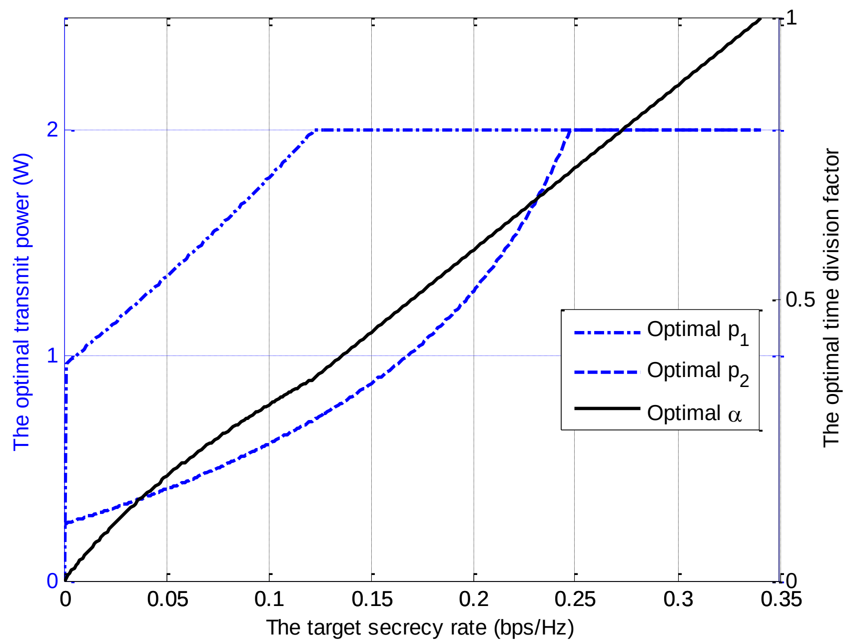

Fig. 7. The optimal α, p_1 and p_2 versus $r_{\mathrm{sec}}^{\mathrm{th}}$

Fig. 7 shows the optimal joint resource allocatioin scheme $(\tilde{\alpha}, \tilde{p}_1, \tilde{p}_2)$ for defferent target secracy rate $r_{\mathrm{sec}}^{\mathrm{th}}$. As proved by the theorem, the optimal resource allocation scheme is found on the curve $r_{\mathrm{sec}}(\alpha, p_1) = r_{\mathrm{sec}}^{\mathrm{th}}$. This figure indicates that $\tilde{p}_1$ and $\tilde{p}_2$ rise to be $p_{\max}$ successively when $r_{\mathrm{sec}}^{\mathrm{th}} = 0.12$ bps/Hz and 0.25 bps/Hz, respectively. The optimal helping power rises to be $p_{\max}$ in order to guarantee the increasing target secrecy rate for the cellular user. When $r_{\mathrm{sec}}^{\mathrm{th}}$ rises to be 0.25 bps/Hz, $\tilde{\alpha}$ and $\tilde{p}_1$ increase to such an extent that $\Delta(p_{\max})$ becomes non-negative, and hence the optimal self-transmitting power becomes $\tilde{p}_2 = p_{\max}$. The optimal $\tilde{\alpha}$ linearly increases with $r_{\mathrm{sec}}^{\mathrm{th}}$ when $r_{\mathrm{sec}}^{\mathrm{th}} \geq 0.12$. This is because $\tilde{\alpha}$ and $\tilde{p}_1 = p_{\max}$ satisfy $r_{\mathrm{sec}}(\tilde{\alpha}, \tilde{p}_1) = r_{\mathrm{sec}}^{\mathrm{th}}$.

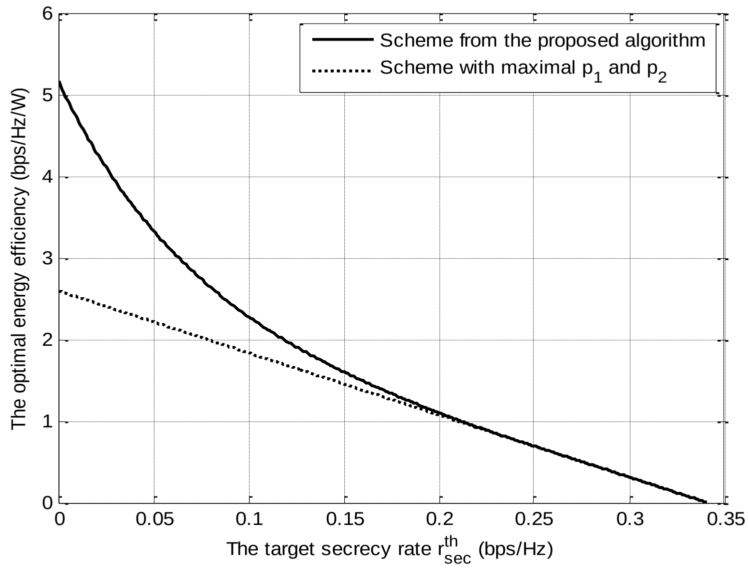

Fig. 8. The optimal ζ versus $r_{\text{sec}}^{\text{th}}$

Fig. 8 shows the energy efficiency for different target secrecy rate $r_{\text{sec}}^{\text{th}}$. Compared to the scheme with maximal p_1 and p_2, the proposed algorithm obtains better energy efficiency for the D2D link. The smaller $r_{\text{sec}}^{\text{th}}$ is, the more the proposed algorithm has the advantage. In small $r_{\text{sec}}^{\text{th}}$ region, given $p_1 = p_{\max}$, the optimal self-transmitting power $\tilde{p}_2$ is much smaller than $p_{\max}$ according to **Fig. 3**. In large $r_{\text{sec}}^{\text{th}}$ region, according to Fig. 7, $\tilde{p}_1$ and $\tilde{p}_2$ equal to $p_{\max}$. As a result, the proposed algorithm can obtain a better energy efficiency performance for small $r_{\text{sec}}^{\text{th}}$, and obtain equivalent energy efficiency to the scheme with maximal p_1 and p_2 for large $r_{\text{sec}}^{\text{th}}$.

5. Conclusion

In this paper, we analyze the energy efficiency of cooperative D2D communications in cellular networks. The spectrum and power resources are jointly allocated to obtain the best energy efficiency for the D2D pair and guarantee the cellular user a target secrecy data rate. Based on the theoretical analysis, we propose a low complex algorithm to induce the best resource allocation scheme. Extensive numerical experiments are presented to verify the propose algorithm. The results show that our proposed algorithm can dramatically improve the energy efficiency of the D2D pair compared with the maximal transmit power scheme.

The results in this paper can provide fundamental insights. Based on the results of this paper, the extension to the system with multiple cellular users and multiple D2D pairs can be considered. We would like to deal with this problem in future.

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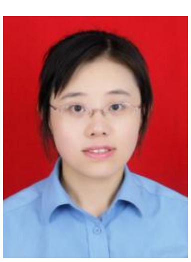

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