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A Two-Stage Energy-Efficient Approach for Joint Power Control and Channel Allocation in D2D Communication

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ABSTRACT A large number of mobile multimedia terminals are prominent features of smart cities. Device-to-device (D2D) communication takes advantage of the limited bandwidth resources of cellular networks to accommodate more mobile devices. However, when D2D pairs reuse cellular users channels, serious interference leads to energy consumption, which dissatisfies the requirements of green communication. This paper focuses on energy efficiency maximization of D2D communication under the constraints of both D2D pairs and cellular users quality of service. The formulated resource allocation problem is NP-hard, which is usually difficult to solve within polynomial time. To make the problem easy to handle, we divide it into power control and channel allocation sub-problems. In particular, we propose a power control algorithm based on the Lambert W function to maximize the energy efficiency of a single D2D pair. The preference values of D2D pairs and cellular users are calculated using the power control results, respectively. A channel allocation scheme based on the Gale–Shapley algorithm utilizes preference values to match two sides, which aims at maximizing the signal to interference plus noise ratio of cellular users and the energy efficiency of D2D pairs. The simulation results show that the proposed algorithm could not only guarantee the transmission rate of cellular users but also improve the system and D2D pairs energy efficiency.

INDEX TERMS Device-to-device (D2D) communication, cellular networks, energy efficiency, resource allocation, green communications.

I. INTRODUCTION

A. BACKGROUND

The construction of smart cities is being carried out on a large-scale. Conceptually, smart cities combine information technology with urban construction, which aim to efficiently exploit urban resources [1]–[5]. In recent years, the development of information and communication technology (ICT) (e.g., the Internet, cloud computing, big data, Internet of Things (IoT), and social networks) has greatly promoted the interconnection and intelligent integration of smart cities [3], [5]. However, the number of multimedia terminals has surged, accordingly, the intelligent information processing will be more complicated and time consuming. In the current society, the huge greenhouse gas emissions have caused global climate change to become more serious [6]–[8]. ICT industry energy consumption is growing at an alarming rate, while causing certain carbon dioxide emissions [7], [9]. Reducing energy consumption is not only beneficial to fighting climate change, but also promotes economic development. Nevertheless, there are still many challenges in achieving large-scale energy-saving equipment.

As one of the key technologies of 5G, device-to-device (D2D) communication is a short-distance low-power communication technology, which directly interacts information instead of transmitting by base station (BS) [10]–[12]. D2D communication can increase network capacity and improve spectrum efficiency in the cellular network, it is critical to achieve a large amount of information interaction in smart cities. One D2D pair includes a transmitter and a receiver. However, when D2D user equipment (DUE) reuses cellular user equipment (CUE) channel resources, the serious

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signal interference will be caused. If the interference is not eliminated by power control, system performance and battery life of customer premise equipment (CPE) will be reduced. Without a reasonable power coordination mechanism, energy consumption will restrict the development of D2D communication [5]. Thus, in the process of constructing smart city D2D communication, the emphasis should put on how to improve energy efficiency and reduce interference.

B. MOTIVATION

In different D2D communication scenarios, resource allocation algorithms are confronted with various key issues, and the optimization objectives are slightly different. Generally, it can be divided into two major categories, namely improving network performance and improving user performance. The former one includes user experience, reliability [13], fairness, and quality of service (QoS) [14]. The latter one contains energy efficiency [5], [12], spectrum efficiency [15], transmission rate [16], and throughput [11], [17]. With the explosive growth of mobile terminals, the green communication has become a research focus in various fields [18]. As mentioned earlier, improving energy efficiency can greatly promote the development of green communication. The energy consumption of a complete communication process includes transmission, computing and storage [19]–[22]. Compared with the latter two, we are more concerned about the widespread transmission energy consumption. For this reason, we aim to propose a resource allocation algorithm for cellular and D2D hybrid networks that maximizes energy efficiency.

However, prior works mostly only focused on optimizing D2D pairs performance and ignored cellular users performance, which limited improvement of the whole network performance. Moreover, some studies adopt methods of fixed power allocation, without considering the power collaboration between D2D pairs and cellular users.

C. CONTRIBUTION

This study has the conditions to ensure the minimum signal to interference plus noise ratio (SINR) of cellular users. We formulate the problem as a mixed integer nonlinear programming (MINLP) problem, which is NP-hard. Generally, this kind of problem cannot be solved within polynomial time [15], [23]. Therefore, we transform the original problem into two sub-problems based on the cross-layer optimization method. The main contributions of this study are summarized as follows:

1) The cellular and D2D hybrid networks model is proposed and analyzed. We derive an optimal energy efficiency formulation under the constraints of power and SINR. This optimization problem is a MINLP problem that is difficult to solve directly. Hence, the optimization problem is divided into two sub-problems and solved in a tractable way.
2) A power control scheme is presented to solve the first sub-problem. We derive the closed-form expression of power allocation. Then, we propose a power allocation algorithm based on Lambert W function [24] to optimize the energy efficiency of D2D pairs and guarantee the SINR of cellular users.
3) A channel allocation scheme is designed to further improve the whole network energy efficiency. We propose a channel allocation algorithm based on Gale-Shapley marriage matching algorithm [25], which uses the optimal power allocation results to match cellular users and D2D pairs. Channel matching algorithm is proved to be stable and weak Pareto optimum.
4) The proposed resource allocation algorithm is verified by simulation. Two algorithms are used for comparison. The simulation results show that the proposed algorithm can improve the D2D energy efficiency, and performs better than existing algorithms.

The remainder of this paper is introduced as follows. Section II reviews related works. Section III shows the system model and describes problem formulation. A power allocation algorithm based on Lambert W function and a channel matching algorithm based on Gale-Shapley algorithm are proposed in section IV. Section V presents the simulation results. The conclusion is summarized in section VI.

II. RELATED WORK

The D2D communication network architecture should meet the QoS requirements of cellular users as well as solve the problem of spectrum efficiency and energy efficiency [10]. Three D2D communication scenarios including D2D pairs communicate directly, D2D pairs communicate via BS, and D2D pairs communicate through another D2D pair, were studied in [26]. Yang *et al.* [27] pointed out the energy efficiency is mainly affected by the discovery process and the control mode of D2D communication.

D2D resource allocation scheme has been widely discussed in the past five years. A single-hop or multi-hop routing establishment algorithm, which utilized power control to reduce the interference of D2D pairs to macro users and BSs was proposed in [13]. Wang *et al.* [14] investigated the D2D communication source selection problem that exploited a game model to match the appropriate source nodes and allocate the optimal power. In [28], a distributed algorithm was proposed to achieve optimal power control. However, these works only considered the power control for reducing interference in the resource allocation of D2D communication. The combination of power control and channel allocation can improve system performance more effectively.

In [12], the energy efficiency of all possible DUEs and relays was maximized by establishing priority list for matching and then further reducing transmission power. Chen *et al.* [17] maximized network throughput under the constraints of minimum user data rate with fixed bandwidth allocated to D2D links. A resource allocation algorithm that prioritizes D2D pairs and cellular users with the goal of maximizing overall performance was proposed in [29].

Hu *et al.* [30] utilized an iterative algorithm to obtain the optimal transmit power, and then utilized channel gain to match D2D pairs and cellular users. A power control game scheme, which converted the problem of minimizing energy consumption and maximizing data rate to iteratively updating transmission power, was proposed in [31]. Jiang *et al.* [32] transformed fractional form optimization problem into solvable subtraction problem, and iteratively solved joint resource allocation and power control problems. Although most of the above works considered the matching problem between D2D pairs and cellular users, the performance of cellular users was not guaranteed during the optimization process.

In [16], the sum rate of system was maximized by a coalition formation game method that was stable and near optimum solution. Zulhasnine *et al.* [33] proposed a greedy heuristic algorithm that utilized channel gain information to reduce the interference between the primary cellular network and D2D links. Hoang *et al.* [34] first assigned the optimal power to the determined sub-band, and then allocated sub-band to D2D pairs based on a graph-based iterative algorithm. These resource allocation algorithms aimed at optimizing overall performance. Although this optimization objective improved the system performance, the performance improvement for D2D pairs was limited.

Research on energy-efficient D2D communication is popular in green cellular networks. Generally, the definition of energy efficiency is the ratio of total rate to power loss. A successive convex approximation method for power allocation was designed in [5] to minimize power consumption. Zhou *et al.* [19] proposed an energy-efficient content transmission system for D2D communication. In [23], a resource allocation scheme that allocated iterative power of non-cooperative game for Gale-Shapley matching was discussed. Based on the iterative calculation of the optimal transmit power, Zhou *et al.* [36] proposed a preference establishment algorithm to match D2D pairs and cellular users. In [37], a reverse iterative combinatorial auction algorithm, which considered the CUEs as bidders, DUEs as goods, and the cellular network as the auctioneer was proposed to allocate resources.

Different from the above related work, this study combines power control and channel allocation for resource allocation. Particularly, we maximize the energy efficiency of D2D pairs and whole system, while guaranteeing the performance of cellular users.

III. SYSTEM MODEL AND PROBLEM FORMULATION

This section first introduces a one-to-one system and its channel model, where the channel resource of a cellular user can only be reused by a single D2D pair. Then the D2D pairs energy efficiency maximization problem is formulated.

A. SYSTEM MODEL

In a single-cell network model for frequency division duplex (FDD) communication (as shown in Fig. 1), there are N cellular users and M D2D pairs. The set of cellular users is represented as $C = 1, 2, 3, \ldots N$. The set of D2D pairs is represented as $D = 1, 2, 3, \ldots M$. In this scene, N available orthogonal frequency resource blocks are allocated to the cellular users so that they would not interfere with each other. The D2D pairs reuse the uplink channel resources of cellular users in an underlay mode [12]. The channel resource of a cellular user can only be reused by one D2D pair, and one D2D pair can only reuse the channel resource of one cellular user. Therefore, there are two types of interferences existing in the cell, i.e., one is from cellular user's transmitted signal to D2D receiver and the other is from D2D transmitter to BS receiver. In addition, we assume that the BS can obtain three kinds of link information, which are the cellular user or D2D pair to the BS, the D2D pair to the other D2D pair, and the cellular user to the D2D pair.

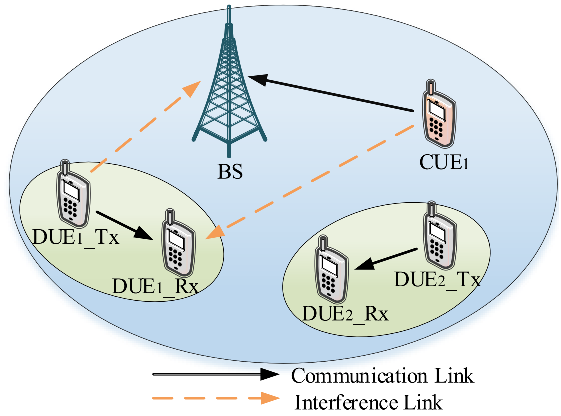


FIGURE 1. Schematic diagram of interference in one-to-one reusing scenario (upstream).

B. CHANNEL MODEL

Considering the effects of multipath fading and shadow fading, we use the path loss model in [13]. The path gain of different links can be expressed as

$$g_{n,m} = K\beta_{n,m}\lambda_{n,m}d_{n,m}^{-\alpha}. \tag{1}$$

Here, $g_{n,m}$ indicates the path gain from cellular link n to D2D link m and K denotes the constant affected by the system. $\beta_{n,m}$ represents the multipath gain from link n to m and it obeys the exponential distribution. $\lambda_{n,m}$ represents the shadow fading channel gain from link n to m, which obeys a lognormal distribution. $d_{n,m}$ is the distance from link n to m and α is a path loss factor. Moreover, the D2D communication link is expressed as $D_{m,m}$ and the path gain is expressed as $g_{D_{m,m}}$. The communication link from cellular user to BS is expressed as $C_{n,B}$ and the path gain is expressed as $g_{C_{n,B}}$. The communication link from D2D pair to BS is expressed as $D_{m,B}$ and the path gain is $g_{D_{m,B}}$. The communication link from cellular user to D2D pair is expressed as $C_{n,m}$ and the path gain is expressed as $g_{C_{n,m}}$.

We describe the problem to be solved as follows: when D2D pairs reuse cellular users resources, how to improve the energy efficiency of D2D pairs while suppressing interference between users? To solve this problem, this study employs power control and channel allocation, under the premise of satisfying the QoS requirements of D2D pairs and cellular users. Thereinto, energy efficiency is defined as the ratio of data rate to power loss [38].

According to the system model in Fig. 1, we assume that one D2D pair can only reuse one channel resource with at most one cellular user. Meanwhile, the signal received by BS includes not only the transmission signal of cellular user, but also the interference with D2D transmitter. The received signal y_n at BS is

$$y_n = \sqrt{p_n^c} g_{C_{n,B}} x_n + \sqrt{p_m^d} g_{D_{m,B}} t_m + \zeta_n, \tag{2}$$

where p_n^c indicates the transmit power of the cellular user n and p_m^d indicates the transmit power of the D2D pair m. x_n is the transmit signal of cellular user. t_m is the transmit signal of D2D pair. ζ_n represents a Gaussian white noise with the mean of zero and the power of δ^2.

If D2D pair m reuses the channel resource of cellular user n, the signal interference occurs between two users. In this circumstance, we set $\chi_{m,n} = 1$. The SINR of cellular user at BS is expressed as

$$\gamma_n = \frac{p_n^c g_{C_{n,B}}}{\delta^2 + \chi_{m,n} p_m^d g_{D_{m,B}}}. \tag{3}$$

If D2D pair m does not reuse the channel resource of cellular user n, there is no signal interference between the users. In this case, we set $\chi_{m,n} = 0$. The SINR of cellular user at BS is maximized, i.e.,

$$\gamma_n = p_n^c g_{C_{n,B}} / \delta^2. \tag{4}$$

In this one-to-one scenario, the received signal of D2D pair consists of three parts, namely the transmission signal of D2D pair, the interference caused by cellular user, and the channel noise. In consequence, the received signal of D2D pair m is expressed as

$$z_m = \sqrt{p_n^c} g_{C_{n,m}} x_n + \sqrt{p_m^d} g_{D_{m,m}} t_m + \zeta_m. \tag{5}$$

Therefore, the SINR in receiver of D2D pair m is

$$\gamma_m = \frac{p_m^d g_{D_{m,m}}}{\delta^2 + p_n^c g_{C_{n,m}}}. \tag{6}$$

The transmission rate of D2D pair m is

$$R_m = \log_2\left(1 + \frac{p_m^d g_{D_{m,m}}}{\delta^2 + p_n^c g_{C_{n,m}}}\right). \tag{7}$$

C. PROBLEM FORMULATION

In cells, the total transmission rate of D2D pairs is equal to the sum rate of all D2D pairs that access the network. The total power loss of D2D pairs is equal to the sum power loss of different devices. According to the definition of energy efficiency, its physical significance represents the average transmission bits per power unit. The total energy efficiency of D2D pair is defined as the ratio of total transmission rate to total power loss. When P_0 indicates the circuit power loss of a single device, the total power loss of D2D terminals is expressed as $p_m^d + 2P_0$. Therefore, the energy efficiency of D2D pair m is given by

$$\eta_{ee} = \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} \chi_{m,n} R_m}{\sum_{m=1}^{M} \sum_{n=1}^{N} \chi_{m,n} p_m^d + \sum_{m=1}^{M} 2P_0}. \tag{8}$$

In this study, we aim to maximize the energy efficiency of the D2D pair while satisfying the QoS requirements of both D2D pairs and cellular users. Hence, the optimization problem can be described as

$$\max_{p_m^d, p_n^c, \chi_{m,n}} \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} \chi_{m,n} \log_2\left(1 + \frac{p_m^d g_{D_{m,m}}}{\delta^2 + p_n^c g_{C_{n,m}}}\right)}{\sum_{m=1}^{M} \sum_{n=1}^{N} \chi_{m,n} p_m^d + \sum_{m=1}^{M} 2P_0}, \tag{9a}$$

$$s.t. \sum_{m} \chi_{m,n} \leq 1, \quad \chi_{m,n} \in \{0, 1\}, \ \forall m \in D_A, \ \forall n \in C, \tag{9b}$$

$$\sum_{n} \chi_{m,n} \leq 1, \quad \chi_{m,n} \in \{0, 1\}, \ \forall m \in D_A, \ \forall n \in C, \tag{9c}$$

$$0 \leq p_n^c \leq p_c^{\max}, \quad \forall n \in C, \tag{9d}$$

$$0 \leq p_m^d \leq p_d^{\max}, \quad \forall m \in D_A, \tag{9e}$$

$$\gamma_n \geq \xi_{\min}^{CUE}, \quad \forall n \in C, \tag{9f}$$

$$\gamma_m \geq \xi_{\min}^{D2D}, \quad \forall m \in D_A. \tag{9g}$$

In (9a), the users transmit power (p_n^c, p_m^d) and channel allocation mode $\chi_{m,n}$ are optimization variables. The energy efficiency of D2D pair is an optimization objective. The purpose that we increase the constraint condition (9b)-(9g) for this optimization problem is to ensure that D2D pairs and cellular users meet the SINR requirements. $\chi_{m,n}$ is the identifier of resource reuse. $\chi_{m,n} = 1$ when D2D pair m reuses the same channel resource with the cellular user n, otherwise $\chi_{m,n} = 0$. D_A ($D_A \subseteq D$) indicates a set of D2D pairs that can access the network. The D2D pairs in D_A access the network can not only meet D2D pair and cellular user SINR requirements, but also improve the energy efficiency of D2D pairs. $p_c^{\max}$ and $p_d^{\max}$ are maximum transmit power for cellular users and D2D pairs, respectively. $\xi_{\min}^{CUE}$ and $\xi_{\min}^{D2D}$ represent the minimum SINR requirements for cellular users and D2D pairs, respectively.

Constraint (9b) shows that the channel resource of a cellular user can only be reused by one D2D pair. Similarly, constraint (9c) shows that a D2D pair can only reuse the channel resource of one cellular user. Inequalities (9d) and (9e) indicate that the cellular users transmit power and the D2D pairs transmit power must meet the maximum power limitation, respectively. Constraint (9f) introduces that the cellular user SINR must be no less than the minimum SINR.

The purpose of (9f) is to ensure the performance of cellular users. Constraint (9g) indicates that the D2D pair SINR must meet the minimum SINR requirement.

It can be seen from (9) that the objective function which contains an integer variable $\chi_{m,n}$ is not a linear function. In particular, this MINLP problem is NP-hard, which is difficult to find the optimal solution directly. Aiming at solving MINLP problem, we transform the original problem into two sub-problems based on the cross-layer optimization method. Sub-problem 1 maximizes the energy efficiency of a single D2D pair under the condition of satisfying the minimum SINR requirements of cellular user and D2D pair. Sub-problem 2 allocates channels for cellular users and D2D pairs to optimize D2D pairs overall energy efficiency.

IV. ENERGY-EFFICIENT MAXIMIZATION RESOURCE ALLOCATION ALGORITHM ON D2D COMMUNICATION

This section addresses the previously formulated problem of maximizing energy efficiency. The first sub-section assigns optimal transmit power for each D2D pair based on Lambert W function. The second sub-section matches D2D pairs and cellular users based on Gale-Shapley algorithm. At last, we analyze the performance of the proposed algorithm.

A. OPTIMAL POWER CONTROL ALGORITHM

In this sub-section, we mainly solve the sub-problem 1 that is user transmit power control. The optimization objective is to maximize the energy efficiency of a single D2D pair. To implement sub-problem 1, we control the access state of the D2D pair. The basis for this is that the transmission rates of cellular user and D2D pair meet QoS requirements, when a single D2D pair reuses a cellular user resource. Then, we obtain the optimal transmit power of the access users, according to the closed-form expression of the derived transmit power.

p_{th}^d represents the minimum threshold constraint value of p_m^d and p_{th}^c represents the minimum threshold constraint value of p_n^c. Combining (9f) and (9g) to solve the minimum constraints of p_m^d and p_n^c as follows

$$p_m^d \geqslant p_{th}^d, \quad p_{th}^d = \frac{\xi_{\min}^{CUE}\delta^2(g_{C_{n,B}} + \xi_{\min}^{D2D} g_{C_{n,m}})}{g_{D_{m,m}} g_{C_{n,B}} - \xi_{\min}^{CUE}\xi_{\min}^{D2D} g_{D_{m,B}} g_{C_{n,m}}}, \tag{10}$$

$$p_n^c \geqslant p_{th}^c, \quad p_{th}^c = \frac{\xi_{\min}^{D2D}\delta^2(g_{D_{m,m}} + \xi_{\min}^{CUE} g_{D_{m,B}})}{g_{D_{m,m}} g_{C_{n,m}} - \xi_{\min}^{CUE}\xi_{\min}^{D2D} g_{D_{m,B}} g_{C_{n,m}}}. \tag{11}$$

Combining (9a) and (11), we can conclude that the smaller p_n^c is, the greater the energy efficiency is. Therefore, p_n^c must be the minimum value that satisfies the constraint condition when η_{ee} gets the maximum value. Thus, the minimum constraint value for transmit power of cellular user is given by

$$^*p_n^c = \begin{cases} p_{th}^c, & 0 \leqslant p_{th}^c \leqslant p_c^{\max} \\ 0, & p_{th}^c < 0 \text{ or } p_{th}^c > p_c^{\max}. \end{cases} \tag{12}$$

Specifically, $^*p_n^c = 0$ in two situations, which means that D2D pairs are prohibited from including in the accessible set of channel resources. One is $p_{th}^c < 0$, $^*p_n^c = 0$ indicates that the obtained minimum constraint value for the transmit power of cellular user is less than 0. The other is $p_{th}^c > p_c^{\max}$, $^*p_n^c = 0$ indicates that the obtained minimum constraint value for the transmit power of cellular user is greater than the maximum transmit power of cellular user. In both situations, $^*p_n^c$ is meaningless. As such, we must maximize the energy efficiency of D2D communication under the constraints of the minimum cellular user SINR. Otherwise, energy efficiency maximization will be meaningless. After obtaining p_n^c, we find it is a known constant. Then the optimization variables in this problem include p_m^d and $\chi_{m,n}$ only.

On account of one cellular user only reuses resource with one D2D pair at most, there is no mutual interference between D2D pairs. Therefore, the first sub-problem to be solved is power control when a single D2D pair reuses the cellular user resource. The second sub-problem is channel allocation for D2D pairs. We assume that D2D pair m reuses the channel resource of cellular user n, i.e., the reuse relationship is deterministic. Then, the optimization problem can be transformed as

$$\eta'_{ee} = \max_{p_m^d} \frac{\log_2\left(1 + \frac{p_m^d g_{D_{m,m}}}{\delta^2 + {}^*p_n^c g_{C_{n,m}}}\right)}{p_m^d + 2P_0}. \tag{13}$$

In order to simplify the above formula, we set variable T as follows

$$T = \frac{g_{D_{m,m}}}{\delta^2 + {}^*p_n^c g_{C_{n,m}}}. \tag{14}$$

Let $b = 2P_0$, the above equation can be expressed as

$$\eta'_{ee} = \max_{p_m^d} \frac{\log_2(p_m^d T + 1)}{p_m^d + b}, \quad p_m^d \geqslant 0,\ T > 0,\ b > 0. \tag{15}$$

The analysis shows that (15) is a convex function that one can always obtain the optimal solution. The function ψ is given by

$$\psi = \frac{\log_2(p_m^d T + 1)}{p_m^d + b}, \quad p_m^d \geqslant 0,\ T > 0,\ b > 0. \tag{16}$$

Theorem 1: The function ψ can obtain the maximum value at $^*p_m^d = (t_0 - 1)/T$ by using Lambert W function. The value of t_0 is shown in (17), where w represents the Lambert W function.

$$t_0 = \begin{cases} \exp\left(w\left(\frac{2P_0T - 1}{e}\right) + 1\right), & 2P_0T - 1 \neq 0 \\ e, & 2P_0T - 1 = 0. \end{cases} \tag{17}$$

Proof: We assume that $t = p_m^d T + 1$ and $t > 1$, then $p_m^d = (t_0 - 1)/T$. Thus, (16) can be simplified as

$$\psi = \frac{T \ln t}{(t - 1 + 2P_0 T)\ln 2}. \tag{18}$$

We take the derivative of the variable t in (18) and make its derivative greater than zero, i.e., $\frac{\partial \psi}{\partial t} > 0$.

$$\frac{\partial \psi}{\partial t} = \frac{\frac{T}{t}(t - 1 + 2P_0 T)\ln 2 - T \ln t \ln 2}{((t - 1 + 2P_0 T)\ln 2)^2}. \tag{19}$$

We set ψ_n=$t - t\ln t + 2P_0T - 1$ and take the derivative of ψ_n to get $\frac{\partial \psi_n}{\partial t} = -\ln t$. Due to $t > 1$, the derivative $\frac{\partial \psi_n}{\partial t} < 0$ is true and ψ_n is monotonically decreasing over $t \in (1, +\infty)$. When $t \to +\infty$, the function $\psi_n < 0$. However, when $t = 1$, $\psi_n = 2P_0T$ is greater than zero. Thus, there must be $t = t_0$ for $\psi_n(t_0) = 0$ to be established, that is, the inequality $\frac{\partial \psi_n}{\partial t} > 0$ has a solution. In other words, it exists $p_m^d = (t_0 - 1)/T$ which makes ψ monotonically increase over the interval $(0, p_m^d)$ while monotonically decrease over the interval $(p_m^d, +\infty)$, i.e., ψ takes the maximum at $p_m^d = (t_0 - 1)/T$. Finally, we make $\psi_n(t_0) = 0$, the specific value t_0 that obtained by the Lambert W function is shown in (17). Furthermore, the optimal value ${}^*p_m^d = (t_0 - 1)/T$ of the function ψ can be obtained. The proof is completed.

The optimal transmit power $({}^*p_m^d, {}^*p_n^c)$ is obtained by combining (17) with the maximum constraint (9e) and the minimum constraint (10) of p_m^d. The three cases with different p_{th}^d of the optimal solution are as follows

1) If $0 < p_{th}^d \leq p_d^{\max}$, the optimal solution of p_m^d is

$$\begin{aligned} {}^*p_m^d &= \begin{cases} p_{th}^d, & \frac{t_0-1}{T} < p_{th}^d \\ \frac{t_0 - 1}{T}, & p_{th}^d \leq \frac{t_0 - 1}{T} \leq p_d^{\max} \\ p_d^{\max}, & p_d^{\max} < \frac{t_0 - 1}{T}, \end{cases} \\ {}^*p_n^c &= \begin{cases} p_{th}^c, & 0 \leq p_{th}^c \leq p_c^{\max} \\ 0, & p_{th}^c < 0 \; or \; p_{th}^c > p_c^{\max}. \end{cases} \end{aligned} \tag{20}$$

2) If $p_{th}^d \leq 0$, the optimal solution of p_m^d is

$$\begin{aligned} {}^*p_m^d &= \begin{cases} p_d^{\max}, & p_d^{\max} < \frac{t_0 - 1}{T} \\ \frac{t_0 - 1}{T}, & \frac{t_0 - 1}{T} \leq p_d^{\max}, \end{cases} \\ {}^*p_n^c &= \begin{cases} p_{th}^c, & 0 \leq p_{th}^c \leq p_c^{\max} \\ 0, & p_{th}^c < 0 \; or \; p_{th}^c > p_c^{\max}. \end{cases} \end{aligned} \tag{21}$$

3) If $p_{th}^d > p_d^{\max}$, the corresponding D2D pair is forbidden to access the network.

As mentioned earlier, D2D pairs who do not meet the conditions should be prohibited from being included in the set of accessible channels. It is conducive to ensure the communication performance of cellular users and D2D pairs as well as maximize the energy efficiency of D2D pairs. In the cell, the transmission power allocation process for cellular users and D2D pairs has been described. To summarize, there are three categories that D2D pairs cannot be included in the set of accessible channels as follows and the power control process is shown in **Algorithm 1**.

1) When $p_{th}^c < 0$, the minimum constraint value for transmitted power of cellular user is less than 0, which is meaningless. The D2D pair is prohibited from being included in the accessible set of channel resources, because the minimum SINR requirement of cellular users cannot be met.
2) When $p_{th}^c > p_c^{\max}$, the obtained minimum constraint value for transmit power of cellular user is greater than the maximum one. This moment, the D2D pair is prohibited from being included in the accessible set of channel resources. The reason is that maximizing the D2D communication energy efficiency must be done under the conditions of satisfying cellular users performance, which includes minimum SINR and maximum transmit power. Otherwise, maximizing energy efficiency will be meaningless.
3) When $p_{th}^d > p_d^{\max}$, the obtained minimum constraint value for transmit power of D2D pair is greater than the maximum one. In order to guarantee the minimum SINR requirement within the maximum transmit power of the D2D pair, such D2D pairs are not included in the accessible set of channel resources.

Algorithm 1 Power Control Algorithm for Obtaining ${}^*p_m^d$ and ${}^*p_n^c$

```
1:  Initialization : D_A ⇐ D;
2:  while m ∈ D_A do
3:    for n ∈ C, m ∈ D_A do
4:      Calculate the minimum threshold p_th^d and p_th^c based
        on constraints (10) and (11);
5:      Calculate the optimal transmit power *p_n^c of the
        cellular user n according to (12);
6:      Calculate the optimal transmit power *p_m^d of the
        D2D pair m according to (20) and (21);
7:      if p_th^c < 0 or p_th^c > p_c^max or p_th^d > p_d^max then
8:        Remove user m from D_A;
9:      end if
10:   end for
11: end while
```

B. ENERGY-EFFICIENT CHANNEL ALLOCATION ALGORITHM

In this sub-section, we will focus on the second sub-problem. The optimization objective of this sub-problem is to maximize the whole energy efficiency of D2D pairs. Gale-Shapley marriage matching algorithm is used to allocate channel resources for D2D pairs who have already been allocated power. First of all, we calculate the preference values for D2D pairs and cellular users according to power control results. Gale-Shapley marriage matching algorithm is a stable matching algorithm. The main idea is that two sides of matching are based on the priority list (the order of preference values).

Then one side sends request from the highest to the lowest to the other side in priority list. The other side matches the user who makes the request according to the rule of delay approval in its own priority list. According to the resource allocation characteristics of maximizing energy efficiency, we propose a channel allocation scheme based on Gale-Shapley algorithm.

For the purpose of maximizing the whole energy efficiency of D2D pairs, we need to find the optimal value of the reuse mode $\chi_{m,n}$. Meanwhile, cellular user transmission rate should be guaranteed. The optimal transmit power $({}^*p_m^d, {}^*p_n^c)$ has been obtained by power allocation in the first sub-problem. After that, the channel assignment problem is formulated as

$$\max_{\chi_{m,n}} \sum_{n\in C, m\in D_A} \frac{\sum_m \sum_n \chi_{m,n} \log_2\left(1+\frac{{}^*p_m^d g_{D_{m,m}}}{\delta^2+{}^*p_n^c g_{C_{n,m}}}\right)}{\sum_m \sum_n \chi_{m,n} {}^*p_m^d + \sum_{m=1}^{M} 2P_0}, \tag{22a}$$

$$s.t. \sum_m \chi_{m,n} \leq 1, \quad \chi_{m,n} \in \{0,1\}, \ \forall m \in D_A, \tag{22b}$$

$$\sum_n \chi_{m,n} \leq 1, \quad \chi_{m,n} \in \{0,1\}, \ \forall n \in C. \tag{22c}$$

The flow of user preference list creation is shown in **Algorithm 2**. In this algorithm, the preference value for D2D pair is represented by the energy efficiency of D2D pair in (23). The preference value for cellular user is represented by the SINR of cellular user in (24).

$$\frac{\log_2({}^*p_m^d T+1)}{{}^*p_m^d + b}. \tag{23}$$

$$\frac{{}^*p_n^c g_{C_{n,B}}}{\delta^2 + {}^*p_m^d g_{D_{m,B}}}. \tag{24}$$

Algorithm 2 User Preference List Creation

Declare the availability of each cellular user and D2D pair;
M is the number of available D2D pairs;
N is the number of available cellular users;
for $m = 1$ to M **do**
    Sort the available cellular users corresponding to D2D pair m in descending order, according to the preference values in (23);
end for
for $n = 1$ to N **do**
    Sort the available D2D pairs corresponding to cellular user n in descending order, according to the preference values in (24);
end for

The channel allocation algorithm is based on user preference list. First of all, we calculate the preference values for each D2D pair according to (23). With these preference values, we determine the priority list of cellular users that the D2D pair expect to match. The D2D pair reuses channel with the higher ranked cellular user in priority list. Consequently, the energy efficiency that D2D pair obtained is higher. Next, we calculate the preference values for each cellular user according to (24). We determine the priority list of D2D pairs that the cellular user expect to match. The higher D2D pair priority, the higher transmission rate of cellular users that match it. The above sorting process is shown in **Algorithm 2**. Then, we prohibit some D2D pairs who do not meet the conditions from being included into the channel resource reusing set. At the meantime, these D2D pairs will be marked. Last but not least, we use the Gale-Shapley algorithm for matching D2D pairs and cellular users. In summary, the optimal channel allocation scheme is shown in **Algorithm 3** for obtaining the reuse mode $\chi_{m,n}$.

Algorithm 3 Energy-Efficient Channel Matching Algorithm for Obtaining $\chi_{m,n}$

Declare the availability of each cellular user and D2D pair;
Mark cellular users who cannot reuse resources with D2D pairs;
while D2D pair m is available and has not yet made matching requirements for all unmarked cellular users in the priority list **do**
    n is the first cellular user in the priority list of the D2D pair m, which is unmarked and has not been matched;
    if n is available **then**
        Cellular user n matches D2D pair m temporarily;
    else
        if in the preference list of cellular user n, the user m is ranked in front of the previously matched user m' **then**
            Cellular user n matches D2D pair m temporarily;
            m' becomes freely available;
        else
            n refuses m and m becomes free;
        end if
    end if
end while
D2D pair matches the cellular user.
Obtaining the matching set $X\{\chi_{m,n} = 1\}$.

To sum up the problem description, the resource allocation problem of cellular and D2D hybrid networks is decomposed into two stages, which are power control and channel allocation. Firstly, the energy efficiency of a single D2D pair is maximized under the condition of satisfying the minimum SINR of the cellular user. The power allocation closed-form expression is derived by using the Lambert W function. Then, the optimization problem aims at maximizing the cellular users SINR and D2D pairs energy efficiency. A channel allocation algorithm based on Gale-Shapley method is proposed to obtain the optimal channel matching. In this model, a cellular user can only reuse resource with at most one D2D pair. At the same time, a D2D pair can only reuse one cellular user channel resource. There is no mutual interference between D2D pairs. A D2D pair only interferes with one cellular user at most. Hence, we can obtain a resource allocation algorithm for D2D communication that maximizes energy efficiency by adding a cooperative power control process before the channel allocation.

C. PERFORMANCE OF THE RESOURCE ALLOCATION ALGORITHM

This sub-section analyzes the performance of the proposed matching algorithm. It is proved that the matching algorithm is stable and weak Pareto optimum.

1) STABILITY

Theorem 2: The matching set $X\{\chi_{m,n} = 1\}$ obtained by Algorithm 3 is stable.

Proof: The stability of the algorithm means that there is no unstable pair. In the proposed matching algorithm, stability is that any D2D pair and cellular user cannot violate Algorithm 3 to improve energy efficiency. Firstly, we assume that there are two matching pairs, i.e., $\chi_{m_a,n_1} = \chi_{m_b,n_2} = 1$, for $m_a, m_b \in D$, $n_1, n_2 \in C$, and χ_{m_a,n_2} is a blocking pair.

Then, we can analyze that there are two possibilities for the occurrence of blocking pairs. One is m_a did not send a match request to n_2, the other is n_2 refused m_a. For the first possibility, we can derive from Algorithm 3 that m_a prefers n_1 instead of n_2, so m_a and n_2 are stable. For the other one, we can conclude that n_2 prefers m_b instead of m_a, so m_a and n_2 are stable. Therefore, there is no blocking pair in all cases, the matching algorithm is stable.

2) OPTIMALITY

Theorem 3: The obtained transmit power ${}^*p_m^d$ in Algorithm 1 is the global optimal solution.

Proof: It can be known from theorem 1, ${}^*p_m^d$ is the local optimal solution. Since ψ is a convex function and its partial derivative is continuous, ${}^*p_m^d$ is the global optimal solution.

Theorem 4: The obtained energy-efficient matching set $X\{\chi_{m,n} = 1\}$ is weak Pareto optimum for D2D pairs and cellular users.

Proof: The Pareto improvement is to make at least one person better off on the basis that all team members agree to change the allocation scheme. Thus, if there exists no Pareto improvement, the resource allocation algorithm is weak Pareto optimum.

We assume that there exists a Pareto improvement matching set X; that is at least one D2D pair m has an improved matching user n. One case is that n has no matching user in X. According to our assumption, m prefers to match n than others. m and n become a blocking pair based on Algorithm 3. This contradicts theorem 3 that the proposed matching algorithm is stable. In other case, n once matched m, but now matches m'. Since n is an improved match for m, m prefers n. However, it can be seen from Algorithm 3 that m was rejected by n, hence n cannot be an improved match for m.

According to the above analysis, there is no Pareto improvement in the matching set, thus the energy-efficient matching algorithm is weak Pareto optimum.

V. SIMULATION AND ANALYSIS

In order to verify the performance of D2D communication, we select the energy efficiency of the whole network and D2D communication links as the performance evaluation index for the algorithm. The sum energy efficiency refers to the sum of the energy efficiency which contains all D2D pairs and cellular users in the network. The expression is

$$\eta_{\text{sum}} = \frac{R_{\text{sum}}}{\sum_{m=1}^{M}(p_m^d + 2P_0) + \sum_{n=1}^{N}(p_n^c + P_0)} \text{ (bit/J/Hz)}, \qquad (25)$$

where R_{sum} is the total rate of the cellular network, N is the number of cellular users, and M is the number of D2D pairs. p_m^d represents the transmit power of D2D pair. p_n^c represents the transmit power of the cellular user who reuses spectrum with D2D pair m,

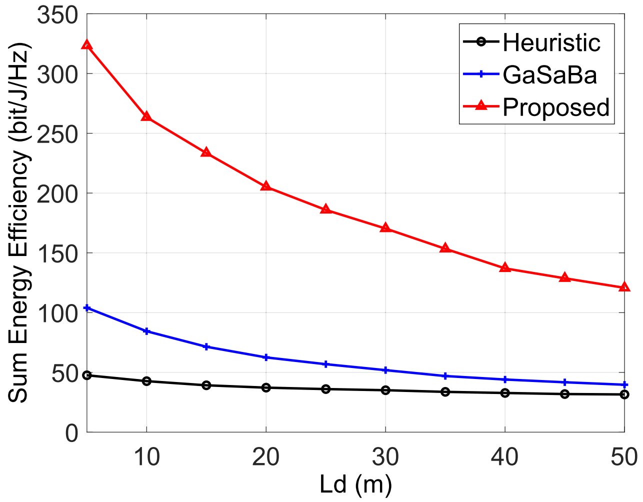
To verify the validity of the proposed algorithm, two algorithms [29], [33] are included for the purpose of comparison. The algorithm proposed in this paper is replaced by Proposed below. GaSaBa represents the algorithm in [29]. Algorithm in [33] is represented by Heuristic. The setting of the simulation parameters is shown in Table 1, and the parameter selection is the same as [30].

TABLE 1. Simulation parameters.

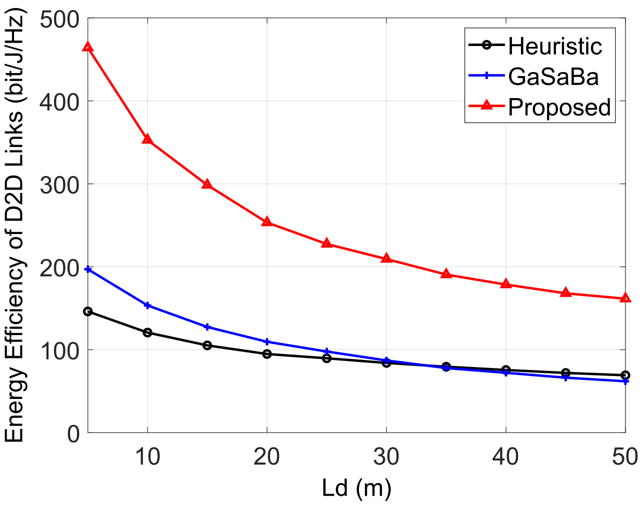
Parameter	Value(s)
Cell radius/m	250
DUE maximum transmit distance L_d/m	25, [5, 10, ..., 50]
Equipment circuit loss /dBm	10
Number of cellular users	8
Number of D2D pairs	6, 1∼8
Multipath fading parameter λ	1
Shadow fading /dB	8
Path loss factor α	4
Noise power spectral density /(dBm/Hz)	-174
CUE maximum transmit power/dBm	24
DUE maximum transmit power /dBm	21
CUE SINR requirements /dB	$U \sim [0, 25]$
DUE SINR requirements /dB	$U \sim [0, 25]$

A. IMPACT OF D2D COMMUNICATION DISTANCE ON CELLULAR NETWORK PERFORMANCE

The number of D2D pairs is set to $M = 6$. The maximum transmit power of D2D communication $p_d^{\max}$ is 21dBm. Fig. 2 illustrates the relationship between sum energy efficiency, transmission rate and D2D communication distance L_d. Fig. 2 (a) shows the relationship between the sum energy efficiency of the whole network and L_d. Fig. 2 (b) shows the relationship between the energy efficiency of D2D links and L_d. It can be seen from Fig. 2 that the energy efficiency of three algorithms decreases with the increase of communication distance. It is evident that the sum energy



(a)



(b)

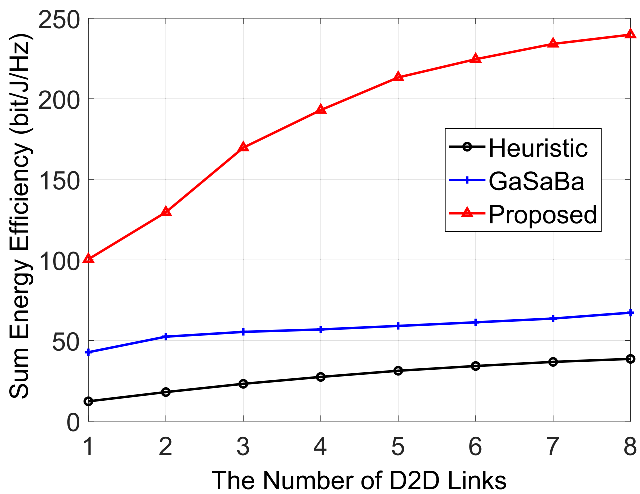
FIGURE 2. Network energy efficiency with D2D communication distance. (a) Sum energy efficiency versus difference D2D communication distance. (b) Energy efficiency of D2D links versus difference D2D communication distance.

efficiency and D2D pairs energy efficiency of the proposed algorithm are higher than that of the other two algorithms.

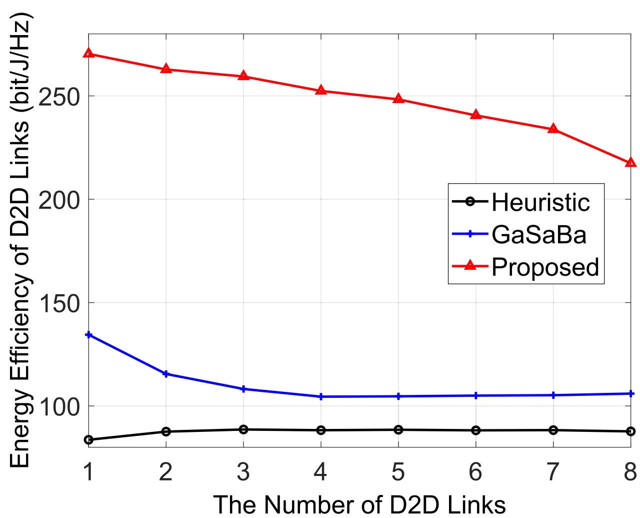
The channel gain and the data transmission rate decrease when D2D communication distance increases. If the transmission power is increased to improve the transmission rate, the interference and power consumption will be caused. Therefore, we can conclude that the energy efficiency decreases with the increase of communication distance. The GaSaBa and Heuristic algorithms transmit data in a fixed transmission power or a fixed power allocation mode, and they match channels based on channel gain. Consequently, they cannot better adapt to the rate loss caused by channel gain reduction. However, the proposed algorithm allocates optimal transmit power for cellular users and D2D pairs based on maximizing energy efficiency. Simultaneously, it controls the interference and rate reduction within a certain range. Besides, the proposed algorithm maximizes the energy efficiency of D2D pairs in channel allocation scheme. Thus, the energy efficiency of the proposed algorithm is better than that of the other two algorithms.

B. IMPACT OF NUMBER OF D2D LINKS ON CELLULAR NETWORK PERFORMANCE

Fig. 3 (a) shows the relationship between system energy efficiency and the number of D2D links. It can be seen that the system energy efficiency of three algorithms increases along with the increase of the number of D2D links. This is because the more D2D pairs are, the more cellular users are added to the reuse set. So that the energy efficiency of cellular users becomes larger, thereby the system energy efficiency increases. Fig. 3 (b) shows that the D2D energy efficiency of Proposed and GaSaBa decrease slightly with



(a)



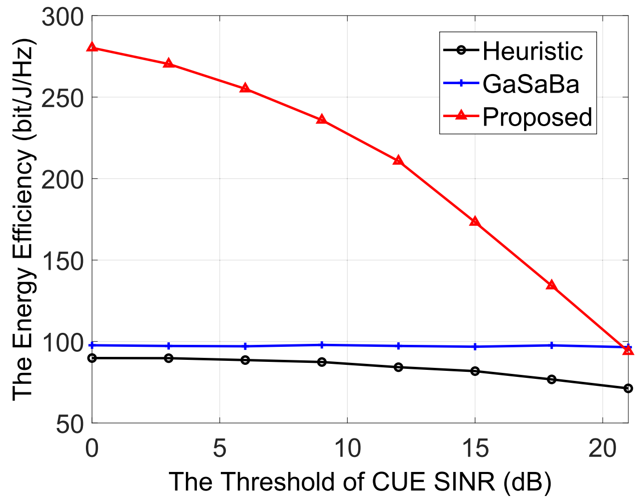
(b)

FIGURE 3. Network energy efficiency with number of D2D links . (a) Sum energy efficiency versus difference number of D2D links. (b) Energy efficiency of D2D links versus difference number of D2D links.

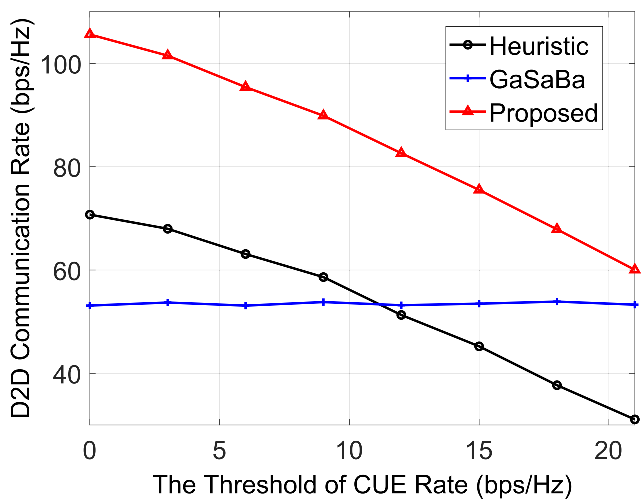
the increase of D2D pairs. The performance of proposed algorithm is significantly better than that of the other two. The available cellular users resources become less with the increase of D2D pairs. Means that the probability that the D2D pair matches the channel resource of lower interference cellular user becomes smaller, so the interference increases. The D2D energy efficiency of Heuristic algorithm does not change much with the number of D2D pairs.

C. IMPACT OF MINIMUM CUE SINR ON CELLULAR NETWORK PERFORMANCE

In Fig. 4 (a), the relationship between the energy efficiency of D2D pairs and the SINR threshold of cellular users is shown. It can be seen from Fig. 4 (a) that the performance of proposed algorithm is significantly better than that of the other two. The GaSaBa algorithm is not affected by changes in the minimum SINR of cellular users. The proposed algorithm and the Heuristic algorithm reduce the energy efficiency of D2D pairs as the minimum SINR threshold of the cellular users increases. The reason is that, in order to guarantee the cellular users transmission rate, some D2D pairs performance will be sacrificed when the minimum SINR threshold of cellular user is higher. The GaSaBa algorithm does not perform power allocation, so there is no similar problem. Figure 4 (b) analyzes the relationship between the transmission rate and the SINR threshold of cellular users. The transmission rate decreases rapidly as the SINR threshold of cellular users increases. This is because, in order to ensure the performance of the cellular users, the power allocation of proposed algorithm takes the minimum SINR requirements of cellular users as the primary constraint. So that the distribution results are greatly affected by CUE SINR threshold. However, the curves show that the D2D pairs transmission rate of proposed algorithm is still higher than that of the other two algorithms.



(a)



(b)

FIGURE 4. System performance with cellular user SINR threshold. (a) D2D energy efficiency versus difference CUE SINR threshold. (b) Rate of D2D communication versus difference CUE SINR threshold.

According to the subsection A, B, and C, the proposed algorithm is superior to the other two algorithms in D2D pairs energy efficiency, the D2D transmission rate, and the system energy efficiency. The proposed algorithm achieves optimal power allocation by optimizing a single D2D energy efficiency. Meanwhile, the proposed algorithm utilizes the channel allocation algorithm based on Gale-Shapley method to obtain the optimal channel resource matching and effectively controls the interference between users. These guarantee the SINR requirements of cellular users and maximizes the whole performance of the network. The other two algorithms use a fixed power allocation method (Heuristic) or directly use a fixed power transmission signal (GaSaBa), which are less flexible and have a higher energy consumption for D2D pairs. Their channel allocation do not jointly consider the cellular users and D2D pairs performance requirements resulting in the large interference in the system. Hence, the energy efficiency of proposed algorithm is better than two comparison algorithms.

VI. CONCLUSION

In this paper, we studied the resource allocation problem in cellular and D2D hybrid networks. For the energy consumption problem caused by severe interference in the one-to-one resource reuse scenario, the resource allocation problem was divided into two stages, i.e., power control and channel allocation. With the objective of maximizing the energy efficiency of a single D2D pair, the optimal transmit power of the D2D pair was obtained by Lambert W function. Based on the power allocation results, the D2D pairs were allocated appropriate cellular users channel resources by Gale-Shapley matching algorithm. The simulation results showed that compared with existing solutions, the proposed algorithm had better performance in D2D pair energy efficiency, D2D transmission rate, and system energy efficiency. In addition, the results showed that the energy efficiency of D2D pairs was improved with optimal power allocation. Moreover, the proposed algorithm considered the performance requirements of cellular users and D2D pairs in the channel allocation process.

REFERENCES

[1] M. Pouryazdan, B. Kantarci, T. Soyata, and H. Song, "Anchor-assisted and vote-based trustworthiness assurance in smart city crowdsensing," *IEEE Access*, vol. 4, pp. 529–541, 2016.

[2] H. Menouar, I. Guvenc, K. Akkaya, A. S. Uluagac, A. Kadri, and A. Tuncer, "UAV-enabled intelligent transportation systems for the smart city: Applications and challenges," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 22–28, Mar. 2017.

[3] Y. Li, W. Dai, Z. Ming, and M. Qiu, "Privacy protection for preventing data over-collection in smart city," *IEEE Trans. Comput.*, vol. 65, no. 5, pp. 1339–1350, May 2016.

[4] R. Ullah, Y. Faheem, and B. S. Kim, "Energy and congestion-aware routing metric for smart grid ami networks in smart city," *IEEE Access*, vol. 5, pp. 13799–13810, 2017.

[5] C. Kai, H. Li, L. Xu, Y. Li, and T. Jiang, "Energy-efficient device-to-device communications for Green smart cities," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1542–1551, Apr. 2018.

[6] S. Fang *et al.*, "An integrated system for regional environmental monitoring and management based on Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1596–1605, May 2014.

[7] D. Feng, C. Jiang, G. Lim, L. J. Cimini, Jr., G. Feng, and G. Y. Li, "A survey of energy-efficient wireless communications," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 167–178, 1st Quart., 2013.

[8] W. S. Jeon and D. G. Jeong, "Energy-efficient distributed resource allocation with low overhead in relay cellular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 11137–11150, Dec. 2017.

[9] D. Jiang, P. Zhang, Z. Lv, and H. Song, "Energy-efficient multi-constraint routing algorithm with load balancing for smart city applications," *IEEE Internet Things J.*, vol. 3, no. 6, pp. 1437–1447, Dec. 2016.

[10] L. Jiang *et al.*, "Social-aware energy harvesting device-to-device communications in 5G networks," *IEEE Wireless Commun.*, vol. 23, no. 4, pp. 20–27, Aug. 2016.

[11] P. Gandotra, R. K. Jha, and S. Jain, "Sector-based radio resource allocation (SBRRA) algorithm for better quality of service and experience in device-to-device (D2D) communication," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 5750–5765, Jul. 2018.

[12] W. Chang and J.-C. Teng, "Energy efficient relay matching with bottleneck effect elimination power adjusting for full-duplex relay assisted D2D networks using mmWave technology," *IEEE Access*, vol. 6, pp. 3300–3309, 2018.

[13] B. Kaufman, J. Lilleberg, and B. Aazhang, "Spectrum sharing scheme between cellular users and ad-hoc device-to-device users," *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 1038–1049, Mar. 2013.

[14] Q. Wang, W. Wang, S. Jin, H. Zhu, and N. T. Zhang, "Quality-optimized joint source selection and power control for wireless multimedia D2D communication using Stackelberg game," *IEEE Trans. Veh. Technol.*, vol. 64, no. 8, pp. 3755–3769, Aug. 2015.

[15] P. Phunchongharn, E. Hossain, and D. I. Kim, "Resource allocation for device-to-device communications underlaying LTE-advanced networks," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 91–100, Aug. 2013.

[16] Y. Li, D. Jin, J. Yuan, and Z. Han, "Coalitional games for resource allocation in the device-to-device uplink underlaying cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3965–3977, Jul. 2014.

[17] B. Chen, C. Yang, and G. Wang, "High throughput opportunistic cooperative device-to-device communications with caching," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7527–7539, Aug. 2017.

[18] P. Gandotra, R. K. Jha, and S. Jain, "Green NOMA with multiple interference cancellation (MIC) using sector-based resource allocation," *IEEE Trans. Netw. Service Manage.*, vol. 15, no. 3, pp. 1006–1017, Sep. 2018.

[19] L. Zhou, D. Wu, J. Chen, and Z. Dong, "Greening the smart cities: Energy-efficient massive content delivery via D2D communications," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1626–1634, Apr. 2018.

[20] G. Xie *et al.*, "Reliability enhancement toward functional safety goal assurance in energy-aware automotive cyber-physical systems," *IEEE Trans. Ind. Inform.*, vol. 14, no. 12, pp. 5447–5462, Dec. 2018.

[21] Y. Chen, G. Xie, and R. Li, "Reducing energy consumption with cost budget using available budget preassignment in heterogeneous cloud computing systems," *IEEE Access*, vol. 6, pp. 20572–20583, 2018.

[22] G. Xie, J. Jiang, Y. Liu, R. Li, and K. Li, "Minimizing energy consumption of real-time parallel applications using downward and upward approaches on heterogeneous systems," *IEEE Trans. Ind. Informat.*, vol. 13, no. 3, pp. 1068–1078, Jun. 2017.

[23] Z. Zhou, K. Ota, M. Dong, and C. Xu, "Energy-efficient matching for resource allocation in D2D enabled cellular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 6, pp. 5256–5268, Jun. 2017.

[24] R. M. Corless, G. H. Gonnet, D. E. G. Hare, D. J. Jeffrey, and D. E. Knuth, "On the Lambert W function," *Adv. Comput. Math.*, vol. 5, no. 1, pp. 329–359, Dec. 1996.

[25] D. Gale and L. S. Shapley, "College admissions and the stability of marriage," *Amer. Math. Monthly*, vol. 69, no. 1, pp. 9–15, Jan. 1962.

[26] L. Wei, R. Q. Hu, Y. Qian, and G. Wu, "Energy efficiency and spectrum efficiency of multihop device-to-device communications underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 367–380, Jan. 2016.

[27] M. J. Yang, S. Y. Lim, H. J. Park, and N. H. Park, "Solving the data overload: Device-to-device bearer control architecture for cellular data offloading," *IEEE Veh. Technol. Mag.*, vol. 8, no. 1, pp. 31–39, Mar. 2013.

[28] Y. Wu, J. Wang, L. Qian, and R. Schober, "Optimal power control for energy efficient D2D communication and its distributed implementation," *IEEE Commun. Lett.*, vol. 19, no. 5, pp. 815–818, May 2015.

[29] W. Chang, Y.-T. Jau, S.-L. Su, and Y. Lee, "Gale-Shapley-algorithm based resource allocation scheme for device-to-device communications underlaying downlink cellular networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Doha, Qatar, Apr. 2016, pp. 1–6.

[30] J. Hu, W. Heng, X. Li, and J. Wu, "Energy-efficient resource reuse scheme for D2D communications underlaying cellular networks," *IEEE Commun. Lett.*, vol. 21, no. 9, pp. 2097–2100, Sep. 2017.

[31] Y. Li, Z. Zhang, H. Wang, and Q. Yang, "SERS: Social-aware energy-efficient relay selection in D2D communications," *IEEE Trans. Veh. Technol.*, vol. 67, no. 6, pp. 5331–5345, Jun. 2018.

[32] Y. Jiang, Q. Liu, F. Zheng, X. Gao, and X. You, "Energy-efficient joint resource allocation and power control for D2D communications," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6119–6127, Aug. 2016.

[33] M. Zulhasnine, C. Huang, and A. Srinivasan, "Efficient resource allocation for device-to-device communication underlaying LTE network," in *Proc. 6th IEEE Int. Conf. Wireless Mobile Comput. Netw. Commun. (WiMOB)*, Niagara Falls, ON, Canada, Oct. 2010, pp. 368–375.

[34] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Resource allocation for D2D communication underlaid cellular networks using graph-based approach," *IEEE Trans. Wireless Commun.*, vol. 15, no. 10, pp. 7099–7113, Oct. 2016.

[35] Z. Zhou, C. Gao, C. Xu, T. Chen, D. Zhang, and S. Mumtaz, "Energy-efficient stable matching for resource allocation in energy harvesting-based device-to-device communications," *IEEE Access*, vol. 5, pp. 15184–15196, 2017.

[36] Z. Zhou, G. Ma, M. Dong, K. Ota, C. Xu, and Y. Jia, "Iterative energy-efficient stable matching approach for context-aware resource allocation in D2D communications," *IEEE Access*, vol. 4, pp. 6181–6196, Apr. 2016.

[37] F. Wang, C. Xu, L. Song, and Z. Han, "Energy-efficient resource allocation for device-to-device underlay communication," *IEEE Trans. Wireless Commun.*, vol. 14, no. 4, pp. 2082–2092, Apr. 2015.

[38] V. Rodoplu and T. H. Meng, "Bits-per-joule capacity of energy-limited wireless networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 3, pp. 857–865, Mar. 2007.

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