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Towards Energy-Efficient Underlaid Device-to-Device Communications: A Joint Resource Management Approach

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ABSTRACT With increasing demands of green wireless communications, energy-efficient device-to-device (D2D) communications have attracted increasing attention. However, with resource sharing in an underlying manner, the system performance may be greatly degraded by the co-channel interference. For friendly coexistence of D2D and cellular communications, in this paper, we propose a joint resource management scheme where direct mode, two-hop mode, and cooperative mode are supported. Specifically, the joint resource management is formulated as a three-dimensional (3-D) *power-mode-channel* problem that maximizes the overall energy efficiency (EE) of D2D communications while guaranteeing the quality of service (QoS) of both D2D and cellular communications. To solve the formulated problem, the 3-D problem is decoupled by employing the orthogonality of different D2D links and the uniqueness of transmission mode for one D2D pair. Besides, considering that the introduction of cooperative mode increases the complexity of 3-D resource allocation algorithm, on the basis of the optimal scheme, we further propose a sub-optimal scheme to reduce the average time complexity. The simulation results verify the viability of the proposed schemes and reveal the impacts of system parameters such as the QoS, the distance between D2D source and destination, the location of the relay, and the number of D2D pairs on the EE of D2D systems.

INDEX TERMS Device-to-device communications, energy efficiency, power allocation, mode selection, channel assignment.

I. INTRODUCTION

Without extra hops through base station (BS), Device-to-Device (D2D) communications underlaying licensed cellular networks have great potentials to alleviate the extra construction and maintenance costs in the exponential explosion of smart devices and mobile applications [1], [2]. Besides, being able to reduce end-to-end delay, the D2D communication is also conceived as an alternative paradigm to support local area services [3], [4], intelligent transportation systems [5], and smart cities [6]. In particular, due to the nature of proximity services, D2D communications can reduce the power consumption and increase the spectral efficiency (SE) significantly. As a result, the energy efficiency (EE) may be improved, supporting the low-carbon wireless communications in the incoming fifth generation (5G) networks [7].

Although the superiority of reusing cellular channels has been demonstrated in [8], the mutual interference caused by channel reusing is still a major obstacle in achieving EE promotion of D2D communications and guaranteeing the performance of the existing cellular users [9], [10]. Therefore, effective interference management schemes are eager to be employed to mitigate the negative impacts of the mutual interference. Power allocation and channel assignment are

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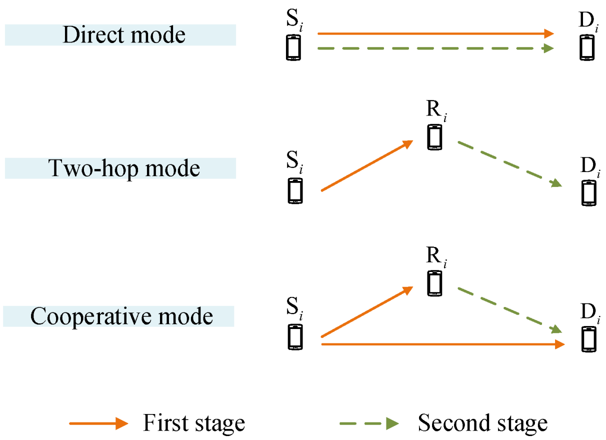

FIGURE 1. **The three transmission modes of D2D communications.**

two effective approaches to mitigate the interference and therefore can improve the EE. In addition, the transmission mode of D2D pairs also has a significant impact on the performance of the system. As shown in Figure 1, three typical modes, namely, direct-mode, two-hop mode, and cooperative mode, are illustrated. In two-hop mode, the D2D receiver only receive signals from relay user in second phase. In cooperative mode, D2D receiver receive signals from D2D transmitter in the first phase and signals from relay users in second phase, and conduct combination of signals of different phases. With the assistance of the relay, the D2D communication in two-hop mode [11], [12] or cooperative mode experiences smaller pathloss attenuation and then the received signal is stronger. Thus, they outperform the D2D communication in direct mode in terms of SE and are widely utilized in emergency communications and social-aware local area networks [13], [14]. But the circuit power, which is included in the total power consumed, increases with the additional reception/transmission of the relay and destination [15]. Therefore cooperative mode or two-hop mode may not be superior to direct mode in terms of EE. From the above understanding, it is desired to investigate a 3-D *power-mode-channel* resource management approach for D2D communications to optimize EE, which is a critical performance metric for 5G networks but has not been well studied in D2D communications with different transmission modes in Figure 1.

II. BACKGROUND AND CONTRIBUTIONS

In the regard of resource management, various schemes and algorithms have been proposed to improve the performance of D2D communications underlaying cellular networks. For power allocation, Lee *et al.* [16], Liu *et al.* [17] studied the problem when the D2D communication is in direct mode. In [16], the proposed centralized algorithm calculated the optimal power values of D2D pairs to maximize the signal-to-interference-plus-noise ratio (SINR) of the cellular user, while the proposed distributed algorithm maximize the SE of D2D users. In [17], the geometric programming technique was adopted to optimize the sum rate of the cellular user and the D2D user when giving priority to cellular communications. In order to get power values of the source and relay simultaneously, an effective iterative method was proposed by applying the nonlinear fractional programming when considering the SE of cellular users in [18]. In addition, for channel assignment in [19] and [20] optimizing the sum rate, Hussain *et al* [19] focused the scenario where one D2D pair shared multiple cellular channels, as well as multiple D2D pairs shared a single cellular channel. The solution for D2D communications underlaying full duplex cellular networks was proposed in [20].

These aforementioned studies conducted resource management from the perspective of power allocation or channel assignment separately. To further improve the system performance, two-dimensional (2-D) resource management schemes were adopted in [21]–[29]. The power allocation and channel assignment were discussed in [21]–[25] to maximize EE. Xu *et al.* [21], Jiang *et al.* [22], and Zhou *et al.* [23] decoupled the problem and proposed iteration algorithms. A iteration algorithm with low complexity was proposed in [21]. In [22], the optimal power values on all candidate channels were obtained firstly and then channel assignment finished. A many-to-one matching algorithm was proposed to solve the problem with varying preferences in [23]. Besides, Zhou *et al.* [24], [25] considered a multi-objective optimization problem, maximizing the EE of D2D users and maximizing the EE of cellular users, and the intracell interference respectively. Furthermore, the authors discussed 2-D *power-mode* algorithms in [26]–[28] and 2-D *mode-channel* algorithms in [29]. From the perspective of candidate working modes, cellular mode and overlay mode were discussed in [26], while overlay mode and underlay mode were considered in [27]. More specifically, Ma *et al.* [28] compared cellular mode, overlay mode, and underlay mode to achieve the minimum power consumption. Considering the three working modes, the algorithm in [29] was proposed to increase the sum rate.

Although the resource management algorithms have been widely studied, these papers concentrating on the one-dimensional (1-D) or the 2-D resource management cannot fully exploited the possible enhancement of system performance [30]. For D2D communications with relays, Guo *et al.* [31], Hoang *et al.* [32], Ma *et al.* [33] only focused on direct mode and two-hop mode. The cooperative mode, which brings higher SE but consumes more power, has not been carefully measured. Thus, cooperative mode should be deliberated with direct mode and two-hop mode to increase EE.

Until now, 3-D resource allocation schemes for D2D communication with direct mode, two-hop mode, and cooperative mode have not been investigated. For such a D2D communication scenario with various transmission modes and multiple dimensions of resource, it is imperative to investigate a general resource allocation scheme to achieve EE enhancement and friendly coexistence of D2D and cellular communications. Moreover, since the introduction of cooperative mode increases the complexity of 3-D resource allocation, it is challenging to design a low-complexity 3-D resource allocation algorithm. The main contributions of our work are summarized as follows:

- To realize energy efficient D2D communications, a joint power allocation, mode selection, and channel assignment scheme for underlaid D2D communications is proposed in this paper, where three transmission modes,[1] i.e., direct mode, two-hop mode, and cooperative mode, are all taken into account. In particular, for friendly coexistence of D2D and cellular communications, the 3-D resource allocation problem is formulated to maximize EE of D2D communications while guaranteeing the quality of service (QoS) of both D2D and cellular communications.
- We design a specific procedure for the complicated 3-D resource allocation problem, where transmit power, reusing channel, and transmission mode are coupled to each other. Employing the orthogonality of different D2D links and the uniqueness of transmission mode for one D2D pair, we firstly decouple the original 3-D problem. Then, an alternating Dinkelbach algorithm is proposed to obtain the optimal transmit power of D2D communications in different transmission mode.
- Considering that the cooperative mode increase EE of D2D communications at the expense of high complexity of algorithm, a low-complexity sub-optimal 3-D resource allocation algorithm is proposed for the sake of practical implementation. Referring to the fact that the transmission mode that can obtain largest EE of one D2D pair does not obviously vary from one channel to another, thus, we utilize the mode selection result on on random channel as the final result, reducing the complexity of 3-D resource allocation algorithm. Also, theoretical analysis of time complexity is presented to demonstrate the reduction.

A summary of notations and key parameters in this paper is given in Table 1.

The remainder of this paper is organized as follows. Section III introduces the system model. In Section IV, we present the problem formulation, simplify the objective function, and give the optimal scheme. Section V shows the low-complexity sub-optimal scheme and the time complexity analysis. In Section VI, the performance of our proposed algorithms is illustrated by the simulation results. Finally, conclusions are drawn in Section VII.

III. SYSTEM MODEL

We consider a single cell scenario with M cellular user equipments (CUEs) (i.e., $\mathcal{C} = \{C_j\}$) communicating with BS on

TABLE 1. A summary of the notations and key parameters.

Notation	Description
$\mathcal{C}$	Set of cellular users
$\bar{\gamma}$	Average received SNR
$\mathcal{CN}(\cdot)$	Complex additive white Gaussian distribution
$1/\lambda$	Drain efficiency of power amplifier
η	EE of D2D pairs
μ_{ij}	Coefficient of channel assignment
ω_{ij}^{k}	Coefficient of mode selection
$\Upsilon_{\text{th}}^{\text{D}}$, $\Upsilon_{\text{th}}^{\text{C}}$	Rate threshold of D2D pairs, and cellular users
Π	EE Matrix
Ω, Φ, Θ	Feasible region of variables
ε	Permissible error in Algorithm 1
$\mathcal{O}(\cdot)$	Time complexity
Parameter	**Description**
M, N	Number of cellular users, and number of D2D pairs
C_j	j-th cellular user
$\text{S}_i, \text{R}_i, \text{D}_i$	Source user, relay user and destination user of the i-th D2D pair
h_{XY}	Channel coefficient of X$\rightarrow$Y link
P_{X}	Transmit power of user X
P_{cps}^{k}	Circuit power in the k-th mode
R_{X}^{k}	SE of user X in the k-th mode

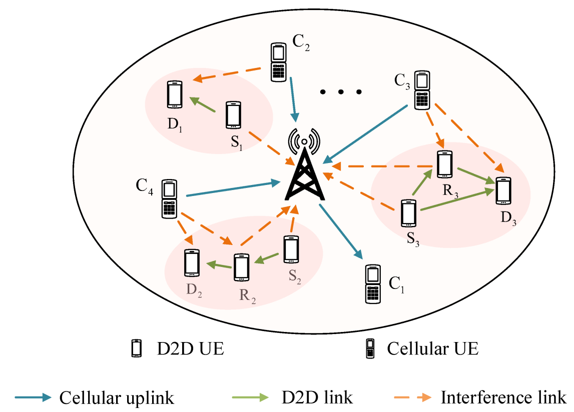

FIGURE 2. A single-cell scenario with D2D communications underlaying the cellular network.

orthogonal channels and N ($M \geq N$) D2D pairs, as shown in Figure 2. No idle orthogonal cellular channel can be used by D2D pairs, and they will reuse the channels when CUEs upload to BS. Notice that each D2D pair can only reuse one cellular channel, and each cellular channel is reused by only one D2D pair. The D2D pair consists of a source user equipment(i.e., S_i) and a paired destination user equipment (i.e., D_i). Besides, there are many idle user equipments (UEs) serve as candidate relays for D2D pairs to realize two-hop or cooperation communication. Our paper focuses on the

[1] We do not discuss cellular mode and overlay mode. On one hand, the simulations in [34] illustrated that the percentage of cellular mode being selected as the optimal mode under EE-based scheme is the lowest compared with overlay mode and underlay mode. On the other hand, the co-channel interference is not considered in overlay mode. The solution in this paper can be extended to the overlay situation.

scene that relay selection has been accomplished considering remaining battery time, pathloss and social relationship. The D2D pair may have one appropriate relay (i.e., R_i) or not.

Network resource usage information and channel state information (CSI) between users and BS are also essential for resource management for original cellular networks without D2D communications. Only CSI between D2D users is the extra information needed, which can be obtained through neighbor discovery [35], [36]. Thus, BS can have CSI of all links. It is assumed that each UE is equipped with a single antenna. Meanwhile, BS controls the transmit power of CUEs such that the uplink signals are received with the same signal-to-noise ratio (SNR), and allocates power, selects mode, assigns channel for D2D pairs. In this paper, let h_{XY} denote the channel coefficient of X→Y link. Specifically, $h_{\mathrm{s}_i\mathrm{d}_i}$, $h_{\mathrm{s}_i\mathrm{r}_i}$, $h_{\mathrm{r}_i\mathrm{d}_i}$, and $h_{\mathrm{c}_j\mathrm{e}}$ are the channel coefficients of $\mathrm{S}_i \rightarrow \mathrm{D}_i$, $\mathrm{S}_i \rightarrow \mathrm{R}_i$, $\mathrm{R}_i \rightarrow \mathrm{D}_i$, and $\mathrm{C}_j \rightarrow$BS communication links, respectively. $h_{\mathrm{c}_j\mathrm{r}_i}$, $h_{\mathrm{c}_j\mathrm{d}_i}$, $h_{\mathrm{r}_i\mathrm{e}}$, and $h_{\mathrm{s}_i\mathrm{e}}$ are the channel coefficients of $\mathrm{C}_j \rightarrow \mathrm{R}_i$, $\mathrm{C}_j \rightarrow \mathrm{D}_i$, $\mathrm{R}_i \rightarrow$BS, and $\mathrm{S}_i \rightarrow$BS interfering links, respectively. We model the channel coefficient as $h_{\mathrm{XY}} = g^{\mathrm{pl}}_{\mathrm{XY}} \cdot g'_{\mathrm{XY}}$, where $g^{\mathrm{pl}}_{\mathrm{XY}}$ denotes the pathloss, and g'_{XY} denotes the fast fading coefficient. The Nakagami-m channel model, which can simulate different signal fading environments, is employed to characterize above channels.[2] In this case, the probability density function (PDF) of $\left|g'_{\mathrm{XY}}\right|^2$ is expressed as follows:

$$f_{\left|g'_{\mathrm{XY}}\right|^2}(\gamma) = \frac{\gamma^{m-1}}{\Gamma(m)}\left(\frac{m}{\bar{\gamma}}\right)^m e^{-\frac{m}{\bar{\gamma}}\bar{\gamma}}, \quad \bar{\gamma} \geq 0, m \geq \frac{1}{2} \tag{1}$$

where m denotes the fading parameter and $\bar{\gamma}$ denotes the average SNR [38]. The fading environment can be described from serious, moderate, slight to no fading by adjusting m. Specifically, we denote m_1 for the communication links and m_2 for the interference links.

A. DIRECT MODE

Now we give a detail description of the three transmission modes, and derive the SE and the power consumption respectively. As shown in Figure 2, When i-th D2D pair is in direct mode reusing the channel of C_j, S_i sends its data to D_i and C_j uploads to BS. During the transmission, S_i causes interference to BS, while D_i receives interference from C_j. The signals received at D_i and BS, which are denoted by $z_{\mathrm{d}_{ij}}$ and $y_{\mathrm{c}_{ij}}$, respectively, can be expressed by

$$z_{\mathrm{d}_{ij}} = \sqrt{P_{\mathrm{s}_{ij}}}h_{\mathrm{s}_i\mathrm{d}_i}x_{\mathrm{s}} + \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{d}_i}x_{\mathrm{c}} + n_1 \tag{2}$$

$$y_{\mathrm{c}_{ij}} = \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{e}}x_{\mathrm{c}} + \sqrt{P_{\mathrm{s}_{ij}}}h_{\mathrm{s}_i\mathrm{e}}x_{\mathrm{s}} + n_2 \tag{3}$$

where $P_{\mathrm{s}_{ij}}$ and P_{c_j} denote the transmit power of S_i and C_j, respectively, x_{s} and x_{c} denote the signals transmitted from S_i and C_j, respectively, n_1 and n_2 denote the noises. In this paper, all the noises are complex additive white Gaussian noises (AWGNs) with distribution $\mathcal{CN}(0, N_0)$.

[2] Our work focuses on the resource management problem, thus the Nakagami-m channel model is employed. In the future, we will consider a more general channel model, such as [37].

Accordingly, the SE of the i-th D2D link and the j-th cellular link, denoted by $R^1_{\mathrm{d}_{ij}}$ and $R^1_{\mathrm{c}_{ij}}$, respectively, are expressed by

$$R^1_{\mathrm{d}_{ij}} = \log_2\left(1 + \alpha_{ij}P_{\mathrm{s}_{ij}}\right) \tag{4}$$

$$R^1_{\mathrm{c}_{ij}} = \log_2\left(1 + \frac{P_{\mathrm{c}_j}\left|h_{\mathrm{c}_j\mathrm{e}}\right|^2}{P_{\mathrm{s}_{ij}}\left|h_{\mathrm{s}_i\mathrm{e}}\right|^2 + N_0}\right) \tag{5}$$

where $\alpha_{ij} = \frac{\left|h_{\mathrm{s}_i\mathrm{d}_i}\right|^2}{P_{\mathrm{c}_j}\left|h_{\mathrm{c}_j\mathrm{d}_i}\right|^2 + N_0}$. Then, the power consumption in direct mode $P^1_{\mathrm{d}_{ij}}$ is

$$P^1_{\mathrm{d}_{ij}} = \lambda P_{\mathrm{s}_{ij}} + P^1_{\mathrm{cps}} \tag{6}$$

where $P^1_{\mathrm{cps}} = P_{\mathrm{ss}} + P_{\mathrm{dd}}$, $\lambda P_{\mathrm{s}_{ij}}$ is the radio-frequency power of S_i, with $1/\lambda \in (0, 1]$ denoting the drain efficiency of power amplifier. Besides, P_{ss} denotes the circuit power of transmitting data at S_i, P_{dd} denotes the circuit power of receiving data at D_i.

B. TWO-HOP MODE

If the D2D pair has an appropriate relay, two-hop mode and cooperative mode are available. As shown in Figure 2, when i-th D2D pair is in two-hop mode reusing the channel of C_j, one complete transmission finishes in two phases. In the first phase, S_i sends its data to R_i. At the same time, S_i causes interference to BS, and R_i receives interference from C_j. The signals received at R_i and BS, denoted by x_{r}, and $y_{\mathrm{c1}_{ij}}$, respectively, can be expressed by

$$x_{\mathrm{r}} = \sqrt{P_{\mathrm{s}_{ij}}}h_{\mathrm{s}_i\mathrm{r}_i}x_{\mathrm{s}} + \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{r}_i}x_{\mathrm{c}} + n_3 \tag{7}$$

$$y_{\mathrm{c1}_{ij}} = \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{e}}x_{\mathrm{c}} + \sqrt{P_{\mathrm{s}_{ij}}}h_{\mathrm{s}_i\mathrm{c}_j}x_{\mathrm{s}} + n_4. \tag{8}$$

In the second phase, R_i amplifies and forwards the received signal in the first stage to D_i. At the same time, R_i causes interference to BS, and D_i receives interference from C_j. According to [39], the amplifier gain of R_i can be expressed by $G_{ij} = 1\Big/\sqrt{P_{\mathrm{s}_{ij}}\left|h_{\mathrm{s}_i\mathrm{r}_i}\right|^2 + P_{\mathrm{c}_j}\left|h_{\mathrm{c}_j\mathrm{r}_i}\right|^2 + N_0}$. The signals received at D_i and BS, denoted by $z_{\mathrm{d}_{ij}}$ and $y_{\mathrm{c2}_{ij}}$, respectively, can be expressed by

$$z_{\mathrm{d}_{ij}} = \sqrt{P_{\mathrm{r}_{ij}}}h_{\mathrm{r}_i\mathrm{d}_i}G_{ij}x_{\mathrm{r}} + \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{d}_i}x_{\mathrm{c}} + n_5 \tag{9}$$

$$y_{\mathrm{c2}_{ij}} = \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{e}}x_{\mathrm{c}} + \sqrt{P_{\mathrm{r}_{ij}}}h_{\mathrm{r}_i\mathrm{c}_j}x_{\mathrm{r}} + n_6 \tag{10}$$

where $P_{\mathrm{r}_{ij}}$ denotes the transmit power of R_i.

From (7) - (10), the SE of the i-th D2D link and the j-th cellular link, denoted by $R^2_{\mathrm{d}_{ij}}$ and $R^2_{\mathrm{c}_{ij}}$, respectively, are expressed by

$$R^2_{\mathrm{d}_{ij}} = \frac{1}{2}\log_2\left(1 + \frac{\beta_{ij}\gamma_{ij} \cdot P_{\mathrm{s}_{ij}}P_{\mathrm{r}_{ij}}}{1 + \gamma_{ij}P_{\mathrm{r}_{ij}} + \beta_{ij}P_{\mathrm{s}_{ij}}}\right) \tag{11}$$

$$R^2_{\mathrm{c}_{ij}} = \frac{1}{2}\left(\log_2\left(\kappa_{ij}P_{\mathrm{c}_j}\right) + \log_2\left(\rho_{ij}P_{\mathrm{c}_j}\right)\right) \tag{12}$$

where $\beta_{ij} = \frac{|h_{\mathrm{s}_i\mathrm{r}_i}|^2}{P_{\mathrm{c}_j}|h_{\mathrm{c}_j\mathrm{r}_i}|^2+N_0}$, $\gamma_{ij} = \frac{|h_{\mathrm{r}_i\mathrm{d}_i}|^2}{P_{\mathrm{c}_j}|h_{\mathrm{c}_j\mathrm{d}_i}|^2+N_0}$, $\kappa_{ij} = \frac{|h_{\mathrm{c}_j\mathrm{e}}|^2}{P_{\mathrm{s}_{ij}}|h_{\mathrm{s}_i\mathrm{c}_j}|^2+N_0}$, $\rho_{ij} = \frac{|h_{\mathrm{c}_j\mathrm{e}}|^2}{P_{\mathrm{r}_{ij}}|h_{\mathrm{r}_i\mathrm{c}_j}|^2+N_0}$. Note that the coefficient 1/2 accounts for the fact that the two-hop D2D occurs during two phases. Then, the power consumption in two-hop mode $P^2_{\mathrm{d}_{ij}}$ is

$$P^2_{\mathrm{d}_{ij}} = \frac{1}{2}\left(\lambda P_{\mathrm{s}_{ij}} + \lambda P_{\mathrm{r}_{ij}} + P^2_{\mathrm{cps}}\right) \tag{13}$$

where $P^2_{\mathrm{cps}} = P_{\mathrm{ss}} + P_{\mathrm{dd}} + 2P_{\mathrm{rr}}$, $\lambda P_{\mathrm{r}_{ij}}$ is the radio-frequency power of R_i, and P_{rr} denotes the circuit power of reception and transmission at R_i.

C. COOPERATIVE MODE

As shown in Figure 2, when i-th D2D pair is in cooperative mode reusing the channel of C_j, D_i receives the data from S_i and R_i, and then combines the signals using the maximal ratio combining (MRC) to achieve the cooperation diversity. The complete transmission consists of two time phases. In the first phase, S_i broadcasts signal while R_i and D_i listen. R_i and D_i receive interference from C_j. The signals received at R_i and BS are similar to (7) and (8), respectively, while the signal received at D_i, denoted by $z_{\mathrm{d}1_{ij}}$, can be expressed by

$$z_{\mathrm{d}1_{ij}} = \sqrt{P_{\mathrm{s}_{ij}}}h_{\mathrm{s}_i\mathrm{d}_i}x_{\mathrm{s}} + \sqrt{P_{\mathrm{c}_j}}h_{\mathrm{c}_j\mathrm{d}_i}x_{\mathrm{c}} + n_7. \tag{14}$$

The second phase is similar to that in two-hop mode. The signals received at D_i and BS are similar to (9) and (10), respectively.

Similar to direct mode and two-hop mode, the SE of the i-th D2D link and the j-th cellular link, denoted by $R^3_{\mathrm{d}_{ij}}$ and $R^3_{\mathrm{c}_{ij}}$, respectively, are expressed by

$$R^3_{\mathrm{d}_{ij}} = \frac{1}{2}\log_2\left(1 + \alpha_{ij}P_{\mathrm{s}_{ij}} + \frac{\beta_{ij}\gamma_{ij}\cdot P_{\mathrm{s}_{ij}}P_{\mathrm{r}_{ij}}}{1+\gamma_{ij}P_{\mathrm{r}_{ij}}+\beta_{ij}P_{\mathrm{s}_{ij}}}\right) \tag{15}$$

$$R^3_{\mathrm{c}_{ij}} = \frac{1}{2}\left(\log_2\left(\kappa_{ij}P_{\mathrm{c}_j}\right) + \log_2\left(\rho_{ij}P_{\mathrm{c}_j}\right)\right). \tag{16}$$

Then, the power consumption in cooperative mode $P^3_{\mathrm{d}_{ij}}$ is

$$P^3_{\mathrm{d}_{ij}} = \frac{1}{2}\left(\lambda P_{\mathrm{s}_{ij}} + \lambda P_{\mathrm{r}_{ij}} + P^3_{\mathrm{cps}}\right) \tag{17}$$

where $P^3_{\mathrm{cps}} = P_{\mathrm{ss}} + 2P_{\mathrm{dd}} + 2P_{\mathrm{rr}}$.

IV. JOINT RESOURCE MANAGEMENT FOR ENERGY-EFFICIENT D2D COMMUNICATIONS

In this section, we formulate the 3-D *power-mode-channel* optimization problem of our system model. By employing the orthogonality in different D2D links and the uniqueness of transmission mode, the problem is decoupled without loss of optimality. The specific steps of the optimal scheme will be presented at last.

A. PROBLEM FORMULATION

To better adapt to the requirements of green wireless communications in 5G, especially the low power consumption and high throughput, we intend to improve the overall EE of D2D communications. Meanwhile, from a practical perspective, both D2D and cellular users expect high data rate to support various services and applications like Internet access and data downloading. Thus, the a 3-D *power-mode-channel* resource management approach is formulated to maximize the EE of D2D communications while guaranteeing the QoS of both D2D and cellular users. According to [40], the EE of the i-th D2D pair reusing the j-th channel, denoted by η_{ij}, can be expressed by

$$\eta_{ij} = \frac{R_{ij}}{P_{ij}} \tag{18}$$

where

$$R_{ij} = \sum_{k=1}^{3}\omega^k_{ij}R^k_{\mathrm{d}_{ij}} \tag{19}$$

$$P_{ij} = \sum_{k=1}^{3}\omega^k_{ij}P^k_{\mathrm{d}_{ij}} \tag{20}$$

where $\omega^k_{ij} = 1$ denotes that the corresponding mode k is selected and otherwise $\omega^k_{ij} = 0$. If the D2D pair has no relay, the direct mode will be selected, which means $\omega^1_{ij} = 1$.

In summary, by denoting the system EE as η, the optimization problem can be formulated as

$$\underset{\left\{P_{ij},\omega^k_{ij},\mu_{ij}\right\}}{\text{maximize}}\ \eta = \sum_{i=1}^{N}\sum_{j=1}^{M}\mu_{ij}\eta_{ij} \tag{21}$$

$$\text{subject to}\quad \sum_{i=1}^{N}\mu_{ij} \le 1 \tag{22}$$

$$\sum_{j=1}^{M}\mu_{ij} = 1 \tag{23}$$

$$\mu_{ij} \in \{0, 1\} \tag{24}$$

$$\sum_{k=1}^{3}\omega^k_{ij} = 1,\ \omega^k_{ij} \in \{0, 1\} \tag{25}$$

$$R^k_{\mathrm{d}_{ij}} \ge \Upsilon^{\mathrm{D}}_{\mathrm{th}},\ R^k_{\mathrm{c}_{ij}} \ge \Upsilon^{\mathrm{C}}_{\mathrm{th}} \tag{26}$$

$$P_{\mathrm{s}_{ij}} \le P_{\max},\ P_{\mathrm{r}_{ij}} \le P_{\max} \tag{27}$$

where $\mu_{ij} = 1$ denotes that the i-th D2D pair reuses the j-th channel and otherwise $\mu_{ij} = 0$. Constraint (22) guarantees that each cellular channel is reused by only one D2D pair, but not all channels will be reused. Constraint (23) guarantees each D2D pair reuses only one cellular channel. Constraints (22)-(24) ensure the orthogonality of different D2D links. Constraint (25) guarantees the uniqueness of transmission mode for one D2D pair. Constraints (26) assures the minimum required rate $\Upsilon^{\mathrm{D}}_{\mathrm{th}}$ of D2D links and $\Upsilon^{\mathrm{C}}_{\mathrm{th}}$ of cellular links. Constraint (27) restricts maximal transmit power of S_i and R_i by $P_{\max}$.

In this problem, the transmit power, the transmission mode and the reusing channel are unknown. Clearly, the assignment of channels impacts the channel gains between the D2D pairs and CUEs, and hence influences the optimal power values. Furthermore, the optimal power values depend on the transmission mode of D2D pairs. Therefore, there is a mutual dependence among three variables. More complicated, the function is nonlinear fractional and non-concave. As we know, Exhaustive Attack method is effective but with high complexity even for a small-size system. Therefore, we concentrate on an efficient solution.

B. AN OPTIMAL SOLUTION TO THE 3-D RESOURCE PROBLEM

According to [22] and [41], constraints (23) and (24) guarantee that for the i-th D2D pair, $\exists j' \in j$, $\mu_{ij'} = 1$, then $\mu_{ij} = 0\ (j \neq j')$. The optimal solution of the original problem is also the optimal solution of the following equivalent optimization problem:

$$\begin{aligned} &\underset{\{P_{ij},\omega_{ij}^k,\mu_{ij}\}}{\text{maximize}} \quad \eta = \sum_{i=1}^{N} \mu_{ij}\eta_{ij} \\ &\text{subject to} \quad (22)-(27). \end{aligned} \tag{28}$$

Constraint (22) and (24) guarantee that for the j-th channel, $\forall i' \in i$, if $\mu_{i'j} = 1$, then $\mu_{ij} = 0\ (i \neq i')$, which means the channels reused by two D2D pairs are different and hence there is no co-channel interference between D2D pairs. Therefore, the problem in (28) can be further expressed as the following equivalent independent optimization problems:

$$\begin{aligned} &\underset{\{P_{ij},\omega_{ij}^k\}}{\text{maximize}} \quad \eta_{ij} \\ &\text{subject to} \quad (25)-(27) \end{aligned} \tag{29}$$

$$\begin{aligned} &\underset{\{\mu_{ij}\}}{\text{maximize}} \quad \eta = \sum_{i=1}^{N} \mu_{ij}\eta_{ij} \\ &\text{subject to} \quad (22)-(24). \end{aligned} \tag{30}$$

Problem (29) means to get the optimal EE for D2D pairs in all candidate channels. To solve (29), we need to compare the EE values of three modes and decide which mode is suitable for the i-th D2D pair on the j-th channel considering the uniqueness of transmission mode. Obviously, direct mode is selected for the D2D pairs without relays. Moreover, problem (30) can be regarded as a maximum match problem of a bipartite graph, which can be solved by Hungarian algorithm. As in Figure 3, η_{ij} can be regarded as the weight of two vertex sets, cellular channels and D2D pairs in our problem. If the i-th D2D pair cannot reuse the j-th channel because of serious interference, we set η_{ij} as $+\infty$.

In the light of our analysis, the number of candidate modes depends on on the existence of the relay, it is necessary to divide D2D pairs into two groups. Therefore, the procedure of our solution to the original joint power allocation, mode selection and channel assignment optimization problem is composed of the following steps:

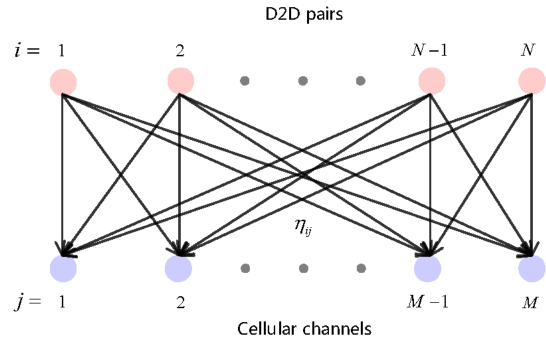

FIGURE 3. Bipartite graph of problem (30).

1) Group D2D pairs according to whether the relay exists.
2) For each D2D pair without relays in all candidate cellular channels, obtain the optimal power and EE values in direct mode, and select the EE as η_{ij}. For each D2D pair with relays in all candidate cellular channels, obtain the optimal power and EE values of three transmission modes, compare the EE values and select the largest one as η_{ij}.
3) For N D2D pairs and M cellular links, we have an EE matrix Π, which can be expressed as
$$\Pi = [\eta_{ij}]_{N\times M}. \tag{31}$$
4) Employ Hungarian algorithm to find the maximum match.
5) Determine the transmit power and mode according to the channel results.

From previous discussions, it can be seen that power allocation is the foundation of the whole solution. Thus, in the following, we firstly analyze power allocation in different modes separately and then, we propose a general algorithm to obtain optimal transmit power for D2D communications in different modes.

In direct mode, which means $\omega_{ij}^1 = 1$, the problem (29) can be expressed as

$$\begin{aligned} &\underset{\{P_{s_{ij}}\}}{\text{maximize}} \quad \eta_{ij} = \frac{\log_2\left(1+\alpha_{ij}P_{s_{ij}}\right)}{\lambda P_{s_{ij}} + P_{\text{cps}}^1} \\ &\text{subject to} \quad (26) \text{ and } (27). \end{aligned} \tag{32}$$

The objective function in (32) is nonlinear and non-concave, thus we cannot apply standard convex optimization techniques to solve the fractional programming (FP) problem. For the optimal power value, Theorem 1 is introduced according to [42]. By denoting Ω and η_{ij}^* as the feasible region and the maximal EE respectively, we have Theorem 1,

Theorem 1: η_{ij}^* is available if and only if

$$\underset{\{P_{s_{ij}}\}\in\Omega}{\text{maximize}} \left\{R_{\text{d}_{ij}}^1 - \eta_{ij}^*\left(\lambda P_{s_{ij}} + P_{\text{cps}}^1\right)\right\} = 0. \tag{33}$$

Proof: The proof is similar to [43].

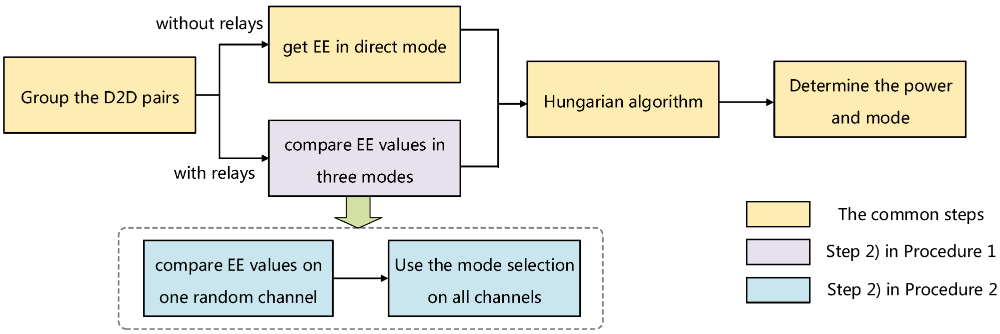

FIGURE 4. The illustration of Procedure 1 and Procedure 2.

It can be seen from Theorem 1 that an equivalent objective function in subtractive form exists for the considered objective function of (32) by exploiting the fractional programming form. According to [42], we can apply the Dinkelbach algorithm to solve it because the function is concave in $P_{\mathrm{s}_{ij}}$. Although the Dinkelbach algorithm is widely utilized, we also present the details of this algorithm in Appendix to intuitively illustrate the power solution derivation.

In two-hop mode, we have $\omega_{ij}^2 = 1$. The problem (29) can be expressed as

$$\begin{aligned} \underset{\left\{P_{\mathrm{s}_{ij}}, P_{\mathrm{r}_{ij}}\right\}}{\text{maximize}} \quad & \eta_{ij} = \frac{\frac{1}{2}\log_2\left(1+\frac{\beta_{ij}\gamma_{ij}\cdot P_{\mathrm{s}_{ij}}P_{\mathrm{r}_{ij}}}{1+\gamma_{ij}P_{\mathrm{r}_{ij}}+\beta_{ij}P_{\mathrm{s}_{ij}}}\right)}{\frac{1}{2}\left(\lambda P_{\mathrm{s}_{ij}}+\lambda P_{\mathrm{r}_{ij}}+P_{\mathrm{cps}}^2\right)} \\ \text{subject to} \quad & (26) \text{ and } (27). \end{aligned} \tag{34}$$

According to Theorem 1, η_{ij}^* is available if and only if

$$\underset{\left\{P_{\mathrm{s}_{ij}}, P_{\mathrm{r}_{ij}}\right\}\in\Phi}{\text{maximize}} \left\{R_{\mathrm{d}_{ij}}^2 - \frac{1}{2}\eta_{ij}^*\left(\lambda P_{\mathrm{s}_{ij}}+\lambda P_{\mathrm{r}_{ij}}+P_{\mathrm{cps}}^2\right)\right\} = 0 \tag{35}$$

where Φ denotes the feasible region in (34).

Similarly, in cooperative mode, the problem (29) can be expressed as

$$\begin{aligned} \underset{\left\{P_{\mathrm{s}_{ij}}, P_{\mathrm{r}_{ij}}\right\}}{\text{maximize}} \quad & \eta_{ij} = \frac{\frac{1}{2}\log_2\left(1+\alpha_{ij}P_{\mathrm{s}_{ij}}+\frac{\beta_{ij}\gamma_{ij}\cdot P_{\mathrm{s}_{ij}}P_{\mathrm{r}_{ij}}}{1+\gamma_{ij}P_{\mathrm{r}_{ij}}+\beta_{ij}P_{\mathrm{s}_{ij}}}\right)}{\frac{1}{2}\left(\lambda P_{\mathrm{s}_{ij}}+\lambda P_{\mathrm{r}_{ij}}+P_{\mathrm{cps}}^3\right)} \\ \text{subject to} \quad & (26) \text{ and } (27). \end{aligned} \tag{36}$$

According to Theorem 1, η_{ij}^* is available if and only if

$$\underset{\left\{P_{\mathrm{s}_{ij}}, P_{\mathrm{r}_{ij}}\right\}\in\Theta}{\text{maximize}} \left\{R_{\mathrm{d}_{ij}}^3 - \frac{1}{2}\eta_{ij}^*\left(\lambda P_{\mathrm{s}_{ij}}+\lambda P_{\mathrm{r}_{ij}}+P_{\mathrm{cps}}^3\right)\right\} = 0 \tag{37}$$

where Θ denotes the feasible region in (36).

Compared with (33), the objective functions in (35) and (37) are non-concave in $P_{\mathrm{r}_{ij}}$ and $P_{\mathrm{s}_{ij}}$. However, they are concave in $P_{\mathrm{s}_{ij}}$ for a fixed $P_{\mathrm{r}_{ij}}$ and concave in $P_{\mathrm{r}_{ij}}$ for a fixed $P_{\mathrm{s}_{ij}}$. Thus, we can utilize Dinkelbach algorithm to obtain optimal $P_{\mathrm{s}_{ij}}/P_{\mathrm{r}_{ij}}$ for a fixed $P_{\mathrm{r}_{ij}}/P_{\mathrm{s}_{ij}}$. According to the alternating maximization (AM) algorithm in [44], we propose an alternating Dinkelbach algorithm to obtain the optimal

Algorithm 1 Alternating Dinkelbach algorithm

1: **Initialization**:
$P_{\mathrm{s}}^{(0)}$, $P_{\mathrm{r}}^{(0)}$, $l = 0$, permissible error $\varepsilon = 10^{-3}$.
2: $P_{\mathrm{s}}^{*(0)} = P_{\mathrm{s}}^{(0)}$, $P_{\mathrm{r}}^{*(0)} = P_{\mathrm{r}}^{(0)}$, calculate $\eta^{(0)}$.
3: **Iteration begins**:
4: Optimize over $P_{\mathrm{s}}^{*(l+1)}$ for a given $P_{\mathrm{r}}^{*(l)}$ by Dinkelbach algorithm.
5: Optimize over $P_{\mathrm{r}}^{*(l+1)}$ for a given $P_{\mathrm{s}}^{*(l+1)}$ by Dinkelbach algorithm.
6: Update the index $l = l + 1$.
7: Calculate $\eta^{(l)}$, if $\left|\eta^{(l)} - \eta^{(l-1)}\right| > \varepsilon$, return 4, otherwise continue.
8: **Iteration ends**.
9: Output $P_{\mathrm{s}}^{*(l)}$, $P_{\mathrm{r}}^{*(l)}$, $\eta^* = \eta^{(l)}$.

transmi power for D2D communications in two-hop and cooperative modes. As illustrated in Algorithm 1, the alternating Dinkelbach algorithm is an extension of Dinkelbach algorithm . For simplicity, we ignore i and j. Permissible error ε represents the maximum error between the output and the optimal point in fact.

As a conclusion, the aforementioned power allocation algorithms are employed for D2D pairs on all candidate channels. We compare the results and regard the largest EE value as the weight for each possible match. Then Hungarian algorithm is used and we can obtain the transmit power, transmission mode and reusing channel for each D2D pair. As illustrated in Figure 4, the specific procedure for the 3-D resource allocation are summarized as Procedure 1.

V. A LOW-COMPLEXITY SOLUTION TO THE 3-D PROBLEM

To this end, we can employ Procedure 1 to conduct 3-D resource allocation for underlaid D2D communications including direct mode, two-hop mode, and cooperative mode. However, the introduction of cooperative mode increases the complexity of 3-D resource allocation algorithm. Thus, it is imperative to design a low-complexity 3-D resource allocation algorithm to facilitate practical application.

As can be seen from Figure 4, Procedure 1 is composed of three algorithms, Dinkelbach algorithm, AM algorithm and Hungarian algorithm. Firstly, it is shown that for non-linear fractional programming problems, Dinkelbach algorithm converges superlinearly in [45]. However, we can not quantitatively analyze the time complexity while it is related to the initial values and the permissible error. Thus we denote W_1 and W_2 as the iteration times for Dinkelbach algorithm and the outer iteration in AM algorithm, respectively. The time complexity for AM algorithm is $\mathcal{O}(W_1W_2)$. Besides, we have N D2D pairs and M $(M \geq N)$ cellular channels in this paper. The time complexity for Hungarian algorithm is $\mathcal{O}\left(M^3\right)$. If we assume that all D2D pairs are equipped with relays, the average time complexity of Procedure 1 is $\mathcal{O}\left(2M^2W_1W_2 + M^3\right)$. When the cooperative mode is not involved, the average time complexity of Procedure 1 is $\mathcal{O}\left(M^2W_1W_2 + M^3\right)$. From the above discussion we can find that the complexity of the optimal algorithm is high when the cooperative mode is involved, especially when the number of users is large.

In Procedure 1, we calculate the EE values with three modes for relay-aided D2D pairs in all candidate cellular channels, a total of $3M^2$ times at most. But for one relay-aided D2D pair, the mode with largest EE values in all channels may remain same. That means we can use the mode selection result on one random channel as the final result. Therefore, we can modify the step 2) of Procedure 1 as follows:

- For each D2D pair without relays in all candidate cellular channels, obtain the optimal power and EE values in direct mode, and select the EE as η_{ij}. For each D2D pair with relays in one random cellular channel, obtain the optimal power and EE values of three transmission modes, compare the EE values and select the largest one as η_{ij}. For the other channels, use the result of mode selection on the random channel as the final result, and obtain the EE values as η_{ij}.

The proposed low-complexity sub-optimal resource allocation scheme, i.e., Procedure 2, is summarized as in Figure 4. Compared to Procedure 1, the average time complexity of Procedure 2 decreases from $\mathcal{O}\left(2M^2W_1W_2 + M^3\right)$ to $\mathcal{O}\left(\frac{2}{3}M^2W_1W_2 + M^3\right)$.

VI. SIMULATION RESULTS

In this section, simulation results are presented to evaluate the performance of the proposed procedures and prove the effectiveness of the 3-D resource management scheme. Initially, we research the factors which influence the results of mode selection for one D2D pair. Then the system simulation for multiple D2D pairs is presented.

The simulation parameters are illustrated in Table 2. The circuit power of transmitting data and receiving data is the same to all UEs, denoted by P_0. In the following, the proposed algorithms are evaluated by Monte Carlo simulations. At each simulation trial, the CUEs, the D2D pairs, and the idle CUEs serve as candidate relays are randomly dropped. We focus on the scenario that relay selection has been done, and the large number of idle CUEs ensures that each D2D pair has one relay. As shown in Figure 5, R_i may be located at any point in the circle whose center is the midpoint of the straight line between S_i and D_i. The location is described by radius and angle. To be specific, the radius denotes the distance from R_i to the midpoint, and the angle is in the range of $[0, 2\pi)$. BS is at the center of the cell and the uplink cellular signals without the co-channel interference are received at BS with the same SNR, i.e. 15 dB.

TABLE 2. Simulation parameters.

Parameter	Value
M	10
N	4
Spectrum bandwidth	10 MHz
Noise PSD	-174 dBm/Hz
D2D pathloss	148.1+40lg[d(km)] [46]
Cellular pathloss	128.1+37.6lg[d(km)] [46]
m_1	1
m_2	2
$P_{\max}$	23 dBm
$\Upsilon_{\mathrm{th}}^{\mathrm{D}}$	0.5 bps/Hz
$\Upsilon_{\mathrm{th}}^{\mathrm{C}}$	0.5 bps/Hz
P_0	50 mW
Permissible error (ε)	10^{-3}

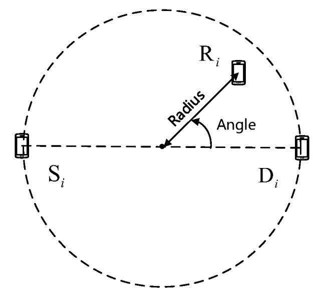

FIGURE 5. The location of relay.

In following simulations, the proposed 3-D resource allocation algorithm is compared with three categories of existing works to reveal the contributions of this paper.

- *SE-max* algorithm in [17]: The transmit power is optimized to maximize SE under the constraints (26) and (27).
- 2-D resource allocation scheme, where only two dimensions of resource are optimized to maximize the EE of D2D communications, including *power-mode* scheme [26]–[28] and *mode-channel* scheme [29].
- Direct & two-hop scheme in [31]–[33] : 3-D resource allocation algorithm for D2D communications without cooperative mode.

A. SIMULATION FOR ONE D2D PAIR

Figure 6 performs η_{ij} in direct mode of Dinkelbach algorithm and *SE-max* algorithm versus the distance of D2D,

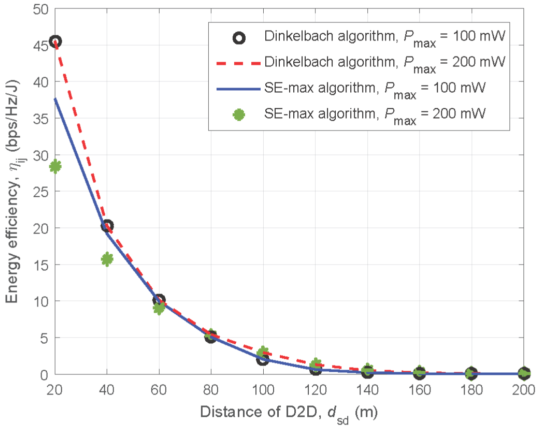

FIGURE 6. EE in direct mode versus d_{sd} with different P_{max} and different algorithms.

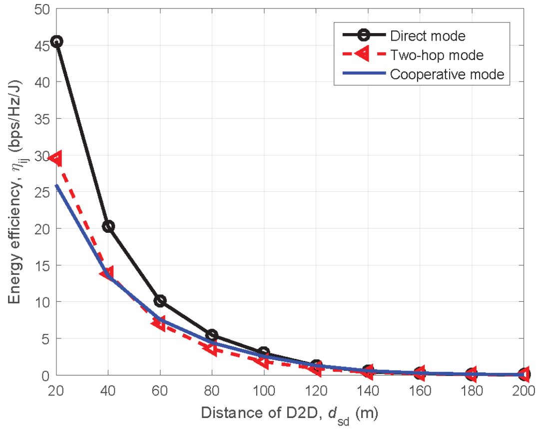

FIGURE 8. EE in three modes versus d_{sd}.

denoted by d_{sd}, with $P_{max} = 100\,mW$ and $P_{max} = 200\,mW$. For a given P_{max}, Dinkelbach algorithm has higher η_{ij} than *SE-max* algorithm. Besides, in short range, η_{ij} of Dinkelbach algorithm with $P_{max} = 100\,mW$ and $P_{max} = 200\,mW$ are the same, which proves the optimal power value is less than $100\,mW$. When d_{sd} is more than 60 m, η_{ij} with $P_{max} = 200\,mW$ is higher due to the change of the optimal power value. In long range, η_{ij} approaches zero.

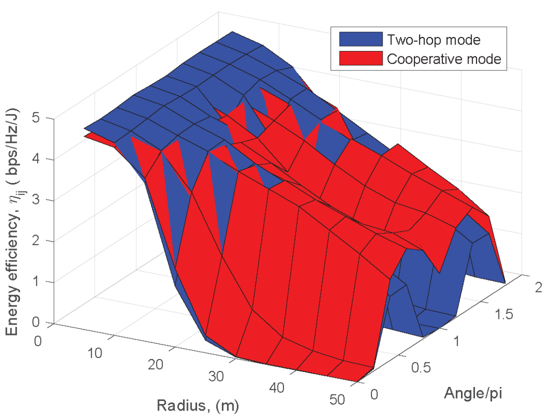

FIGURE 7. EE in two-hop mode and cooperative mode with AM algorithm versus the location of relay (d_{sd} = 100 m).

As shown in Figure 7, we compare η_{ij} in two-hop mode and cooperative mode with AM algorithm versus the relay location when d_{sd} is 100 m. η_{ij} reaches the top when R_i is near the midpoint, and decreases when far away. Meanwhile, η_{ij} in two-hop mode is higher than that in cooperative mode when the radius is small, and the situation is opposite when radius is more than 20 m, indicating that the results of mode selection change. It is noticed that in cooperative mode η_{ij} drops slower with the relay moving because we exploit the $S_i \rightarrow D_i$ communication link.

Figure 8 compares η_{ij} in three transmission modes versus d_{sd}. We observe that η_{ij} decreases with d_{sd} increasing. In direct mode, η_{ij} in 20 m is 35 bps/Hz/J higher than η_{ij} in 60 m. The gap is 23 bps/Hz/J in two-hop mode and 18 bps/Hz/J in cooperative mode. Besides, in short range and medium range, η_{ij} in direct mode is the highest because the direct link is reliable and the power consumption of the relay can be saved. In long range, η_{ij} in cooperative mode is the highest due to the cooperation diversity at the destination. Therefore, it's necessary to select mode according to the link quality.

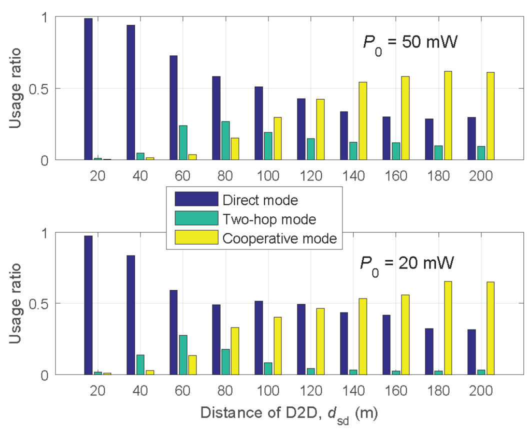

FIGURE 9. Usage ratio of three modes versus d_{sd} with different P_0.

To illustrate the specific influences of d_{sd} on the results of mode selection, the usage ratio versus d_{sd} with different P_0 is plotted in Figure 9. Usage ratio refers to the ratio of total times when the specific mode is selected to the simulation times. As observed, the results of mode selection vary with d_{sd}, and the mode, which achieves the highest η_{ij} in Figure 8, is more likely to be selected. Two-hop mode has a lower ratio than the others because it suffers more negative influences from the random location of relays. It also shows differences between $P_0 = 50\,mW$ and $P_0 = 20\,mW$. The superiority of cooperative mode is more obvious if P_0 is smaller.

Figure 10 shows the effects of thresholds Υ_{th}^{D} and Υ_{th}^{C} on η_{ij} with different mode selection schemes. The thresholds

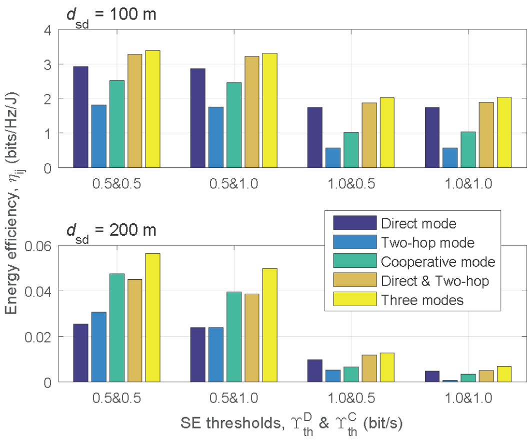

FIGURE 10. EE versus Υ_{th}^{D} and Υ_{th}^{C} with different mode selection schemes ($m_2 = 1$).

guarantee the quality of service but limit the transmit power of D2D. Υ_{th}^{D} determines the minimum required transmit power while Υ_{th}^{C} bounds the maximal power. When d_{sd} remains unchanged, higher Υ_{th}^{D} causes lower η_{ij}, and higher Υ_{th}^{C} also brings loss. This situation is more noticeable when d_{sd} is larger. Besides, the mode selection scheme focusing direct mode and two-hop mode obtains lower EE than the mode selection scheme with three transmission mode, demonstrating the benefits of introducing cooperative mode. In some special case, such as $d_{sd} = 200$ m, $\Upsilon_{th}^{D} = 0.5$bit/s, and $\Upsilon_{th}^{C} = 0.5$bit/s, the mode selection scheme only involves cooperative mode outperforms the mode selection scheme focusing direct mode and two-hop mode.

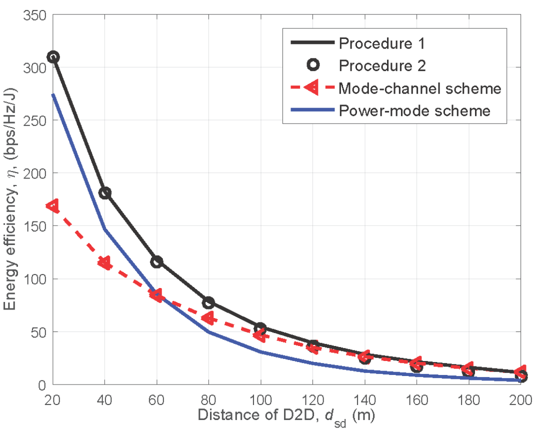

FIGURE 11. EE of Procedure 1, Procedure 2, and the 2-D schemes versus d_{sd}.

B. SIMULATION FOR THE SYSTEM

Figure 11 compares η of Procedure 1, Procedure 2 and the 2-D schemes versus d_{sd}. Procedure 1 achieves higher η than the 2-D schemes. But the gap between Procedure 1 and the *mode-channel* scheme is not obvious in long range. Meanwhile, compared with the *power-mode* scheme, the *mode-channel* scheme has a more serious degradation on the system performance in short range. We can draw a conclusion that power allocation performs outstanding in short range and poor in long range, and channel assignment always performs well. Besides, it can be observed that Procedure 2 approximates Procedure 1 better in short range. The reason is that as d_{sd} increases, η suffers more influences from the difference in the results of mode selection when one D2D pair reuses different channels.

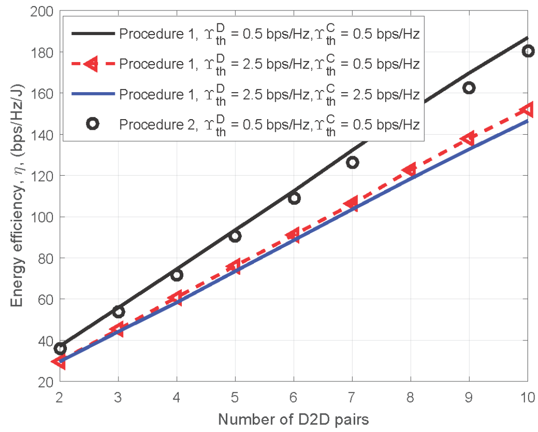

FIGURE 12. EE versus the number of D2D pairs with different Υ_{th}^{D} and Υ_{th}^{C} ($m_2 = 1$, $d_{sd} \in [20\text{m}, 200\text{m}]$).

Figure 12 depicts η versus the number of D2D pairs with different Υ_{th}^{D} and Υ_{th}^{C}. Different from Figure 10, each D2D pair has a random d_{sd}, leading to more complicated resource management according to the previous analysis and simulations. It can be observed that η increases with the number of D2D pairs, while drops with higher Υ_{th}^{D} and Υ_{th}^{C}. For the system of D2D communications, higher received thresholds cause that the transmit power is far away from the optimal point and η decreases. Besides, the simulation results show that η by Procedure 2 reaches about 96.2% of η by Procedure 1 on average.

VII. CONCLUSION

In this paper, we have discussed the joint power allocation, mode selection and channel assignment for underlaid D2D communications in a multi-user scenario. The 3-D *power-mode-channel* problem has been decoupled into several steps without loss of optimality. Based on the optimal algorithm, a sub-optimal algorithm has been proposed to lower the complexity. Specifically, we have given the procedure of the proposed algorithms, and derived the average time complexity to prove the improvement. Simulation results have been provided to verify that the result of mode selection is affected by various factors, such as D2D distance, the location of relay, the circuit power and the QoS. Last but not least, the 3-D algorithm has better performance than 2-D algorithms, supporting the low-carbon wireless communications in 5G.

APPENDIX

Here, taking power allocation for D2D communications in direct mode as an example, we present the detailed process of employing Dinkelbach Algorithm to obtain optimal transmit power.

Algorithm 2 Dinkelbach Algorithm

1: **Initialization**:
$j = 0$, $\eta^{(0)} = 10^{-4}$, permissible error $\varepsilon = 10^{-3}$.
2: **Iteration begins**:
3: Solve the following optimization problem to obtain the transmit power $P_{\mathrm{s}}^{*(j)}$:
$\underset{\left\{P_{\mathrm{s}}^{(j)}\right\}\in\Omega}{\text{maximize}} \left\{R_{\mathrm{d}}^{1}\left(P_{\mathrm{s}}^{(j)}\right) - \eta^{(j)}\left(\lambda P_{\mathrm{s}}^{(j)} + \mathrm{P}_{\mathrm{cps}}^{1}\right)\right\}.$
4: Set $f\left(\eta^{(j)}\right) = R_{\mathrm{d}}^{1}\left(P_{\mathrm{s}}^{*(j)}\right) - \eta^{(j)}\left(\lambda P_{\mathrm{s}}^{*(j)} + P_{\mathrm{cps}}^{1}\right)$.
5: If $\left|f\left(\eta^{(j)}\right)\right| \geq \varepsilon$, update $\eta^{(j)} = \frac{R_{\mathrm{d}}^{1}(P_{\mathrm{s}}{}^{*(j)})}{\lambda P_{\mathrm{s}}^{*(j)} + P_{\mathrm{cps}}^{1}}$, $j = j + 1$, return 3, otherwise continue.
6: **Iteration ends**
7: Output $P_{\mathrm{s}}^{*(j)}$, $\eta^{*} = \eta^{(j)}$.

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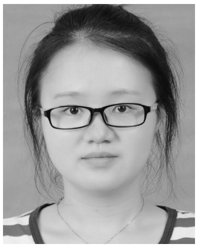

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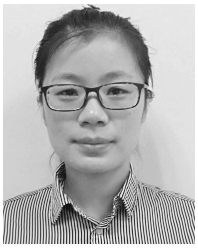

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