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Energy-Efficient Resource Sharing Scheme With Out-Band D2D Relay-Aided Communications in C-RAN-Based Underlay Cellular Networks

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ABSTRACT Device-to-Device (D2D) communications and cloud radio access network (C-RAN) can improve Spectrum Efficiency (SE). However, extremely severe intra-cell interference and inter-cell interference hinder the improvement of energy efficiency (EE). In the existing typical work, a centralized interference mitigation algorithm is deployed in cellular infrastructure to try to eliminate these types of interferences. Although this method improves the quality of service, it hardly reduces the energy consumption of cellular user equipments (UEs). Moreover, it increases the energy consumption of cellular infrastructure. In this paper, we first introduce out-band D2D relays to assist the cellular communications, which can shorten the average transmission distance of cellular UEs and thus make them improve their EE and reduce the inter-cell interference for each other. Then, we propose an energy-efficient resource sharing scheme to determine channel selection and power allocation. Next, we formulate the resource sharing problem as the noncooperative game model, where each UE optimizes its EE respectively with the aid of the remote radio heads in C-RAN. Finally, in order to obtain the optimal EE of each UE, we let the non-concave optimization problem be transformed into the concave form by using constraint relaxation and nonlinear fractional programming and solve the transformed problem by Dinkelbach's method and the Lagrangian duality theory. The simulation results show that the SE and EE of cellular UEs can be improved by 64.63% and 24.97%, respectively when adopting the parameters with the best values in our relay selection strategies.

INDEX TERMS Cloud radio access network, out-band D2D relay-aided communication, noncooperative game, resource sharing, energy efficiency.

I. INTRODUCTION

With explosive growth of wireless terminals, mobile devices, and smart objects [1]–[5], it is predicted that mobile Internet data traffic will reach 3.3 ZB per year by 2021, which will account for more than 63 percent of global IP traffic [6]. To cope with such rapid increase of traffic demand, mobile network operators have to build radio access networks with ultra-high capacity [7], [8].

For mobile network operators, on the one hand, it is a simple and effective way to ultra-densely deploy various base stations to improve network access capacity. On the other hand, it requires a huge investment and thus imposes a huge burden on mobile network operators. Cloud Radio Access Network (C-RAN) [9], [10] is mainly composed of a relatively small number of centralized BaseBand Units (BBUs) and a relatively large number of distributed Remote Radio Heads (RRHs). Since the costs of RRHs are much lower than those of traditional base stations, C-RAN is helpful to reduce capital and operational expenditure costs for mobile network operators while guaranteeing ultra-dense coverage.

When a pair of User Equipments (UEs) are in the proximity of each other and also they are a pair of source and destination terminals in a communication session, Device-to-Device (D2D) communication mode [11], [12] can allow them to communicate directly without the relay of RRH, which can greatly reduce the burden of cellular infrastructure.

This makes RRHs have more potential to offer the access service for more UEs that must establish communication sessions through RRHs.

In view of the above advantages, C-RAN and D2D will be considered in the upcoming cellular standards (e.g., the fifth generation (5G) mobile communication network). Although the ultra-dense deployment of RRHs improves spectrum reusing ratio, it is still a prerequisite for introducing D2D communication mode into C-RAN to efficiently share the scarce spectrum resources. Thus, in-band D2D communication, which can share the cellular resources to achieve better Spectrum Efficiency (SE), has attracted many researchers to explore an underlay D2D mode in C-RAN, and thus it is the key element of the existing resource sharing schemes [13]–[15].

Nevertheless, the combination of in-band D2D communications and C-RAN brings lots of new problems. Most typically, because of the dense deployment of the RRHs and the excessive reuse or share of the spectrum resources, the cellular UEs suffer extremely severe intra-cell interference and inter-cell interference. Thus, on the one hand, these cellular UEs have the very bad Quality of Service (QoS). On the other hand, they will quickly run out of their energy due to their efforts to meet the QoS requirement which usually means the increase of their transmission powers. To improve QoS, the work in [16] proposed a centralized interference mitigation algorithm run in BBUs. However, it hardly reduces the energy consumption of cellular UEs. Moreover, it increases the energy consumption of BBUs.

To tackle the above problem, using D2D relays to assist the cellular communications will be a good choice. This is because, D2D relay-assisted cellular communications can shorten the average transmission distance of cellular UEs, and thus make cellular UEs improve their QoS and reduce the inter-cell interference for each other. Furthermore, compared with in-band D2D UEs, out-band D2D UEs have several advantages to act as D2D relays. First, out-band D2D communications use unlicensed spectrum, and thus will not compete for the scarce cellular spectrum resources (i.e., licensed spectrum). Then, out-band D2D communications are receiving more attention since the standardization of in-band D2D communications progresses slowly due to the significant modifications to make in-band D2D UEs appropriately use the cellular spectrum [17]. Finally, there have been lots of research achievements facing the challenges in coordinating the in-band and out-band radio interfaces (e.g., the integrated protocol stacks [18], LTE-w [19]).

Hence, in this paper, we propose an energy-efficient resource sharing scheme to determine channel selection and power allocation in in-band D2D communications underlaying C-RAN by exploiting out-band D2D relays to assist cellular communications. The main contributions are as follows.

First, for each cellular UE, we try to allocate an out-band D2D relaying UE to it, especially those who are on the edge of the cell, where they are easier to suffer inter-cell interference. However, it is not difficult to prove that finding out a global optimal out-band D2D relaying UE allocation scheme is NP-hard. Therefore, we propose a suboptimal scheme, which can assign an appropriate out-band D2D relaying UE for each cellular UE based on our selection strategies.

Then, since there are conflicts among all the UEs' Energy Efficiency (EE) optimization, the proposed resource sharing scheme is formulated as a noncooperative game model, where each in-band player (i.e., cellular UE or in-band D2D UE) optimizes its EE respectively with the aid of the RRH. And if a cellular UE gets assistance from an out-band D2D relaying UE, the EE optimization will be converted to a joint one of itself and its out-band D2D relaying UE.

Next, a Nash Equilibrium (NE) is just the desired solution in the proposed scheme. In order to obtain it, we let the non-concave optimization problem be transformed into the concave form by using constraint relaxation and nonlinear fractional programming. And we solve the transformed problem by Dinkelbach's method and Lagrangian duality theory. Finally, the achievable performances of the proposed scheme mainly effected by our relaying selection strategies are analyzed through simulations in detail.

The remainder of this paper is organized as follows. In Section II, we briefly overview the works related to in-band D2D communications underlaying C-RAN. In Section III and IV, we introduce the system model of out-band D2D relay-aided communications underlaying C-RAN and the problem formulation respectively. In Section V, we introduce the proposed energy-efficient resource sharing scheme in detail. We give the simulation parameters and results, and then discuss and analyze the results in Section VI. Finally, we summarize our results and give the conclusions in Section VII.

II. RELATED WORK

Since in-band D2D communications underlaying C-RAN has combined the benefits of in-band D2D communications and C-RAN, lots of research efforts from industry and academia have been addressed to overcome the shortcomings brought by this combination in recent years. A Heterogeneous C-RAN (H-CRAN) with non-uniformly deployed D2D communication was studied in [20] to achieve lower average traffic delivery latency, where D2D links were only allocated outside a specified distance from any high power node. And the work in [21] integrated D2D communications with coordinated multi-point in C-RAN to improve the SE, where a distance-based mode selection rule for downlink users was adopted. Moreover, the work in [22] designed a matching game to assign the sub-channels with different bandwidths to multiple D2D pairs and the RRH users, which significantly improved the system throughput. The work in [23] proposed a D2D service selection framework in C-RAN by using queuing theory and convex optimization to improve the QoS. The work in [24] modeled the resource allocation of D2D pairs as a coalition formation game and solved it through a distributed algorithm, which enhanced the system throughput. The work in [25] proposed a scheme to allocate transmitting powers and channels to maximize the number of the D2D pairs and the reused channels, which increased the total capacity of the system.

As we can see, the works mentioned above mainly consider optimizing SE (i.e., throughput, capacity, etc.) or delivery latency, disregarding the energy consumption of UEs. Few works focus on optimizing EE in D2D communications underlaying C-RAN. The work in [26] proposed a user-centric local mobile cloud assisted D2D communications underlaying H-CRAN by introducing D2D communications into computation offloading, which reduced the transmission energy consumption. The work in [16] modeled an energy-efficient resource allocation problem as a distributed noncooperative game among UEs, and proposed a centralized interference mitigation algorithm carried out in the centralized BBUs, including an interference cancellation technique and a transmission power constraint optimization technique.

However, the above two works have not exploited out-band D2D relaying UEs to assist cellular communications for the purpose of improving the EE. Moreover, although the work in [16] has taken advantages of centralized interference mitigation algorithm to improve the QoS performance, the strong intercell interference caused by cellular UEs will make this algorithm be invoked frequently, which will increase the computational burden and energy consumption of the centralized BBUs.

Unlike the work in [16], considering the advantages of out-band D2D communications, we improve the SE and EE by adopting out-band D2D relays to assist cellular communications, where the centralized interference mitigation algorithm is seldom (almost not) invoked. Furthermore, an exhaustive search of all the cells is needed by the work in [16], which means a high time complexity. In this paper, our scheme can reduce the time complexity of cell searching process to a constant level by employing a local search method on the basis of the division of cells.

III. SYSTEM MODEL

A. C-RAN ARCHITECTURE AND DIVISION OF CELLS

An example of D2D communications underlaying C-RAN with three cells is illustrated in Fig.1, where the general architecture of D2D communications underlaying C-RAN can be inferred by changing the number of cells. Generally, a D2D communication mode underlaying C-RAN includes a BBU pool, RRHs, fronthaul links, backhaul links, cellular UEs, and D2D UEs (including in-band D2D pairs and out-band D2D relaying UEs in this paper). And for clarity, all UEs are temporarily omitted in Fig.1. In general, RRHs have simple front Radio Frequency (RF) and signal processing functionalities (e.g., RF amplification, filtering, etc.) so that they can communicate with UEs. The RRHs and BBU pool are connected by fronthaul links with low latency and high bandwidth. The BBU pool performs further baseband signal processing, resource allocation, and load balancing with

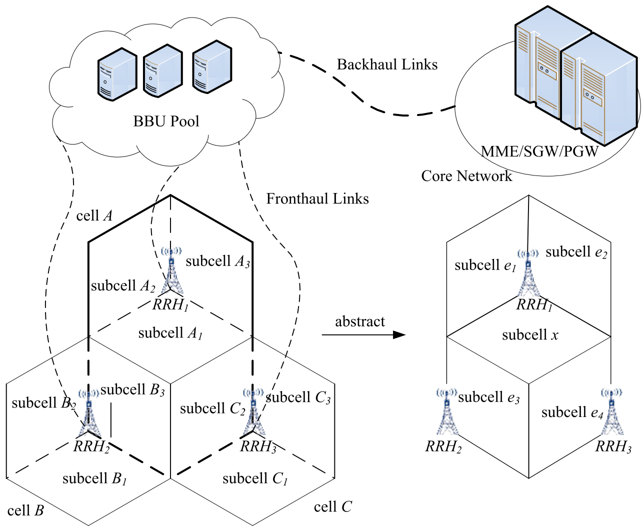

FIGURE 1. Example of D2D communications underlaying C-RAN with three cells.

powerful centralized processors, and communicates with the core network through high-speed backhaul links.

Since the introduction of out-band D2D relays is beneficial to reduce transmission powers of cellular UEs and thus reduce the inter-cell interference, it is unnecessary to consider all the adjacent cells when estimating the inter-cell interference suffered by a receiving-end in a cell. Therefore, we divide a cell (e.g., cell A in Fig.1) into three subcells and take a subcell (e.g., subcell A_1 in Fig.1) as the object of concern to discuss its interference range. Taking Fig.1 for an example, when we take subcell A_1 as the object of concern, the intra-cell interference from subcell A_2 and A_3 to subcell A_1 can be regarded as the inter-subcell interference of subcell A_1, and the inter-cell interference from cell B and C to subcell A_1 is mainly coming from subcell B_3 and C_2, which is also the inter-subcell interference of subcell A_1. Under this condition, inter-subcell interference of subcell A_1 is mainly coming from subcell A_2, subcell A_3, subcell B_3 and subcell C_2. And this view is suitable for any subcell in any cell of any scene, i.e., not only the scene shown in Fig.1, thus the interference discussion about one subcell can be based on itself (i.e., intra-subcell interference) and 4 subcells around it (i.e., inter-subcell interference). Without loss of generality, we abstract subcell x, e_1, e_2, e_3 and e_4 from subcell A_1, A_2, A_3, B_3 and C_2, as shown in Fig.1. When we take any other subcell as the object of concern, we also can regard it as subcell x, and find out the corresponding subcells from e_1 to e_4. As for those marginal subcells, which usually lack subcell e_3, e_4 or both of them, we do not consider the lack of subcells.

What we should notice is, subcell x, e_1 and e_2 make up a complete cell while subcell e_3 and e_4 are parts of other cells. Hence, for an illustrative purpose, we use IISC to denote the inter-subcell interference from the same cell (e.g., the IISC from subcell e_1 or e_2 to x) and use IIDC to denote the inter-subcell interference from different cells (e.g., the IIDC from subcell e_3 or e_4 to x).

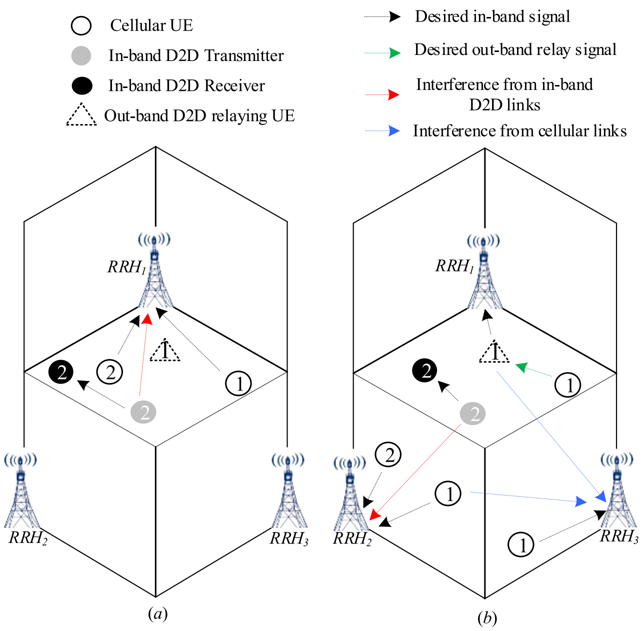

FIGURE 2. Interferences to RRHs in D2D communications underlaying C-RAN.

B. INTERFERENCES TO RRHS AND ROLES OF UEs

We focus on the uplink scenario where in-band D2D UEs reuse the uplink spectrum resources allocated to cellular UEs and RRHs transmit signals from cellular UEs to the BBU pool for further processing [27]. Fig. 2 illustrates the complex interference that the RRHs suffer in the environment of the active aforementioned 5 subcells, where the circles with different fillers or the triangle represent the UEs with different identities, and the number in each circle or triangle represents the ID of channel used by the UE.

Since every cellular UE of a cell is allocated in an orthogonal way in LTE-A, there is no IISC among cellular UEs in subcell x, e_1 and e_2, while there is IIDC among cellular UEs located in adjacent subcell x, e_3 and e_4. As a result, when the RRH_1 is receiving the data from a cellular UE that is using the channel 2 in subcell x, it suffers from the intra-subcell interference caused by the in-band D2D transmitter which is reusing the channel 2 in the same subcell as shown in Fig. 2(a). Also, when the RRH_2 is receiving the data from a cellular UE that is using the channel 2 in subcell e_3, it suffers from the IIDC caused by the in-band D2D transmitter that is reusing the channel 2 in the adjacent subcell x as shown in Fig. 2(b). In addition, when the RRH_3 is receiving the data from a cellular UE that is using the channel 1 in subcell e_4, it suffers from the IIDC caused by both the cellular UE and the out-band D2D relaying UE that are using the channel 1 in the adjacent subcell e_3 and x respectively as shown in Fig. 2(b). However, the RRH_3 will suffer from the smaller IIDC (i.e., inter-cell interference), since its interfering source adopts the lower transmission power with the aid of out-band D2D relay.

In addition, when a cellular UE decides to use out-band D2D relay, its cellular link from itself to the RRH (denoted as original link) will convert to a composite link (denoted as optimized link) including an out-band D2D link from itself to the out-band D2D relaying UE (denoted as the out-band part) and a cellular link from the out-band D2D relaying UE to the RRH (denoted as the cellular part). According to this, we should note that once a cellular UE decides to use the out-band D2D relay, the out-band D2D relaying UE will take the place of the cellular UE to act as a cellular transmitter using the same in-band channel. In other words, a cellular transmitter can be either a cellular UE or an out-band relay D2D UE, depending on whether the cellular UE uses the out-band D2D relay. An example of above scenario is also shown in Fig. 2(b). Therefore, to avoid confusion, we define that the nouns contain UE (e.g. cellular UE) only describe the original function of the UE, i.e., the function before using the out-band D2D relay. Table 1 summarized the various roles acted by different kinds of UEs in this paper.

TABLE 1. Various roles acted by different kinds of UEs.

Roles	Actors
in-band D2D transmitter (interferer)	in-band D2D UE
in-band D2D receiver	in-band D2D UE
cellular transmitter (interferer)	cellular UE or out-band D2D relaying UE
cellular receiver	RRH
out-band D2D transmitter (interferer)	cellular UE
out-band D2D receiver	out-band D2D relaying UE
in-band D2D link	an in-band D2D transmitter and an in-band D2D receiver
cellular link	a cellular transmitter and the associated RRH
out-band D2D link	an out-band D2D transmitter and an out-band D2D receiver
in-band gamer	in-band D2D transmitter or cellular transmitter
out-band gamer	out-band D2D transmitter

C. SE AND POWER CONSUMPTIONS OF DIFFERENT LINKS

For a more general case, we consider a total of X ($X \geq 2$) adjacent cells. And obviously, there will be $3X$ adjacent subcells. As mentioned above, when we take any one of these $3X$ subcells as the object of concern, i.e., as subcell x ($1 \leq x \leq 3X$), we should find out the corresponding adjacent subcell e_1, e_2, e_3 and e_4, so we could consider a total of these 5 adjacent subcells. In subcell e_m ($m = 1, 2, 3, 4$), the set of in-band D2D links is denoted as N_m, and the set of cellular UEs and out-band D2D relaying UEs are denoted as K_m and M_m respectively. For convenience, in subcell x, we let N_0 denote the sets of in-band D2D links and let K_0 and M_0 denote the set of cellular UEs and out-band D2D relaying UEs respectively. Moreover, to further simplify the problem and reduce the intra-subcell interference, we forbid in-band D2D UEs to reuse the in-band channels that the cellular UEs have used in the same subcell. And the cross-subcell out-band D2D communication is not allowed. Finally, an out-band D2D relaying UE only works for one cellular UE in the same time.

The achievable SE (defined as bits/s/Hz) of the ith in-band D2D link in subcell x ($i \in N_0$) is given by

$$C_{i,x}^{d} = \sum_{k \in K_1 \cup K_2} log_2 \left(1 + \frac{s_{i,x}^{k} p_{i,x}^{k} g_{i,x}^{k}}{I_{i,x}^{d,A} + I_{i,x}^{d,B} + I_{i,x}^{c,B} + N'}\right) \quad (1)$$

where $p_{i,x}^{k}$ represents the transmission power allocated to the ith in-band D2D transmitter on the kth in-band channel ($k \in K_0$) in subcell x. $g_{i,x}^{k}$ represents the channel attenuation of the ith in-band D2D link. $s_{i,x}^{k}$ is a binary indicator, where $s_{i,x}^{k} = 1$ represents the ith in-band D2D link reuse the kth in-band channel in subcell x, and otherwise, $s_{i,x}^{k} = 0$. N' is the thermal noise power.

$I_{i,x}^{d,A}$ and $I_{i,x}^{d,B}$ are the intra-subcell interference and inter-subcell interference caused by other in-band D2D links, and are given by

$$I_{i,x}^{d,A} = \sum_{i' \in N_0 \setminus \{i\}} s_{i',x}^{k} p_{i',x}^{k} g_{(i',x),(i,x)}^{k} \quad (2)$$

$$I_{i,x}^{d,B} = \sum_{m \in \{1,2,3,4\}} \sum_{i' \in N_m} s_{i',e_m}^{k} p_{i',e_m}^{k} g_{(i',e_m),(i,x)}^{k} \quad (3)$$

where $s_{i',x}^{k} p_{i',x}^{k} g_{(i',x),(i,x)}^{k}$ represents the intra-subcell interference from the i'th in-band D2D interferer to the ith in-band D2D receiver on the kth in-band channel, i.e., $i' \neq i$. $s_{i',e_m}^{k} p_{i',e_m}^{k} g_{(i',e_m),(i,x)}^{k}$ represents the IISC (i.e., $m = 1, 2$) or the IIDC (i.e., $m = 3, 4$) on the kth in-band channel from the ith in-band D2D interferer in subcell e_m to the ith in-band D2D receiver in subcell x.

$I_{i,x}^{c,B}$ is the inter-subcell interference caused by cellular links, and is given by

$$I_{i,x}^{c,B} = \sum_{m \in \{1,2,3,4\}} (1 - s_{k,e_m}^{c}) p_{k,e_m}^{c} g_{(k,e_m),(i,x)}^{c} + s_{k,e_m}^{c} p_{j,e_m}^{k} g_{(j,e_m),(i,x)}^{k} \quad (4)$$

where s_{k,e_m}^{c} is also a binary indicator and $s_{k,e_m}^{c} = 1$ means the kth cellular UE in subcell e_m has been assigned an out-band D2D relaying UE, and $s_{k,e_m}^{c} = 0$ is on the contrary. $p_{k,e_m}^{c} g_{(k,e_m),(i,x)}^{c}$ represents the IISC or the IIDC from the kth cellular UE in subcell e_m to the ith in-band D2D receiver in subcell x, while $p_{j,e_m}^{k} g_{(j,e_m),(i,x)}^{k}$ represents the IISC or the IIDC from the jth ($j \in M_m$) out-band D2D relaying UE in subcell e_m to the ith in-band D2D receiver in subcell x on the kth in-band channel.

The SE of the kth cellular link in subcell x before and after assigning the jth ($j \in M_0$) out-band D2D relaying UE are given by

$$C_{k,x}^{c} = log_2 \left(1 + \frac{p_{k,x}^{c} g_{k,x}^{c}}{I_{k,x}^{d,B} + I_{k,x}^{c,B} + N'}\right) \quad (5)$$

$$C_{j,x}^{k} = log_2 \left(1 + \frac{p_{j,x}^{k} g_{j,x}^{k}}{I_{j,x}^{d,B} + I_{j,x}^{c,B} + N'}\right) \quad (6)$$

where $p_{k,x}^{c} g_{k,x}^{c}$ and $p_{j,x}^{k} g_{j,x}^{k}$ represent the expected signal from the kth cellular UE and the jth out-band D2D relaying UE to the corresponding RRH on the kth in-band channel respectively. Note that (5) and (6) have a similar form, and so do the interferences in them, which we put together for comparison.

In (5) and (6), $I_{k,x}^{d,B}$ and $I_{j,x}^{d,B}$ are the inter-subcell interference caused by in-band D2D links, and are given by

$$\begin{cases} I_{k,x}^{d,B} = \sum_{m \in \{1,2,3,4\}} \sum_{i \in N_m} s_{i,e_m}^{k} p_{i,e_m}^{k} g_{(i,e_m),(k,x)}^{k} \\ I_{j,x}^{d,B} = \sum_{m \in \{1,2,3,4\}} \sum_{i \in N_m} s_{i,e_m}^{k} p_{i,e_m}^{k} g_{(i,e_m),(j,x)}^{k} \end{cases} \quad (7)$$

where $s_{i,e_m}^{k} p_{i,e_m}^{k} g_{(i,e_m),(k,x)}^{k}$ and $s_{i,e_m}^{k} p_{i,e_m}^{k} g_{(i,e_m),(j,x)}^{k}$ are the IISC or the IIDC from the ith in-band D2D transmitter on the kth in-band channel in subcell e_m.

$I_{k,x}^{c,B}$ and $I_{j,x}^{c,B}$ are the inter-subcell interference caused by other cellular links, and are given by

$$\begin{cases} I_{k,x}^{c,B} = \sum_{m \in \{3,4\}} \begin{matrix} (1 - s_{k,e_m}^{c}) p_{k,e_m}^{c} g_{(k,e_m),(k,x)}^{c} \\ + s_{k,e_m}^{c} p_{j,e_m}^{k} g_{(j,e_m),(k,x)}^{k} \end{matrix} \\ I_{j,x}^{d,B} = \sum_{m \in \{3,4\}} \begin{matrix} (1 - s_{k,e_m}^{c}) p_{k,e_m}^{c} g_{(k,e_m),(j,x)}^{c} \\ + s_{k,e_m}^{c} p_{j,e_m}^{k} g_{(j,e_m),(j,x)}^{k} \end{matrix} \end{cases} \quad (8)$$

where it represents the IIDC from either the kth cellular UE or the jth out-band D2D relaying UE using the kth in-band channel in subcell e_3 ore_4. Note that there is only IIDC here.

After assigning the jth ($j \in M_0$) out-band D2D relaying UE to the kth cellular UE, the SE of the out-band D2D link from the latter to the former on the rth out-band channel ($r \in \{1, 6, 11\}$, no-collision channels of 2.4Ghz Wi-Fi) in subcell x is given by

$$C_{k,j,x}^{r} = log_2 \left(1 + \frac{p_{k,j,x}^{r} g_{(k,x),(j,x)}^{r}}{I_{k,j,x}^{r,A} + I_{k,j,x}^{r,B} + N'}\right) \quad (9)$$

where $p_{k,j,x}^{r}$ represents the transmission power from the kth cellular UE on the rth out-band channel in subcell x. $g_{(k,x),(j,x)}^{r}$ represents the channel attenuation from the kth cellular UE to the jth out-band D2D relaying UE in subcell x.

$I_{k,j,x}^{r,A}$ and $I_{k,j,x}^{r,B}$ are the intra-subcell interference and the inter-subcell interference caused by other out-band D2D links, and are given by

$$I_{k,j,x}^{r,A} = \sum_{k' \in K_0 \setminus \{k\}} s_{k',x}^{c} p_{k',j',x}^{r} g_{(k',x),(j,x)}^{r} \quad (10)$$

$$I_{k,j,x}^{r,B} = \sum_{m \in \{1,2,3,4\}} \sum_{k' \in K_m} s_{k',e_m}^{c} p_{k',j',e_m}^{r} g_{(k',e_m),(j,x)}^{r} \quad (11)$$

where $s_{k',x}^{c}$ and s_{k',e_m}^{c} are indicators similar to s_{k,e_m}^{c} in (4). $p_{k',j',x}^{r} g_{(k',x),(j,x)}^{r}$ represents the intra-subcell interference from the k'th out-band D2D interferer (i.e., the k'th cellular UE) to the jth out-band D2D relaying UE on the rth out-band channel in subcell x, i.e., $k' \neq k$. $p_{k',j',e_m}^{r} g_{(k',e_m),(j,x)}^{r}$ represents the IISC or the IIDC from the k'th out-band D2D interferer in subcell e_m to the jth out-band D2D relaying UE in subcell x on the rth out-band channel.

According to Shannon Theorem, the average SE of the optimized link of the kth cellular UE is given by

$$C^{r,c}_{k,j,x} = \frac{\min\{B^r_{k,j,x}C^r_{k,j,x}, B^k_{j,x}C^k_{j,x}\}}{(B^r_{k,j,x}+B^k_{j,x})/2} \tag{12}$$

where $B^r_{k,j,x}$ and $B^k_{j,x}$ are the bandwidths of the out-band part and the cellular part respectively, and $C^r_{k,j,x}$ and $C^c_{j,x}$ are estimated by the formula (9) and (6) respectively. Besides, the SE of the original link of the kth cellular UE is obviously estimated by formula (5).

The total power consumptions of different kinds of links mentioned above are given by

$$p^{d,t}_{i,x} = \sum_{k\in K_0}\frac{1}{\eta}s^k_{i,x}p^k_{i,x} + 2p_{cir} \tag{13}$$

$$p^{c,t}_{k,x} = \frac{1}{\eta}p^c_{k,x} + p_{cir} \tag{14}$$

$$p^{k,t}_{j,x} = \frac{1}{\eta}p^k_{j,x} + p_{cir} \tag{15}$$

$$p^{r,t}_{k,j,x} = \frac{1}{\eta}p^r_{k,j,x} + 2p_{cir} \tag{16}$$

where $p^{d,t}_{i,x}$ in (13) is the total power consumption of the ith in-band D2D link in subcell x, which is constituted by the transmission power on all K_0 channels, i.e., $\sum_{k\in K_0}\frac{1}{\eta}s^k_{i,x}p^k_{i,x}$, and the circuit power of both the in-band D2D transmitter and receiver, i.e., $2p_{cir}$. Similarly, $p^{r,t}_{k,j,x}$ in (16) is the total power consumption of the out-band D2D link from the kth cellular UE to the jth out-band D2D relaying UE, which is constituted by the transmission power $\frac{1}{\eta}p^r_{k,j,x}$, and the circuit power of both the cellular UE and out-band D2D relaying UE. $p^{c,t}_{k,x}$ in (14) or $p^{k,t}_{j,x}$ in (15) is the total power consumption of the kth cellular link before or after assigning the jth out-band D2D relaying UE, which is constituted by the transmission power $\frac{1}{\eta}p^c_{k,x}$ or $\frac{1}{\eta}p^k_{j,x}$ and the circuit power of the transmitter, where the receiver (i.e., the RRH) is usually powered by external grid power and is not taken into consideration. We assumed that every UE has the same circuit power p_{cir}. And η $(0 < \eta < 1)$ is the power amplifier (PA) efficiency.

D. RELAYING UE AND CHANNEL SELECTION STRATEGIES

In our resource sharing scheme, the out-band D2D relaying UE selection strategy for the kth cellular UE in subcell x is given by

$$\begin{cases} D_{k,x} \geq \lambda R & (17-1)\\ \min \dfrac{\rho\left(D_{k,j,x}+D_{j,x}\right)}{\sum\limits_{j\in M_0}\left(D_{k,j,x}+D_{j,x}\right)} + \dfrac{(1-\rho)|D_{j,x}-\theta D_{k,x}|}{\sum\limits_{j\in M_0}|D_{j,x}-\theta D_{k,x}|} & (17-2)\\ k\in K_0, \quad j\in M_0 & (17-3)\\ 0.5 \leq \lambda \leq \frac{\sqrt{3}}{2}, \quad 0\leq\rho\leq 1, \ 0\leq\theta\leq 1 & (17-4)\end{cases} \tag{17}$$

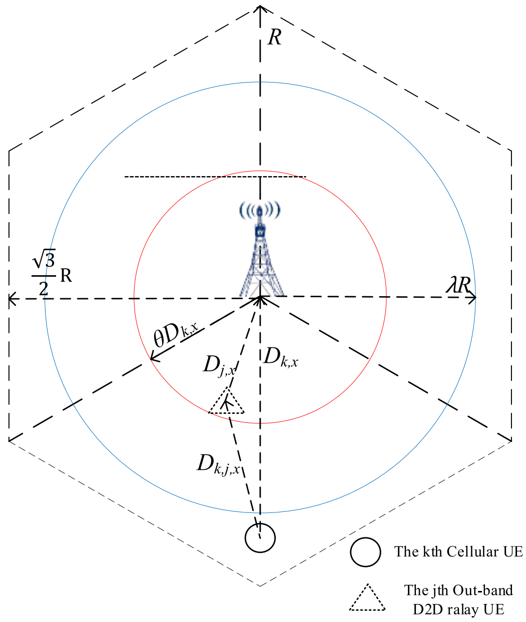

FIGURE 3. The out-band D2D relaying UE selection strategy for cellular UEs.

In (17), $D_{k,x}$ denotes the distance between the kth cellular UE and the corresponding RRH in subcell x. $D_{j,x}$ denotes the distance between the jth out-band D2D relaying UE and the RRH in subcell x. $D_{k,j,x}$ denotes the distance between the kth cellular UE and the jth out-band D2D relaying UE in subcell x. R denotes the transmission radius of the RRH. θ, ρ, and λ are parameters. As shown in Fig.3, (17-1) guarantees that the kth cellular UE is at least λR away from the RRH, i.e., outside the blue circle. (17-3) guarantees that the kth cellular UE and the jth out-band D2D relaying UE are in the same subcell (i.e., subcell x). (17-2) is a weighted consideration of both the length of the optimized link and the degree of the proximity to $\theta D_{k,x}$, i.e., the red circle. In other words, λ divides the cell into two parts, where the cellular UEs can use out-band D2D relays in the outer part and can't do that in the inner part. θ controls the location tendency of the jth out-band D2D relaying UE, i.e., closer to the kth cellular UE or closer to the RRH. ρ comprehensively considers the length of the optimal link of the kth cellular UE and the location tendency of the jth out-band D2D relaying UE. θ, ρ, and λ influence the effects of out-band D2D relays, which will be discussed with simulation results.

Since the out-band communications are not orthogonal, the interferences on out-band channels are not avoidable. Hence, the out-band channel selection strategy of the out-band D2D link from the kth cellular UE to the jth out-band D2D relaying UE is given by

$$\begin{cases} r_{k,j,x} = r_{k',j',x} \neq r_{k'',j'',x} \\ k' = \underset{k'\in K_0\backslash\{k\}\cup K_m}{\operatorname{argmax}} \{D_{k',j,x}, D_{k',j,e_m}\}, \quad m=\{1,2,3,4\} \\ k'' = \underset{k''\in K_0\backslash\{k\}\cup K_m}{\operatorname{argmin}} \{D_{k'',j,x}, D_{k'',j,e_m}\}, \quad m=\{1,2,3,4\}\end{cases} \tag{18}$$

where $r_{k,j,x}$ denotes the out-band channel used by the out-band D2D link from the kth cellular UE to the jth out-band D2D relaying UE in subcell x. Actually, (18) means selecting an out-band channel which is the same with the channel of the farthest out-band link and different from the channel of the nearest out-band link.

E. CHANNEL ATTENUATIONS AND NOISE POWER

In this paper, all channel attenuations are estimated by the free space model and the two-ray ground model [28], which are given by

$$g_{t,r} = \begin{cases} \dfrac{G_t G_r \Lambda^2}{(4\pi)^2 \left(d_{t,r}\right)^2 l}, & d_{t,r} \le \dfrac{4\pi\sqrt{l} h_t h_r}{\Lambda} \\ \dfrac{G_t G_r h_t h_r}{\left(d_{t,r}\right)^4}, & d_{t,r} > \dfrac{4\pi\sqrt{l} h_t h_r}{\Lambda} \end{cases} \tag{19}$$

where $g_{t,r}$ denotes the channel attenuation from transmitter t to receiver r and $d_{t,r}$ is the distance between them. G_t and G_r are transmitting antenna gain and the receiving antenna gain respectively, while h_t and h_r are the transmitting antenna height and receiving antenna height respectively. Λ and l are the signal wavelength and system loss factor.

The thermal noise has a nearly Gaussian distribution, and the power of it is estimated by

$$N' = k_B T B \tag{20}$$

where k_B is the Boltzmann's constant, T is the absolute temperature, and B is the bandwidth over which the noise is estimated.

To improve the clarity, Table 2 has summarized the notations of key parameters in this paper, where subcell S denotes subcell x or e_m, $m = 1, 2, 3, 4$.

TABLE 2. Parameter notations.

Parameter	Description
N_m	The set of in-band D2D links in subcell x (i.e., m=0) or e_m (i.e., m=1, 2, 3, 4).
K_m	The set of cellular UEs in subcell x (i.e., m=0) or e_m (i.e., m=1, 2, 3, 4).
M_m	The set of out-band D2D relaying UEs in subcell x (i.e., m=0) or e_m (i.e., m=1, 2, 3, 4).
$C_{i,\mathbb{S}}^d$	The SE of the ith in-band D2D link in subcell $\mathbb{S}$.
$s_{i,\mathbb{S}}^k$	The channel selecting binary indicator of the ith in-band D2D link in subcell $\mathbb{S}$ on the kth in-band channel.
$p_{i,\mathbb{S}}^k$	The transmission power of the ith in-band D2D link in subcell $\mathbb{S}$ on the kth in-band channel.
$g_{i,\mathbb{S}}^k$	The channel attenuation of the ith in-band D2D link in subcell $\mathbb{S}$ on the kth in-band channel.
$g_{(i',\mathbb{S}),(i,x)}^k$	The channel attenuation from the i'th in-band D2D interferer in subcell $\mathbb{S}$ to the ith in-band D2D receiver in subcell x on the kth in-band channel.
$g_{(i,\mathbb{S}),(k,x)}^k$	The channel attenuation from the ith in-band D2D interferer in subcell $\mathbb{S}$ to the kth cellular receiver in subcell x on the kth in-band channel.
$s_{k,\mathbb{S}}^c$	The out-band D2D relay using binary indicator of the kth cellular UE in subcell $\mathbb{S}$.
$C_{k,\mathbb{S}}^c$	(1) The SE of the kth cellular link in subcell $\mathbb{S}$ before assigning the out-band D2D relaying UE. (2) The SE of the original link of the kth cellular UE in subcell $\mathbb{S}$.
$p_{k,\mathbb{S}}^c$	The transmission power of the kth cellular link in subcell $\mathbb{S}$ before assigning the out-band D2D relaying UE.
$g_{k,\mathbb{S}}^c$	The channel attenuation of the kth cellular link in subcell $\mathbb{S}$ before assigning the out-band D2D relaying UE.
$g_{(k,e_m),(k,x)}^c$	The channel attenuation from the kth cellular UE in subcell e_m to the kth cellular UE in subcell x before assigning the out-band D2D relaying UE.
$C_{j,\mathbb{S}}^k$	The SE of the kth cellular link in subcell $\mathbb{S}$ after assigning the jth out-band D2D relaying UE.
$p_{j,\mathbb{S}}^k$	The transmission power of the kth cellular link in subcell $\mathbb{S}$ after assigning the jth out-band D2D relaying UE.
$g_{j,\mathbb{S}}^k$	The channel attenuation of the kth cellular link in subcell $\mathbb{S}$ after assigning the jth out-band D2D relaying UE.
$g_{(j,e_m),(k,x)}^k$	The channel attenuation from the jth out-band D2D relaying UE in subcell e_m to the kth cellular UE in subcell x after assigning the out-band D2D relaying UE.
$C_{k,j,x}^r$	The SE of the out-band D2D link from the kth cellular UE to the jth out-band D2D relaying UE in subcell x after assigning the out-band D2D relaying UE.
$p_{k,j,\mathbb{S}}^r$	The transmission power of the out-band D2D link from the
	kth cellular UE to the jth out-band D2D relaying UE in subcell $\mathbb{S}$ on the rth out-band channel after assigning the out-band D2D relaying UE.
$g_{(k,\mathbb{S}),(j,x)}^r$	The channel attenuation of the out-band D2D link from the kth cellular UE in subcell $\mathbb{S}$ to the jth out-band D2D relaying UE in subcell x on the rth out-band channel after assigning the out-band D2D relaying UE.
$C_{k,j,x}^{r,c}$	The average SE of the optimized link of the kth cellular UE in subcell x.
$(S_{i,x}^d, P_{i,x}^d)$	The channel selection and transmission power strategy set of the ith in-band link in subcell x.
$P_{k,x}^c$	The transmission power strategy set of the kth cellular link in subcell x before assigning the out-band D2D relaying UE.
$P_{j,x}^k$	The transmission power strategy set of the kth cellular link in subcell x after assigning the jth out-band D2D relaying UE.
$P_{k,j,x}^r$	The transmission power strategy set of the out-band D2D link from the kth cellular UE to the jth out-band D2D relaying UE in subcell x on the rth out-band channel after assigning the out-band D2D relaying UE.
$q_{i,x}^d$、$E_{i,x}^d$	The EE of the ith in-band link in subcell x.

IV. PROBLEM FORMULATION

Since each UE is only interested in maximizing its individual benefit rationally and selfishly in the distributed resource allocation scenario, we modeled a noncooperative game G to address the distributed power allocation problem for all UEs, which can be denoted as the triplet G =< U, A, S >. U $= \{u_1, u_2, \ldots, u_{3X}\}$ is the set of gamers (i.e., cellular UEs, in-band D2D UEs and out-band D2D relaying UEs) participating in the game. A $= \{a_1, a_2, \ldots, a_{3X}\}$ is the set of possible actions that UEs can take in the game. S $= \{s_1, s_2, \ldots, s_{3X}\}$ is the set of UEs' utilities. For example, $a_x = [0, p_{max}]$ means u_x is allowed to transmit at the power range from 0 to p_{max} and will get the utility s_x, where p_{max} is the maximum transmission power, $x = \{1, 2, \ldots, 3X\}$.

To be more specifically, the channel selection and transmission power strategy set of the ith in-band D2D transmitter ($i \in N_0$) in subcell x is denoted as $(S_{i,x}^d, P_{i,x}^d) = \{s_{i,x}^k, p_{i,x}^k | s_{i,x}^k = \{0, 1\}, 0 \le \sum_{k \in K_0} s_{i,x}^k p_{i,x}^k \le p_{i,x}^{d,max}\}$. The transmission power strategy set of the kth cellular UE in subcell x before assigning the out-band D2D relaying UE is denoted as $P_{k,x}^c = \{p_{k,x}^c | 0 \le p_{k,x}^c \le p_{k,x}^{c,max}\}$. After assigning the jth out-band D2D relaying UE to the kth cellular UE in subcell x, on the one hand, the jth out-band D2D relaying UE will represent the kth cellular UE to participate in the in-band resource allocation game on the kth in-band channel, and the transmission power strategy set is denoted as $P^k_{j,x} = \{p^k_{j,x}|0 \leq p^k_{j,x} \leq p^{k,max}_{j,x}\}$. On the other hand, the kth cellular UE will participate in the out-band resource allocation game on the rth out-band channel, and the transmission power strategy set is denoted as $P^r_{k,j,x} = \{p^r_{k,j,x}|0 \leq p^r_{k,j,x} \leq p^{o,max}_{k,j,x}\}$. $p^{d,max}_{i,x}$, $p^{c,max}_{k,x}$, $p^{k,max}_{j,x}$ and $p^{o,max}_{k,j,x}$ are maximum transmission powers.

The utility function is defined as the EE (bits/J/Hz), which is the ratio of the SE to the total power consumption [29]. Accordingly, the EE of the ith in-band D2D link in subcell x is given by

$$E^d_{i,x}\left(S^d_{i,x}, P^d_{i,x}\right) = \frac{C^d_{i,x}\left(S^d_{i,x}, P^d_{i,x}\right)}{p^{d,t}_{i,x}\left(S^d_{i,x}, P^d_{i,x}\right)} \tag{21}$$

The corresponding EE optimization problem is formulated as

$$\begin{cases} \max\limits_{(S^d_{i,x}, S^d_{i,x})} E^d_{i,x}\left(S^d_{i,x}, P^d_{i,x}\right) \\ s.t.\ C_1 : 0 \leq \sum\limits_{k \in K_1 \cup K_2} s^k_{i,x} p^k_{i,x} \leq p^{d,max}_{i,x} \\ C_2 : s^k_{i,x} = \{0, 1\}, \quad \forall k \in K_0 \end{cases} \tag{22}$$

In (22), C_1 and C_2 are the transmission power constraint and the channel selection constraint which are both mentioned as the strategy set hereinbefore. Since in-band D2D UEs usually communicate in a short distance, which means a good performance of the SE, there is no QoS requirement for them.

Similarly, the EE of the kth cellular link in subcell x before and after assigning the jth out-band D2D relaying UE are given by

$$E^c_{k,x}\left(P^c_{k,x}\right) = \frac{C^c_{k,x}\left(P^c_{k,x}\right)}{p^{c,t}_{k,x}\left(P^c_{k,x}\right)} \tag{23}$$

$$E^k_{j,x}\left(P^k_{j,x}\right) = \frac{C^k_{j,x}\left(P^k_{j,x}\right)}{p^{k,t}_{j,x}\left(P^k_{j,x}\right)} \tag{24}$$

where (23) is the EE of the kth cellular UE, while (24) is the EE of the jth out-band D2D relaying UE. The corresponding EE optimization problem are formulated as

$$\begin{cases} \max\limits_{(P^c_{k,x})} E^c_{k,x}\left(P^c_{k,x}\right) \\ s.t.\ C_3 : 0 \leq p^c_{k,x} \leq p^{c,max}_{k,x} \end{cases} \tag{25}$$

$$\begin{cases} \max\limits_{(P^c_{j,x})} E^k_{j,x}\left(P^k_{j,x}\right) \\ s.t.\ C_4 : 0 \leq p^k_{j,x} \leq p^{k,max}_{j,x} \end{cases} \tag{26}$$

The EE and the corresponding EE optimization problem of the out-band D2D link from the kth cellular UE to the jth out-band D2D relaying UE on the rth out-band channel in subcell x are given by

$$E^r_{k,j,x}\left(P^r_{k,j,x}\right) = \frac{C^r_{k,j,x}\left(P^r_{k,j,x}\right)}{p^{r,t}_{k,j,x}\left(P^r_{k,j,x}\right)} \tag{27}$$

$$\begin{cases} \max\limits_{(P^r_{k,j,x})} E^r_{k,j,x}\left(P^r_{k,j,x}\right) \\ s.t.\ C_5 : 0 \leq p^r_{k,j,x} \leq p^{o,max}_{k,j,x} \end{cases} \tag{28}$$

Note that there is no constraint specifying the QoS requirement in (25), (26) and (28), either. In fact, the appropriate λ in (17) can guarantee that the outer cellular UEs include the cellular UEs which usually can't meet the QoS requirements, while other inner cellular UEs have no QoS requirement due to the short distances to the associated RRHs, i.e., $C^c_{k,x}$ is large enough. And the appropriate ρ and θ in (17) can guarantee that the $C^r_{k,j,x}$ and $C^k_{j,x}$ are also large enough. That is to say, the QoS problems in (25), (26) and (28) have been implicitly solved.

According to (12), (26) and (28), the average EE of the optimized link of the kth cellular UE and the corresponding optimization problem can be expressed as

$$E^{r,c}_{k,j,x}\left(P^r_{k,j,x}, P^k_{j,x}\right) = \frac{C^{r,c}_{k,j,x}\left(P^r_{k,j,x}, P^k_{j,x}\right)}{p^{r,t}_{k,j,x}\left(P^r_{k,j,x}\right) + p^{k,t}_{j,x}\left(P^k_{j,x}\right) - p_{cir}} \tag{29}$$

$$\begin{aligned} &\max\limits_{(P^r_{k,j,x}, P^k_{j,x})} \quad E^{r,c}_{k,j,x}\left(P^r_{k,j,x}, P^k_{j,x}\right) \\ &s.t.\ C_4, C_5 \end{aligned} \tag{30}$$

while the EE of the original link of the kth cellular UE is (23) and the corresponding optimization problem is (25) exactly.

There are two challenges when addressing the above EE optimization problems. First, they are non-concave due to the Boolean variables and the fractional form. Second, if we maximize the EE of the out-band part and the cellular part of the optimized link, i.e., optimize problem (28) and (26) respectively, it will result in a waste of spectrum source because the values of $B^r_{k,j,x} C^r_{k,j,x}$ and $B^k_{j,x} C^k_{j,x}$ must be a large one and a small one in (12) (i.e., the numerator of (29)). Thus, the optimum value of (30) is not a satisfactory result, and it will lead to the instability of the game actually.

V. THE ENERGY-EFFICIENT RESOURCE SHARING SCHEME

To face the above challenges, we suggest an energy-efficient resource sharing scheme in this section. First, we realize the joint optimization of the two individual parts of the optimized link through some mathematical processing. Second, we transform the non-concave optimization problem into the concave form by introducing constraint relaxation and nonlinear fractional programming. Third, we propose a two-layer iterative algorithm consists of Dinkelbach's method and Lagrangian duality theory to solve the transformed problem. Finally, we analyze the Nash equilibrium of the noncooperative game and describe the game process.

A. JOINT OPTIMIZATION FOR OPTIMIZED LINK

Since optimizing the EE of the out-band part and the cellular part of the optimized link (i.e., problem (28) and (26)) individually will result in a large value and a small value of $B^r_{k,j,x}C^r_{k,j,x}$ and $B^k_{j,x}C^k_{j,x}$, both of which will be equal finally in the transmitting procedure, we can consider our resource sharing scheme to base on the equality in the beginning, i.e., $B^r_{k,j,x}C^r_{k,j,x} = B^k_{j,x}C^k_{j,x}$. Under this consideration, we have the relationship between $p^r_{k,j,x}$ and $p^k_{j,x}$ given by

$$p^r_{k,j,x} = \varphi(p^k_{j,x}) = \frac{\left(1+\frac{p^k_{j,x}g^k_{j,x}}{I^{d,B}_{k,x}+I^{c,B}_{k,x}+N'}\right)^{\frac{B^k_{j,x}}{B^r_{k,j,x}}}-1}{\frac{g^r_{(k,x),(j,x)}}{I^{r,A}_{k,j,x}+I^{r,B}_{k,j,x}+N'}} \tag{31}$$

Therefore, (29) and (30) can be rewritten as

$$E^{r,c}_{k,j,x}\left(P^k_{j,x}\right) = \frac{\frac{2}{\frac{B^r_{k,j,x}}{B^k_{j,x}}+1}C^k_{j,x}\left(P^k_{j,x}\right)}{p^{r,t}_{k,j,x}\left(\varphi(P^k_{j,x})\right)+p^{k,t}_{j,x}\left(P^k_{j,x}\right)-p_{cir}} \tag{32}$$

$$\begin{cases}\max\limits_{(P^k_{j,x})} E^{r,c}_{k,j,x}\left(P^k_{j,x}\right)\\ s.t.\ C_6 : 0 \le p^k_{j,x} \le \min\{p^{k,max}_{j,x}, \varphi^{-1}(p^{o,max}_{k,j,x})\}\end{cases} \tag{33}$$

Note that (32) and (33) have another form related to $P^r_{k,j,x}$ rather than $P^k_{j,x}$, which are not adopted in this paper. In the above mathematical processing, the EE optimization problem of the optimized link is converted to the form only relevant to $p^k_{j,x}$ by building a relationship between $p^r_{k,j,x}$ and $p^k_{j,x}$. In this situation, there are strong interactions in the in-band resource allocation game and the out-band resource allocation game for the optimized link, where we can just optimize the EE by (33) to confirm the resource allocation of the two games in the same time. In other words, the out-band resource allocation game has been absorbed into the in-band resource allocation game. In our proposed resource sharing scheme, there are three kinds of gamer actually, where the first one is the in-band D2D UEs whose EE is optimized by (22), the second one is the cellular UEs without the aid of out-band D2D relays whose EE is optimized by (25), and the last one is the cellular UEs with the aid of out-band D2D relays whose EE is optimized by (33).

B. OBJECTIVE FUNCTION TRANSFORMATION

Since the Boolean variables lead to an exhaustive search in the non-concave optimization problem (22), we relax $s^k_{i,x}$ in constraint C_2 from a Boolean value to a real number between 0 and 1 (i.e., $0 \le s^k_{i,x} \le 1$) to handle the problem just like [30]. Thus, $s^k_{i,x}$ can be explained as a time-sharing factor for N_0 users to utilize the kth in-band channel. The duality gap of the relaxation becomes negligible as the number of channels becomes sufficiently large [31]. Under this relaxing, we can use a new variable $\tilde{p}^k_{i,x}$ to replace $s^k_{i,x}p^k_{i,x}$ in the above formulas. Thus (21) and (22) can be rewritten as

$$E^d_{i,x}\left(\tilde{P}^d_{i,x}\right) = \frac{C^d_{i,x}\left(\tilde{P}^d_{i,x}\right)}{p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right)} \tag{34}$$

$$\begin{cases}\max\limits_{(\tilde{P}^d_{i,x})} E^d_{i,x}\left(\tilde{P}^d_{i,x}\right)\\ s.t.\ C'_1 : 0 \le \sum\limits_{k\in K_1\cup K_2}\tilde{p}^k_{i,x} \le p^{d,max}_{i,x}\end{cases} \tag{35}$$

Here, C'_1 indicates a convex feasible set. Note that the binary indicators in (4) (8) (10) and (11) are known after the out-band D2D relays are established such that they are not variables. For the next discussion, we let $q^{d*}_{i,x}$ denote the maximum EE of the ith in-band D2D link in the subcell x and then we have

$$q^{d*}_{i,x} = \max_{(\tilde{p}^d_{i,x})} E^d_{i,x}\left(\tilde{P}^d_{i,x}\right) = \frac{C^d_{i,x}\left(\tilde{P}^{d*}_{i,x}\right)}{p^{d,t}_{i,x}\left(\tilde{P}^{d*}_{i,x}\right)} \tag{36}$$

The literature [32] proposed and proved a theorem about solving a problem with the objective function in the fractional form by solving the transformed problem with the objective function in the subtractive form, which we can introduce into our resource sharing scheme as the following Theorem 1.

Theorem 1: $q^{d*}_{i,x}$ is achieved if and only if

$$\max_{(\tilde{p}^d_{i,x})} C^d_{i,x}\left(\tilde{P}^d_{i,x}\right) - q^{d*}_{i,x}p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right) = C^d_{i,x}\left(\tilde{P}^{d*}_{i,x}\right) - q^{d*}_{i,x}p^{d,t}_{i,x}\left(\tilde{P}^{d*}_{i,x}\right) = 0 \tag{37}$$

Proof: The proof of Theorem 1 is given in the Appendix.

According to Theorem 1, the EE optimization problem (35) can be rewritten as

$$\begin{cases}\max\limits_{(\tilde{p}^d_{i,x})} C^d_{i,x}\left(\tilde{P}^d_{i,x}\right) - q^{d*}_{i,x}p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right)\\ s.t.\ C'_1\end{cases} \tag{38}$$

We can find that, the transformed objective function is concave. Similarly, defining $q^{c*}_{k,x}$ and $q^{r,c*}_{k,j,x}$ are the maximum EE of the original link and the optimized link of the kth cellular UE in subcell x, the corresponding EE optimization problem (25) and (33) can be rewritten as

$$\begin{cases}\max\limits_{(P^c_{k,x})} C^c_{k,x}\left(P^c_{k,x}\right) - q^{c*}_{k,x}p^{c,t}_{k,x}\left(P^c_{k,x}\right)\\ s.t.\ C_3\end{cases} \tag{39}$$

$$\begin{cases}\max\limits_{(P^c_{j,x})} \frac{2}{\frac{B^r_{k,j,x}}{B^k_{j,x}}+1}C^k_{j,x}\left(P^k_{j,x}\right)\\ -q^{r,c*}_{k,j,x}[p^{r,t}_{k,j,x}\left(\varphi(P^k_{j,x})\right)+p^{k,t}_{j,x}\left(P^k_{j,x}\right)-p_{cir}]\\ s.t.\ C_6\end{cases} \tag{40}$$

Our target is to find out the appropriate values of $q^{d*}_{i,x}$, $q^{c*}_{k,x}$ and $q^{r,c*}_{k,j,x}$ to make the maximum values in (38), (39) and (40) to be zero (or very near to zero) respectively. However, such values of $q^{d*}_{i,x}$, $q^{c*}_{k,x}$ and $q^{r,c*}_{k,j,x}$ are still unknown. In next subsection, we will introduce a two-layer iterative algorithm to find them.

C. TWO-LAYER ITERATIVE RESOURCE ALLOCATION ALGORITHM

In this subsection, a two-layer iterative algorithm is proposed to find $q^{d*}_{i,x}$, $q^{c*}_{k,x}$ and $q^{r,c*}_{k,j,x}$ for solving the transformed problems. In the first layer, we adopt Dinkelbach's method [32] to find the above optimum EE. Taking (38) for example, we set $q^d_{i,x}$ as a very small positive number (e.g., $q^d_{i,x} = 10^{-4}$) in the beginning, then we solve the following problem (41) in each iteration.

$$\begin{cases} \max\limits_{(\tilde{p}^d_{i,x})} C^d_{i,x}\left(\tilde{P}^d_{i,x}\right) - q^d_{i,x} p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right) \\ s.t.\ C_1' \end{cases} \tag{41}$$

Once the maximum of the objective function in (41) is 0 (or very near to 0), the maximum EE $q^{d*}_{i,x}$ has been found and $q^{d*}_{i,x} = q^d_{i,x}$, otherwise we set $q^d_{i,x} = \frac{C^d_{i,x}\left(\tilde{P}^d_{i,x}\right)}{p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right)}$ for the next iteration. Similarly, the maximum EE $q^{c*}_{k,x}$ and $q^{r,c*}_{k,j,x}$ in problem (39) and (40) can be found by iteratively solving the following problems.

$$\begin{cases} \max\limits_{(P^{xc}_{k,x})} C^c_{k,x}\left(P^c_{k,x}\right) - q^c_{k,x} p^{c,t}_{k,x}\left(P^c_{k,x}\right) \\ s.t.\ C_3 \end{cases} \tag{42}$$

$$\begin{cases} \max\limits_{(P^k_{j,x})} \frac{2}{\frac{B^r_{k,j,x}}{B^k_{j,x}}+1} C^k_{j,x}\left(P^k_{j,x}\right) \\ -q^{r,c}_{k,j,x}[p^{r,t}_{k,j,x}\left(\varphi(P^k_{j,x})\right) + p^{k,t}_{j,x}\left(P^k_{j,x}\right) - p_{cir}] \\ s.t. C_6 \end{cases} \tag{43}$$

For clarity, the above process is summarized as algorithm 1-1, where Δ_1 is the convergence tolerance (i.e., the precision) of the iteration.

Algorithm 1-1 Dinkelbach's Method

Runner: in-band D2D UE or cellular UE
Input: Δ_1
Output: $q^{d*}_{i,x}$, $q^{c*}_{k,x}$ or $q^{r,c*}_{k,j,x}$

$q^d_{i,x} \leftarrow 10^{-4}$, $q^c_{k,x} \leftarrow 10^{-4}$, or $q^{r,c}_{k,j,x} \leftarrow 10^{-4}$
while true **do**
  Solve (41) (42) or (43) to obtain the maximum.
  if maximum $\leq \Delta_1$ **then**
    $q^{d*}_{i,x} \leftarrow q^d_{i,x}$, $q^{c*}_{k,x} \leftarrow q^c_{k,x}$, or $q^{r,c*}_{k,j,x} \leftarrow q^{r,c}_{k,j,x}$
    return $q^{d*}_{i,x}$, $q^{c*}_{k,x}$, or $q^{r,c*}_{k,j,x}$
  else update $q^d_{i,x}$ by (34), update$q^c_{k,x}$ by (23), or update $q^{r,c}_{k,j,x}$ by (32)
  end if
end while

But we still lack a method to solve problem (41) (42) and (43). Since they all have concave objective functions and convex feasible sets, we can introduce Lagrange duality theory to address them [33]. Still taking (41) for example, we can rewrite the objective function with the inequality constraint C_1' as the following Lagrangian function.

$$L(\tilde{P}^d_{i,x}, \alpha^d_{i,x}) = C^d_{i,x}\left(\tilde{P}^d_{i,x}\right) - q^d_{i,x} p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right) - \alpha^d_{i,x}\Big(\sum_{k\in K_0} \tilde{p}^k_{i,x} - p^{d,max}_{i,x}\Big) \tag{44}$$

where $\alpha^d_{i,x} \geq 0$ is the Lagrange multiplier associated with C_1'.

Thus, problem (41) can be solved by iteratively solving Lagrange dual problem (45), which is the second layer in the proposed two-layer algorithm.

$$\min_{\alpha^d_{i,x}\geq 0} \max_{\tilde{P}^d_{i,x}} L(\tilde{P}^d_{i,x}, \alpha^d_{i,x}) \tag{45}$$

We set $\alpha^d_{i,x} = 1$ (a value which is not too large and not too small) in the beginning. Then in each iteration, we first obtain the currently optimal solution $\tilde{P}^d_{i,x}$ on overall in-band channels, i.e., K_0 by (46), which is from $\frac{L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})}{\partial \tilde{p}^k_{i,x}} = 0$. Then we calculate $L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})$ in this iteration and compare it with the value in the last iteration. Once the difference between them is smaller than a threshold, we consider the maximum of the objective function in (41) is achieved. Otherwise, for the next iteration, we update $\alpha^d_{i,x}$ by (47) which uses the gradient method [34].

$$\tilde{p}^k_{i,x} = \left[\frac{\eta log_2 e}{q^d_{i,x} + \eta\alpha^d_{i,x}} - \frac{I^{d,A}_{i,x} + I^{d,B}_{i,x} + I^{c,A}_{i,x} + N'}{g^k_{i,x}}\right]^+ \tag{46}$$

$$\alpha^d_{i,x} = \left[\alpha^d_{i,x} + \mu^d_{i,x}\left\{-\frac{\partial L\left(\tilde{P}^d_{i,x}, \alpha^d_{i,x}\right)}{\partial \alpha^d_{i,x}}\right\}\right]^+ \tag{47}$$

where $[x]^+ = \max0, x$. In (47), $\mu^d_{i,x}$ is the positive step size, while the minus indicates the negative gradient direction. The iteration should produce a sequence of decreasing values of $L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})$. Hence, the initial value of $L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})$ can be set as a big number, e.g., 10000. And once the new $L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})$ in a certain iteration is larger than the old one in the last iteration, which means the step size $\mu^d_{i,x}$ in the last iteration is too big, we let it reduce to one tenth of it, then recompute the $\alpha^d_{i,x}$ in the last iteration and the new $L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})$ in this iteration until the new $L(\tilde{P}^d_{i,x}, \alpha^d_{i,x})$ is smaller than the old one. Taking the converge speed into consideration, we suggest the initial value of $\mu^d_{i,x}$ is also set as a big number.

Similarly, the Lagrangian function associated with (42) and (43) are given by (48) and (51) [Shown at the top of the next page]. The optimal solution of power allocation and the updated Lagrange multiplier in each iteration for solving problem (42) and (43) can be obtained by (49) (50) and (52) [Shown at the top of the next page] (53).

$$L(P^c_{k,x}, \alpha^c_{k,x}) = C^c_{k,x}\left(P^c_{k,x}\right) - q^c_{k,x} p^{c,t}_{k,x}\left(P^c_{k,x}\right) - \alpha^c_{k,x}(p^c_{k,x} - p^{c,max}_{k,x}) \tag{48}$$

$$L\left(P_{j,x}^{k},\alpha_{k,j,x}^{r,c}\right)=\frac{2C_{j,x}^{k}\left(P_{j,x}^{k}\right)}{\frac{B_{k,j,x}^{r}}{B_{j,x}^{k}}+1}-q_{k,j,x}^{r,c}\left[p_{k,j,x}^{r,t}\left(\varphi(P_{j,x}^{k})\right)+p_{j,x}^{k,t}\left(P_{j,x}^{k}\right)-p_{cir}\right]-\alpha_{k,j,x}^{r,c}(p_{j,x}^{k}-\min p_{j,x}^{k,max},\varphi^{-1}(p_{k,j,x}^{o,max})) \tag{51}$$

$$\left(p_{j,x}^{k}+\frac{I_{k,x}^{d,B}+I_{k,x}^{c,B}+N'}{g_{j,x}^{k}}\right)$$

$$\times\left(\frac{q_{k,j,x}^{r,c}g_{j,x}^{k}}{g_{(k,x),(j,x)}^{r}}\frac{I_{k,j,x}^{r,A}+I_{k,j,x}^{r,B}+N'}{I_{k,x}^{d,B}+I_{k,x}^{c,B}+N'}\frac{B_{j,x}^{k}}{B_{k,j,x}^{r}}\left(1+\frac{p_{j,x}^{k}g_{j,x}^{k}}{I_{k,x}^{d,B}+I_{k,x}^{c,B}+N'}\right)^{\frac{B_{j,x}^{k}}{B_{k,j,x}^{r}}-1}+q_{k,j,x}^{r,c}+\eta\alpha_{k,j,x}^{r,c}\right)=\frac{\eta log_{2}e}{\frac{B_{k,j,x}^{r}}{B_{j,x}^{k}}+1} \tag{52}$$

$$p_{k,x}^{c}=\left[\frac{\eta log_{2}e}{q_{k,x}^{c}+\eta\alpha_{k,x}^{c}}-\frac{I_{k,x}^{d,B}+I_{k,x}^{c,B}+N'}{g_{k,x}^{c}}\right]^{+} \tag{49}$$

$$\alpha_{k,x}^{c}=\left[\alpha_{k,x}^{c}+\mu_{k,x}^{c}\left\{-\frac{\partial L\left(P_{k,x}^{c},\alpha_{k,x}^{c}\right)}{\partial\alpha_{k,x}^{c}}\right\}\right]^{+} \tag{50}$$

$$\alpha_{k,j,x}^{r,c}=\left[\alpha_{k,j,x}^{r,c}+\mu_{k,j,x}^{r,c}\left\{-\frac{\partial L\left(P_{j,x}^{k},\alpha_{k,j,x}^{r,c}\right)}{\partial\alpha_{k,j,x}^{r,c}}\right\}\right]^{+} \tag{53}$$

Note that when $\frac{B_{j,x}^{k}}{B_{k,j,x}^{r}}\neq 1,2$, (52) is an equation of high power or non-integral power, thus it is hard or impossible to find the analytical solution of $p_{j,x}^{k}$ for (52). In this case, we can only obtain the arithmetic solution by some method, e.g., Bisection method, Lagrange interpolation method, Newton iteration method, etc.

For clarity, the above process is also summarized as algorithm 1-2, where Δ_2 is the precision and μ_0 is the initial step size.

D. NASH EQUILIBRIUM AND HYBRID ARCHITECTURE

According to [35], a Nash equilibrium exists if the utility function is continuous and quasi-concave, and the set of strategies is a nonempty compact convex subset of a Euclidean space. In our proposed noncooperative game, the utility functions of the three kinds of gamers are given by (34) (23) and (32), where numerators are concave and denominators are affine functions. Furthermore, the corresponding strategy sets C_1', C_3 and C_6 are all nonempty compact convex subsets of Euclidean spaces. Hence, it is easy to prove that a Nash equilibrium exists in our proposed noncooperative game.

In addition, the noncooperative game has a hybrid architecture. In the first stage, the RRHs collect every UE's information (e.g. location) and send it to the BBU pool. After calculating for allocating the out-band D2D relaying UEs and out-band channels, the BBU pool broadcasts the associated game information (including the allocation result) to every gamer through the RRHs. In the second stage, every gamer optimizes it's EE individually after receiving new game information and reports the new transmission power strategy to the associated RRH. The RRHs periodically broadcast the new collected game information to every associated gamer, until the average transmission power of all gamers is stable i.e., changes very a little. Then, the game is over and a Nash equilibrium has been reached.

For clarity, the complete process is described as algorithm 2, 3-1, and 3-2. Algorithm 2 describes the out-band D2D UEs and out-band channels allocation. Line 2 to 5 in algorithm 3-1 describes the first stage of the noncooperative game. Algorithm 3-2 and line 6 to 27 in algorithm 3-1 describe the second stage of the noncooperative game. Besides, as a center of centralized processors, the BBU pool has the following data structures to store the UEs' information, which is also helpful to describe algorithms.

1) P_K is the transmission power allocation array of cellular links before assigning the out-band D2D relaying UE, where the value of any element (e.g., p_k) denotes the transmission power that is allocated to the kth ($k\in\{1,\ldots,K\}$) cellular UE.
2) $P_{N,K}$ is the transmission power allocation matrix of inband-D2D links, where the value of any element (e.g., p_{ik}) denotes the transmission power that is allocated to the ith ($i\in\{1,\ldots,N\}$) in-band D2D transmitter on in-band channel $k(k\in\{1,\ldots,K\})$.
3) $P_{M,K}$ is the transmission power allocation matrix of cellular links after assigning the out-band D2D relaying UE, where the value of any element (e.g., p_{jk}) denotes the transmission power that is allocated to the jth ($j\in\{1,\ldots,M\}$) out-band D2D relaying UE on in-band channel $k(k\in\{1,\ldots,K\})$.
4) $P_{K,M}$ is the transmission power allocation matrix of out-band D2D links, where the value of any element (e.g., p_{kj}) denotes the transmission power that is allocated to the out-band D2D link from the kth ($k\in\{1,\ldots,K\}$) cellular UE to the jth ($j\in\{1,\ldots,M\}$) out-band D2D relaying UE.
5) $C_{K,M}$ is the out-band channel allocation matrix of out-band D2D links. If the value of any element (e.g., c_{kj}) is $r(r\in\{1,6,13\})$, it denotes that the rth out-band channel is allocated to the out-band D2D link from the kth ($k\in\{1,\ldots,K\}$) cellular UE to the jth ($j\in\{1,\ldots,M\}$) out-band D2D relaying UE. Otherwise, we set $r=0$ to denote that there is no out-band channel allocation.

Algorithm 1-2 Lagrange Duality

Runner: in-band D2D UE or cellular UE
Input: Δ_2, μ_0
Output: maximum in (41), (42) or (43)

$\alpha_{i,x}^{d} \leftarrow 1$, $\alpha_{k,x}^{c} \leftarrow 1$, or $\alpha_{k,j,x}^{r,c} \leftarrow 1$
$\mu_{i,x}^{d} \leftarrow \mu_0$, $\mu_{k,x}^{c} \leftarrow \mu_0$, or $\mu_{k,j,x}^{r,c} \leftarrow \mu_0$
$L^{old}(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}) \leftarrow 10000$, $L^{old}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right) \leftarrow 10000$, or $L^{old}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right) \leftarrow 10000$
while true **do**
  Calculate $\tilde{p}_{i,x}^{k}$ on K_0 by (46), calculate $p_{k,x}^{c}$ by (49) or calculate $p_{j,x}^{k}$ by (52).
  Calculate $L^{new}(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d})$ by (44), calculate $L^{new}(P_{k,x}^{c}, \alpha_{k,x}^{c})$ by (48), or calculate $L^{new}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right)$ by (51)
  if $L^{new}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right) > L^{old}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right)$ **or** $L^{new}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right) > \left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right)$ **or** $L^{new}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right) > L^{old}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right)$ **then**
    $\mu_{i,x}^{d} \leftarrow \mu_{i,x}^{d}/10$, $\mu_{k,x}^{c} \leftarrow \mu_{k,x}^{c}/10$, $\mu_{k,j,x}^{r,c} \leftarrow \mu_{k,j,x}^{r,c}/10$
    $\alpha_{i,x}^{d} \leftarrow \alpha_{i,x}^{d,last}$, $\alpha_{k,x}^{c} \leftarrow \alpha_{k,x}^{c,last}$ or $\alpha_{k,j,x}^{r,c} \leftarrow \alpha_{k,j,x}^{r,c,last}$
    goto 5
  else if $L^{new}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right) - L^{old}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right) \le \Delta_2$ **or** $L^{new}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right) - L^{old}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right) \le \Delta_2$ **or** $L^{new}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right) - L^{old}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right) \le \Delta_2$ **then**
    maximum $\leftarrow L^{new}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right)$, $L^{new}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right)$ or $L^{new}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right)$
    return maximum
  else
    $\alpha_{i,x}^{d,last} \leftarrow \alpha_{i,x}^{d}$, $\alpha_{k,x}^{c,last} \leftarrow \alpha_{k,x}^{c}$ or $\alpha_{k,j,x}^{r,c,last} \leftarrow \alpha_{k,j,x}^{r,c}$
    update $\alpha_{i,x}^{d}$ by (47), update $\alpha_{k,x}^{c}$ by (50), or update $\alpha_{k,j,x}^{r,c}$ by (53)
    $L^{old}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right) \leftarrow L^{new}\left(\tilde{P}_{i,x}^{d}, \alpha_{i,x}^{d}\right)$, $L^{old}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right) \leftarrow L^{new}\left(P_{k,x}^{c}, \alpha_{k,x}^{c}\right)$ or $L^{old}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right) \leftarrow L^{new}\left(P_{j,x}^{k}, \alpha_{k,j,x}^{r,c}\right)$
  end if
End while

VI. SIMULATION RESULTS

This section presents the simulation results of our proposed energy-efficient resource sharing scheme. Base on the simulation results, the performance of the proposed scheme in different conditions (i.e., different parameters) will be shown with explanation and discussion. The values of simulation parameters are summarized in Table 3. In each simulation, the location of every UE is random. We focus on one parameter and change it in a certain range while others stay the same. To make the effects of the variable parameters easy to

Algorithm 2 Allocating the Out-Band D2D Relaying UE to Cellular UEs and Assigning the Out-Band Channel

Runner: BBU pool
Input: K_0 and M_0 of any subcell x
Output: $C_{K0,M0}$ in subcell x

For $k \in K_0$ **do**
  Sort M_0 in ascending order according to (17).
  For $j \in M_0'$ **do**
    If the jth out-band D2D relaying UE doesn't work for any cellular UE **then**
      For u$\in\{1, 6, 13\}$ **do**
        If out-band channel u isn't allocated to any cellular UE **then**
          $c_{kj} \leftarrow u$, $k \leftarrow k+1$, **goto**2
        End if
      End for
      According to (18), let $K' = K_0 k \cup K_m$, and sort K' in descending order according to $D_{k',j,x}$ or D_{k',j,e_m}.
      For $k' \in K'$ **do**
        Let k'' be the last element of K'
        If $r_{k',j',x} \neq r_{k'',j'',x}$ **then**
          $c_{kj} \leftarrow r_{k',j',x}$, $k \leftarrow k+1$, **goto**2
        End if
      End for
    End if
  End for
End for

observe, plenty of out-band D2D relaying UEs are employed. Besides, since both the in-band signal and out-band signal can be transmitted at the frequency about 2400 MHz (e.g., Band 40 of the LTE Frequency allocated to China Telecom is 2370∼2390 MHz, and 2.4GHz Wi-Fi works on 2400∼2500 MHz frequency), we assume both of them have the same wavelength. We use 2.4GHz Wi-Fi to realize the out-band links in our simulation, thus the bandwidth of out-band links is fixed on 20MHz since it can't be changed flexibly. And we can get different bandwidth ratios through changing the bandwidth of cellular links.

A. EFFECT OF TENDENCY FACTOR θ ON THE SE AND EE OF GAMERS

Fig. 4 and Fig. 5 show the average SE and EE of in-band D2D UEs and cellular UEs versus θ in the range from 0 to 1, respectively. It's demonstrated that with the growing θ, both the average SE and EE of cellular UEs increase rapidly and then decrease slowly, while the average SE and EE of in-band D2D UEs are on the contrary and are even lower than the SE and EE in no-relay scenario when $\theta \ge 0.3$. Since we target on improving the EE of cellular UEs, the best value of θ is 0.3. Comparing with $\theta = 0.1$, which is the best value of θ for the EE of in-band D2D UEs, $\theta = 0.3$ can improve the average SE and EE of cellular UEs by 25.09% and 20.45%

Algorithm 3-1 Initialization and Scheduling Process

Runner: BBU pool
Input: Δ_3
Output: null

1. $avg \leftarrow 0$
2. **For** $x \in \{1, 2, \ldots, 3X\}$ **do**
3. Collect the information of N_0, K_0 and M_0 of subcell x
4. Invoke Algorithm 2 to obtain $C_{K0,M0}$ in subcell x
5. **End for**
6. **For** $x \in \{1, 2, \ldots, 3X\}$ **do**
7. According to N_0 of subcell x, determine N_1, N_2, N_3 and N_4
8. According to K_0 of subcell x, determine (P_{K0}, $P_{N0,K0}$) and its corresponding (K_1, P_{K1}, $P_{N1,K1}$), (K_2, P_{K2}, $P_{N2,K2}$), (K_3, P_{K3}, $P_{N3,K3}$), and (K_4, P_{K4}, $P_{N4,K4}$)
9. According to M_0 of subcell x, determine ($P_{M0,K0}$, $C_{K0,M0}$, $P_{K0,M0}$) and its corresponding (M_1, $P_{M1,K1}$, $C_{K1,M1}$, $P_{K1,M1}$), (M_2, $P_{M2,K2}$, $C_{K2,M2}$, $P_{K2,M2}$), (M_3, $P_{M3,K3}$, $C_{K3,M3}$, $P_{K3,M3}$), and (M_4, $P_{M4,K4}$, $C_{K4,M4}$, $P_{K4,M4}$)
10. Broadcast the above information to the gamers N_0 and K_0 of subcell x
11. **End for**
12. *waiting time* $\leftarrow 0$
13. **While** waiting time<period **do**
14. **If** receive $\tilde{P}^{d*}_{i,x}$ from any gamer in N_0 of subcell x **then** {update $P_{N0,K0}$ of subcell x} **End if**
15. **If** receive $P^{c*}_{k,x}$ from any gamer in K_0 of subcell x **then** {update P_{K0} of subcell x} **End if**
16. **If** receive ($P^{k*}_{j,x}$, $P^{r*}_{k,j,x}$) from any gamer in K_0 of subcell x **then**
17. update $P_{M0,K0}$ and $P_{K0,M0}$ of subcell x
18. **End if**
19. **End while**
20. **If** *avg*- average power of all gamers>Δ_3 **then**
21. $avg \leftarrow$ average power of all gamers
22. **goto** 6
23. **Else**
24. **For** $x \in \{1, 2, \ldots, 3X\}$ **do**
25. Broadcast ending package to the gamers N_0 and K_0 of subcell x
26. **End for**
27. **End if**

Algorithm 3-2 Gamer Process

Runner: in-band D2D UE or cellular UE
Input: new game information
Output: new $\tilde{P}^{d*}_{i,x}$, $P^{c*}_{k,x}$ or ($P^{k*}_{j,x}$, $P^{r*}_{k,j,x}$)

1. **While** don't receive the ending package **do**
2. **If** receive new game information **do**
3. Invoke Algorithm 1-1 and 1-2 to obtain optimal solution $\tilde{P}^{d*}_{i,x}$, $P^{c*}_{k,x}$ or $P^{k*}_{j,x}$.
4. **If** the current runner is a cellular UE with the aid of an out-band D2D relaying UE **do**
5. Calculate $P^{r*}_{k,j,x}$ according to $P^{k*}_{j,x}$ by (31)
6. **End if**
7. Send $\tilde{P}^{d*}_{i,x}$, $P^{c*}_{k,x}$ or ($P^{k*}_{j,x}$, $P^{r*}_{k,j,x}$) to the associated RRH.
8. **End if**
9. **End while**

TABLE 3. Simulation parameters.

Parameter	Value	Varied in Figure(s)
Cell radius R	300m	
Max in-band D2D transmission distance	25m	
Number of in-band D2D pairs in each cell	16	
Number of cellular UEs in each cell	16	
Number of out-band D2D relaying UEs in each cell	42	
PA efficiency η	35%	
Number of RRHs X	3	
convergence tolerance Δ_1 and Δ_2	10^{-7}	
convergence tolerance Δ_3	1	
Initial value of every UE's step size μ_0	10000	
Tendency factor θ	0.3	Fig. 4, Fig. 5
weighting factor ρ	0.7	Fig. 6, Fig. 7
Dividing factor λ	0.68	Fig. 8, Fig. 9
Max in-band transmission power $p^{d,max}_{i,x}$, $p^{c,max}_{k,x}$ and $p^{k,max}_{j,x}$	0.2W	
Max out-band transmission power $p^{o,max}_{k,j,x}$	0.1W	
Circuit power p_{cir}	0.01W	
Transmitting antenna gain G_t	1	
Receiving antenna gain G_r	1	
UE's antenna height	1m	
RRH's antenna height	2m	
System loss factor l	1	
Signal wavelength Λ	0.125m	
Bandwidth ratio $\frac{B^k_{j,x}}{B^r_{k,j,x}}$	1	Fig. 10 to Fig. 13
Out-band link bandwidth $B^r_{k,j,x}$	20MHz	
Temperature T	300K	

respectively, while the price is that the average SE and EE of in-band D2D UEs decline by 2.57% and 3.83% respectively.

We can find that, due to the high-quality communication brought from the short distance between every in-band D2D pair, the negative effects on the SE and EE of in-band D2D UEs are not significant when maximizing the average EE of cellular UEs. In other words, it's worth adopting $\theta = 0.3$. In fact, a too large value or a too small value of θ will not benefit improving the average SE and EE of cellular UEs. In fact, if θ is too large, the out-band D2D relaying UEs will tend to be closer to their corresponding cellular UEs, where the cellular parts of optimized links will be similar to the original links of cellular UEs, i.e., $C^k_{j,x} \approx C^c_{k,x}$. Since our discussion is based on a small value of $C^c_{k,x}$ (otherwise there is no need in relays), $C^k_{j,x}$ is small in $B^r_{k,j,x}C^r_{k,j,x} = B^k_{j,x}C^k_{j,x}$. And if θ is too small, the out-band D2D relaying UEs will tend to be closer to the RRHs, which will cause serious out-band interference near the RRH, hence the out-band parts of optimized links have low SE either, i.e., $C^r_{k,j,x}$ in $B^r_{k,j,x}C^r_{k,j,x} = B^k_{j,x}C^k_{j,x}$ will be also too small. Therefore, the SE of optimal links of cellular UEs estimated by (12) is small and influence the associated

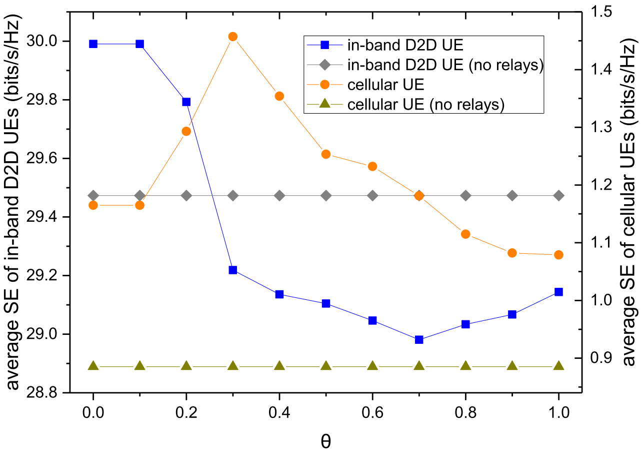

FIGURE 4. Average SE of gamers versus θ.

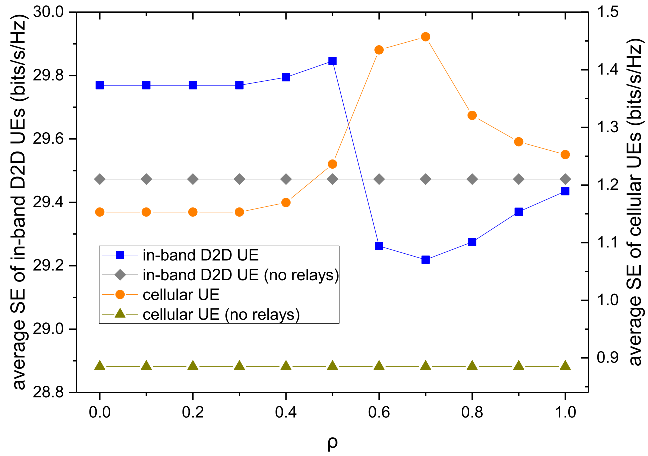

FIGURE 6. Average SE of gamers versus ρ.

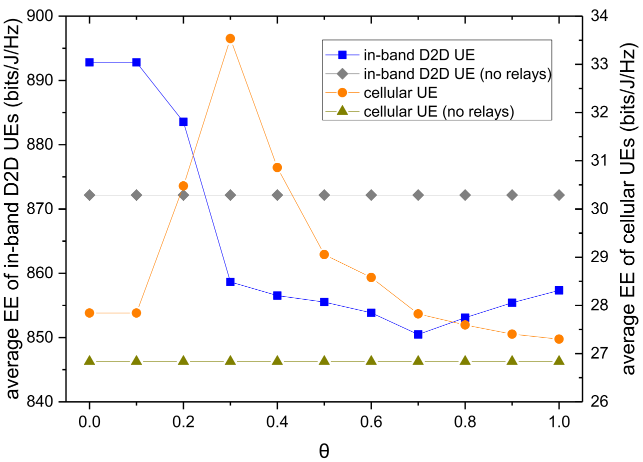

FIGURE 5. Average EE of gamers versus θ.

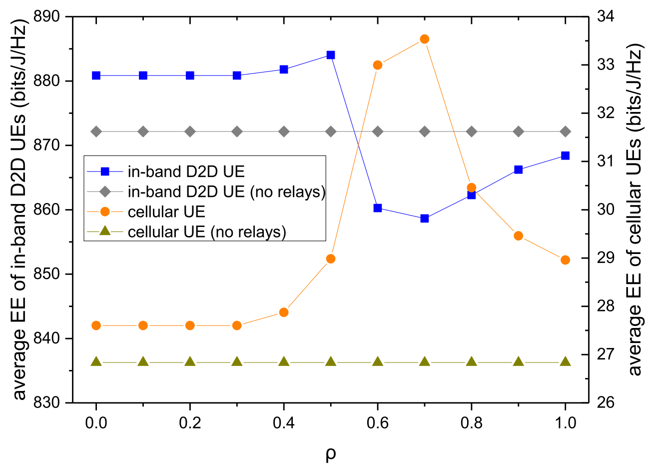

FIGURE 7. Average EE of gamers versus ρ.

EE. The simulation results suggest that we should choose the out-band D2D relaying UEs which are a little closer to the corresponding RRHs, i.e., $\theta = 0.3$.

B. EFFECT OF WEIGHTING FACTOR ρ ON THE SE AND EE OF GAMERS

Fig. 6 and Fig. 7 show the average SE and EE of in-band D2D UEs and cellular UEs versus ρ in the range from 0 to 1, respectively. It's illustrated that with the growing ρ, both the average SE and EE of cellular UEs increase and then decrease, while the average SE and EE of in-band D2D UEs are roughly on the contrary. The average SE and EE of in-band D2D UEs can be even lower than that in no-relay scenario when $\rho \geq 0.6$, which is possible and reasonable because the emphasis of our scheme is the EE of cellular UEs. For the same reason, the best value of ρ is 0.7. Comparing with the best value of ρ for the EE of in-band D2D UEs, i.e., $\rho = 0.5$, $\rho = 0.7$ can improve the average SE and EE of cellular UEs by 17.87% and 15.71% respectively, while the cost is that the average SE and EE of in-band D2D UEs decline by 2.10% and 2.87% respectively.

Since the negative effects on the SE and EE of in-band D2D UEs are weak when maximizing the average EE of cellular UEs, it's worthy to adopt $\rho = 0.7$. Clearly, $\rho = 1$ means we choose out-band D2D relaying UEs only based on the length of the optimal links, while $\rho = 0$ means it's just based on the location tendency of out-band D2D relaying UEs. In fact, shorter lengths of optimal links are not always good for the SE and EE because they cannot avoid the two problems about the location tendency mentioned in the last subsection. Hence, we should also take the location tendency into consideration. And the simulation results show that we should mainly consider the length of the optimal links, but also take a little concern of the location tendency, i.e., $\rho = 0.7$.

C. EFFECT OF DIVIDING FACTOR λ ON THE SE AND EE OF GAMERS

Fig. 8 and Fig. 9 show the average SE and EE of in-band D2D UEs and cellular UEs versus λ in a specific series of values respectively, where the explanation is given in Appendix. It's demonstrated that with the growing λ, both the average SE

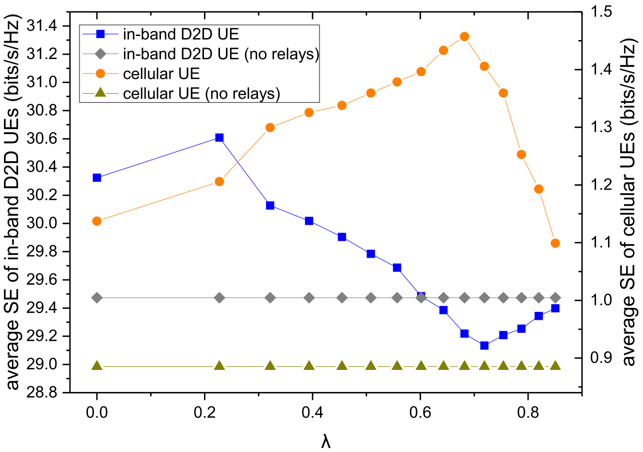

FIGURE 8. **Average SE of gamers versus λ.**

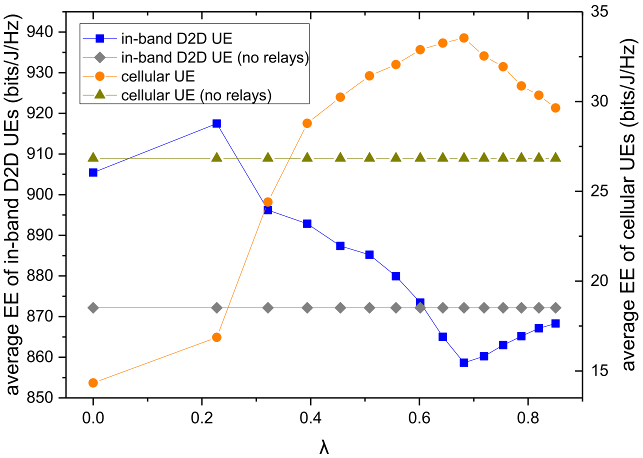

FIGURE 9. **Average EE of gamers versus λ.**

and EE of cellular UEs increase firstly and then decrease, while the average SE and EE of in-band D2D are roughly on the contrary. Aiming at the maximum of the EE of cellular UEs, the best value of λ is 0.68. Comparing with the best value of λ for the EE of in-band D2D UEs, i.e., $\lambda = 0.23$, $\lambda = 0.68$ can improve the average SE and EE of cellular UEs by 20.84% and 98.83% respectively, while the cost is that the average SE and EE of in-band D2D UEs decline by 4.54% and 6.41% respectively.

Again, the negative effects on the SE and EE of in-band D2D UEs are weak when maximizing the average EE of cellular UEs and thus $\lambda = 0.68$ is worthy to be adopted. Actually, a too small value of λ will allow most of cellular UEs to use out-band D2D UEs and may lead to strong out-band D2D interferences in the cells and around the RRHs, which will cause low average SE and EE of cellular UEs. In fact, the simulation results of $\lambda \leq 0.68$ validate our idea. Especially when $\lambda \leq 0.32$, the average EE of cellular UEs are much lower than that in no-relay scenario, which is why there is a huge improvement in the average EE of cellular UEs in the comparison in the last paragraph. And the simulation results suggest that when the out-band D2D relaying UEs are sufficient, all cellular UEs which are more than $0.68R$ away from the RRHs should use out-band D2D relays to achieve their best SE and EE.

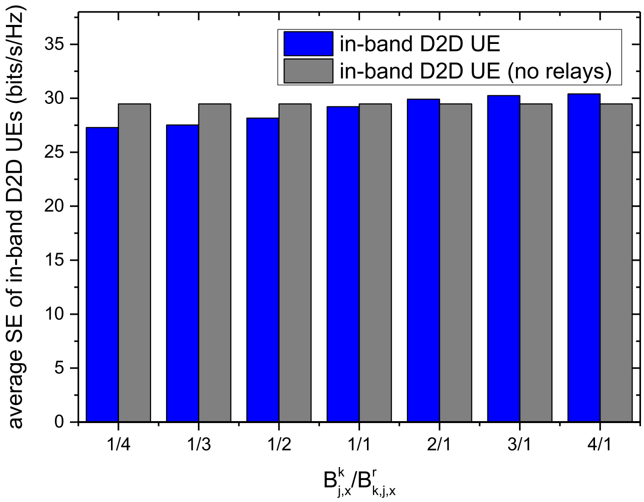

FIGURE 10. **Average SE of in-band D2D UEs versus $\frac{B^k_{j,x}}{B^r_{k,j,x}}$.**

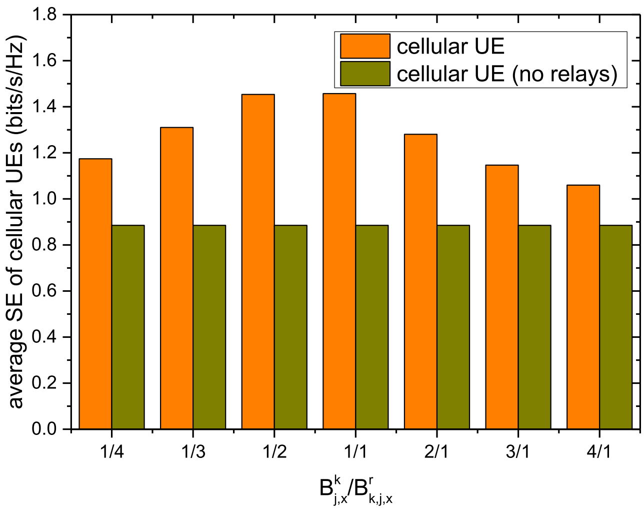

FIGURE 11. **Average SE of cellular UEs versus $\frac{B^k_{j,x}}{B^r_{k,j,x}}$.**

D. EFFECT OF BANDWIDTH RATIO $\frac{B^k_{j,x}}{B^r_{k,j,x}}$ ON THE SE AND EE OF GAMERS

Fig. 10∼Fig. 13 show the average SE and EE of in-band D2D UEs and cellular UEs versus different $\frac{B^k_{j,x}}{B^r_{k,j,x}}$, respectively. As we can see in Fig.10 and Fig. 12, both the average SE and EE of in-band D2D UEs increase all the time with the growing $B^k_{j,x}$ ($B^r_{k,j,x}$ do not change as mentioned above). That is to say, the in-band interferences decrease with the growing $B^k_{j,x}$. Furthermore, it can be observed in Fig.11 and Fig. 13 that both the average SE and EE of cellular UEs increase firstly and then decrease with the growing $B^k_{j,x}$.

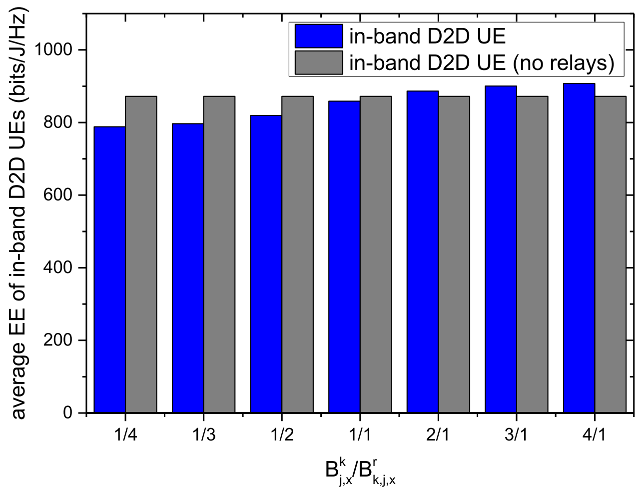

FIGURE 12. Average EE of in-band D2D UEs versus $\frac{B^k_{j,x}}{B^r_{k,j,x}}$.

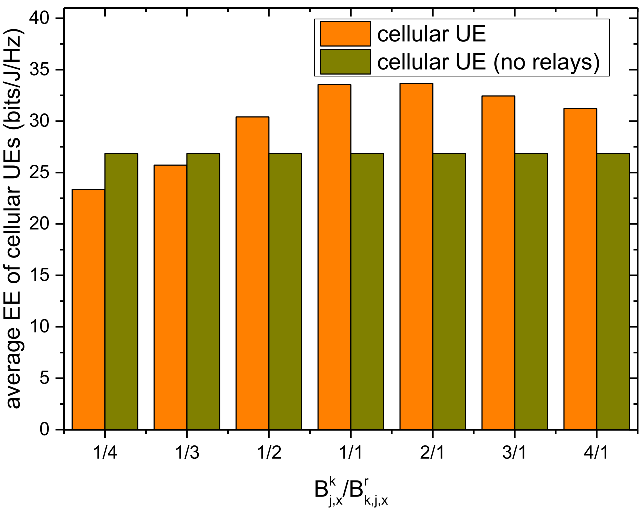

FIGURE 13. average EE of cellular UEs versus $\frac{B^k_{j,x}}{B^r_{k,j,x}}$.

The average SE of optimized links of cellular UEs is mainly subject to the cellular parts when $\frac{B^k_{j,x}}{B^r_{k,j,x}} < 1$, while it is mainly subject to the out-band parts when $\frac{B^k_{j,x}}{B^r_{k,j,x}} > 1$. When it is subject to the cellular parts, the average SE of optimized links of cellular UEs increases with the decreasing in-band interference naturally. Also, when it is subject to the out-band parts, the average SE of optimized links of cellular UEs cannot increase with the decreasing in-band interference but the average SE of in-band D2D UEs can do such, which will make the average SE of cellular UEs decrease in some degree.

The simulation results show that our scheme has the best performance when $\frac{B^k_{j,x}}{B^r_{k,j,x}} = 1$. However, it's better to consider that $\frac{B^k_{j,x}}{B^r_{k,j,x}}$ is a usage condition rather than a parameter in our scheme since the bandwidths of different signals cannot be controlled flexibly due to the difference of communication protocols.

Last, we compare the performance in the scenario adopting all the parameters with the best values in out-band D2D relays with that in no-relay scenario. As we can find in every figure in this section, the average SE and EE of cellular UEs can be improved by 64.63% and 24.97% respectively at the cost of reducing the SE and EE of in-band D2D UEs by 0.86% and 1.55% respectively. Moreover, the improvement of 64.63% in the average SE of cellular UEs underpins the feasibility of implicitly solving QoS problems in our scheme. Since the methods of searching cells, estimating channel attenuations and the thermal noise power, and solving QoS problems in our scheme are different with those in [16], we do not compare our simulation results with those in [16].

VII. CONCLUSION

In this paper, we propose an energy-efficient resource sharing scheme in in-band D2D communications underlaying C-RAN by adopting out-band D2D relay-aided communication and noncooperative game theory. The proposed resource sharing scheme consists of two parts, the one is the out-band D2D relaying strategies and the other is the noncooperative game model, where each player optimizes its EE respectively with the aid of the RRH. The simulation results show that the positive and negative effects on the SE and EE of in-band D2D UEs are little due to the high-quality communication brought by the short distance between each pair of in-band D2D UEs. However, the SE and EE of cellular UEs can be improved by 64.63% and 24.97% respectively when the out-band D2D relaying parameters with best values are adopted. The results validate the effectiveness of the proposed scheme. In this paper, we only consider the inter-subcell interferences coming from the subcells that share an edge with the target subcell. In our future works, we plan to consider them from the subcells that share a vertex with the target subcell to improve our work further.

APPENDIX

A. PROOF OF THEOREM 1

Let $A \Rightarrow B$ denote A is the sufficient condition of B. Accordingly, the proof of Theorem 1 is equal to proofing $q^{d*}_{i,x} = \max\limits_{(\tilde{p}^d_{i,x})} \frac{C^d_{i,x}(\tilde{P}^d_{i,x})}{p^{d,t}_{i,x}(\tilde{P}^d_{i,x})} \Leftrightarrow \max\limits_{(\tilde{p}^d_{i,x})} C^d_{i,x}(\tilde{P}^d_{i,x}) - q^{d*}_{i,x}p^{d,t}_{i,x}(\tilde{P}^d_{i,x}) = 0$, which relates to the following two problems.

$$\max_{(\tilde{p}^d_{i,x})} \frac{C^d_{i,x}\left(\tilde{P}^d_{i,x}\right)}{p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right)} \tag{54}$$

$$\max_{(\tilde{p}^d_{i,x})} C^d_{i,x}\left(\tilde{P}^d_{i,x}\right) - q^{d*}_{i,x}p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right) \tag{55}$$

First, let $\tilde{P}^{d*}_{i,x}$ be a solution of problem (35), such that $q^{d*}_{i,x} = \frac{C^d_{i,x}(\tilde{P}^{d*}_{i,x})}{p^{d,t}_{i,x}(\tilde{P}^{d*}_{i,x})} \geq \frac{C^d_{i,x}(\tilde{P}^d_{i,x})}{p^{d,t}_{i,x}(\tilde{P}^d_{i,x})}$. Hence,

$$C^d_{i,x}\left(\tilde{P}^d_{i,x}\right) - q^{d*}_{i,x}p^{d,t}_{i,x}\left(\tilde{P}^d_{i,x}\right) \leq 0 \tag{56}$$

From (54) we have $C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)-q_{i,x}^{d*}p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)=0$, i.e., 0 is the maximum of problem (38). Here we have proved $q_{i,x}^{d*}=\max_{\left(\tilde{P}_{i,x}^{d}\right)}\frac{C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)}{p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)}\Rightarrow\max_{\left(\tilde{P}_{i,x}^{d}\right)}C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)-q_{i,x}^{d*}p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)=0$.

Second, let $\tilde{P}_{i,x}^{d*}$ be a solution of problem (38), and then we have $C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)-q_{i,x}^{d*}p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)\leq C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d*}\right)-q_{i,x}^{d*}p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d*}\right)=0$. Hence,

$$C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)-q_{i,x}^{d*}p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)\leq 0 \tag{57}$$

From (55) we have $q_{i,x}^{d*}\geq\frac{C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)}{p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)}$, i.e., $q_{i,x}^{d*}$ is the maximum of problem (35). Here we have proved $q_{i,x}^{d*}=\max_{\left(\tilde{P}_{i,x}^{d}\right)}\frac{C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)}{p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)}\Leftarrow\max_{\left(\tilde{P}_{i,x}^{d}\right)}C_{i,x}^{d}\left(\tilde{P}_{i,x}^{d}\right)-q_{i,x}^{d*}p_{i,x}^{d,t}\left(\tilde{P}_{i,x}^{d}\right)=0$. Therefore, Theorem 1 has been proved.

B. VALUES OF λ

It's not difficult to understand that the cellular UEs are not distributed uniformly with the radius of the cells. Still taking Fig. 3 for example, when $\lambda=0.5$, it's obvious that the amounts of cellular UEs outside and inside the blue circle are not equal. Since the probability of existence is proportional to the area, only when the area outside the blue circle equals the area inside the blue circle, the amounts of cellular UEs are equal. For a more general case, the area of the regular hexagon in Fig. 3 is given by

$$S_{cell}=\frac{3\sqrt{3}}{2}R^{2} \tag{58}$$

And the area of the blue circle is given by

$$S_{in}=2\pi(\lambda R)^{2} \tag{59}$$

From (56) and (57) we have

$$\lambda\left(\frac{S_{in}}{S_{cell}}\right)=\sqrt{\frac{3\sqrt{3}}{4\pi}\cdot\frac{S_{in}}{S_{cell}}} \tag{60}$$

Then, we plug $\frac{S_{in}}{S_{cell}}=\{0,\frac{1}{16},\frac{2}{16},\ldots,\frac{14}{16}\}$ into (56) and will get a series value of λ. When $\lambda(\frac{15}{16})>\frac{\sqrt{3}}{2}$, (56) does not apply due to the blue circle intersects the regular hexagon. We don't handle this problem since the number of cellular UEs outside $\frac{\sqrt{3}}{2}R$ is already very little. As a result, the cellular UEs are distributed uniformly with the λR of cells, where λ is $\lambda\left(0\right),\lambda\left(\frac{1}{16}\right),\lambda\left(\frac{2}{16}\right),\ldots,\lambda\left(\frac{14}{16}\right),1$ and the amount of cellular UEs in every interval is $1,1,\ldots,1,2$.

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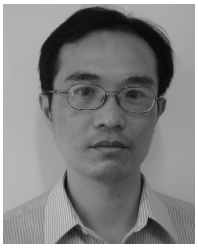

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