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Multi-Hop Relay-Aided Underlay D2D Communications for Improving Cellular Coverage Quality

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ABSTRACT The future wireless networks need to improve spectrum and energy efficiency to satisfy the increasing demand for high data rate. Device-to device (D2D) communications have the ability to address this problem. This paper focuses on the underlay D2D relay function to improve cellular coverage quality. Although there are a few relevant works in this aspect, there is room for further improvement. For example, there is the constraint on the number of relays in a transmission path, which hardly meets the requirement of the cell-edge devices to fully improve their cellular throughput. Also, there is little energy constraint for underlay D2D relay selection, which is difficult to guarantee the service life of underlay D2D relaying links. Furthermore, without careful regulation of transmission power in terms of cellular coverage improvement, it is not conducive to the improvement of spectrum and energy efficiency in this aspect. Therefore, this paper proposes the improved scheme to deal with these problems, which can: 1) improve spectrum efficiency by using underlay spectrum sharing mode and alleviating its weakness (e.g., co-channel interference); 2) enhance comprehensive performance of underlay D2D relaying links by jointly considering multiple Quality-of-Service (QoS) metrics; 3) reduce overhead of relay selection by proposing a greedy algorithm based on a distributed local search; and 4) improve both energy efficiency and convergence time by designing a new power adjustment scheme based on the improved potential game decision algorithm. The theoretical analysis proves the existence of Nash equilibrium, and the simulation results show that the proposed game decision algorithm accelerates convergence and the proposed whole scheme improves cellular coverage quality.

INDEX TERMS Underlay cellular network, D2D communication, multi-hop relay-aided, potential game, cellular coverage quality.

I. INTRODUCTION

With the increasing heterogeneity of user requirements in the future wireless networks [1]–[4] and the rapid growth for wireless broadband services (e.g., augment (or virtual) reality application, mobile high-definition television, instant file sharing and online gaming, as well as sensitive data collection [5], smart sensing [6], mobile target tracking [7] for smart cities), currently the evolution of cellular networks to the fifth generation (5G) mobile communication networks makes great efforts to meet these demands by new technologies [8], including Device-to Device (D2D) communications.

D2D communications can improve cellular network performance from different aspects (e.g., overall throughput, spectrum efficiency, energy efficiency), which is mainly embodied in the following application scenarios. 1) The wireless application terminals in proximity communicate with each other instead of relay via a Base Station (BS), which can offload the data traffic of nearby User Equipments (UEs) from the BS. Therefore, the BS is capable to relay more data traffic for any communication pair far away from each other. 2) When the wireless application terminals at the edge of cell coverage want to communicate with the application servers in the core network, in order to improve the network service quality, they can fall back on other UEs to relay data traffic from the BS to themselves and vice versa.

Usually, D2D communication modes include underlay in-band D2D, overlay in-band D2D, and out-band D2D communications, where underlay D2D UEs share the

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same cellular frequency bands with cellular UEs, overlay D2D UEs adopt the dedicated licensed frequency bands, and out-band D2D UEs employ unlicensed frequency bands. On the one hand, underlay mode potentially outperforms the other two in terms of spectral efficiency, since it allows D2D UEs and cellular UEs to share the same channel within each cell. On the other hand, within an underlay mode, the higher transmission power will generate the stronger intended received signals, while it will lead to the more severe interference to other signals. Therefore, co-channel interference should be effectively controlled.

In order to enable the benefits of D2D communications underlay cellular networks, a number of efforts have been devoted to the research of efficient spectrum sharing D2D systems in underlay mode. For example, many researchers focus on the scenario where the source and destination UEs are within the communication range of each other. For convenience, this is referred to as D2D communication pair. With the aid of relaying UEs, the transmission quality of such D2D communication pair can be further improved, which has attracted the attention of many researchers. In particular, the source and destination UEs are not within the transmission range of each other, the establishment of a relaying link between each other can avoid forwarding data traffic via a BS.

When a UE with poor coverage communicates with an application server in the core network, by using a UE that is close to both a BS and itself to forward data from the BS to itself and vice versa, it can improve cellular coverage quality. Although there are a few relevant works in this aspect, there is room for further improvement. For example, in the most recent relevant literatures, Asadi *et al.* [9], [10] design a delay-aware D2D opportunistic relay enforcement framework (for short, DORE), which aims at maximizing cellular downlink throughput under delay constraint by performing relay and mode selection for UEs. Learning from the idea in [9] and [10], Zhou *et al.* [11] increase Quality-of-Service (QoS) constraints for relay selection and extend the maximum number of relays from one to two (for short, DTO-MROD).

The wireless signal energy will decay quickly with the increase of propagation path length. Even if the propagation path becomes relatively short, the signal strength may drop sharply due to natural barriers and artificial obstacles (e.g., trees and buildings). Therefore, poor coverage is common in actual cellular environments. However, in the existing schemes, the maximum number of relays is limited to the fixed value, which hardly improves such poor coverage. Furthermore, in the aspect of the improvement of cellular coverage quality, transmission powers of underlay D2D relaying links should be carefully adjusted to improve energy efficiency, just like that in topology control for wireless networks [12], [13]. The above problems motivate our work in this paper and the main contributions are as follows.

1) Different from DORE and DTO-MROD that adopt out-band D2D communication mode, we employ underlay in-band D2D to avoid interference coming from other wireless technologies (e.g., WiFi, Bluetooth, ZigBee) working in unlicensed frequency bands. Also, in order to alleviate cellular co-channel interference in underlay mode, we try to avoid reusing the same cellular frequency bands in one-hop communication range of any receiving-end.

2) Existing works related to underlay in-band D2D focus on the allocation of reusable cellular frequency bands for a D2D communication pair either adopting direct communication mode or with the help of relaying UEs, where the aim is to offload cellular traffic and improve D2D traffic. The work in this paper pays attention to pre-allocating reusable cellular frequency bands for D2D relaying links, where the aim is to provide a choice for any cellular receiving UE to enhance its cellular traffic.

3) Different from the distance-based cellular spectrum reusing mode to mitigate co-channel interference, we explore reusing mode by combining distance with antenna emission angle of BS to control co-channel interference.

4) In view of the heterogeneity of receiving sensitivity at receiving-ends, the setting of Signal to Interference plus Noise Ratio (SINR) threshold should also be varied to satisfy a good application experience, which brings complexity to system design. Different from the existing link power adjustment based on SINR threshold, we propose a new method based on Bit Error Rate (BER) threshold, which directly expresses user experience and simplifies system parameter setting.

5) Unlike DORE and DTO-MROD that use a greedy algorithm based on a centralized search, we explore a greedy algorithm based on a distributed local search to find an appropriate relaying UE for a receiving UE, which effectively relieves the burden of cellular infrastructure.

6) Different from DORE and DTO-MROD with the constrained number of relays, in this paper, there is no limit imposed on the maximum number of relays that are located in the path from the BS to any receiving UE, which improves downlink throughput of receiving UEs in poor coverages, in particular, cell-edge UEs without line-of-sight.

7) Unlike DORE and DTO-MROD without the adjustment of transmission power, we design a power adjustment scheme based on potential game to improve energy efficiency in terms of cellular coverage quality, where we accelerate convergence of game decision algorithm in power adjustment process by the first-bin-search-then-sequential-search in the action space of the potential game.

The remainder of this paper is organized as follows: In Section II, we give a brief overview of the state of the art in D2D communications underlay cellular networks in terms of resource allocation and relay-aided service. In Section III, we describe system model, and give problem formulation and analysis of potential game theory. In Section IV, we present the scheme for improving cellular coverage quality, including the detailed discussions for pre-allocation of relaying channels, adjustment of transmission powers, and selection of data receiving modes. In Section V, we describe the simulation scenarios and settings, and analyze the simulation results. In Section VI, we summarize our results, give the conclusions, and look forward to future works.

II. RELATED WORK

In underlay D2D mode, the reasonable distribution of spectrum resource in space and adjustment of transmitting power are conducive to controlling co-channel interference and improving throughput.

The existing works focus on the allocation of reusable cellular spectrum for D2D communication pairs. For example, in [14], a cellular UE's spectrum can be reused by a D2D pair as soon as the distance between the cellular UE and D2D receiver is more than the preset minimum distance. However, it never takes advantage of antenna emission angle for BS to form interference-free subspace.

Also, co-channel interference can be efficiently managed by adopting power control mechanisms in underlay D2D mode. The existing works [15]–[17] focus on adjusting power level for each link by setting individual SINR targets for all links. As mentioned in the previous text, in order to satisfy a good application experience, the setting of SINR threshold should be varied, which will complicate system parameter settings.

By balancing the real-time load of different cellular regions, the service capacity of the whole cellular network can be further enhanced. For example, the literatures [18]–[20] utilize D2D communications as bridges to flexibly detour traffic among different tier cells, which takes advantage of both the direct traffic offloading (e.g., via one-hop D2D communications) and the relay-aid traffic offloading (e.g., via two-hop D2D communications) to efficiently detour traffic from congested regions. However, these works assume that any BS can dynamically dispatch the allocated cellular spectrum resources and efficiently coordinate with other BSs, which increase the burden of BSs.

In a damaged infrastructure environment, the multi-hop D2D communication mode without involvement of cellular infrastructure is used to keep end-to-end connectivity and improve data transmission performance. A D2D system "Relay-by-Smartphone" [21] is a typical example, which is developed for disaster relief applications. Since it uses Industrial Scientific Medical (ISM) band, the potential impact on Wi-Fi and Bluetooth services still needs to be explored.

Even if cellular infrastructure is in good condition, such a multi-hop D2D communication mode can efficiently offload cellular traffic and enhance whole network capacity. For example, in [22]–[26], a source UE communicates with a destination UE via a relay, where the literatures [22], [23], [26] usually select a UE to act as a relay while the literatures [24], [25] adopt a dedicated access node as a relay. They both reduce BS load and improve D2D traffic.

The relay functionality of D2D communications can be exploited to improve cellular coverage quality (e.g., coverage extension, capacity improvement), which draws researchers' attention [27]–[32]. However, some works do not consider how the relay is selected if more UEs can be used for this purpose (e.g., the literature [27]). Some works tackle relay selection problem (e.g., the literatures [28], [29] select relaying UEs based on graph theory, while the literatures [30]–[32] do so based on the collaboration for both obtaining in-band spectrum for D2D pair and improving traffic of cellular UE), but they do not consider multiple QoS constraints (e.g., both delay and energy) for relay selection.

There are also works that consider energy constraints to select relays. For example, the literature [33] aims at helping UEs with low battery level by selecting neighboring UEs with high battery level to relay their traffic. However, it doesn't necessarily ensure that the network capacity is increased.

The literature [34] summarizes a group of research works which focus on exploring the throughput and delay scaling laws of hybrid wireless networks, where there exist two types of network elements: BSs which are assumed to have infinite-bandwidth wireline connections between each other, and UEs which are able to operate in D2D mode and cellular mode. Therefore, the routing path between a source-destination pair may consist of D2D links, cellular links, as well as wired links, where D2D communications use dedicated frequency band, ISM band, or other unused band.

The literatures [35]–[37] investigate the relay selection and resource allocation problem for the purpose of coverage quality (e.g., improving throughput for cell-edge UEs), where only the literature [36] considers transmitting power adjustment for D2D links to control the power radiated into neighboring cells. The works in [35] and [36] focus on uplink throughput optimization, whereas the work in [37] considers downlink one. Moreover, these works will consider one relay at most if bit rate is increased, while other QoS constraints (e.g., both delay and energy) are not considered for relay selection.

Some works explore downlink D2D relaying mode to extend coverage for mmWave networks (e.g., the literature [38]). The other works also consider improving performance of small cell network by indirect transmission or direct transmission mode (e.g., the literature [39]). In addition, the literature [40] investigates both coverage extension and proximity communication. The literature [41] uses a full-duplex relay to assist a cellular uplink transmission, while the literatures [42], [43] employ a full-duplex relay to assist a cellular downlink transmission. Furthermore, the literature [44] adopts a hybrid half-duplex/full-duplex relaying mode to address cellular downlink transmission problem. In these works, a relay is selected only for the purpose of traffic increase, and the maximum number of hops in a transmission path is usually limited to the fixed value (i.e., two).

The works in the literatures [9]–[11] are closest to the topic of our paper. However, as mentioned in the previous text, their D2D relaying links employ the unlicensed spectrum, and the maximum number of relays is limited to the fixed value. Moreover, there is not fine regulation of transmission power in their schemes.

Distributed transmission power adjustment can effectively control co-channel interference in underlay mode. At the same time, it can reduce the load of cellular infrastructure and avoid the single point of failure. Game theory is widely used in various network information systems [45], [46], which is one of the most investigated tools because it offers an efficient distributed framework.

An exact potential game can characterize the set of Nash Equilibria (NE), in which a potential function can track the changes in the payoff due to the unilateral deviation of a player, and one or more NE points may exist and coincide with the points that maximize the potential function. As long as one can identify potential functions for a potential game, it can find at least one NE of the potential game by solving for the potential maximizers [47], [48]. Therefore, some existing works [49]–[51] have modeled their power control problems as potential games. However, these works mainly focus on offloading cellular traffic and improving performance of D2D communication pairs, rather than enhancing cellular coverage quality. Also, the game decision-making algorithms used by them to get NE also need to be further improved.

In a potential game, there are usually two algorithms to get its NE (i.e., a best response algorithm and a better response algorithm). In the former, whenever a game player has an opportunity to make decision (i.e., adjusting its power), it chooses an action (e.g., a transmitting power level) that maximizes its utility. In the latter, each game player makes a small decrement in its action if the change improves its utility; otherwise, the player still adopts its previous action.

For the potential game for power control, a main drawback of the best response algorithm is that, being greedy, it leads to a biased steady-state power-level distribution due to the "first-mover advantage" [47]. Following the better response algorithm, the transmitting power distribution is much fairer than that produced by the best response algorithm. However, the best response algorithm converges faster than the better response algorithm. In general, there may be a fundamental conflict between efficiency and fairness. In this paper, we will adopt the better response algorithm due to its fairness, but we will try to speed up its convergence.

III. THE SYSTEM MODEL, PROBLEM FORMULATION, AND THEORETICAL ANALYSIS

A. SYSTEM MODEL

In order to improve coverage quality for a single underlay cellular network, we need to consider the optimization problem of downward throughput in such a scenario, where an *eNB* (evolved Node B) is located at the center of the cell, and UEs are randomly distributed in the cell. Although the maximum transmission power of the *eNB* can be designed to be large enough in theory, the actual value is limited due to the problem of adjacent cellular interference management. Usually, this maximum transmission power hardly ensures that the UEs at cell edge can reach an ideal BER level (e.g., 10^{-10}). For a UE that is closer to the *eNB*, it only needs a smaller transmission power to achieve the same BER level.

The throughput optimization problem is closely related to the BER level of each link in the network. When the BER level of a link (e.g., one with a long distance) is relatively large (or bad), by building a path that consists of some links (e.g., each with a short distance), throughput can be improved if the BER level of this path is smaller (or better) than that of the long link.

We assume that all cellular spectrum resources in a cell are uniformly divided into N groups of Resource Blocks (RBs). The N groups of RBs form a *set* of channels, which is denoted as C (e.g., c_j represents the jth channel in C). Also, we assume that the number of UEs in the cell is M, and such a *set* of these UEs is denoted as U.

When a UE wants to communicate with an application server in the core network, it firstly needs to obtain some RBs as its communication frequency band, where, based on Time Division Duplexing (TDD) mode, this communication frequency band may act as an upward channel from itself to the *eNB* and a downward channel from the *eNB* to itself. Such a UE is referred to as a target UE, which does not necessarily succeed in obtaining the channel when the number of RBs is limited.

The channels in C are scheduled and pre-allocated to the target UEs by the *eNB*. Each channel is pre-allocated to one target UE at most, but it may be reused by the UEs that are acting as relays. The question we want to study is that, when the number of target UEs is far larger than the number of channels (i.e., N), how to utilize the relaying UEs in order to maximize the throughput from the *eNB* to the target UEs that obtain a group of RBs. In terms of the above described scenario, only N target UEs can receive their data from the *eNB* simultaneously. They form a set of receiving UEs, which is denoted as U_c. Except for the UEs in U_c, the other UEs in U can act as potential relays, which belong to the set U_r.

When the *eNB* broadcasts data at its maximum transmission power, the UEs in the approximate circular region centered at the *eNB* can guarantee that their receiving BER levels are not larger than the desired BER level (e.g., 10^{-10}). The radius of this approximate circular region is denoted as R_{th}. Also, in order to avoid selecting a relay close to the *eNB*, we assume that the distance of any potential relaying UE from the *eNB* to itself must be more than a preset value r_{th} (e.g., 120m).

The *eNB* is equipped with at least N adaptive directional antennas and the same number of cellular interfaces, and each UE is equipped with at least two omnidirectional antennas and the same number of cellular interfaces. Therefore, the *eNB* can transmit data to at least N target UEs simultaneously, while each UE can transmit and receive data at the same time. For example, in Fig.1, the *eNB* can transmit data to UE_i, UE_j, UE_k simultaneously, since they obtain their own channels from the *eNB* respectively and thus become the members of U_c. Due to the limited channels, UE_a, UE_b, UE_c, UE_d, UE_e do not get their desired channels. Therefore, they may act as potential relays and thus become the members

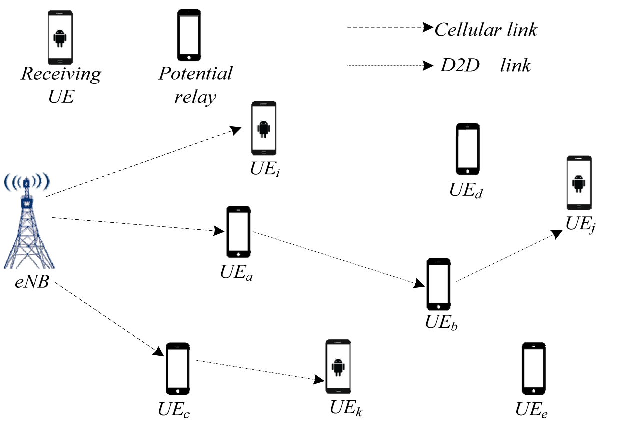


FIGURE 1. Example for cellular network topology with underlay D2D communications.

of U_r. These potential relays have ability to receive and transmit data simultaneously.

B. PROBLEM FORMULATION

We firstly outline some basic formulas, and then discuss problem formulation. According to the Shannon capacity formula, the throughput of UE i (i.e., $i \in U_c$) who receives it's data directly from the *eNB* can be expressed as follows.

$$T_{0i} = b_{0i} \cdot \log_2(1 + \gamma_{0i}) \tag{1}$$

In (1), T_{0i} and γ_{0i} are the throughput and the SINR for UE i respectively when the *eNB* (i.e., node 0) transmits data to it over a cellular channel, and b_{0i} is the allocated channel bandwidth for UE i' directly communicating with the *eNB*. Also, the relaying throughput of UE j (i.e., $j \in U_r$) from the *eNB* can be estimated by the formula that is similar to (1).

UE j (i.e., $j \in U_r$) relays data for UE i over a cellular channel from UE j to i, where the throughput T_{ji} is computed by the following formula.

$$T_{ji} = b_{ji} \cdot \log_2(1 + \gamma_{ji}) \tag{2}$$

In (2), γ_{ji} is the SINR for UE i when UE j transmits data to UE i over a cellular channel, and b_{ji} is the available cellular channel bandwidth to UE i from UE j. Based on (1) and (2), the throughput of UE i that receives its traffic from the *eNB* via UE j is expressed as follows.

$$T^{ji}_{d2d} = \min(T_{0j}, T_{ji}) \tag{3}$$

In (3), T^{ji}_{d2d} is the throughput when the *eNB* transmits data to UE i via UE j. If UE i receives its traffic from the *eNB* via UE k (i.e., $k \in U_r$) and UEj, its throughput (denoted as T^{kji}_{d2d}) is computed as follows.

$$T^{kji}_{d2d} = \min(T_{0k}, T_{kj}, T_{ji}) \tag{4}$$

When the *eNB* transmits data to UE i by using the transmission power p_{0i} over a cellular channel, the SINR for UE i is estimated by the following formula.

$$\gamma_{0i} = \frac{g_{0i} \cdot p_{0i}}{N_i + F_i} \tag{5}$$

In (5), N_i is the noise power perceived by UE i; g_{0i} is a channel attenuation coefficient of a link from the *eNB* to UE i, which includes the path loss, multipath fading, and shadowing fading effects etc., which is usually evaluated and quantified by the receiving end (i.e., UE i), and then fed back to the transmitting end (i.e., the *eNB*); F_i is the interference power perceived by UE i over a cellular channel, which is mainly caused by the potential emission sources in the same frequency channel near the receiving terminal (i.e., UE i), and estimated by the following formula.

$$F_i = \sum\nolimits_{k \in I_i} g_{ki} \cdot p_k \tag{6}$$

In (6), g_{ki} is a channel attenuation coefficient of a link from the interfering UE k to the interfered UE i, which includes the same factors as that of g_{0i}; p_k is the transmission power of the interfering UE k; I_i is the *set* of the interfering UEs of UE i. When a UE j relays data to a UE i by using a transmission power p_{ji} over a cellular channel, the SINR for UE i is estimated by the following formula.

$$\gamma_{ji} = \frac{g_{ji} \cdot p_{ji}}{N_i + F_i} \tag{7}$$

In (7), g_{ji} is a channel attenuation coefficient of a link from UE j to UE i, which includes the same factors as that of g_{0i}.

Based on the above, the throughput of each link can be calculated by the corresponding individual UE. The location information of any individual UE can be obtained by the GPS device built into it. According to the architecture proposed by 3GPP, any individual UE also reports its location information, battery capacity, data forwarding delay, and the link throughput associated with it to the *eNB*.

The delay from the *eNB* to UE i when j is the relay ($j = 0$ when no relay) is denoted by d^{ji}. Also, the delay from the *eNB* to UE i when k and j are its relays ($k = 0$ and $j = 0$ when there is not any relay) is denoted by d^{kji} (the explanation of d^{lkji} can be analogous according to that of d^{kji}). Given these definitions, we can formulate our cellular coverage quality problem as the throughput maximization problem with delay constraint d_{th} and remaining energy constraint e_{th} for N receiving UEs as follows.

$$\begin{cases} Max \sum\nolimits_{i \in U_c} \sum\limits_{\substack{j \in U_r \\ k \in U_r \{j\}}} \begin{pmatrix} +(1-\alpha_{ji}) \cdot T_{0i} \\ \alpha_{ji} \cdot ((1-\alpha_{kji}) \cdot T^{ji}_{d2d} \\ +\alpha_{kji} \cdot T_k) \end{pmatrix} \\ T_k = \begin{cases} T^{kji}_{d2d} & T_{0k} \geq T^{kji}_{d2d} \\ \forall l \in U_r, \begin{pmatrix} T^{lkj}_{d2d} & T_{0l} \geq T^{lkj}_{d2d} \\ T_k & otherwise \end{pmatrix} & otherwise \end{cases} \end{cases}$$

$$\begin{aligned} \text{s.t. } & \alpha_{ji} \in \{0, 1\}, \quad \forall i, j \in \{0, 1, \ldots, M\} \\ & \alpha_{ii} = 0, i \neq 0 \\ & \alpha_{00} = 1 \\ & \sum\nolimits_{i \in U_c} \alpha_{ji} = 1, \quad \forall j \in \{0, 1, \ldots, M\} \\ & \sum\nolimits_{j \in U_r} \alpha_{ji} - (M - 1 + 2\delta_{0i})\alpha_{0i} \leq 0, \\ & \forall i \in \{0, 1, \ldots, M\}\} \end{aligned}$$

$$\alpha_{kji}, \alpha_{lkj} \in \{0,1\}, \quad \forall i \in U_c,\ \forall j,k,l \in U_r$$
$$(\sum\nolimits_{k\in U_r\ \{j\}} \alpha_{kji}) \in \{0,1\}, \quad if\ \alpha_{ji} = 1$$
$$(\sum\nolimits_{l\in U_r\ \{k,j\}} \alpha_{lkj}) \in \{0,1\}, \quad if\ \alpha_{kji} = 1$$
$$e^j \geq e_{th}; \quad e^k \geq e_{th};\ e^l \geq e_{th}$$
$$d^{ji} \leq d_{th}; \quad d^{kji} \leq d_{th};\ d^{lkji} \leq d_{th} \tag{8}$$

In (8), α_{ij} and α_{kji} are binary decision variables, in which α_{ij} determines whether UE i transmits to user j or not, and α_{kji} determines whether UE k relays the data of UE i to UE j or not (The meaning of α_{lkj} is similar to that of α_{kji}); δ_{ij} is 1 for $i = j$ and 0 otherwise. For notational convenience, we mark the *eNB* as user 0. The first constraint and the sixth constraint force the decision variable to be binary. The second and third constraints avoid a UE to transmit to itself with the exception of the *eNB*. This exception is for notational convenience and it does not have a physical meaning. The fourth constraint enforces the UEs to receive either from the *eNB* or a relay. The fifth constraint limits the number of receivers of a relay below $M - 1$. The seventh constraint and the eighth constraint limit that a UE can select one relay at most when it itself also acts as a relay. The ninth constraint keeps the remaining energy of each relay above a threshold. Finally, the last constraint keeps the total delay below a threshold.

The BER level of wireless receiving end directly affects the user's application experience, so we set a BER threshold as BE_{th}. If the actual BER is lower than BE_{th}, it will meet the user's application experience. The *SINR* value (i.e., γ_{th}) corresponding to BE_{th} is estimated by the following formula.

$$\gamma_{th} = -2 \ln BE_{th} \tag{9}$$

For a D2D relaying link $j \to i$, in order to ensure that the BER level of UE i is not higher than BE_{th}, the transmission power of UE j should not be lower than p_{ji}^{th}, which is estimated as follows.

$$p_{ji}^{th} = \frac{\gamma_{th} \cdot (N_i + F_i)}{g_{ji}} \tag{10}$$

In fact, the transmission powers of the potential interference sources of the receiving UE i may be adjusted at any time, so the value of F_i can only be estimated based on what is currently known. The currently obtained value of F_i may also be further adjusted due to the availability of the updated information. Since the transmitting UE j may also be a potential interference source of the other receiving ends, its power adjustment may also trigger the new power adjustments on the transmitting ends of other co-channel links. The whole system can be stabilized when the transmitting ends of all the co-channel links do not adjust their transmission powers.

Therefore, we introduce Ordinal Potential Game (OPG) theory to model this distributed power adjustment problem, including utility function and game decision algorithm design. In the proposed model, the participants (i.e., players) in the game are all the potential communication links (i.e., all the communication pairs with the allocated channels), and each participant has a utility function that evaluates its own earnings and a set of actions (or strategies). For any D2D relaying link $j \to i$ or cellular link $0 \to i$, the utility function is expressed as follows.

$$\mu_i(P) = \begin{cases} w_g \cdot \dfrac{T_s}{P_s} + w_l \cdot \dfrac{T_{ji}}{p_{ji}} & j \to i \\ w_g \cdot \dfrac{T_s}{P_s} + w_l \cdot \dfrac{T_{0i}}{p_{\ 0i}} & 0 \to i \end{cases} \tag{11}$$

The first item on the right of the formula (11) represents the expected individual utility, which will come from the improvement of potential throughput of the entire network. The second item on the right of the formula (11) represents the actual individual utility. In this paper, the specific meaning of utility is energy efficiency, which is the amount of data transmitted by unit energy consumption. In (11), $P = \{\bigcup_{i\in U, d_{0,i}<R_{th}} p_{0i}, \bigcup_{j\in U, d_{0,j}>r_{th};\ i\in U, d_{0,i}>d_{0,j}} p_{ji}\}$, $U = \{1, 2, \times M\}$, $d_{0,i}$ and $d_{0,j}$ are the distances from the *eNB* to UE i and UE j respectively; $\mu_i(P)$ is the utility of link $j \to i$ or $0 \to i$ when UE j (or the *eNB*) transmits data at p_{ji} (or p_{0i}); w_g and w_l are the weight coefficient, and the sum of both is 1; P_s represents the sum of transmission powers of all the potential communication links (including D2D relaying links and cellular links) in the entire network, while T_s represents the total throughput of potential communication links throughout the network, which is estimated by the following formula.

$$\begin{cases} P_s = \sum_{i\in U, d_{0,i}<R_{th}} p_{0i} \\ \qquad + \sum_{j\in U, d_{0,j}>r_{th}} \sum_{i\in U, d_{0,i}>d_{0,j}} p_{ji} \\ T_s = \sum_{i\in U, d_{0,i}<R_{th}} T_{0i} \\ \qquad + \sum_{j\in U, d_{0,j}>r_{th}} \sum_{i\in U, d_{0,i}>d_{0,j}} T_{ji} \end{cases} \tag{12}$$

A set of actions of a participant (i.e. a communication link) can be regarded as a set of discrete power levels with a small step length. Different from the best response algorithm and the better response algorithm, we propose an improved better response algorithm to search an appropriate power level in the set of discrete power levels.

C. THEORETICAL ANALYSIS FOR POTENTIAL GAME

In this subsection, we prove the convergence of the utility function in this paper. To this end, some basic concepts of potential game are summarized as follows. As mentioned in [47] and [48], a formal representation of potential game is $\Gamma =< U, A, \mu >$, where $U = \{1, 2, \ldots, n\}$ is the set of players; $A = \Pi_{i=1}^{n} A_i$ is the space of all action vectors , and A_i is the set of possible actions for the ith player; $\mu = (\mu_1, \mu_2, \ldots, \mu_i, \ldots, \mu_n)$ denotes the vector of all utility functions that measure players' preferences over action profiles, and μ_i is the ith player's utility.

Vector a belongs to A. The a_i is a component in vector a, which belongs to A_i. In general, $a = (a_i, a_{-i})$ denotes an action profile, where a_i is the player i's action, and a_{-i} is the actions of the other $n - 1$ players. Similarly, $A_{-i} = \Pi_{j\neq i} A_j$

denotes the set of action profiles for all players except i, as described in [47] and [48]. The formal definitions of Nash Equilibrium (NE), ordinal potential game (OPG), and ordinal potential function (OPF) are as follows [47], [48].

Definition 1: An action profile $a^* = (a_i^*, a_{-i}^*)$ *is a NE if* $\forall i \in U$ *and* $\forall a_i \in A_i$

$$\mu_i(a^*) \geq \mu_i(a_i, a_{-i}^*) \tag{13}$$

Definition 2: A game $\Gamma =< U, A, \mu >$ *is an OPG if there exists a function* $F : A \rightarrow R$ *such that* $\forall i \in U$, $\forall a_{-i} \in A_{-i}$ *and for all* $a_i, b_i \in A_i$

$$F(a_i, a_{-i}) - F(b_i, a_{-i}) > 0 \Leftrightarrow \mu_i(a_i, a_{-i}) - \mu_i(b_i, a_{-i}) > 0 \tag{14}$$

According to [47] and [48], if an OPG (e.g., $\Gamma =< U, A, \mu >$) can maximize its corresponding OPF (e.g., F), there is an NE in it. Therefore, the potential maximizers form a subset of the NE of a potential game. If the potential functions for a game can be identified, some NE of the game can be immediately identified by solving for the potential maximizers.

Theorem 1: The game $\Gamma =< U, A, \mu >$*, where individual utilities are given by (11), is an OPG. An OPF is given by*

$$F(P) = \begin{cases} \sum_{\substack{j \in U, d_{0,j} > r_{th} \\ i \in U, d_{0,i} > d_{0,j}}} (w_g \cdot \frac{T_s}{P_s} + w_l \cdot \frac{T_{ji}}{p_{ji}}) & j \rightarrow i \\ \sum_{i \in U, d_{0,i} < R_{th}} (w_g \cdot \frac{T_s}{P_s} + w_l \cdot \frac{T_{0i}}{p_{0i}}) & 0 \rightarrow i \end{cases} \tag{15}$$

Proof: We prove by applying the asserted OPF in (15). For simplicity and without loss of generality, we only consider D2D links in the Proof. First, we have $\Delta\mu_i$, as shown at the bottom of this page.

Let $A = \sum_{i \in U, d_{0,i} < R_{th}} T_{0i} + \sum_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} T_{nm}$ and $B = \sum_{i \in U, d_{0,i} < R_{th}} p_{0i} + \sum_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm}$, therefore, we have $\Delta\mu_i = (w_g \cdot \frac{A+T_{ji}(p_{ji})}{B+p_{ji}} + w_l \cdot \frac{T_{ji}(p_{ji})}{p_{ji}}) - (w_g \cdot \frac{A+T_{ji}(q_{ji})}{B+q_{ji}} + w_l \cdot \frac{T_{ji}(q_{ji})}{q_{ji}})$ Where $T_{ji}(p_{ji}) = b_{ji} \cdot \log_2(1 + \frac{g_{ji} \cdot p_{ji}}{N_i + F_i})$ and $T_{ji}(q_{ji}) = b_{ji} \cdot \log_2(1 + \frac{g_{ji} \cdot q_{ji}}{N_i + F_i})$

Similarly

$$\begin{aligned} \Delta F &= F(p_{ji}, \bigcup_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm}) - F(q_{ji}, \bigcup_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm}) \\ &= \sum_{\substack{j \in U, d_{0,j} > r_{th} \\ i \in U, d_{0,i} > d_{0,j}}} (w_g \cdot \frac{A + T_{ji}(p_{ji})}{B + p_{ji}} + w_l \cdot \frac{T_{ji}(p_{ji})}{p_{ji}}) - \sum_{\substack{j \in U, d_{0,j} > r_{th} \\ i \in U, d_{0,i} > d_{0,j}}} (w_g \cdot \frac{A + T_{ji}(q_{ji})}{B + q_{ji}} + w_l \cdot \frac{T_{ji}(q_{ji})}{q_{ji}}) \\ &= \sum_{\substack{j \in U, d_{0,j} > r_{th} \\ i \in U, d_{0,i} > d_{0,j}}} ((w_g \cdot \frac{A + T_{ji}(p_{ji})}{B + p_{ji}} + w_l \cdot \frac{T_{ji}(p_{ji})}{p_{ji}}) - (w_g \cdot \frac{A + T_{ji}(q_{ji})}{B + q_{ji}} + w_l \cdot \frac{T_{ji}(q_{ji})}{q_{ji}})) \end{aligned}$$

Therefore, the sign of ΔF is same as that of $\Delta\mu_i$, which shows that $F(P)$ is an OPF and $\Gamma =< U, A, \mu >$ is an OPG according to Definition 2. □

According to Theorem 1, the utility function proposed in this paper has the characteristics of potential game, which ensures that there is at least one NE. According to [47] and [48], we know that the better response algorithm can solve a better NE than the best response algorithm at the cost of slow convergence. Our first-bin-search-then-sequential-search algorithm follows the basic principle and idea of the better response algorithm, so it also solves a better NE than the best response algorithm. However, we use a large step length in the first round of game decision process, and then employ a small step length adopted in the better response algorithm, which can reduce time for convergence.

IV. THE SCHEME FOR IMPROVING CELLULAR COVERAGE QUALITY

In this section, we first analyze the characteristics of the optimization problem described in the previous section, and then propose the detailed solutions.

If a receiving UE (i.e., any member of U_c) decides to use a relay, besides choosing an appropriate relay, it is also necessary to allocate a pair of transceiver channels to the selected relay so that the relaying service can be provided concurrently for the receiving UE.

$$\begin{aligned} \Delta\mu_i &= \mu_i(p_{ji}, \bigcup_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm}) - \mu_i(q_{ji}, \bigcup_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm}) \\ &= (w_g \cdot \frac{\sum_{i \in U, d_{0,i} < R_{th}} T_{0i} + \sum_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} T_{nm} + T_{ji}(p_{ji})}{\sum_{i \in U, d_{0,i} < R_{th}} p_{0i} + \sum_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm} + p_{ji}} + w_l \cdot \frac{T_{ji}(p_{ji})}{p_{ji}}) \\ &\quad - (w_g \cdot \frac{\sum_{i \in U, d_{0,i} < R_{th}} T_{0i} + \sum_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} T_{nm} + T_{ji}(q_{ji})}{\sum_{i \in U, d_{0,i} < R_{th}} p_{0i} + \sum_{\substack{n \in U\ j,\ d_{0,n} > r_{th} \\ m \in U\ i,\ d_{0,m} > d_{0,n}}} p_{nm} + q_{ji}} + w_l \cdot \frac{T_{ji}(q_{ji})}{q_{ji}}) \end{aligned}$$

Due to the adoption of underlay in-band resource assignment mode, the new space reuse method should be designed in order to ensure that co-channel interference is effectively controlled.

Also, the transmitting ends of links with co-channels should adjust their transmission powers to further reduce co-channel interference and thus improve energy efficiency.

Finally, the data receiving mode (i.e., either receiving data directly from the *eNB* or falling back on the relaying UEs to forward data from the *eNB*) should be determined for each receiving UE in order to improve downward throughput.

Because of the complexity of considering the above problems as the whole one to solve it, we regard them as the three cascaded problems related to relaying channel pre-allocation, transmission power adjustment, and data receiving mode selection.

A. RELAYING CHANNEL PRE-ALLOCATION

We propose a centralized relaying channel pre-allocating scheme, which is run on the *eNB*. The goal of this scheme is to avoid the channels with the same frequency within the 1-hop communication range of a receiving-end or the region covered by *eNB* antenna transmission angle. The details of the scheme are described below.

As mentioned in the previous text, if a receiving UE is located in the approximate round area with radius R_{th} at the center of the *eNB*, its receiving BER level will not be higher than the desired threshold value. The R_{th} can be estimated by the following formula.

$$R_{th} = \begin{cases} \sqrt{\dfrac{p_0^{\max} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot L \cdot \gamma_{th} \cdot N_{avg}}} & R_{th} < d_{crossover} \\ \sqrt[4]{\dfrac{p_0^{\max} \cdot G_t \cdot G_r \cdot h_t^2 \cdot h_r^2}{\gamma_{th} \cdot N_{avg}}} & R_{th} \geq d_{crossover} \end{cases} \tag{16}$$

In (16), p_0^{max} denotes the maximum transmission power of the *eNB*, and N_{avg} is the average noise power in underlay cellular networks; G_t and G_r are the transmitting and receiving antenna's gains respectively; h_t and h_r are denoted as the height of the transmitting and receiving antenna on the ground respectively; λ is the wavelength of the signal carrier; and L is the system loss coefficient which is not related to propagation; $d_{crossover}$ is the crossover distance, which is computed by formula (17) as described in [52].

$$d_{crossover} = \frac{4\pi\sqrt{L}h_t h_r}{\lambda} \tag{17}$$

Obviously, in the members of U_c (e.g., the grey UEs shown in Fig.2, which are referred to as the cellular receiving UEs), the members outside the circular region with the radius R_{th} need to select relaying UEs to help them to reduce their BER levels. The members of U_r inside the circular region with the radius R_{th} are more suitable for receiving data from the *eNB* and then forward them to a destination UE, which are referred to as the cellular relaying UEs (e.g., the black UEs shown in Fig.2). The members of U_r outside the circular region with the radius R_{th} are more suitable for receiving data from other UEs and then forward them to a destination UE, which are referred to as the D2D relaying UEs (e.g., the hollow UEs shown in Fig.2).

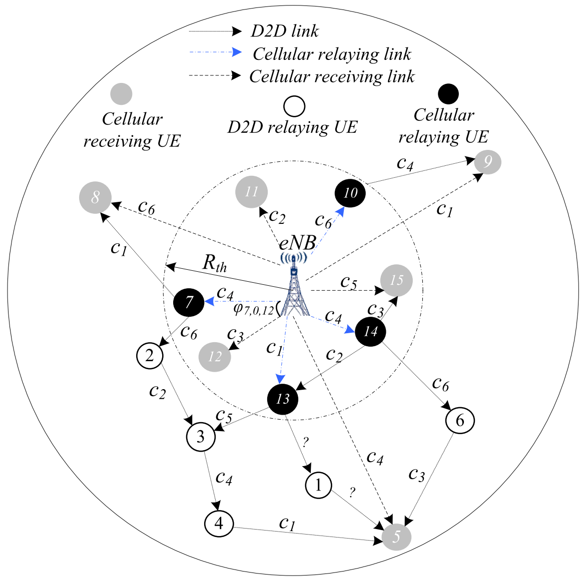


FIGURE 2. Example for assignment of potential relaying channels.

In this paper, the channels pre-allocated for relays are derived from the cellular channels of the members in U_c. In order to effectively reuse these channels as the relaying channels and avoid the same frequency interference as much as possible, we combine distance with *eNB*'s antenna transmitting angle to control co-channel interference, and adopt the following strategies for relaying channel pre-allocation.

1) CELLULAR RELAYING UEs' RECEIVING CHANNEL ALLOCATION STRATEGY

In the triangle area formed by the *eNB*, the UE (e.g., k) whose channel is reused by another UE, and the UE (e.g., j) that reuses the channel, the angle (e.g., $\varphi_{j,0,k}$) must be greater than the *eNB*'s antenna transmitting angle (e.g., φ_{th}). Otherwise, in order to avoid co-channel interference, UE j cannot reuse the channel of UE k. For example, in Fig.2, the channel c_3 is a direct communication channel between the *eNB* and the grey UE 12. If the channel c_3 is reused by the black UE 7 to receive other UE's data from the *eNB* and $\varphi_{7,0,12}$ is less than φ_{th}, there is co-channel interference between the grey UE 12 and the black UE 7. Given the coordinates of any two UEs (e.g., UE_j and UE_k) and the *eNB*, such as (x_j, y_j), (x_k, y_k) and (x_0, y_0), the angle with *eNB* as the center, such as $\varphi_{j,0,k}$, can be estimated by the following formula.

$$\begin{cases} \varphi_{j,0,k} = \arccos(\dfrac{d_{0,j}^2 + d_{0,k}^2 - d_{j,k}^2}{2 \cdot d_{0,j} \cdot d_{0,k}}) \\ d_{0,j} = \sqrt{(x_0 - x_j)^2 + (y_0 - y_j)^2} \\ d_{0,k} = \sqrt{(x_0 - x_k)^2 + (y_0 - y_k)^2} \\ d_{j,k} = \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \end{cases} \tag{18}$$

2) POTENTIAL RELAYING UEs' TRANSMITTING CHANNEL ALLOCATION STRATEGY

Firstly, we exclude the channels that cannot be allocated from the *set* C, and then randomly select one from the *set* C for reuse. The channels with the following characteristics need to be excluded. *a*) The allocated receiving channels of the relaying UEs, including the channels used for receiving data from the *eNB* (e.g., the receiving channel c_1 of the black UE 13 in Fig.2), and the channels used for receiving data from other relaying UEs (e.g., the receiving channel c_2 of the black UE 13 in Fig.2); *b*) The allocated transmitting channels of the relaying UEs (e.g., the transmitting channel c_5 of the black UE 13 in Fig.2); *c*) The allocated receiving channels of other relaying UEs in the relaying UEs' neighborhood range (e.g., in Fig.2, the receiving channel c_2 of the neighborhood hollow UE 3 of the black UE 13, the receiving channel c_3 of the neighborhood grey 12 of the black UE 13, and the receiving channel c_4 of the neighborhood black UE 14 of the black UE 13).

To facilitate to describe the algorithms, we define the following data structures. 1) $L^c_{M,N}$ is the channel allocating relation matrix which indicates which UE to employ which channel to directly communicate with the *eNB*. If the value of an element (e.g., $l^c_{j,k}$) in $L^c_{M,N}$ is *True*, it denotes that the channel k (i.e., $k \in \{1, \ldots, N\}$) is allocated to UE j (i.e., $j \in \{1, \ldots, M\}$) to directly communicate with the *eNB*. Otherwise, it denotes that no channel is allocated to UE j. As mentioned in the previous text, when a UE (e.g, j) wants to communicate with an application server in the core network, it needs to apply to the *eNB* for a communication frequency band (e.g, an available channel k). If the *eNB* agrees to its request, it will set the value of $l^c_{j,k}$ in $L^c_{M,N}$ as *True*. 2) $L^r_{M,M}$ is the relaying channel allocation relation matrix between UEs. If the value of an element (e.g., $l^r_{i,j}$) in $L^r_{M,M}$ is k (i.e., $k \in \{1, \ldots, N\}$), it denotes that the channel k is allocated to the link from UE i (i.e., $i \in \{1, \ldots, M\}$) to UE j (i.e., $j \in \{1, \ldots, M\}$). Otherwise, it denotes that no channel is allocated to the link $i \rightarrow j$. 3) L^r_M is the relaying channel allocation relation vector between the *eNB* and each UE. If the value of an element (e.g., l^r_j) in L^r_M is k (i.e., $k \in \{1, \ldots, N\}$), it denotes that the channel k is allocated to the link from the *eNB* to UE j (i.e., $j \in \{1, \ldots, M\}$). Otherwise, it denotes that no channel is allocated to the link *eNB* $\rightarrow j$. 4) V_i denotes the *set* of neighborhood UEs of UE i when UE i transmits data at its maximum power.

The pseudo code of cellular relaying UEs' receiving channel allocation process is described as follows.

In Algorithm 1-*a*, after the initialization of the related variables (see line 1), including each element (e.g., l^r_j) in L^r_M as well as U_c and U_r, the members in U_c and U_r are determined according to the values of elements in $L^c_{M,N}$ (see line 2~6) and the receiving channel of each cellular relaying UE is allocated according to the cellular relaying UEs' receiving channel allocation strategy (see line 7~16). In line 8, the *set* D is initialized as $\emptyset$ in order to record the channels that should not be allocated. For a cellular relaying UE (e.g., j) that

Algorithm 1-*a* Receiving Channel Assignment for Cellular Relaying UEs

Run at *eNB*
Input: $L^c_{M,N} = \{l^c_{j,k} | j \in \{1, \ldots, M\}, k \in \{1, \ldots, N\}\}$;
$C = \{c_j | j \in \{1, \ldots, N\}\}$;
Output: L^r_M

1. Initialize: $l^r_j = 0, \forall j \in \{1, \ldots, M\}$; $U_c = \emptyset$; $U_r = \emptyset$
2. **For** $j \in \{1, \ldots, M\}$ **do**
3. **For** $k \in \{1, \ldots, N\}$ **do**
4. **If** $l^c_{j,k} == True$ **then** $U_c = U_c \cup \{j\}$ **Else** $U_r = U_r \cup \{j\}$ **End if**
5. **End for**
6. **End for**
7. **For** $j \in U_r$ and $r_{th} < d_{0,j} < R_{th}$ **do**
8. $D = \emptyset$
9. **For** $k \in U_r\ \{j\}$ and $r_{th} < d_{0,k} < R_{th}$ **do** {**If** $\varphi_{j,0,k} < \varphi_{th}$ and $l^r_k > 0$ **then** $D = D \cup \{l^r_k\}$ **End if**} **End for**
10. **For** $i \in U_c$ **do**
11. **If** $\varphi_{j,0,i} < \varphi_{th}$ **then**
12. **For** $k \in C$ **do** {**If** $l^c_{i,k} == True$ **then** $D = D \cup \{k\}$ **End if**} **End for**
13. **End if**
14. **End for**
15. Take a value from the *set* $C\ D$ randomly (*e.g.*,k) and $l^r_j = k$
16. **End for**

wants to obtain a channel, to avoid co-channel interference, the channel of any other cellular relaying UE (e.g., k) that meets the condition $\varphi_{j,0,k} < \varphi_{th}$ should not be allocated to UE j (see line 9). Also, the channel of any cellular receiving UE (e.g., i) that meets the condition $\varphi_{j,0,i} < \varphi_{th}$ should not be allocated to UE j (see line 10~14). Finally, the channels in the *set* D are excluded from the *set* C, and then a channel is randomly selected from the *set* C and allocated to UE j (see line 15).

The potential relaying UEs' transmitting channel allocation includes the cellular relaying UEs' transmitting channel allocation and the D2D relaying UEs' transmitting channel allocation. The pseudo code of cellular relaying UEs' transmitting channel allocation process is described as follows.

In Algorithm 1-*b*, firstly, each element (e.g., $l^r_{i,j}$) in L^r_{MM} is initialized as 0 (see line 1) to prepare for recording channel assignment information, and then the transmission channel of each cellular relaying UE is determined (see line 2~40) according to potential relaying UEs' transmitting channel allocation strategy. In particular, the *set* D is initialized as an empty *set* $\emptyset$ (see line 3) in order to prepare for recording the channels that need to be excluded. For a cellular relaying UE (e.g., j) that wants to obtain a channel, the following channels should be put in the *set* D in order to avoid being reused by it as its transmitting channel: 1) If it has the receiving channel

Algorithm 1-*b* Transmitting Channel Assignment for Cellular Relaying UEs

Run at *eNB*
Input: $C = \{c_j | j \in \{1, \ldots, N\}\}$; $V_j, \forall j \in \{1, \ldots, M\}$
Output: $L^r_{M,M}$

1. Initialize: $l^r_{i,j} = 0, \forall i, j \in \{1, \ldots, M\}$
2. **For** $j \in U_r$ and $r_{th} < d_{0,j} < R_{th}$ **do**
3. $D = \emptyset$
4. **If** $l^r_j > 0$ **then**
5. $D = D \cup \{l^r_j\}$
6. **For** $i \in U_c$ **do**
7. **If** $i \in V_j$ **then**
8. **For** $k \in C$ **do** {**If** $l^c_{i,k}$ ==*True* **then** $D = D \cup \{k\}$ **End if**}**End for**
9. **End if**
10. **End for**
11. **For** $i \in U_r$ and $r_{th} < d_{0,i} < R_{th}$ **do**
12. **If** $i \in V_j$ and $l^r_i > 0$ **then** $D = D \cup \{l^r_i\}$ **End if**
13. **End for**
14. **For** $i \in V_j$ **do**{**If** $l^r_{i,j} > 0$ **then** $D = D \cup \{l^r_{i,j}\}$ **End if**} **End for**
15. **For** $k \in V_j$ **do**
16. **For** $l \in V_k$ **do**
17. **If** $l^r_{l,k} > 0$ **then** $D = D \cup \{l^r_{l,k}\}$ **End if**
18. **End for**
19. **End for**
20. **For** $i \in V_j$ **do**
21. $E = \emptyset$
22. **If** $d_{0,i} > d_{0,j} + d_s$ and $l^r_{j,i} == 0$ **then**
23. **For** $m \in U_c$ **do**
24. **If** $\varphi_{m,0,i} < \varphi_{th}$ **then**
25. **For** $k \in C$ **do** {**If** $l^c_{m,k}$ ==*True* **then** $E = E \cup \{k\}$ **End if**}**End for**
26. **End if**
27. **End for**
28. **For** $m \in U_r$ *and* $r_{th} < d_{0,m} < R_{th}$ **do**
29. **If** $\varphi_{m,0,i} < \varphi_{th}$ and$l^r_m > 0$ **then** $E = E \cup \{l^r_m\}$ **End if**
30. **End for**
31. **For** $k \in V_i$ **do**
32. **For** $l \in V_k$ **do**
33. **If** $l^r_{k,l} > 0$ **then** $E = E \cup \{l^r_{k,l}\}$ **End if**
34. **End for**
35. **End for**
36. Take a value from the*set C D E* randomly (*e.g.*,k) and $l^r_{j,i} = k$
37. **End if**
38. **End for**
39. **End if**
40. **End for**

between the *eNB* and itself, this channel should be put in the *set D* (see line 4∼5); 2) The allocated channels of the cellular receiving UEs in its neighborhood should be put in the *set D* (see line 6∼10); 3) The allocated channels of the cellular relaying UEs in its neighborhood should be put in the *set D* (see line 11∼13); 4) Its receiving channels should be put in the *set D* (see line 14); 5) Its neighboring UEs' receiving channels should be put in the *set D* (see line 15∼19).

Also, for a cellular relaying UE (e.g., *j*) that wants to obtain a channel, the purpose of line 20∼38 is to allocate channels in links between it and each of its neighboring UEs (e.g., *i*). Specifically, the *set E* is initialized an empty *set* ∅ (see line 21) in order to prepare for recording the channels that need to be excluded; if the distance between it (i.e., UE *j*) and the *eNB* is at least d_s (e.g., 30 m) shorter than that between its neighbor (e.g., UE *i*) and the *eNB* (see line 22), the following steps are executed: Firstly, the channel of any cellular receiving UE (e.g., *m*) that meets the condition $\varphi_{m,0,i} < \varphi_{th}$ should not be allocated in the link between UE *j* and UE *i* (see line 23∼27); Then the channel of any cellular relaying UE (e.g., *m*) that meets the condition $\varphi_{m,0,i} < \varphi_{th}$ should not be allocated in the link between UE *j* and UE *i* (see line 28∼30); Third, the transmitting channels of the neighboring UEs of UE *i* should not be allocated in the link between UE *j* and UE *i* (see line 31∼35); Finally, after removing the *set D* and *E* from the *set C*, a randomly selected channel (e.g., *k*) from the *set C* is allowed to be allocated in the link between UE *j* and UE *i* (see line 36).

The pseudo code of D2D relaying UEs' transmitting channel allocation process is described in Algorithm 1-*c*, where only potential relaying UEs with receiving channels are allowed to assign transmitting channels to them (see line 4∼5), and also the channels that need to be excluded are similar to those of Algorithm 1-*b*.

In the above algorithms, if there is no channel left in the remaining *set C D E*, some potential relaying UEs will not get relaying channels. Although the simulation results later confirm that this case is true, the number of such potential relaying UEs is very small. Furthermore, since the potential relaying UEs with the allocated relaying channels are not necessarily selected as the real relaying UEs, the small number of the potential relaying UEs without the allocated relaying channels hardly affects the relay selection.

B. TRANSMISSION POWER ADJUSTMENT

We introduce potential game theory to design the transmission power adjustment algorithm, where potential communication links are game players. In view of the disadvantages of the game decision algorithms discussed in the previous text, we propose an improved algorithm for game decision making. The basic idea of our improved algorithm is that, the search time in the *set* of action space (i.e., the *set* of transmission power levels) is reduced by means of

Algorithm 1-*c* Transmitting Channel Assignment for D2D Relaying UEs

Run at *eNB*
Input: $C = \{c_j | j \in \{1, \ldots, N\}\}$; $V_j, \forall j \in \{1, \ldots, M\}$
Output: $L^r_{M,M}$

1. Initialize: $l^r_{i,j} = 0, \forall i, j \in \{1, \ldots, M\}$
2. **For** $j \in U_r$ and $d_{0,j} > R_{th}$ **do**
3. $D = \emptyset$
4. **For** $i \in V_j$ **do** {**If** $l^r_{i,j} > 0$ **then** $D = D \cup \{l^r_{i,j}\}$ **End if**} **End for**
5. **If** $D! = \emptyset$ **then**
6. **For** $i \in U_c$ **do**
7. **If** $i \in V_j$ **then**
8. **For** $k \in C$ **do** {**If** $l^c_{i,k}$ ==*True* **then** $D = D \cup \{k\}$ **End if**}**End for**
9. **End if**
10. **End for**
11. **For** $i \in U_r$ and $r_{th} < d_{0,i} < R_{th}$ **do**
12. **If** $i \in V_j$ and $l^r_i > 0$ **then** $D = D \cup \{l^r_i\}$ **End if**
13. **End for**
14. **For** $k \in V_j$ **do**
15. **For** $l \in V_k$ **do**
16. **If** $l^r_{l,k} > 0$ **then** $D = D \cup \{l^r_{l,k}\}$ **End if**
17. **End for**
18. **End for**
19. **For** $i \in V_j$ **do**
20. $E = \emptyset$
21. **If** $d_{0,i} > d_{0,j} + d_s$ and $l^r_{j,i} == 0$ **then**
22. **For** $m \in U_c$ **do**
23. **If** $\varphi_{m,0,i} < \varphi_{th}$ **then**
24. **For** $k \in C$ **do** {**If** $l^c_{m,k}$ == *True* **then** $E = E \cup \{k\}$ **End if**}**End for**
25. **End if**
26. **End for**
27. **For** $m \in U_r$ and $r_{th} < d_{0,m} < R_{th}$ **do**
28. **If** $\varphi_{m,0,i} < \varphi_{th}$ and $l^r_m > 0$ **then** $E = E \cup \{l^r_m\}$ **End if**
29. **End for**
30. **For** $k \in V_i$ **do**
31. **For** $l \in V_k$ **do**
32. **If** $l^r_{k,l} > 0$ **then** $E = E \cup \{l^r_{k,l}\}$ **End if**
33. **End for**
34. **End for**
35. Take a value from the *set C D E* randomly (*e.g.,k*) and $l^r_{j,i} = k$
36. **End if**
37. **End for**
38. **End if**
39. **End for**

binary search, and then adopting sequential search for the appropriate transmission power level from high value to low value.

The transmission power adjustment algorithms for potential communication links (i.e., potential cellular receiving links, potential cellular relaying links, and potential D2D links) are respectively described in Algorithm 2-*a*, Algorithm 2-*b*, and Algorithm 2-*c*. These algorithms are run on the individual nodes with different roles, which need to exchange some information (e.g., reporting the channel state information to the *eNB* (for details, see the literature [11]), and obtaining P_s and T_s from the *eNB*) with the *eNB*. Therefore, the corresponding function of the *eNB* is described in the Algorithm 2-*d*. The above first three algorithms start after receiving the message packets (i.e., (T^{max}_s, P^{max}_s) and (T^{half}_s, P^{half}_s)) from the fourth algorithm, while they exit the running process after receiving the message packet "end". In this way, the transmission powers of potential communication links can be coordinately adjusted with the control of the *eNB*.

Algorithm 2-*a* Transmitting Power Adjustment for Cellular Receiving Links

Run at *any cellular receiving UE j* (e.g., $j \in U_c$), *which receives its own data from eNB directly*
Input: V_j, $\{p^{max}_i | i \in \{0, 1, \ldots, M\}\}$, $\{p^{half}_i | i \in \{0, 1, \ldots, M\}\}, \varepsilon$ //ε is a very small positive real number
Output: p_{0j}

1. **If** receive the (T^{max}_s, P^{max}_s) and (T^{half}_s, P^{half}_s) from *eNB* **then**
2. **If** $d_{0,j} < R_{th}$ **then**
3. **If** $\mu_j(p^{half}_0, P\,p^{half}_0) \geq \mu_j(p^{max}_0, P\,p^{max}_0)$ **then** $p_{0j} = p^{half}_0$
4. **Else** $p_{0j} = p^{max}_0$
5. **End if**
6. **End if**
7. Send the transmission power p_{0j} to *eNB*
8. **While** (*true*) **do**
9. **If** receive the updated value for (T_s, P_s) from *eNB* **then**
10. **If** $d_{0,j} < R_{th}$ **then**
11. **If** $\mu_j(p_{0j}\text{-}\varepsilon, P\,p_{0j}\text{-}\varepsilon) > \mu_j(p_{0j}, P\,p_{0j})$ and $\gamma_{0j} > \gamma_{th}$ **then** $p_{0j} = p_{0j} - \varepsilon$ **End if**
12. **End if**
13. Send the transmission power p_{0j} to *eNB*
14. **End if**
15. **If** receive "end" from *eNB* **then** return **End if**
16. **End while**
17. **End if**

When the transmitting-ends of potential cellular receiving links are in the circular area of radius R_{th}, there is room for power adjustment. In Algorithm 2-*a*, the purpose of line 2∼6 is to adjust the power of this type of transmitting-ends. When all the transmitting-ends transmit at the half value of the maximum power respectively, if the utility of a potential cellular receiving link is better, it adopts the half value of the maximum power, otherwise, it employs the maximum power (see line 3∼5). Each UE needs to report its transmission power to the *eNB* (see line 7). After the above steps are completed, the transmitting-ends execute an infinite loop (see line 8∼16) to search for the appropriate transmission power level in a descending order mode until it receives the message packet"end" from the *eNB* (see line 15). Each iteration is triggered by the updated message package (i.e., (T_s, P_s)) (see line 9), where each transmitting-end makes small decrements in its power level if the change can improve its utility (see line 11). Whether a transmitting-end updates its transmission power level or not, it will report its transmission power level to the *eNB* (see line 13).

The executing process of Algorithm 2-*b* and Algorithm 2-*c* is very similar to that of algorithm 2-*a*. Therefore, the description of the corresponding details is omitted in this paper.

Algorithm 2-*b* Transmitting Power Adjustment for Cellular Relaying Links

Run at *any cellular relaying UE j* (e.g., $j \in U_r$ and $d_{0,j} \leq R_{th}$), *which relays other UE's data from eNB*
Input: V_j, $\{p_i^{max}|i \in \{0,1,\ldots,M\}\}$,$\{p_i^{half}|i \in \{0,1,\ldots,M\}\}$, ε //ε is a very small positive real number
Output: p_{0j}

1. **If** receive the (T_s^{max}, P_s^{max}) and (T_s^{half}, P_s^{half}) from *eNB* **then**
2. **If** $r_{th} < d_{0,j} < R_{th}$ **then**
3. **If** $\mu_j(p_0^{half}, P\, p_0^{half}) \geq \mu_j(p_0^{max}, P\, p_0^{max})$ **then** $p_{0j} = p_0^{half}$
4. **Else** $p_{0j} = p_0^{max}$
5. **End if**
6. **End if**
7. Send the transmission power p_{0j} to *eNB*
8. **While** (*true*) **do**
9. **If** receive the updated value for (T_s, P_s) from *eNB* **then**
10. **If** $r_{th} < d_{0,j} < R_{th}$ **then**
11. **If** $\mu_j(p_{0j} - \varepsilon, P\, p_{0j}\text{-}\varepsilon) > \mu_j(p_{0j}, P\, p_{0j})$ and $\gamma_{0j} > \gamma_{th}$ **then** $p_{0j} = p_{0j} - \varepsilon$ **End if**
12. **End if**
13. Send the transmission power p_{0j} to *eNB*
14. **End if**
15. **If** receive "end" from *eNB* **then** return **End if**
16. **End while**
17. **End if**

In Algorithm 2-*d*, the expected powers of the transmitting-ends in all the potential cellular receiving links are initialized as their maximum values (see line 1∼4), and then T_s^{max} and P_s^{max} are computed according to the formula (11) (see line 5). Also, the expected power of the transmitting-ends in all the potential cellular receiving links are initialized as the half of their maximum values (see line 6∼9), and then T_s^{half} and P_s^{half} are computed according to the formula (11) (see line 10). After (T_s^{max}, P_s^{max}) and (T_s^{half}, P_s^{half}) are broadcast to all UEs (see line 11), the algorithm goes into the infinite loop (see line 12∼25). In the infinite loop, a tag variable (e.g., *flag*) is firstly initialized as 0 (see line 13), which may be changed as 1 (see line 17) to make sure that a UE don't exit from the loop (see line 20). Also, in the infinite loop, a time interval is set (see line 14) to wait for the updated transmission powers. If there is any updated transmission power, the tag variable *flag* is changed as 1 (see line 17). T_s and P_s are rebroadcast to all UEs after they are recomputed according to the formula (11) (see line 21∼22). If the *eNB* does not receive any updated transmission power after the timer timeouts, it broadcasts the message packet "end" to all UEs in order to coordinate all UEs to end the power adjustment process (see line 23).

Algorithm 2-*c* Transmitting Power Adjustment for D2D Links

Run at *any D2D UE j* (e.g., $j \in U_r$)
Input: V_j, $\{p_i^{max}|i \in \{0,1,\ldots,M\}\}$,$\{p_i^{half}|i \in \{0,1,\ldots,M\}\}$, ε //ε is a very small positive real number
Output: $\{p_{ij}|i \in V_j\}$

1. **If** receive the (T_s^{max}, P_s^{max}) and (T_s^{half}, P_s^{half}) from *eNB* **then**
2. **For** $i \in V_j$ **do**
3. **If** $\mu_j(p_i^{half}, P\, p_i^{half}) > \mu_j(p_i^{max}, P\, p_i^{max})$ **then** $p_{ij} = p_i^{half}$
4. **Else** $p_{ij} = p_i^{max}$
5. **End if**
6. **End for**
7. Send the transmission power *set*$\{p_{ij}|i \in V_j\}$ to *eNB*
8. **While** (*true*) **do**
9. **If** receive the updated value for (T_s, P_s) from *eNB* **then**
10. **For** $i \in V_j$ **do**
11. **If** $\mu_j(p_{ij}\text{-}\varepsilon, P\, p_{ij}\text{-}\varepsilon) > \mu_j(p_{ij}, P\, p_{ij})$ and $\gamma_{ij} > \gamma_{th}$ **then** $p_{ij} = p_{ij} - \varepsilon$ **End if**
12. **End for**
13. Send the transmission power *set* $\{p_{ij}|i \in V_j\}$ to *eNB*
14. **End if**
15. **If** receive "end" from *eNB* **then** return **End if**
16. **End while**
17. **End if**

C. DATA RECEIVING MODE SELECTION

In this paper, a distributed solution is proposed to determine the data receiving mode for each receiving UE (i.e., any member in the *set* U_c), including cellular receiving UE's relay selection algorithm and D2D relaying UE's relay selection algorithm. The former (i.e., Algorithm 3-*a*) is executed by any member in the *set* U_c, which can determine whether it should

Algorithm 2-*d* Base-Station-Assisted Function for Power Adjustment

Run at *eNB*
Input: $\{p_j^{max} | j \in \{0, 1, \ldots, M\}\}$, δ //δ are a very small positive real number respectively
Output: (T_s^{max}, P_s^{max}), (T_r^{half}, P_s^{half}), and (T_s, P_s)

For $i \in \{1, \ldots, M\}$ **do**
  $p_{0i} = p_0^{max}$
  For $j \in \{1, \ldots, M\} \{i\}$ **do** $p_{ji} = p_j^{max}$ **End for**
End for
Compute T_s^{max} and P_s^{max} according to the formula (11)
For $i \in \{1, \ldots, M\}$ **do**
  $p_{0i} = 0.5 \cdot p_0^{max}$
  For $j \in \{1, \ldots, M\}$ i **do** $p_{ji} = 0.5 \cdot p_j^{max}$ **End for**
End for
Compute T_s^{half} and P_s^{half} according to the formula (11)
Broadcast (T_s^{max}, P_s^{max}) and (T_r^{half}, P_s^{half}) to all *UEs*
While (*true*) **do**
  Initialize *flag*=0
  Set the timer t_Δ as Δ
  while the timer t_Δ does not expire **do**
    If receive p_{0j} and *set* $\{p_{ij} | i \in V_j\}$ from any UE_j **then**
      If p_{0j} or *set* $\{p_{ij} | i \in V_j\}$ has been changed **then** *flag*=1 **End if**
    End if
  End while
  If *flag*==1 **then**
    Update T_s and P_s according to the formula (11)
    Broadcast the updated (T_s, P_s) to all *UEs*
  Else {broadcast the "end" to all *UEs*; *return*}
  End if
End while

select a relaying UE from its neighbors to help it forward data from the *eNB* to itself, or directly receive data from the *eNB*.

If selecting a relaying UE is better than direct receiving from the *eNB*, the relaying UE that improves throughput and satisfies the constraints of delay and energy is the desired one, which could be the black UE or the hollow UE in Fig.2. For the black UE, the throughput of the corresponding transmission path is determined by the methods described in subsection IV-A and IV-B. For the hollow UE, the channel between the *eNB* and the selected relaying UE (i.e., the hollow UE) is not allocated in advance, so the corresponding link capacity is also unknown. However, the hollow UE can reuse the cellular channel of the receiving UE that selects this hollow UE as its relaying UE in order to use the formula (1) to estimate the link capacity.

However, this link capacity cannot reach the capacity level under the BER threshold, and thus it is not likely to be reused by this hollow UE to receive data from the *eNB*. Therefore, this hollow UE will perform Algorithm 3-*b* to find the alternate path of the relaying link between the *eNB* and this hollow UE.

If the capacity of the found alternative path does not reach the capacity level under the BER threshold, the bottleneck will appear in the relaying link between the *eNB* and the new selected relaying UE. Therefore, the new selected relaying UE will execute Algorithm 3-*b* to improve the capacity of this relaying link (i.e., the bottleneck link). This process will continue until a black UE in Fig.2 is selected as the relaying UE.

Algorithm 3-*a* Cellular Receiving UE's Relay Selection

Run at any *UE i* (e.g., $i \in U_c$)
Input: $V_i \subset \Re$, T_{0i}, T_{d2d}^{ji}, T_{ji}, d^{ji}, d_{th}, e^j, e_{th}, $\forall j \in V_i$
Output: α_{ji}, α_{0j}

1. Initialize: $\alpha_{ji} = 0$, $\alpha_{0j} = 0$, $T_{in}^{ji} = 0$, $T_{out}^{ji} = 0$, $\forall j \in V_i$; $D_i = \emptyset$; $flag = 0$
2.   **For** $i \in U_c$ and $j \in V_i$ **do**
3.   **If** $d_{0,j} < R_{th}$ **then** $T_{in}^{ji} = T_{d2d}^{ji} - T_{0i}$
4.   **Else** $T_{out}^{ji} = T_{d2d}^{ji} - T_{0i}$
5. **End if**
6. **End for**
7. **If** *flag* == 0 **then** {Find $argmax_{(ji)} T_{in}^{ji}, j \in V_i$; $T_{max}^{ji} = T_{in}^{ji}$; $T_{in}^{ji} = 0$}
8. **Else** {Find $argmax_{(ji)} T_{out}^{ji}, j \in V_i$; $T_{max}^{ji} = T_{out}^{ji}$; $T_{out}^{ji} = 0$}
9. **End if**
10. **If** $T_{max}^{ji} > 0$ **then**
11.   **If** $d^{ji} \le d_{th}$ and $e^j \ge e_{th}$ **then**
12.   Send the relay selection request to *UE j*
13.   Set the timer t_τ as τ
14.   **While** the timer t_τ does not expire **do**
15.   **If** receive the relay selection response from *UE j* **then** $\{\alpha_{ji} = 1; \alpha_{0j} = 1; D_i = D_i \cup \{j\}$; *break*} **End if**
16.   **End while**
17.   **If** $\alpha_{ji} == 0$ **then** go to 7 **End if**
18.   **Else** go to 7
19.   **End if**
20. **End if**
21. **If** $\alpha_{ji} == 0$ and *flag* == 0 **then** {*flag* = 1; go to 7} **End if**

In Algorithm 3-*a*, a UE_i (i.e., $i \in U_c$) initializes the related variables in line 1. For example, the channel allocation state variable (i.e., α_{ji}) between UE_i and one of its neighbors (i.e., UE_j) is initialized as 0, and the channel allocation state variable (i.e., α_{0j}) between UE_j and the *eNB* is initialized as 0, which indicates that the relaying channels are not allocated; The *set* of relaying UEs selected by UE i is denoted as D_i, which is initialized as an empty *set* $\emptyset$; the other variables (e.g., T_{in}^{ji}, T_{out}^{ji}, and *flag*) are initialized as 0. The UE_i will estimate the gain which is brought by a black (or hollow) relaying UE (e.g., j), and record it in T_{in}^{ji} (or T_{out}^{ji}) (see line 2∼6).

Although T_{d2d}^{ji} is used in line 3∼4, there is difference between them. For example, in line 3, due to the cellular relaying identity of UE j, T_{0j} of $T_{d2d}^{ji} = \min(T_{0j}, T_{ji})$ can be estimated by the methods described in subsection IV-A and IV-B; In line 4, since UE j is D2D relaying UE, there is not any pre-allocated channel between the *eNB* and UE j. Therefore, it is necessary to temporarily assign a channel between the *eNB* and UE j to estimate the value of T_{0j}. Since a UE i decides to select a relaying UE j to help it receive data from the *eNB*, it will not use its cellular channel, and thus can allow UE j to reuse it.

Since the variable *flag* is initialized as 0, a black relaying UE is guaranteed to be firstly selected as a candidate relaying UE (see line 7). The purpose of line 10∼20 is to determine whether a candidate relaying UE is willing to act as an actual relaying UE. If the related conditions (see line 11 and 15) are met, the relay selection is successfully completed (see line 15). Otherwise, if UE_i does not receive the response from UE_j (i.e.,α_{ji} is still 0) and there is still any optional black *UE*, the UE_i will continue to choose black UE as its relaying UE (see line 17); if the constraint of delay (or energy) is not met and there is still any optional black *UE*, the UE_i will also continue to choose black UE as its relaying UE (see line 18). Only if there is not any optional black *UE* and α_{ji} is still 0, the UE_i will try to choose a hollow UE as its relaying UE (see line 21).

The Algorithm 3-*b* is executed by the relaying UE (e.g., UE i), which is basically similar to Algorithm 3-*a* in the respect of execution process description. However, it is worth noting that, in line 6, if UE k in $T_{d2d}^{jik} = \min(T_{0j}, T_{ji}, T_{ik})$ is a cellular receiving UE (i.e., a grey UE in Fig.2), the cellular channel of UE k is temporarily allocated to UE_i to estimate T_{0i}, and then allocated to UE_j to estimate T_{0j} when UE i selects UE j to act as its relaying UE; T_{ji} and T_{ik} can be get by the methods described in subsection IV-A and IV-B. In addition, when UE_i receives the relay selection request from UE_k, it checks whether it has acted as a relay for one of its neighbors. If not, it sends the relay selection response to UE k, which means to agree to act as the relaying UE of UE_k (see line 26∼32).

Algorithm 3-*b* D2D Relaying UE's Relay Selection

Run at any UE i (e.g., $i \in U_r$)
Input: $V_i \subset \Re$, $V_j \subset \Re$, T_{0i}, T_{ik}, T_{d2d}^{jik}, T_{d2d}^{ik}, d^{jik}, d_{th}, e^j, e_{th}, $\forall j,k \in V_i$
Output:α_{ji}, α_{0j}

1. Initialize: $\alpha_{ji} = 0$,$\alpha_{0j} = 0$, $T_{in}^{jik} = 0$, $T_{out}^{jik} = 0$, $\forall j,k \in V_i$; $D_i = \emptyset$; *flag* $= 0$
2. **For** $i \in U_r$ and $k \in V_i$ **do**
3. **If** $i \in D_k$ and $d_{0,i} \geq R_{th}$ **then**
4. **For** $j \in V_i$ **do**
5. **If** $r_{th} < d_{0,j} < R_{th}$ **then** $T_{in}^{jik} = T_{d2d}^{jik} - T_{d2d}^{ik}$
6. **Else** $T_{out}^{jik} = T_{d2d}^{jik} - T_{d2d}^{ik}$
7. **End if**
8. **End for**
9. **End if**
10. **End for**
11. **If** *flag* $== 0$ **then** {Find $argmax_{(jik)} T_{in}^{jik}$, $\forall j \in E_i$; $T_{max}^{jik} = T_{in}^{jik}$; $T_{in}^{jik} = 0$}
12. **Else** {Find $argmax_{(jik)} T_{out}^{jik}$, $\forall j \in E_i$; $T_{max}^{jik} = T_{out}^{jik}$; $T_{out}^{jik} = 0$}
13. **End if**
14. **If** $T_{max}^{jik} > 0$ **then**
15. **If** $d^{jik} \leq d_{th}$ and $e^j \geq e_{th}$ **then**
16. Send the relay selection request to *UE j*
17. Set the timer t_τ as τ
18. **While** the timer t_τ does not expire **do**
19. **If** receive the relay selection response from *UE j* **then** {$\alpha_{ji} = 1$;$\alpha_{0j} = 1$; $D_i = D_i \cup \{j\}$; *break*} **End if**
20. **End while**
21. **If** $\alpha_{ji} == 0$ **then** go to 11 **End if**
22. **Else** go to 11
23. **End if**
24. **End if**
25. **If** $\alpha_{ji} == 0$ **then** {*flag* $= 1$; go to 11} **End if**
26. **If** receive the relay selection request from *UE k* **then**
27. flag =0
28. **For** $j \in V_i$ **do**
29. **If** $\alpha_{ij} == 1$ **then** {flag =1;*break*} **End if**
30. **End for**
31. **If** flag $== 0$ **then** {$\alpha_{ik} = 1$; send the relay selection response to *UE k* }**End if**
32. **End if**

D. SUMMARY OF THE PROPOSED SCHEME

For the convenience of readers' understanding the proposed scheme, we summarize the relationship of all the algorithms involved in this scheme as shown in Table 1.

V. PERFORMANCE EVALUATION

In this section, we firstly describe the simulation settings, and then evaluate the effect of the proposed scheme in terms of the defined performance metrics at different values of system parameters. The purpose of our simulation is to verify that our scheme can improve cellular coverage quality and accelerate convergence. Cellular coverage quality is mainly reflected in the four aspects (i.e., throughput, delay, service lifetime, energy efficiency). The change of node density, antenna transmitting angle for *eNB*, and power adjustment step length may lead to the performance change in these four aspects. Therefore, we adopt three groups of experiments to simulate each one respectively. Based on the same reason, we employ other three groups of experiments to compare convergence

TABLE 1. The relationship of all the algorithms involved in this scheme.

Execution sequence	Task description	Algorithm	Executor
Stage 1	Relaying channel pre-allocation	Algorithm 1-*a*	*eNB*
		Algorithm 1-*b*	
		Algorithm 1-*c*	
Stage 2	Improved response algorithm for power adjustment	Algorithm 2-*a*	cellular receiving *UE*
		Algorithm 2-*b*	cellular relaying *UE*
		Algorithm 2-*c*	*D2D UE*
		Algorithm 2-*d*	*eNB*
Stage 3	Data receiving mode selection	Algorithm 3-*a*	cellular receiving *UE*
		Algorithm 3-*b*	D2D relaying *UE*

performance of the improved game decision algorithm used by our scheme with the existing related algorithm.

A. SIMULATION SETTING

In the simulations, we consider a single cell scenario with radius of 500 m, where many UEs are randomly located in the cell and the *eNB* is situated at its center. The *eNB* operates on the fixed spectrum resources and allocates them to UEs at a granularity of RBs, where there are total of 600 RBs and each is equivalent to 180 kHz. We assume that each cellular UE only uses 6 RBs at a time, which is regarded as a frequency band (i.e, 1080 kHz). Also, each frequency band is only allocated to a cellular UE at a time, but reused by multiple relaying UEs at a time. The *eNB* has an adaptive directional antenna array, while each UE is only equipped with an omnidirectional antenna. Unless otherwise stated, the other simulation parameters are listed in Table 2.

For convenience, the scheme proposed in this paper is referred to as Scheme One, while the variants compared with it are referred to as Scheme Two, Scheme Three, and Scheme Four respectively. Their characteristics are summarized in Table 3.

From Table 3, we know that, Scheme Two is similar to Scheme One except for the third characteristic of Scheme One, where at most one relay is selected for a receiving UE; Scheme Three is also similar to Scheme One except for the second characteristic of Scheme One; Scheme Four limits the number of relays to at most one, but does not set the energy constraints for relay selections, which retains the first characteristic and the fourth characteristic of Scheme One. In addition, as mentioned in the previous text, the closest scheme to this paper is DTO-MROD. Therefore, it is also compared with our scheme and the variants of our scheme. According to the description for DTO-MROD in the literature [11], it is closest to Scheme Two among the four schemes in Table 3.

The performance metrics used in the evaluation process of the simulations include the average downward throughput, the average downward delay, the average downward continuous service capacity, the average downward energy efficiency, and the average convergence time.

TABLE 2. Simulation parameters.

Description	Parameter	Value
Transmitting antenna gain	G_t	1
Receiving antenna gain	G_r	1
Transmitting antenna height	h_t	1 m
Receiving antenna height	h_r	1 m
Maximum transmission power for UE	p_{ue}	0.1 W
Maximum transmission power for *eNB*	p_c	10 W
Bit Error Rate for UE	BE_{th}	10^{-10}
Noise power for UE	N_i	For a UE i, 2×10^{-11} W
Carrier signal wavelength	λ	0.1224 m
System loss factor	L	1
Crossover distance	$d_{crossover}$	103 m
Path loss exponent	α_{ji}	For $j\rightarrow i$, α_{ji}=2 when $d_{ji} < d_{crossover}$; α_{ji}=4 when $d_{ji} \geq d_{crossover}$
Initial battery capacity	$e_{i,int}$	For a UE i, $e_{i,int}$ is distributed between 0.05 J and 0.2 J
Packet forwarding capacity	t^b_i	For a UE i, t^b_i is 100 ns/bit
Data packet length	l	2500 bit
Transmitting angle of *eNB*	φ_{th}	Take a value from 15~120°
Minimum relaying radius	r_{th}	120 m
Energy constraint for relays	e_{th}	0.1 J
Delay constraint for relays	d_{th}	300 μs

Downward throughput is that, after the allocation of all RBs, the data successfully and simultaneously are transmitted from the *eNB* to the destination UEs during a given unit time. The average downward throughput is the average value of the downward throughput values of all the transmission paths.

Downward delay refers specifically to the forward time of the relaying UE with the worst forward capability in a transmission path when the *eNB* continuously transmits high-capacity data flow to a destination UE. The average downward delay is the average value of the downward delay values of all the transmission paths.

Downward continuous service capacity refers specifically to the amount of data successfully delivered in a transmission path from the *eNB* to a destination UE before the occurrence of the first UE (on the transmission path) that runs out of energy, which can indirectly measure the lifetime of the transmission path. The average downward continuous service capacity is the average value of downward continuous service capacity values of all the transmission paths.

Downward energy efficiency is the ratio of downward throughput to the sum of all the transmitting-ends' powers in a transmission path from the *eNB* to a destination UE. The average downward energy efficiency is the average value of the downward energy efficiency values of all the transmission paths.

TABLE 3. The schemes for simulating comparison.

Characteristic Description	Scheme One	Scheme Two	Scheme Three	Scheme Four
1) A greedy algorithm based on distributed local search is adopted to find an appropriate relaying UE for a receiving UE.	Yes	Yes	Yes	Yes
2) An energy constraint for relay selection scheme is introduced to guarantee the lifetime of D2D relaying links.	Yes	Yes	No	No
3) There is no limit imposed on the maximum number of relays.	Yes	No	Yes	No
4) An improved response algorithm is designed to accelerate the convergence of game decision process during transmission power adjustment.	Yes	Yes	Yes	Yes

Convergence time is defined as the number of rounds of game decision-making of a player before the occurrence of NE point. In a round, each potential communication link only has an opportunity to determine to whether change its transmission power or not. If there is any transmission power change in a round, there is still an opportunity in the next round for any link that changed its transmission power in the last round. Also, the number of rounds will be counted until any potential communication link will not change its transmission power. The average convergence time is the average value of convergence time values for all the players in the game decision process.

B. SIMULATION RESULTS

We use the three groups of experiments (from Fig.3 to Fig.5) to compare our scheme with the other schemes in the performance metrics of the average downward throughput, the average downward delay, the average downward continuous service capacity, and the average downward energy efficiency.

The other schemes for comparison include Scheme Two, Scheme Three, Scheme Four and DTO-MROD in Fig.3. However, DTO-MROD is excluded in Fig.4 and Fig.5 since it is not affected by the change of antenna transmitting angle for the *eNB* and the change of step length for power adjustment.

In Fig.3, when the step length for power adjustment is set as 1% of maximum transmission power and the antenna transmitting angle for the *eNB* is set as 60°, we evaluate the five schemes in terms of the four performance metrics at the different values of the UEs' number (e.g., from 300 to 600).

From Fig.3(*a*), we see that, Scheme Three has the best the average downward throughput among the four schemes except for DTO-MROD, and Scheme Four and Scheme One follow it respectively, while Scheme Two is the worst one. This is because, in Scheme Three and Scheme Four, without constraint of energy, the probability of choosing more optimal relays is usually greater than the other two schemes. Also, in Scheme Three, the UEs on the edge of cell can increase the throughput by the multi-hop relaying path, which is not possible in Scheme Four. Therefore, Scheme Three outperforms Scheme Four in terms of this performance metric.

The above discussion can also be used to explain the performance difference between Scheme One and Scheme Two in terms of the average downward throughput. In addition, we also observe that the average downward throughput of the four schemes except for DTO-MROD decrease with the increase of the number of UEs in an area with a fixed size. The reason is that, as the number of UEs in an area with a fixed size increases, the absolute number of preassigned relaying channels is increasing, which increases the probability of overestimating the number of co-channel interfering sources in the interference estimation of any receiving-end. Accordingly, the average downward throughput is underestimated. However, this is not going to happen in DTO-MROD, since it adopts out-band D2D mode without the need for pre-allocating cellular channel. Therefore, from Fig.3(*a*), we see that, as the number of UEs increases, the change for average downward throughput is very small. Although DTO-MROD outperforms the other four schemes when the number of UEs is greater than 400, the four other schemes have vastly underestimated their capability.

Since delay is usually inversely correlated with throughput, for Scheme Two and Scheme Three, the interpretation of the throughput variation can also be used for the interpretation of delay change shown in Fig.3(*b*). However, it is not so for Scheme One and Scheme Four. This is because the two main factors affect their delay (i.e., delay constraint and hop-count constraint). For Scheme One, delay constraint makes sure that it doesn't choose a relaying UE with very bad delay, while delay (in any path from the *eNB* to any UE at edge of cell) is not also too bad due to unconstraint of hop-count. However, for Scheme Four, hop-count is limited to at most one, which is not conducive to ensuring the delay performance of each UE at edge of cell. In addition, DTO-MROD is the closest approach to scheme Two, but it ignores transmission power adjustment and thus cannot effectively control co-channel interference. Therefore, its delay is not as good as the others when the number of UEs is lower than 450. However, as the number of UEs increases, DTO-MROD outperforms the other four schemes in terms of delay performance metric. This is because the four other schemes have vastly underestimated their capability as mentioned above.

Fig.3(*c*) shows that the schemes with energy constraint can significantly improve continuous service ability, such

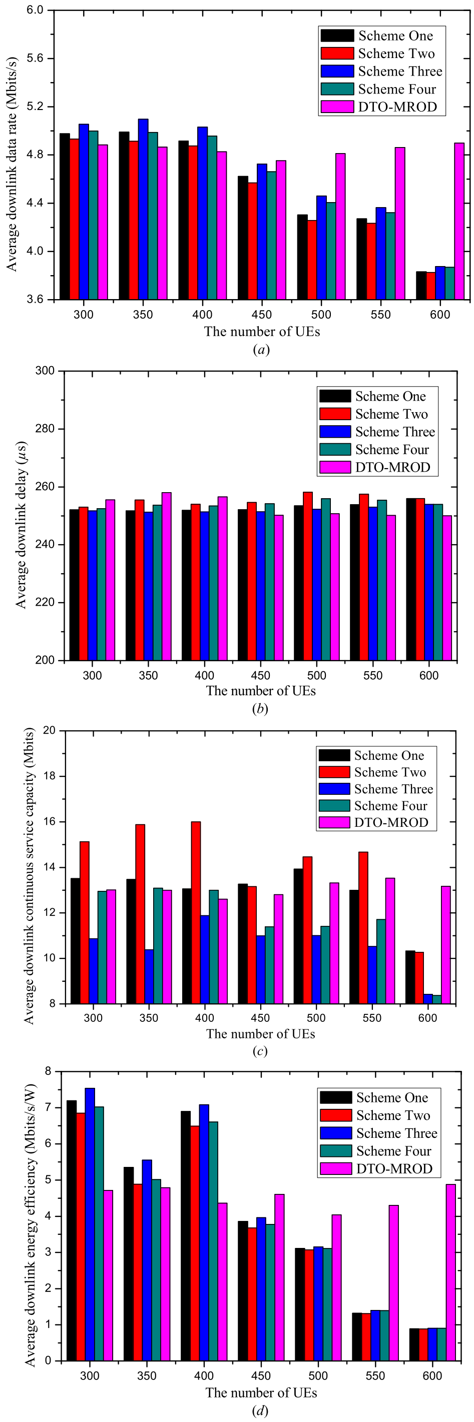


FIGURE 3. Variation trend of cellular network performance with the number of UEs in the fixed area. (a) Downlink throughput. (b) Downlink delay. (c) Continuous service capacity. (d) Energy efficiency.

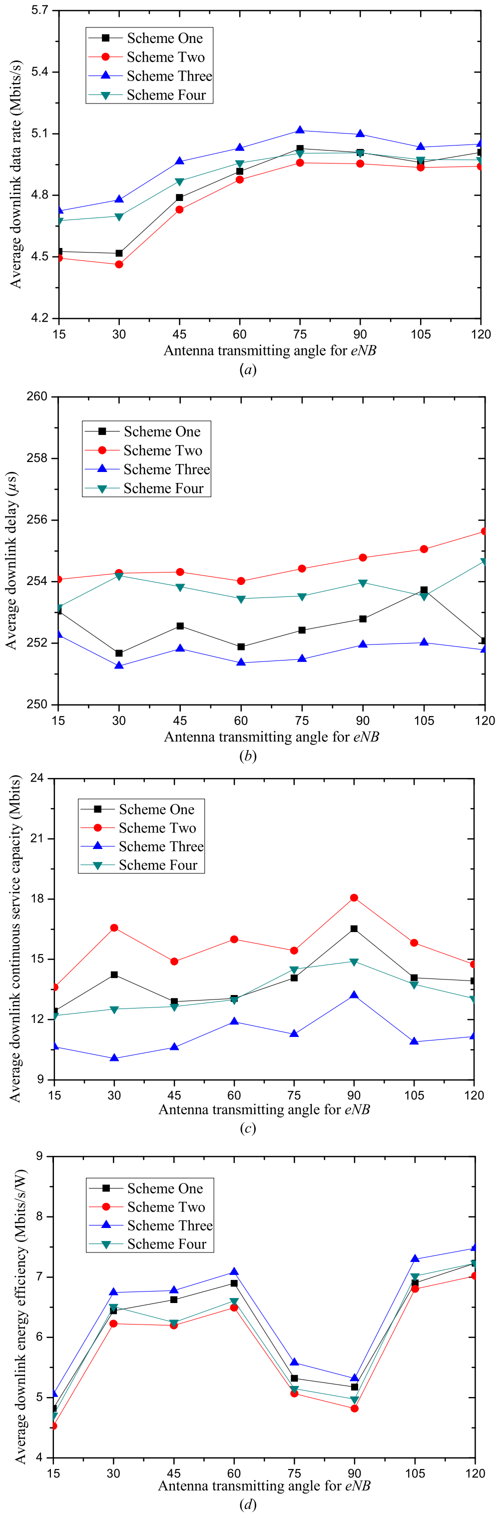


FIGURE 4. Variation trend of cellular network performance with the antenna transmitting angle for *eNB*. (a) Downlink throughput. (b) Downlink delay. (c) Continuous service capacity. (d) Energy efficiency.

as Scheme One and Scheme Two. Here, Scheme Two outperforms Scheme One in terms of this performance metric. This is because, in Scheme One, the average number of hop-count in all the transmission paths is usually greater than that of Scheme Two. Therefore, it is more likely for Scheme One to have a relying UE with low energy reserve in a transmission path. The above interpret can also be used to explain the performance difference between Scheme Three and Scheme Four in terms of the average downward continuous service capacity.

From Fig.3(d), we see that, among the four schemes except for DTO-MROD, Scheme Three has the best average

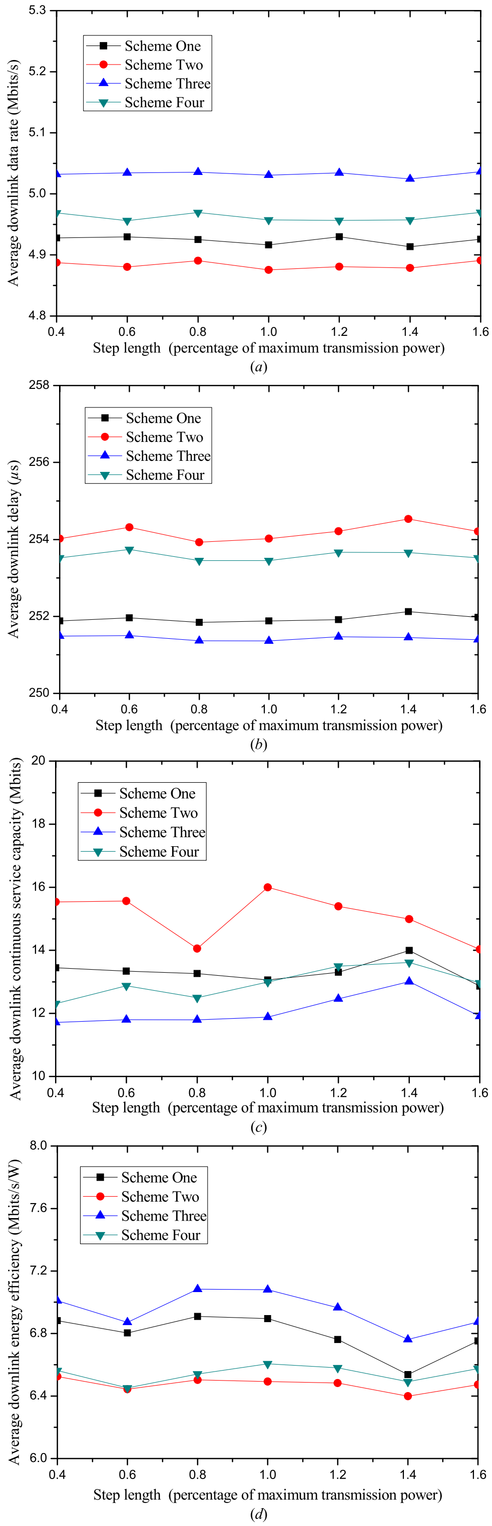


FIGURE 5. **Variation trend of cellular network performance with the step length for power adjustment. (a) Downlink throughput. (b) Downlink delay. (c) Continuous service capacity. (d) Energy efficiency.**

downward energy efficiency, while Scheme Two has the worst one. This is because there are the two main factors that affect this performance metric, which are hop-count and energy reserve. In Scheme Three, due to the unconstraint of both hop-count and energy reserve, for any receiving UE, especially anyone of the receiving UEs at edge of cell, the throughput in the transmission path from the *eNB* to it is usually greater and the corresponding power consumption is relatively smaller, since it is more likely to select the more appropriate relaying UEs to improve forwarding capability and reduce transmission power.

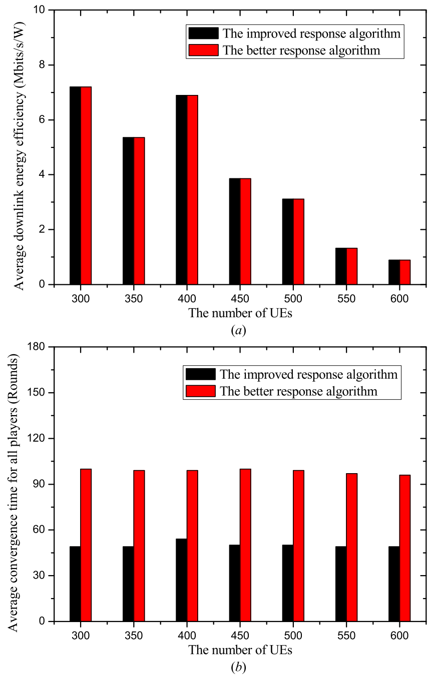


FIGURE 6. **Variation trend of performance of the game decision algorithms with the number of UEs in the fixed area. (a) Energy efficiency. (b) Convergence time.**

Obviously, Scheme Two shows the opposite performance due to the constraint of both hop-count and energy reserve. However, only one constraint of these two main factors is imposed on Scheme One or Scheme Four, which shows the moderate energy efficiency among the four schemes. The unconstraint of hop-count are more beneficial to improve energy efficiency than the unconstraint of energy reserve, so Scheme One can outperform Scheme Four in terms of this performance metric.

It is worth noting that, as the number of UEs increases, the change for continuous service capacity and the change for energy efficiency are all very small in DTO-MROD. The interpretations of Fig.3 (a) also apply to those of Fig.3$(c) \sim (d)$.

In Fig.4, when the UEs' number is set as 400 and the step length for power adjustment is set as 1% of maximum transmission power, we evaluate the four schemes in terms of the four performance metrics at the different values of the antenna transmitting angle for the *eNB* (e.g., from 15° to 120°).

From Fig.4$(a) \sim (d)$, we see that the performance differences among the four schemes in terms of the four metrics are similar to those in Fig.3$(a) \sim (d)$, where the impact of larger transmission angle for the*eNB* is similar to that of smaller

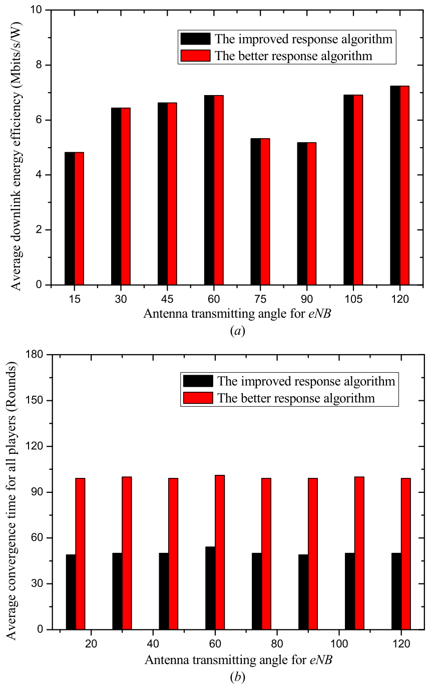


FIGURE 7. Variation trend of performance of the game decision algorithms with the antenna transmitting angle for *eNB*. (a) Energy efficiency. (b) Convergence time.

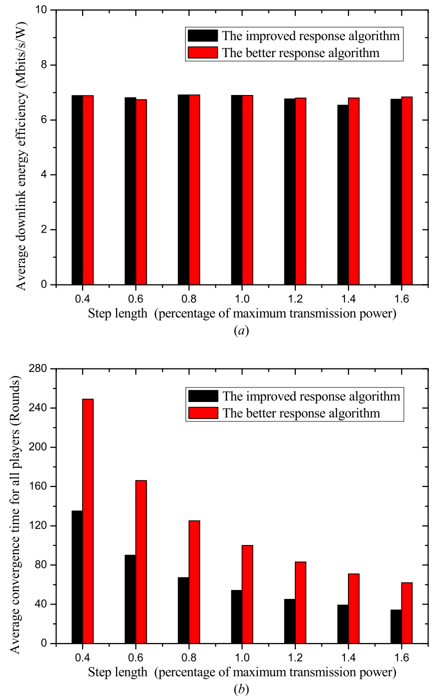


FIGURE 8. Variation trend of performance of the game decision algorithms with the step length for power adjustment. (a) Energy efficiency. (b) Convergence time.

node density, since they tend to reduce the absolute number of preassigned relaying channels. Therefore, the interpretations of Fig.3$(a) \sim (d)$ also apply to those of Fig.4$(a) \sim (d)$.

In Fig.5, when the UEs' number and the antenna transmitting angle for the *eNB* are set as 400 and 60° respectively, we evaluate the four schemes in terms of the four performance metrics at the different values of the step length for power adjustment (e.g., from 0.4% to 1.6%).

From Fig.5$(a) \sim (d)$, we can find that the change of the step length for power adjustment has little impact on the four metrics, in particular, the metrics in Fig.5$(a) \sim (b)$. This is because it hardly has an effect on the number of preassigned relaying channels and thus there is little change in the distribution of the co-channel interference sources.

We use the other three groups of experiments (from Fig.6 to Fig.8) to evaluate Scheme One in the performance metrics of the average downward energy efficiency and the average convergence time. To show the effect of the improved response algorithm used in Scheme One for adjusting transmission power, the better response algorithm is used in Scheme One to replace the improved response algorithm for comparison. In Fig.6, when the step length for power adjustment is set as 1% of maximum transmission power and the antenna transmitting angle for the *eNB* is set as 60°, we evaluate the two algorithms in terms of the two performance metrics at the different values of the UEs' number (e.g., from 300 to 600).

In Fig.7, when the UEs' number is set as 400 and the step length for power adjustment is set as 1% of maximum transmission power, we evaluate the two algorithms in terms of the two performance metrics at the different values of the antenna transmitting angle for the *eNB* (e.g., from 15° to 120°).

In Fig.8, when the UEs' number and the antenna transmitting angle for the *eNB* are set as 400 and 60° respectively, we evaluate the two algorithms in terms of the two performance metrics at the different values of the step length for power adjustment (e.g., from 0.4% to 1.6%).

From Fig.6~Fig.8, we observe that, the average downward energy efficiency hardly has the difference under the two game decision algorithms, while the average convergence time of the improved response algorithm is significantly better than that the better response algorithm. This shows that the scheme in this paper can improve the convergence time of the better response algorithm in the premise of maintaining it superiority.

VI. CONCLUSION

In this paper, we improve cellular coverage quality by designing a flexible cellular downlink throughput optimization mechanism for D2D communications underlay cellular networks, which can efficiently improve downlink throughput and energy efficiency by considering multi-hop relay-aided in-band D2D communication and potential game-based power adjustment. The proposed scheme is regarded as the three cascaded stages related to relaying channel pre-allocation, transmission power adjustment, and data receiving mode selection.

In relaying channel pre-allocation stage, we employ underlay in-band D2D mode to avoid interference coming from other wireless technologies. Also, in order to alleviate co-channel interference in underlay mode, we try to avoid reusing the same frequency bands within either the 1-hop communication range of a receiving-end or the region covered by *eNB* antenna transmission angle.

In transmission power adjustment stage, the power control problem is modeled as an exact potential game defined on a discrete strategy set, and the improved response algorithm is used by players to achieve a pure strategy Nash equilibrium.

In data receiving mode selection stage, we explore a greedy algorithm based on a distributed local search to find an appropriate relaying UE for a receiving UE. Generally, the search performance is not lowered in a local search manner, since the appropriate relaying UE of any receiving UE is usually located in the surrounding area at its center.

We analyze that the set of Nash equilibria is equivalent to the set of potential maximizers, and prove that there is at least a pure strategy Nash equilibrium point. The simulation results demonstrate that the improved response algorithm results in fast convergence to equilibrium, and the proposed whole scheme improves cellular coverage quality.

This work is the first step toward cellular coverage improvement. As such, there are many other problems that we plan to explore in the future. Since our scheme tends to overestimate co-channel interference when the number of UEs (in the fixed area) increases, we plan to explore predication-based pre-allocation mechanism to reduce unnecessary relaying channels in the future.

Another main problem concerning relay functionality is how to encourage a UE to act as a relay for other UEs [34]. Incentive mechanisms [53], [54] are usually used to do such thing, where one core issue is to properly reward a relaying UE according to its actual contributed data traffic.

Although we consider energy consumption of D2D relaying UEs to build benefit function, there is still no consideration for compensating for their power consumption and processing resources. Therefore, it would be interesting to explore a game relationship between relaying UEs in the future. Also, the study combining incentive mechanisms with social awareness methods [55]–[57] and network coding technologies [58], [59] for cellular coverage improvement is another interesting future research direction.

REFERENCES

[1] K. Yang, L. Wang, S. Wang, and X. Zhang, "Optimization of resource allocation and user association for energy efficiency in future wireless networks," *IEEE Access*, vol. 5, pp. 116469–116477, 2017, doi: 10.1109/ACCESS.2017.2722007.

[2] X. Deng, Q. Peng, L. He, and T. He, "Interference-aware QoS routing for neighbourhood area network in smart grid," *IET Commun.*, vol. 11, no. 5, pp. 756–764, 2017.

[3] X. Deng, J. Luo, L. He, Q. Liu, X. Li, and L. Cai, "Cooperative channel allocation and scheduling in multi-interface wireless mesh networks," *Peer-to-Peer Netw. Appl.*, pp. 1–12, 2017, doi: 10.1007/s12083-017-0619-8.

[4] J. Gao, J. Wang, P. Zhong, and H. Wang, "On threshold-free error detection for industrial wireless sensor networks," *IEEE Trans. Ind. Informat.*, to be published. [Online]. Available: https://doi.org/10.1109/TII.2017.2785395

[5] A. Liu, Z. Chen, and N. N. Xiong, "An adaptive virtual relaying set scheme for loss-and-delay sensitive WSNs," *Inf. Sci.*, vol. 424, pp. 118–136, Jan. 2018.

[6] T. Li, Y. Liu, L. Gao, A. Liu, "A cooperative-based model for smart-sensing tasks in fog computing," *IEEE Access*, vol. 5, pp. 21296–21311, 2017.

[7] M. Zhou, M. Zhao, A. Liu, M. Ma, T. Wang, and C. Huang, "Fast and efficient data forwarding scheme for tracking mobile target in sensor networks," *Symmetry*, vol. 9, no. 11, p. 269, 2017.

[8] A. Gupta and R. Jha, "A survey of 5G network: architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015, doi: 10.1109/ACCESS.2015.2461602.

[9] A. Asadi, V. Mancuso, and R. Gupta, "An SDR-based experimental study of outband D2D Communications," in *Proc. INFOCOM*, 2016, pp. 1–9.

[10] A. Asadi, V. Mancuso, and R. Gupta, "DORE: An experimental framework to enable outband D2D relay in cellular networks," *IEEE/ACM Trans. Netw.*, vol. 25, no. 5, pp. 2930–2943, May 2017.

[11] K. Zhou, J. Gui, and N. Xiong, "Improving cellular downlink throughput by multi-hop relay-assisted outband D2D communications," *EURASIP J. Wireless Commun. Netw.*, vol. 2017, p. 209, Dec. 2017, doi: 10.1186/s13638-017-0998-9.

[12] J. Gui and K. Zhou, "Flexible adjustments between energy and capacity for topology control in heterogeneous wireless multi-hop networks," *J. Netw. Syst. Manage.*, vol. 24, no. 4, pp. 789–812, 2016.

[13] J. Gui and J. Deng, "A topology control approach reducing construction cost for lossy wireless sensor networks," *Wireless Pers. Commun.*, vol. 95, no. 3, pp. 2173–2202, 2017.

[14] H. Wang and X. Chu, "Distance-constrained resource-sharing criteria for device-to-device communications underlaying cellular networks," *Electron. Lett.*, vol. 48, no. 9, pp. 528–530, Apr. 2012.

[15] G. Fodor and N. Reider, "A distributed power control scheme for cellular network assisted D2D communications," in *Proc. GLOBECOM*, 2011, pp. 1–6.

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

[17] M. C. Erturk, S. Mukherjee, H. Ishii, and H. Arslan, "Distributions of transmit power and SINR in device-to-device networks," *IEEE Commun. Lett.*, vol. 17, no. 2, pp. 273–276, Feb. 2013.

[18] J. Liu, Y. Kawamoto, H. Nishiyama, N. Kato, and N. Kadowaki, "Device-to-device communications achieve efficient load balancing in LTE-advanced networks," *IEEE Wireless Commun. Mag.*, vol. 21, no. 2, pp. 57–65, Feb. 2014.

[19] Y. Kawamoto, J. Liu, H. Nishiyama, and N. Kato, "An efficient traffic detouring method by using device-to-device communication technologies in heterogeneous network," in *Proc. WCNC*, Apr. 2014, pp. 1–7.

[20] F. Jiang, Y. Liu, B. Wang, and X. Wang, "A relay-aided device-to-device-based load balancing scheme for multitier heterogeneous networks," *IEEE Internet Things J.*, vol. 24, no. 12, pp. 1842–1846, Dec. 2017.

[21] H. Nishiyama, M. Ito, and N. Kato, "Relay-by-smartphone: Realizing multihop device-to-device communications," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 56–65, Apr. 2014.

[22] R. Wang, J. Liu, G. P. Zhang, S. H. Huang, and M. Yuan, "Energy efficient power allocation for relay-aided D2D communications in 5G networks," *China Commun.*, vol. 14, no. 6, pp. 54–64, 2017.

[23] Z. Lin, Y. Li, S. Wen, Y. Gao, X. Zhang, and D. Yang, "Stochastic geometry analysis of achievable transmission capacity for relay-assisted device-to-device networks," in *Proc. IEEE ICC*, Jun. 2014, pp. 2251–2256.

[24] M. Hasa and E. Hossain, "Distributed resource allocation for relay-aided device-to-device communication: A message passing approach," *IEEE Trans. Wireless Commun.*, vol. 13, no. 11, pp. 6326–6341, Nov. 2014.

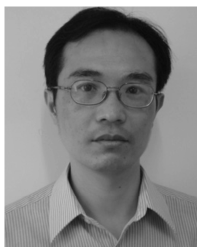
[25] M. Hasan and E. Hossain, "Distributed resource allocation for relay-aided device-to-device communication under channel uncertainties: A stable matching approach," *IEEE Trans. Commun.*, vol. 63, no. 10, pp. 3882–3897, Oct. 2015.

[26] R. Ma, Y. Chang, H. Chen, and C. Chiu, "On relay selection schemes for relay-assisted D2D communications in LTE—A systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8303–8314, Sep. 2017.

[27] K. Vanganuru, S. Ferrante, and G. Sternberg, "System capacity and coverage of a cellular network with D2D mobile relays," in *Proc. IEEE Military Commun. Conf.*, Nov. 2012, pp. 1–6.

[28] L. Wang, T. Peng, Y. Yang, and W. Wang, "Interference constrained relay selection of D2D communication for relay purpose underlaying cellular networks," in *Proc. 8th Int. Conf. WiCOM, Netw. Mobile Comput.*, Sep. 2012, pp. 1–5.

[29] Y. Li, D. Jin, F. Gao, and L. Zeng, "Joint optimization for resource allocation and mode selection in device-to-device communication underlaying cellular networks," in *Proc. IEEE ICC*, Jun. 2014, pp. 2245–2250.
[30] Y. Pei and Y. Liang, "Resource allocation for device-to-device communications overlaying two-way cellular network," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3611–3621, Jul. 2013.
[31] S. Shalmashi and S. Slimane, "Cooperative device-to-device communications in the downlink of cellular networks," in *Proc. IEEE WCNC*, Apr. 2014, pp. 2265–2270.
[32] G. Zhang, K. Yang, and P. Liu, "A distributed algorithm for bandwidth resource sharing in relay-aided wireless cellular networks: from the perspective of economic equilibrium theory," *Wireless Pers. Commun.*, vol. 82, no. 1, pp. 435–449, 2015.
[33] T. Ta, J. S. Baras, and C. Zhu, "Improving smartphone battery life utilizing device-to-device cooperative relays underlaying LTE networks," in *Proc. IEEE ICC*, Jun. 2014, pp. 5263–5268.
[34] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 1923–1940, 4th Quart., 2015.
[35] J. Liu and N. Kato, "Device-to-Device communication overlaying two-hop multi-channel uplink cellular networks," in *Proc. ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, Jun. 2015, pp. 307–316.
[36] J. Deng, A. Dowhuszko, R. Freij, and O. Tirkkonen, "Relay selection and resource allocation for D2D-relaying under uplink cellular power control," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, San Diego, CA, USA, Dec. 2015, pp. 1–6, doi: 10.1109/GLOCOMW.2015.7414091.
[37] J. Deng, O. Tirkkonen, and T. Chen, "D2D relay management in multicell networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, May 2017, pp. 1–6, doi: 10.1109/ICC.2017.7996919.
[38] J. Deng, O. Tirkkonen, R. Freij-Hollanti, T. Chen, and N. Nikaein, "Resource allocation and interference management for opportunistic relaying in integrated mmWave/sub-6 GHz 5G networks," *IEEE Commun. Mag.*, vol. 55, no. 6, pp. 94–101, Jun. 2017.
[39] S. Maghsudi and D. Niyato, "On Transmission Mode Selection in D2D-Enhanced Small Cell Networks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 618–621, May 2017.
[40] J. M. B. da Silva, G. Fodor, and T. F. Maciel, "Performance analysis of network-assisted two-hop D2D communications," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Austin, TX, USA, Dec. 2014, pp. 1050–1056, doi: 10.1109/GLOCOMW.2014.7063572.
[41] B. Zhong, J. Zhang, Q. Zeng, and X. Dai, "Coverage probability analysis for full-duplex relay aided device-to-device communications networks," *China Commun.*, vol. 13, no. 11, pp. 60–67, Nov. 2016.
[42] G. Zhang, K. Yang, P. Liu, and J. Wei, "Power allocation for full-duplex relaying-based D2D communication underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 10, pp. 4911–4916, 2015, doi: 10.1109/TVT.2014.2373053.
[43] D. Hui, F. Ye, and Y. Li, "Transmission power adaption for full-duplex relay-aided device-to-device communication," *Symmetry*, vol. 9, no. 3, p. 38, 2017.
[44] H. Chen and F. Zhao, "A hybrid half-duplex/full-duplex transmission scheme in relay-aided cellular networks," *EURASIP J. Wireless Commun. Netw.*, vol. 3, p. 1, Jan. 2017.
[45] J. Wang, A. Liu, T. Yan, and Z. Zeng, "A resource allocation model based on double-sided combinational auctions for transparent computing," *Peer-to-Peer Netw. Appl.*, pp. 1–8, 2017, doi: 10.1007/s12083-017-0556-6.2017.
[46] J. Gui, Y. Lu, X. Deng, and A. Liu, "Flexible resource allocation adaptive to communication strategy selection for cellular clients using stackelberg game," *Ad Hoc Netw.*, vol. 66, pp. 64–84, Nov. 2017.
[47] R. S. Komali, A. B. Mackenzie, and R. P. Gilles, "Effect of selfish node behavior on efficient topology design," *IEEE Trans. Mobile Comput.*, vol. 7, no. 9, pp. 1057–1070, Sep. 2008.
[48] J. Gui, L. Hui, and N. Xiong, "A game-based localized multi-objective topology control scheme in heterogeneous wireless networks," *IEEE Access*, vol. 5, no. 1, pp. 2396–2416, 2017.
[49] A. Abrardo and M. Moretti, "Distributed power allocation for D2D communications underlaying/overlaying OFDMA cellular networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1466–1479, Mar. 2017.
[50] S. Maghsudi and S. Stanczak, "Hybrid centralized-distributed resource allocation for Device-to-Device communication underlaying cellular networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2481–2495, Apr. 2016.
[51] G. Katsinis and E. E. S. Tsiropoulou Papavassiliou, "Joint resource block and power allocation for interference management in device to device underlay cellular networks: a game theoretic approach," *Mobile Netw. Appl.*, vol. 22, no. 3, pp. 539–551, 2017.
[52] W. B. Heinzelman, "Application-specific protocol architectures for wireless networks," M.S. thesis, Massachusetts Inst. Technol., Cambridge, MA, USA, 2000.
[53] P. Mach, Z. Becvar, and T. Vanek, "In-band device-to-device communication in OFDMA cellular networks: A survey and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 1885–1922, 4th Quart., 2015.
[54] J. Li, R. Bhattacharyya, S. Paul, S. Shakkottai, and V. Subramanian, "Incentivizing sharing in realtime D2D streaming networks: A mean field game perspective," *IEEE/ACM Trans. Netw.*, vol. 25, no. 1, pp. 3–17, Jan. 2017.
[55] X. Wang, M. Chen, T. Kwon, L. Jin, and V. Leung, "Mobile traffic offloading by exploiting social network services and leveraging opportunistic device-to-device sharing," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 28–36, Mar. 2014.
[56] S. Andreev *et al.*, "A unifying perspective on proximity-based cellular-assisted mobile social networking," *IEEE Commun. Mag.*, vol. 54, no. 4, pp. 108–116, Apr. 2016.
[57] J. Gao, J. Wang, J. He, and F. Yan, "Against signed graph deanonymization attacks on social networks," *Int. J. Parallel Program.*, 2017, doi: . [Online]. Available: https://doi.org/10.1007/s10766-017-0546-6.
[58] C. Gao, Y. Li, Y. Zhao, and S. Chen, "A two-level game theory approach for joint relay selection and resource allocation in network coding assisted D2D communications," *IEEE Trans. Mobile Comput.*, vol. 16, no. 10, pp. 2697–2711, Oct. 2017.
[59] J. Huang, H. Gharavi, H. Yan, and C. Xing, "Network coding in relay-based device-to-device communications," *IEEE Netw.*, vol. 31, no. 4, pp. 102–107, Apr. 2017.



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