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Analysis of Joint Relay Selection and Resource Allocation Scheme for Relay-Aided D2D Communication Networks

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ABSTRACT Device-to-device (D2D) communications, as one of the promising technology for the future network, allow two devices in proximity to communicate directly with each other to alleviate the data traffic load for the base station (BS). In this paper, we analysis the joint relay selection and resource allocation scheme for relay-aided D2D communication networks. The objective is to maximize the total transmission data rates of the system while guaranteeing the minimum quality of service (QoS) requirements for both cellular users (CUs) and D2D users (DUs). We first propose a social-aware relay selection algorithm with low computational complexity to obtain the suitable relay nodes (RNs) for D2D links. Then the power control schemes are considered when a D2D link works in the D2D direct or relay mode to maximize the system transmission data rates. On basis of this, we propose a greedy-based mode selection and channel allocation algorithm, which can not only allocate the appropriate channel resource for D2D links, but also select the optimal communication mode for them. Numerical results demonstrate that the proposed scheme is capable of substantially improving the performance of the system compared with the other algorithms.

INDEX TERMS Device-to-device (D2D) communication, relay selection, power control, channel allocation, mode selection.

I. INTRODUCTION

Nowadays, along with the rapid development of wireless and mobile communication technology, the number of intelligent terminals has increased dramatically [1], [2]. Simultaneously, the emergence of new services and scenarios (e.g., autonomous cars and augmented reality, etc.) leads to an exponential increase in wireless mobile data traffic [3]–[5]. To mitigate traffic congestion and increase spectral efficiency, 3rd Generation Partnership Project (3GPP) proposed device-to-device (D2D) communication under the control of cellular networks which can realize direct data transmission between two equipments in proximity without the need of transmitting and receiving data through the base station (BS) [6], [7]. D2D communications can not only substantially reduce the load of BS, but also significantly enhance the spectrum utilization and throughput [8], [9].

However, it is well known that D2D communication is a kind of short range communication service, the effective coverage range of D2D communication is very limited. When the two D2D users (DUs) are communicating with each other, if the channel conditions between them is deeply faded (e.g., due to building occlusion) or the distance between them increases instantaneously (e.g., between the high-speed vehicles and stationary vehicles), the D2D communication will be interrupted [10]. Therefore, the multihop D2D communication is an efficient method to further boost transmission performance where the relay nodes (RNs) can assist DUs for wireless data offloading [11], [12]. Introducing D2D relay communication mode into communication network will have more benefits. On the one hand, D2D relay communication mode can ameliorate the reliability of network, make the deployment of network more flexible, and obviously reduce the communication pressure and request delay. On the other hand, it also can boost the achievable data rates of users at the edge of the network, thereby enhancing the ability of

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network coverage, and optimize the system data rates as well as the utilization of network spectrum resource.

In relay-assisted D2D communication, how to select proper D2D RNs and how to allocate the appropriate channel resource and transmit power are the critical issues to improve the system performance [13]. Firstly, the selection of D2D RN can not only improve the channel quality between D2D source node and its destination node, to guarantee the minimum transmission rates between them, but also reduce the attenuation of signals between the RN and the D2D source node or its destination node, making it easier to demodulate useful information. In addition, as the D2D links share the channel resource that assigned to the original cellular links, the performance of the system may be declined due to the interferences that either imposed on the BS by the D2D source node or imposed on the D2D destination node by the original cellular users (CUs) [14]–[16]. Besides, some system parameters (e.g., number of users, location of RNs, etc.) can also have a significant impact on the performance of the system [17]. It is important to design an effective channel resource reuse strategy. Unordered channel resource reuse may lead to a deterioration of the network performance. Therefore, the reused channel resource must be managed and assigned reasonably in relay-assisted D2D hybrid networks. Meanwhile, intelligent terminals are generally carried by human beings who form a Social Network that reveals relatively stable social relationships. Hence, if the willingness of the RNs or the social relationships among users are not considered in the selection of RNs, this may impose a negative influence on the behavior of the entire network [18]–[20].

In this paper, we study the issue of joint realy selection and resource allocation for relay-assisted D2D communication networks in order to ameliorate the performance of the networks while satisfying the minimum quality of service (QoS) requirements for users. Firstly, a low-complexity relay selection algorithm is designed based on regional delineation mechanism and social attributes among users to select the suitable RNs for D2D links. Subsequently, power control schemes for both D2D direct mode and relay mode are considered to maximize the achievable end-to-end data rates of cellular and D2D links. Finally, a greedy-based mode selection and channel allocation algorithm is proposed, which can not only assign appropriate channel resource for D2D links, but also select communication mode for D2D links flexibly according to the total transmission data rates. The main contributions of this paper are as follows:

- We formulate a general resource assignment problem while considering the minimum data rates requirements for both cellular and D2D links simultaneously. We first compare the achievable end-to-end data rates of D2D direct mode and that of D2D relay mode. Then we transform the original optimization problem into three sub-problems: relay selection problem, power control problem and joint mode selection and channel resource allocation problem.
- We propose a social-aware relay selection algorithm to select suitable RNs for D2D links. In order to decrease the computational complexity of the designed algorithm, we exploit the regional delineation mechanism to determine the candidate set of RNs for D2D links. Then constructing node degree of interest by considering both the willingness of nodes and the social attributes among users to find out the optimal RNs for D2D links.
- We propose a power control scheme to solve the optimum transmit power for both D2D direct mode and D2D relay mode to optimize the achievable end-to-end data rates of all cellular and D2D links.
- We propose a greedy-based mode selection and channel resource allocation algorithm by selecting the appropriate channel resource and flexibly switching between two D2D communication modes (e.g., direct mode and relay mode), the performance of the whole system is dramatically improved.

The rest of the paper is organized as follows. The related works are introduced in Section II. Section III presents the system model and problem formulation. The formulated optimization is resolved in Section IV. Simulation results and analysis are presented in Section V. Finally, Section VI concludes the paper and presents the future work directions.

II. RELATED WORK

In order to ameliorate the performance of the networks, significant efforts have been taken in relay-assisted D2D communications. The most critical issue is to select the optimal RN for a D2D link [21], [22]. A new RN selection scheme is designed in [23], by taking into account both channel state information at physical layer and queue state information for each RN at data link layer, some important system performance parameters, such as the average data transmission delay and packet error probability, are guaranteed. The work in [24] considers the buffer size for every RN in the process of relay selection, a diversity- and delay aware relay selection algorithm is proposed. The method can reduce the outage probability while decreasing the average transmission delay of the system. In the meantime, some other effective resource allocation schemes have been investigated. The work in [25] presents a resource assignment algorithm for relay-based D2D communication networks. This method first transforms the resource allocation problem into a max-sum message passing problem over a graphical, then a distributed method with low signaling overhead, which can be resolved with polynomial time, is designed to handle the optimization problem. In [10], the authors study the resource allocation problem for D2D relays to optimize the transmission rates of D2D links while satisfying the minimum data rates requirements for both cellular and D2D links, in which the maximum transmit power for cellular and D2D links are constrained. The work in [26] formulates the original resource assignment problem as a non-deterministic polynomial hard (NP-hard) problem. The authors first decompose the original problem into two sub-problems, then a novel technology called iterative Hungarian method is proposed to resolve the problem in a suboptimal way. The work in [27] proposes a low-latency reliable D2D relay network framework to handle the joint rate control and power allocation problem. The authors first transform the original long-term optimization problem into a series of optimization problems by using Lyapunov method and solve them separately. Then, in order to reduce the complexity, an alternating direction method of multipliers (ADMM)-based scheme is developed to find the suitable solutions.

In addition, numerous works also investigate the mode selection and resource allocation joint schemes for relay-assited D2D communication networks. The work in [28] considers the mobile relay-based D2D communication scenario, then formulates the optimization problem by considering the issue of mode selection, power control, channel assignment and relay selection at the same time. At last, a heuristic algorithm with polynomial-time is proposed to approximate the global optimality. A new radio protocol architecture is designed for both DUs and RNs to support the various D2D modes in [29]. By using an effective link quality measurement and report approach with low signaling overhead, the scheduling on radio spectrum assignment and mode selection are performed to ensure an acceptable network performance. The work in [30] studies the issue of joint D2D mode selection, resource group assigment and power control for relay-assisted D2D communication systems. The authors first consider the optimal power control method for D2D links, then the original optimization problem is transformed into a job assignment problem and resolved by the Hungarian method. The work in [31] formulates the original resource scheduling problem as a three-dimensional power-mode-channel optimization problem to maximize the energy efficiency of D2D links while satisfying the minimum QoS requirements for cellular and D2D links. Then the original 3-D problem is separated and solved by a suboptimal algorithm with low-complexity.

In total, the aforementioned works propose some reliable solutions for the problem of RN selection, channel resource assignment and D2D mode selection in relay-assisted D2D communication networks. However, there are still many key issues to be solved urgently. For instance, the above literatures do not consider how to reduce the candidate RNs in the case of ultra-dense terminals to reduce the computational complexity and signaling overhead. In addition, the system performance is also influenced by the willingness of RNs and the social attributes among users, which are not considered in the above literatures.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

Since the uplink channel resource are under-utilized as compared with the downlink channel resource, we consider the uplink of a single macro-cell system, where the cell contains M cellular links, N D2D links as well as L D2D RNs (e.g., idle CUs). We use the sets $\mathcal{M} = \{1, \cdots, M\}$, $\mathcal{N} = \{1, \cdots, N\}$ and $\mathcal{L} = \{1, \cdots, L\}$ to represent them, respectively. Each D2D link n in the set $\mathcal{N}$ contains a transmitter s_n and a receiver d_n. It should be mentioned that before establishing a D2D link, peer discovery of D2D communications is necessary. In this paper, the peer discovery process is completed with the assistance of the BS [32]. We assume that the BS can obtain the accurate channel state information of all links [21], and the DFT-Based channel estimation scheme can be used to accomplish the process of channel estimation [33]. In addition, we presume that each cellular link has been pre-assigned an orthogonal uplink channel to alleviate the interference among cellular links, and the D2D link can only be established by reusing these channel resource. To guarantee the performance for both D2D and cellular links, we require that each cellular link can share the same channel resource with at most one D2D link, and each D2D link can share the same channel resource with at most one cellular link [7], [14]–[16], [22], [28], [30]. Besides, each D2D link is permitted to operate either in direct mode or relay mode. In direct mode, the transmitter s_n of D2D link n can communicate directly to its receiver d_n. While in the relay mode, the RNs utilize the Decode and Forward (DF) protocol with the half duplex mode to transfer data, and the data transmission is divided into two parts: in the first part, s_n transfers data to D2D RN $l \in \mathcal{L}$ by reusing the channel resource of a corresponding cellular link $m \in \mathcal{M}$. After that, D2D RN l forwards the data to d_n in the second part though the channel resource that have the same identification as the first part.

The system model is represented in Fig. 1, where the CUs can establish the communication link with the BS directly, meanwhile the transmitter and the receiver of a D2D link can establish the communication link either in direct mode or relay mode. When the D2D link n works in the direct mode by reusing the channel resource that allocated to the cellular link m, let $R_{c,m}^{(\text{direct})}$ and $R_{d,n}^{(\text{direct})}$ define the achievable end-to-end data rates of cellular link m and D2D link n, respectively:

$$R_{c,m}^{(\text{direct})} = B\log_2\left(1 + \frac{p_m^c h_{c,b}}{\sigma_0^2 + p_{m,s_n}^d h_{s_n,b}}\right) \tag{1}$$

and

$$R_{d,n}^{(\text{direct})} = B\log_2\left(1 + \frac{p_{m,s_n}^d h_{s_n,d_n}}{\sigma_0^2 + p_m^c h_{c,d_n}}\right) \tag{2}$$

where B is the uplink channel bandwidth. p_m^c denotes the transmit power of CUs, a constant. p_{m,s_n}^d denotes the transmit power of the DU s_n, when D2D link n reuses the channel resource of cellular link m. $h_{c,b}$ denotes the channel coefficient from CU m to the BS. $h_{s_n,b}$ denotes the channel coefficient from DU s_n to the BS. h_{s_n,d_n} denotes the channel coefficient from the source node of D2D link n to its destination node. h_{c,d_n} denotes the channel coefficient from CU m to the DU d_n. σ_0^2 denotes the Gaussian channel noise.

Different from the direct mode, when the D2D link n works in the relay mode with the assistance of D2D RN l

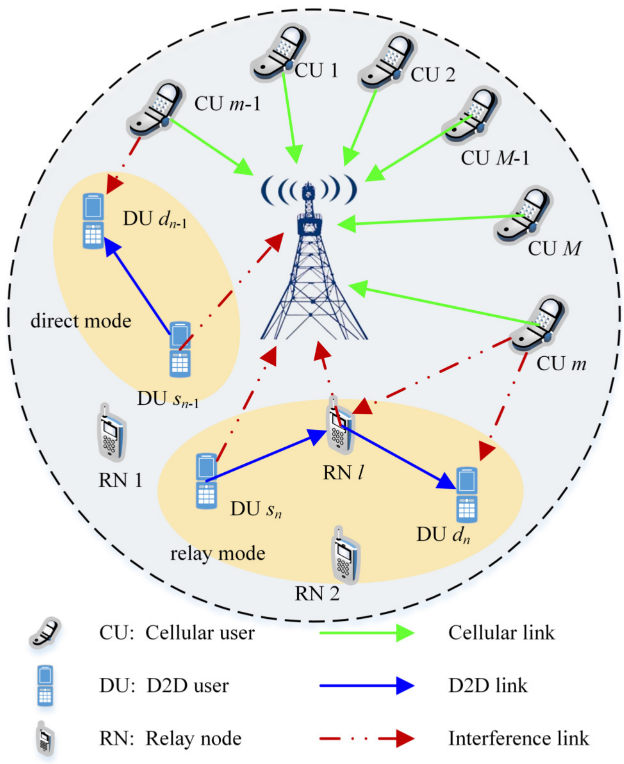

FIGURE 1. System model for relay-aided D2D communication networks, in which CUs are allowed to share the uplink channel resource with DUs. DUs s_n and d_n can establish a D2D link with the assistance of RN l.

by reusing the uplink channel resource that assigned to the cellular link m, the communication period is divided into two parts. We define $R_{c,m}^{(r1)}$ and $R_{d,n}^{(r1)}$ to represent the achievable end-to-end data rates of cellular link m and D2D link n in the first part, respectively:

$$R_{c,m}^{(r1)} = \frac{B}{2}\log_2\left(1+\frac{p_m^c h_{c,b}}{\sigma_0^2 + p_{m,s_n}^d h_{s_n,b}}\right) \tag{3}$$

and

$$R_{d,n}^{(r1)} = \frac{B}{2}\log_2\left(1+\frac{p_{m,s_n}^d h_{s_n,r}}{\sigma_0^2 + p_m^c h_{c,r}}\right) \tag{4}$$

where $h_{s_n,r}$ denotes the channel coefficient from DU s_n to the RN l. $h_{c,r}$ denotes the channel coefficient from CU m to the RN l.

Similar with the first part, let $R_{c,m}^{(r2)}$ and $R_{d,n}^{(r2)}$ define the achievable end-to-end data rates of cellular link m and D2D link n in the second part, respectively:

$$R_{c,m}^{(r2)} = \frac{B}{2}\log_2\left(1+\frac{p_m^c h_{c,b}}{\sigma_0^2 + p_l^r h_{r,b}}\right) \tag{5}$$

and

$$R_{d,n}^{(r2)} = \frac{B}{2}\log_2\left(1+\frac{p_l^r h_{r,d_n}}{\sigma_0^2 + p_m^c h_{c,d_n}}\right) \tag{6}$$

where p_l^r denotes the transmit power of RN l. $h_{r,b}$ denotes the channel coefficient from RN l to the BS. h_{r,d_n}denotes the channel coefficient from RN l to the destination node of D2D link n.

B. PROBLEM FORMULATION

Without loss of generality, we define the matrix $\boldsymbol{x}$ represents the channel selection decisions for D2D links where $[\boldsymbol{x}]_{mn} = x_{mn} = 1$ if D2D link n shares the channel resource with cellular link m and $x_{mn} = 0$, otherwise. Similarly, we define the matrix $\boldsymbol{\alpha}$ to represent the relay selection decisions for the D2D links where $[\boldsymbol{\alpha}]_{nl} = \alpha_{nl} = 1$ if D2D link n forwards the data with the assistance of RN l and $\alpha_{nl} = 0$, otherwise. Finally, we define the vector $\mathbf{u} = [u_1, \cdots, u_N]$ to represent the mode selection decisions for all D2D links where $u_n = 1$ if D2D link n works in the relay mode and $u_n = 0$, otherwise.

We introduce the vector $\mathbf{p}^d = [\mathbf{p}_{s_1}^d, \cdots, \mathbf{p}_{s_N}^d]$ to describe the power level of D2D links where $\mathbf{p}_{s_n}^d = [p_{1,s_n}^d, \cdots, p_{M,s_n}^d]$ denotes the transmit power of s_n when D2D link n shares the same the channel resource with cellular links. Furthermore, we define $\mathbf{p}^r$ is the power vector of the D2D RNs where $[\mathbf{p}^r]_l = p_l^r$ denotes the transmit power of D2D RN l.

Using the symbols mentioned above, the achievable end-to-end data rates of cellular link m and D2D link n can be computed as

$$R_m^c = \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} x_{mn}\left[\left(1-u_n\right)R_{c,m}^{(\text{direct})} + u_n\alpha_{nl}R_{c,m}^{(\text{relay})}\right] \tag{7}$$

and

$$R_n^d = \sum_{m\in\mathcal{M}}\sum_{l\in\mathcal{L}} x_{mn}\left[\left(1-u_n\right)R_{d,n}^{(\text{direct})} + u_n\alpha_{nl}R_{d,n}^{(\text{relay})}\right] \tag{8}$$

respectively. Where $R_{c,m}^{(\text{relay})} = R_{c,m}^{(r1)} + R_{c,m}^{(r2)}$ and $R_{d,n}^{(\text{relay})} = \min\{R_{d,n}^{(r1)}, R_{d,n}^{(r2)}\}$.

In this paper, we discuss the problem of relay selection, channel resource allocation and power control for relay-assisted D2D communication networks under the following constraints. First, the transmit power for DU s_n and RN l must be limited by the maximum transmit power, e.g.,

$$0 \le p_{m,s_n}^d \le p_n^{\max}, \quad \forall n \in \mathcal{N} \tag{9}$$
$$0 \le p_l^r \le p_n^{\max}, \quad \forall l \in \mathcal{L} \tag{10}$$

where $p_n^{\max}$ represents the maximum transmit power constraint.

Second, it is required to maintain the minimum end-to-end data rates of both cellular and D2D links, e.g.,

$$R_{c,m}^{(\text{direct})} \ge R_{c,m}^{th}, R_{d,n}^{(\text{direct})} \ge R_{d,n}^{th}, \quad \forall m \in \mathcal{M}, n \in \mathcal{N} \tag{11}$$
$$R_{c,m}^{(r1)} \ge R_{c,m}^{th}, R_{c,m}^{(r2)} \ge R_{c,m}^{th}, \quad \forall m \in \mathcal{M} \tag{12}$$
$$R_{d,n}^{(r1)} \ge R_{d,n}^{th}, R_{d,n}^{(r2)} \ge R_{d,n}^{th}, \quad \forall n \in \mathcal{N} \tag{13}$$

where $R_{c,m}^{th}$ and $R_{d,n}^{th}$ represent the minimum achievable end-to-end data rates requirements for cellular link and D2D link, respectively.

Third, the binary constraints of relay selection, channel assignment and mode selection decisions can be given as

$$u_n \in \{0,1\}, \quad \forall n \in \mathcal{N}, x_{mn} \in \{0,1\}, \ \forall m \in \mathcal{M}, \ n \in \mathcal{N} \tag{14}$$

$$\alpha_{nl} \in \{0,1\}, \quad \forall n \in \mathcal{N}, l \in \mathcal{L} \tag{15}$$

Finally, similar to [7], [14]–[16], [22], [28], and [30], in order to ensure the interference within the system is controllable, we require that the channel assignment decisions $x_{mn}, \forall m \in \mathcal{M}, n \in \mathcal{N}$ to satisfy the following constraints

$$\sum_{n\in\mathcal{N}} x_{mn} \le 1, \quad \forall m \in \mathcal{M}, \quad \sum_{m\in\mathcal{M}} x_{mn} \le 1, \ \forall n \in \mathcal{N} \tag{16}$$

In this paper, we concentrate on maximizing the achievable end-to-end date rates of both cellular and D2D links under the above-mentioned constraints, the optimization problem can be formulated as

$$\max_{\boldsymbol{x},\boldsymbol{\alpha},\mathbf{u},\mathbf{p}^d,\mathbf{p}^r} \left\{ \sum_{m\in\mathcal{M}} R_c^m + \sum_{n\in\mathcal{N}} R_d^n \right\}$$
$$\text{subject to (9)} - \text{(16)}. \tag{17}$$

We can see that the original optimization problem in (17) is a mixed integer non-linear programming (MINLP) problem, and it is unable to find optimal solutions in the polynomial time [7], [14], [15]. So we decouple the optimization problem into three steps: optimal relay node selection, power control and joint mode selection and channel resource allocation, then solve them in variant algorithms.

IV. SOLUTION APPROACH

A. OPTIMAL RELAY NODE SELECTION

In this subsection, we investigate the optimal RN selection problem by considering social relationships between DUs and RNs. Before that, we consider how to decrease the computational complexity of this problem. So we first limit the candidate RNs for each D2D link by using the regional delineation mechanism, as shown in Fig. 2. Two circles are formed, with the DUs s_n and d_n are the center of two circles respectively, and the radius is d_{s_n,d_n}. Thus, the set of devices that can serve as potential relay nodes of D2D link n can be defined as

$$\mathcal{K}_n \triangleq \{l : d_{s_n,l} \le d_{s_n,d_n}, d_{l,d_n} \le d_{s_n,d_n}, \forall l \in \mathcal{L}\} \tag{18}$$

where $d_{s_n,l}$ represents the distance between s_n and l, d_{l,d_n} is the distance between l and d_n. d_{s_n,d_n} represents the distance between s_n and d_n.

As mentioned above, we can select a candidate set of RNs for each of D2D links. However, as we all know that the wireless intelligent terminals are usually carried by individuals, thus the wireless intelligent terminals indirectly have the attributes of the personal social relationship. This may indirectly influence the system performance of relay-assisted D2D communications. Then we utilize the methods of Social Network to explore the relay selection problem.

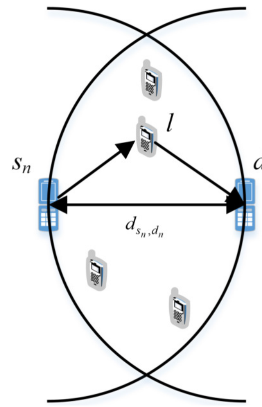

FIGURE 2. Regional delineation mechanism for D2D link.

In Social Network, the willingness of nodes has become an important factor affecting the formation of social relationships and information dissemination. Personal willingness is the initiative of nodes to the outside world or the initiative of users to obtain external information. Personal willingness takes full account of the node's own willingness, so it plays an important role in the formation of social relationships. The stronger the social relationship between two users, the two users are more likely to perform D2D relay communication. We define the node degree of interest to measure the strength of social relationships that may form between two user nodes. The node degree of interest between s_n and l can be expressed as the product of the cosine similarity and the willingness of nodes:

$$\text{Int}(s_n, l) = \frac{\sum_{k=1}^{K} \omega_{s_n,k}\omega_{l,k}}{\sqrt{\sum_{k=1}^{K} \omega_{s_n,k}^2}\sqrt{\sum_{k=1}^{K} \omega_{l,k}^2}} \varepsilon_{s_n,l} \tag{19}$$

where $\omega_{i,k}, i \in \{s_n, l\}$ is defined as a user i's opinion and rating of an item k (e.g., a movie, a product, a photo, etc.). The willingness of nodes $\varepsilon_{s_n,l}$ reflects the degree of mutual communication between s_n and l, and we can get the value of $\varepsilon_{s_n,l}$ according to [34]. The greater the Int(s_n, l), the stronger the social relationship that may exist between s_n and l, vice versa.

In order to select the appropriate RNs for D2D links, we then propose a social-aware relay selection algorithm, as shown in Algorithm 1. Firstly, we calculate $|\mathcal{K}_n|$, the number of D2D RNs in $\mathcal{K}_n$, and then get $\mathcal{N}'$, which contains the D2D links with $|\mathcal{K}_n|$ in increasing order. On this foundation, we assign D2D RNs preferentially to those with less relay candidates. The rule of assignment is to maximize the node degree of interest between s_n and l. Then we pair the rest of D2D links with their relay candidates in the order of $\mathcal{N}'$. From the above discussions, we can see that the proposed relay selection algorithm guarantees the fairness of D2D links while considering the social relationship among wireless communication devices.

Algorithm 1 Social-Aware Relay Selection Algorithm

1: **Initialize:** Set $\alpha_{nl} = 0, \forall n \in \mathcal{N}, l \in \mathcal{L}$.
Calculate $\mathcal{K}_n, \forall n \in \mathcal{N}$, the set of candidate relay nodes for D2D links.
Obtain $\mathcal{N}'$, the set of D2D links with $|\mathcal{K}_n|$ in increasing order.
2: Finding out the first element n^* in $\mathcal{N}'$, then calculate
3: $l^* = \arg\max_{l \in \mathcal{K}_{n^*}} \text{Int}(s_{n^*}, l)$
4: Set $\alpha_{n^* l^*} = 1$.
5: Delete l^* from $\mathcal{K}_n, n \in \mathcal{N}$, then update $\mathcal{K}_n$ and $\mathcal{N}'$.
6: **for all** $n \in \mathcal{N}' \setminus \{n^*\}$
7: Repeat steps 2, 3, 4 and 5 to select optimal relay node in $\mathcal{K}_n$ for D2D link n in the order of $\mathcal{N}'$ and determine $\boldsymbol{\alpha}$.
8: **end for**
9: **Output:** Relay selection decisions $\alpha_{nl}, \forall n \in \mathcal{N}, l \in \mathcal{L}$.

B. POWER CONTROL

Assume that D2D link n shares the same channel resource with cellular link m, the power control problems for D2D link n should be discussed for direct and relay mode, respectively. The power control issues when the D2D link n works in the direct mode can be formulated as

$$\max_{p^d_{m,s_n}} \varphi(p^d_{m,s_n}) = \left\{R^{(\text{direct})}_{c,m} + R^{(\text{direct})}_{d,n}\right\}$$
$$\text{subject to (9), (11).} \tag{20}$$

According to the constraints in (9) and (11), we can obtain that

$$p^{\min}_d \le p^d_{m,s_n} \le p^{\max}_d \tag{21}$$

where the values of variable $p^{\min}_d$ and $p^{\max}_d$ can be expressed as

$$p^{\max}_d = \min\left\{p^{\max}_n, \frac{p^c_m h_{c,b}}{\left(2^{\frac{R^{\text{th}}_{c,m}}{B}} - 1\right) h_{s_n,b}} - \frac{\sigma_0^2}{h_{s_n,b}}\right\} \tag{22}$$

$$p^{\min}_d = \max\left\{0, \frac{\left(2^{\frac{R^{\text{th}}_{d,n}}{B}} - 1\right)\left(p^c_m h_{c,d_n} + \sigma_0^2\right)}{h_{c,d_n}}\right\} \tag{23}$$

Generally, we have $p^{\min}_d \le p^{\max}_d$. If $p^{\min}_d > p^{\max}_d$, it means that D2D link n cannot share the same channel resource with cellular link m.

We can conclude that $\varphi(p^d_{m,s_n})$ is a convex function of p^d_{m,s_n} [35]. The optimal transmit power p^{d*}_{m,s_n} of (20) can be obtained by evaluating the $\varphi(p^d_{m,s_n})$ at all extreme and local optimum points of the power range of p^d_{m,s_n} by taking the one that reaches the larger value. According to the optimization problem in (20), we can get that $\partial\varphi(p^d_{m,s_n})/p^d_{m,s_n} = 0$ is a quadratic polynomial. Suppose that $\{p^{d1}_{m,s_n}, p^{d2}_{m,s_n}\}$ are the two roots of the function $\partial\varphi(p^d_{m,s_n})/p^d_{m,s_n} = 0$. Consequently, the optimal solution of (20) can be expressed as

$$p^{d*}_{m,s_n} = \begin{cases} \arg\max_{p^d_{m,s_n} \in p_d} \varphi(p^d_{m,s_n}) & p^{\min}_d \le p^{\max}_d \\ 0 & p^{\min}_d > p^{\max}_d \end{cases} \tag{24}$$

where $p_d = \left\{p^{d1}_{m,s_n}, p^{d2}_{m,s_n}, p^{\min}_d, p^{\max}_d\right\} \cap \left[p^{\min}_d, p^{\max}_d\right]$ are the possible solutions of (20).

Similar to the direct mode, when D2D link n works in the D2D relay mode with the assistance of RN l, the power control problem can be formulated as

$$\max_{p^d_{m,s_n}, p^r_l} \left\{R^{(\text{relay})}_{c,m} + R^{(\text{relay})}_{d,n}\right\}$$
$$\text{subject to (9), (10), (12) and (13).} \tag{25}$$

We define $\gamma_{s_n,r} = \left(h_{s_n,r}/(\sigma_0^2 + p^c_m h_{c,r})\right)$ is the signal to interference plus noise ratio (SINR) index to manifest the SINR level at the D2D RN l. Similarly, we can define $\gamma_{r,d_n} = \left(h_{r,d_n}/(\sigma_0^2 + p^c_m h_{c,d_n})\right)$ for the receiver of D2D link n. Considering DF protocol, the maximum achievable data rates of D2D link n can be achieved when $p^d_{m,s_n}\gamma_{s_n,r} = p^r_l \gamma_{r,d_n}$ [30]. Therefore, the objective function of (25) can be transformed into the solution of function $\theta(p^d_{m,s_n}) = (1 + \frac{a_1}{a_2 + a_3 p^d_{m,s_n}})(1 + \frac{a_1}{a_2 + a_4 p^d_{m,s_n}})(1 + a_5 p^d_{m,s_n})$, where $a_1 = p^c_m h_{c,b}$, $a_2 = \sigma_0^2$, $a_3 = h_{s_n,b}$, $a_4 = \gamma_{s_n,r}/(\gamma_{r,d_n} h_{r,b})$, $a_5 = h_{s_n,r}/(\sigma_0^2 + p^c_m h_{c,r})$.

According to the constraints in the first part, we can get $p^{\min 1}_r \le p^d_{m,s_n} \le p^{\max 1}_r$, where $p^{\min 1}_r$ and $p^{\max 1}_r$ can be expressed as

$$p^{\max 1}_r = \min\left\{p^{\max}_n, \frac{p^c_m h_{c,b}}{\left(2^{\frac{2R^{\text{th}}_{c,m}}{B}} - 1\right) h_{s_n,b}} - \frac{\sigma_0^2}{h_{s_n,b}}\right\} \tag{26}$$

$$p^{\min 1}_r = \max\left\{0, \frac{\left(2^{\frac{2R^{\text{th}}_{d,n}}{B}} - 1\right)\left(p^c_m h_{c,r} + \sigma_0^2\right)}{h_{s_n,r}}\right\} \tag{27}$$

Similarly, according to the constraints in the second part, we can get $p^{\min 2}_r \le p^d_{m,s_n} \le p^{\max 2}_r$, where $p^{\max 2}_r$ and $p^{\min 2}_r$ can be expressed as

$$p^{\max 2}_r = \min\left\{\frac{p^{\max}_n \gamma_{r,d_n}}{\gamma_{s_n,r}}, \frac{p^c_m h_{c,b} \gamma_{r,d_n}}{\left(2^{\frac{2R^{\text{th}}_{c,m}}{B}} - 1\right) h_{r,b} \gamma_{s_n,r}} - \frac{\sigma_0^2 \gamma_{r,d_n}}{h_{r,b} \gamma_{s_n,r}}\right\} \tag{28}$$

$$p^{\min 2}_r = \max\left\{0, \frac{\gamma_{r,d_n}\left(2^{\frac{2R^{\text{th}}_{d,n}}{B}} - 1\right)\left(p^c_m h_{c,d_n} + \sigma_0^2\right)}{h_{r,d_n} \gamma_{s_n,r}}\right\} \tag{29}$$

Therefore, the optimization problem (25) can be retransformed as

$$\max_{p^d_{m,s_n}} \theta(p^d_{m,s_n}) = \frac{f(p^d_{m,s_n})}{g(p^d_{m,s_n})} = \frac{b_3(p^d_{m,s_n})^3 + b_2(p^d_{m,s_n})^2 + b_1(p^d_{m,s_n}) + b_0}{c_2(p^d_{m,s_n})^2 + c_1(p^d_{m,s_n}) + c_0}$$
$$\text{subject to } p_r = [p^{\min 1}_r, p^{\max 1}_r] \bigcap [p^{\min 2}_r, p^{\max 2}_r]. \tag{30}$$

Algorithm 2 Iteration Algorithm

1: **Initialize:** Set permissible error $\tau = 10^{-6}$, $l = 0$, $\varsigma^{(0)} = 0$.
2: **Iteration begins:**
3: Obtain the optimal solution set $p(\varsigma^{(l)})$ from (32).
4: Get $p_{m,s_n}^{d*} = \arg\max_{p_{m,s_n}^d \in p(\varsigma^{(l)})} \theta(p_{m,s_n}^d)$ and $\theta(p_{m,s_n}^{d*})$ for given $\varsigma^{(l)}$.
5: Update the index $l = l + 1$.
6: Calculate $\varsigma^{(l)} = f(p_{m,s_n}^*)/g(p_{m,s_n}^*)$
7: **if** $|\varsigma^{(l)} - \varsigma^{(l-1)}| \geq \tau$, **then**
8: Return step 3.
9: **else**
10: Return step 13.
11: **end if**
12: **Iteration end.**
13: **Output:** $\varsigma^* = \varsigma^{(l)}$ and p_{m,s_n}^*.

where $b_3 = a_3a_4a_5$, $b_2 = a_3a_4 + a_5(a_1 + a_2)(a_3 + a_4)$, $b_1 = (a_1 + a_2)[a_3 + a_4 + a_5(a_1 + a_2)]$, $b_0 = (a_1 + a_2)^2$, $c_2 = a_3a_4$, $c_1 = a_2(a_3 + a_4)$, $c_0 = (a_2)^2$. p_r is the feasible range of p_{m,s_n}^d in D2D relay mode. If $p_r = \varnothing$, it represents that l cannot forward data as a RN in this situation.

Optimization problem (30) is a partial fractional optimization problem and we can utilize the Dinkelbach based scheme to obtain the optimal solutions [36]. Therefore, problem (30) is equivalent to the following optimization problem for a given parameter ς

$$\max_{p_{m,s_n}^d \in p_r} \theta(p_{m,s_n}^d) = f(p_{m,s_n}^d) - \varsigma g(p_{m,s_n}^d) \tag{31}$$

Similar to the solution of (20), optimization problem (31) can be obtained by searching exhaustively over all extreme and local optimum points of the power range. It is easy to get $\partial\theta(p_{m,s_n}^d)/p_{m,s_n}^d = 0$ is a quadratic polynomial. Suppose that $\{p_{m,s_n}^{r1}, p_{m,s_n}^{r2}\}$ are the two roots of the function $\partial\theta(p_{m,s_n}^d)/p_{m,s_n}^d = 0$. Therefore, the set of optimal solution for the problem (31) can be expressed as

$$p(\varsigma) = \{p_{m,s_n}^{r1}, p_{m,s_n}^{r2}\} \bigcap p_r \tag{32}$$

We can obtain the optimal solution of problem (31) by comparing all the possible solutions in $p(\varsigma)$. Set $p_{m,s_n}^{d*} = \arg\max_{p_{m,s_n}^d \in p(\varsigma)} \theta(p_{m,s_n}^d)$. Then we have the following theorem.

Theorem 1: Suppose that the optimum solution of (30) is ς^*. Then, ς^* can be achieved if and only if $\max_{p_{m,s_n}^d} f(p_{m,s_n}^d) - \varsigma^* g(p_{m,s_n}^d) = f(p_{m,s_n}^{d*}) - \varsigma^* g(p_{m,s_n}^{d*})$.

We can prove Theorem 1 by utilizing the method proposed in [37], the proof process is omitted here. By using the Theorem 1, we can obtain ς^* and p_{m,s_n}^{d*} by iteratively optimizing ς and p_{m,s_n}^d until convergence. The operations of the specific steps is shown in Algorithm 2. Through Algorithm 2, we can find the optimal transmit power of s_n, then the optimal transmit power of D2D RN l can be expressed as $p_l^{r^*} = (p_{m,s_n}^{d*}\gamma_{s_n,r})/\gamma_{r,d_n}$.

C. JOINT MODE SELECTION AND CHANNEL ALLOCATION

In this subsection, we consider the issue of joint mode selection and channel allocation for relay-aided D2D communication networks. Let us first consider how to select the suitable communication mode between direct and relay D2D mode once we determine the optimal RN, optimal transmit power and the channel allocation relationship between cellular and D2D links. We can compare the achievable end-to-end data rates of two candidate D2D communication modes for selecting the optimal communication mode to maximize system performance.

Denote $R_{m,n}^{r^*} = R_{c,m}^{(\text{relay}^*)} + R_{d,n}^{(\text{relay}^*)}$ as the optimal achievable end-to-end data rates in the case that D2D link n shares the same channel resource with cellular link m in D2D relay mode. Correspondingly, denote $R_{m',n}^{d^*} = R_{c,m'}^{(\text{direct}^*)} + R_{d,n}^{(\text{direct}^*)}$ as the optimal achievable end-to-end data rates in the case that D2D link n shares the same channel resource with cellular link m' in D2D direct mode. It should be mentioned that m and m' may be the same or different. Therefore, we can determine the optimal D2D transmission mode as follows. If $R_{m,n}^{r^*} \geq R_{m',n}^{d^*}$, the D2D link n works in the relay mode and $u_n = 1$, otherwise, the D2D link n should work in the direct mode and $u_n = 0$. Therefore, the mode selection problem discussed above can be transformed into how to assign channel resource for D2D link n to maximize the total transmission data rates.

As we all know that when a D2D link shares the same channel resource with a cellular link, the severe inter-interference may have a bad influence on both cellular and D2D links. Therefore, how to design the channel allocation schemes in the case that D2D link n works in the direct mode and relay mode becomes a major problem. When D2D link n works in the direct mode, the channel allocation problem can be resolved by utilizing the resource sharing algorithm proposed in [38]. Thus, we mainly deliberate the channel allocation problem when D2D link n works in the relay mode.

In order to maximize the total achievable end-to-end data rates of both cellular and D2D links, we must find the optimal channel resource for D2D link n. From (3), (4), (5) and (6) we can find that with a fixed transmit power of s_n and l, as the increasing of $\gamma_{s_n,r}$ and γ_{r,d_n}, the transmission rates of D2D link n increases. At the same time, with the increasing of $h_{s_n,b}$ and $h_{r,b}$, the interference from D2D link n to cellular link m increases. Then, we define the channel assignment factor as

$$\beta_{m,n} = \frac{\Gamma_{m,n}}{\Psi_{m,n}} \tag{33}$$

where $\Gamma_{m,n}$ is the harmonic mean of $\gamma_{s_n,r}$ and γ_{r,d_n}. $\Psi_{m,n}$ is the harmonic mean of $h_{s_n,b}$ and $h_{r,b}$. Therefore, cellular link m with the maximum $\beta_{m,n}$ can share the same channel resource with D2D link n.

In order to maximize the total transmission data rates, a low complexity greedy-based joint mode selection and channel allocation algorithm is proposed, as shown in Algorithm 3.

Algorithm 3 Greedy-Based Joint Mode Selection and Channel Allocation Algorithmm

Initialize: Set $x_{mn} = 0, \forall m \in \mathcal{M}, n \in \mathcal{N}$, $u_n = 0, \forall n \in \mathcal{N}$.
Set $\mathcal{C} = \mathcal{M}$ and $\mathcal{D} = \mathcal{N}$.
Obtain optimal RN selection decisions $\boldsymbol{\alpha}$ and power control strategy $\mathbf{p}^d$ and $\mathbf{p}^r$.
Calculate channel assignment factor according to the channel state information.
while $\mathcal{D} \neq \varnothing$ **do**
  Calculate $(m^*, n^*) = \arg\max_{(m,n):m\in\mathcal{C},n\in\mathcal{D}} \beta_{m,n}$.
  Calculate $m'^* = \arg\max_{m'\in\mathcal{C}}\{R^{(\text{direct})}_{c,m'} + R^{(\text{direct})}_{d,n^*}\}$ according to to the resource sharing algorithm in [39].
  if $R^{(r*)}_{m^*,n^*} \geq R^{(d^*)}_{m'^*,n^*}$ **then**
    Set $x_{m^*,n^*} = 1, u_n = 1, \mathcal{C} = \mathcal{C} \setminus \{m^*\}$ and $\mathcal{D} = \mathcal{D} \setminus \{n^*\}$.
  else
    Set $x_{m'^*,n^*} = 1, u_n = 0, \mathcal{C} = \mathcal{C} \setminus \{m'^*\}$ and $\mathcal{D} = \mathcal{D} \setminus \{n^*\}$.
  end if
end while
Output: Channel Allocation decisions $x_{mn}, \forall m \in \mathcal{M}, n \in \mathcal{N}$ and mode selection decisions $u_n, \forall n \in \mathcal{N}$.

D. COMPLEXITY ANALYSIS

The computational complexity of the proposed scheme in this paper can be counted roughly as follows. First, the relay selection step requires to resolve at most NL relay selection problems with the computational complexity of $\mathcal{O}(1)$. Subsequently, the computational complexity of the relay selection step is $\mathcal{O}(NL)$. Then, the power control step requires to resolve $2N$ power control issues corresponding to D2D direct mode and relay mode, respectively. Therefore, the computational complexity of the power control step is $\mathcal{O}(2N)$. Finally, the mode selection and channel allocation step requires to resolve at most $2MN$ mode selection and channel assigment issues. So the computational complexity of the mode selection and channel allocation step is $\mathcal{O}(2MN)$. To sum up, the whole computational complexity of proposed scheme is $\mathcal{O}(NL) + \mathcal{O}(2N) + \mathcal{O}(2MN)$, which is linear to N.

V. NUMERICAL RESULTS AND PERFORMANCE ANALYSIS

To illustrate the effect of the proposed method, numerical results are presented in this section to demonstrate the system performance. We consider a single-cell scenario with the radius of 500 meters. The channel bandwidth is 180kHz and the power spectral density of Gaussian channel noise is −114dBm/Hz. In order to measure the channel coefficient between two devices, we consider both distant dependent macroscopic path loss and shadow fading. The shadow fading obeys the lognormal distributions, and the standard deviation of lognormal distributions for cellular link and D2D link are 10dB and 12dB, respectively. In addition, in order to stimulate the social relationships between two users, we adopt a data set, called *Movielens*, which is collected by the University of Minnesota [39]. We select some of the data in this data set to illustrate the performance of the system. The specific simulation parameters are shown in Table 1 [29], [40]. All simulation data in this section are the average of 1000 Monte-Carlo experiments to achieve statistically significant results.

TABLE 1. Simulation parameters.

Parameters	Value
Cell radius	500m
Channel bandwidth (B)	180kHz
Noise spectral density (σ_0^2)	-114dBm/Hz
Number of cellular links (M)	60
Number of D2D links (N)	[25, 60]
Number of RNs (L)	150
Distance between two DUs (d_{s_n,d_n})	[50m, 200m]
Path loss model for cellular link	128.1+37.6log10(d)
Path loss model for D2D link	148+40log10(d)
Transmit power for CUs	24dBm
Minimum data rates of CUs and DUs	5bps/Hz
Transmit power constraint for DUs $(p_n^{\max})$	[2dBm, 20dBm]

In order to validate the performance of the proposed algorithm in this paper, other three algorithms are compared as references:

- MSRRAPC algorithm, which is a mode selection, radio resource allocation and power coordination method for all D2D links, as described in [29].
- RRSRA algorithm, which is a random relay selection and resource allocation method.
- RRS algorithm, which is a random relay selection method without considering the social relationships among users. Different from RRSRA, the RRS algorithm only chooses the RN randomly from the candidate relay set in the relay selection step, the other two steps are identical to the proposed algorithm in this paper.

To get insight into the effect of the proposed algorithm, we first utilize the cumulative distribution function (CDF), which is frequently used to evaluate the performance metrics, to show the numerical results in Fig. 3. Intuitively, the achievable end-to-end data rates of the proposed algorithm in this paper is obviously higher than the other three algorithms, and the maximum achievable end-to-end data rates of the proposed algorithm is 8.34%, 14.47% and 14.82% higher than that of MSRRAPC, RRS and RRSRA, respectively. It clearly shows that the proposed algorithm achieves a significant improvement on the system performance. This is caused by variety of factors. First, the proposed algorithm in this paper can always obtain the analytical solution for optimal transmit power of DUs in a closed-form, rather a discrete approximate solution. Second, compared with the other algorithms, the relay node selection and channel resource allocation

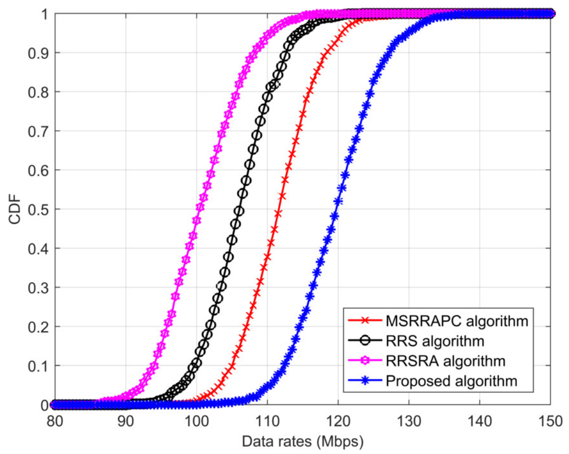

FIGURE 3. CDF of the achievable end-to-end data rates, where $N = 40$, $d_{s_n,d_n} = 150$m and $p_n^{max} = 20$dBm.

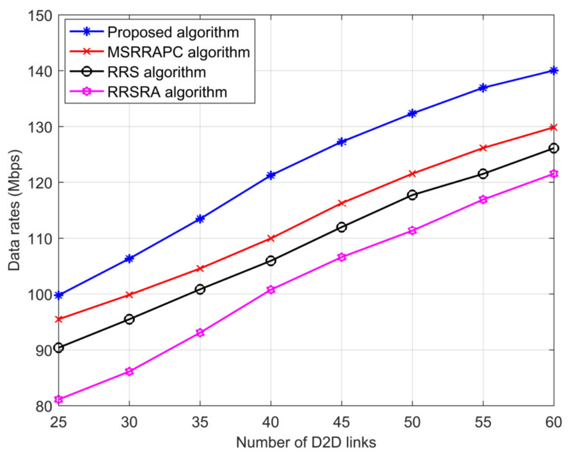

FIGURE 4. Achievable end-to-end data rates versus the number of D2D links, where $d_{s_n,d_n} = 150$m and $p_n^{max} = 20$dBm.

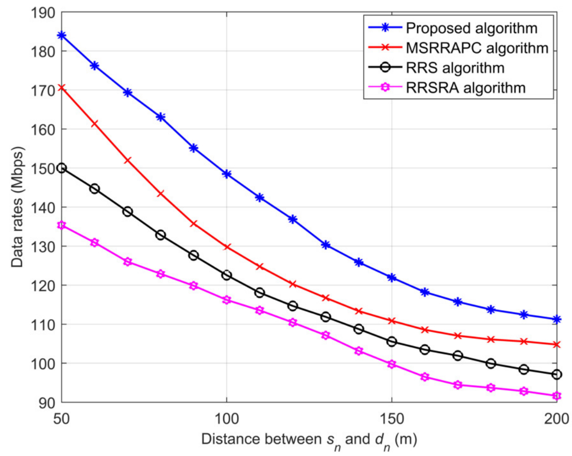

FIGURE 5. Achievable end-to-end data rates versus the distance between two DUs, where $N = 40$ and $p_n^{max} = 20$dBm.

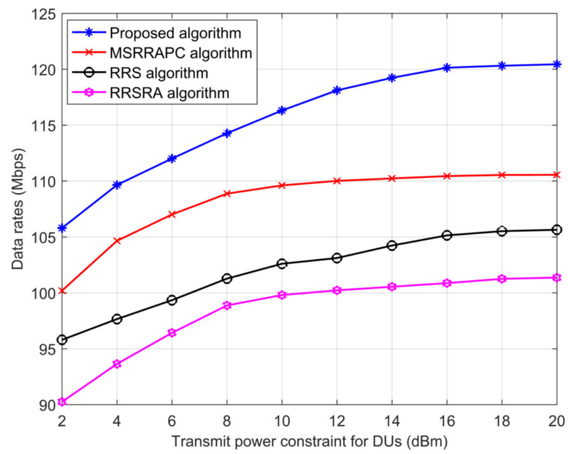

FIGURE 6. Achievable end-to-end data rates versus the maximum transmit power constraint for DUs, where $N = 40$ and $d_{s_n,d_n} = 150$m.

strategies proposed in this paper can achieve a remarkable result. This is because in the process of selecting optimal relay nodes, the algorithm proposed in this paper considers not only the impact of physical limitations but also the social attributes among user nodes, the performance of the network is fully guaranteed. Then, in the process of allocating channel resource, the proposed greedy-based mode selection and channel selection strategy can assign the appropriate channel resource for D2D links by taken into account the instantaneous state of the system. This not only can effectively reduce the interference between cellular and D2D links, thereby ensuring the achievable end-to-end data rates of the system, and can also make the problem mathematically tractable. It is commonly known that the RRSRA algorithm has the worst performance as the relay node selection and channel resource allocation of RRSRA are all randomly, which is also can be verified in the Fig. 3.

Fig. 4 illustrates the achievable end-to-end data rates of the system with respect to the number of D2D links N. We can see that as N increases, the achievable end-to-end data rates of all algorithms increase sharply. The proposed algorithm in this paper is performs drastically better than the other three algorithms. Moreover, when $N = 40$, the achievable end-to-end data rates of the proposed algorithm is 10.27%, 14.43% and 20.34% higher than that of MSRRAPC, RRS and RRSRA, respectively. This demonstrates the superiority of the proposed algorithm in improving the transmission data rates of the system.

Fig. 5 gives the effect of the distance between two DUs s_n and d_n on the achievable end-to-end data rates of the system. We can see that with the increase of the distance between s_n and d_n, the achievable end-to-end data rates of the system decrease gradually. However, the achievable end-to-end data rates of the proposed algorithm is always better than the other three algorithms. From Fig. 5 we can also get that when $d_{s_n,d_n} = 100$m, the transmission data rates of the proposed algorithm is 14.41%, 21.13% and 27.8% higher than that of MSRRAPC, RRS and RRSRA, respectively.

Fig. 6 illustrates the achievable end-to-end data rates of the system with respect to the maximum transmit power constraint for DUs. We can see that the performance of the designed algorithm in this paper is significantly better than the other three algorithms. This observation verifies that the designed algorithm can better utilize the gain of data rates brought by the RNs. We can also observe that the data rates of the system increase quickly with the increasing of maximum transmit power constraint for DUs at the beginning and the slope of the curve becomes constant in the end. This is because with the increasing of maximum transmit power constraint, the interference to CUs increases and when the interference to CUs reaches the threshold, the data rates of the system stop increasing in spite of the increase of maximum transmit power constraint for DUs. When the curve becomes constant, we can conclude that the achievable end-to-end data rates of the proposed algorithm is 8.95%, 14.11% and 18.84% higher than that of MSRRAPC, RRS and RRSRA, respectively.

VI. CONCLUSION

In this paper, we investigate the issue of joint relay selection and resource allocation for relay-assisted D2D communication networks. We formulate the original optimization problem into a MINLP problem, which aims at maximizing the transmission data rates of the system while guaranteeing the minimum QoS requirements for both CUs and DUs. Then a three-step approach is designed to handle this optimization problem. We first propose a low-complexity social-aware relay selection algorithm based on regional delineation mechanism and social relationships among users to select the suitable RNs for D2D links. On basis of that, power control algorithms for both D2D direct mode and relay mode are considered to maximize the achievable transmission data rates of cellular and D2D links. Finally, a greedy-based joint mode selection and channel allocation algorithm for all D2D links is proposed, which can not only allocate appropriate channel resource for D2D links, but also switch the communication mode for D2D links flexibly according to the sum transmission data rates. Simulation results demonstrate that the proposed algorithm in this paper can greatly enhance the total transmission data rates of the system and dramatically improve the heterogeneous D2D network performance compared with other algorithms. In the future work, we will continue to study the impact of social attributes among users on the performance of D2D communication networks.

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