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Accelerating Content Delivery via Efficient Resource Allocation for Network Coding Aided D2D Communications

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ABSTRACT Device-to-device (D2D) communication is one of the emerging paradigms in 5G networks to facilitate ever-increasing demands for local area services. For content delivery, direct transmission via D2D communications among proximity nodes and cooperative content downloading from base stations can enhance system capacity, which on the other hand cause interference to regular cellular networks due to spectrum sharing. Random linear network coding is capable of improving robustness to the varying channel state with severe interference. It also increases collaborative efficiency between users for content sharing. This paper investigates cooperative relaying scheme (RNCC) for cooperative D2D communications, which is aided by the random linear network coding. This is achieved by allocating the downlink resource among multiple cellular users, cooperative relays, and D2D pairs. First a binary integer linear programming-based resource allocation problem is modeled by introducing D2D pairs' clustering concept, which is an NP-hard problem. For the optimal solution, we leverage the branch-and-cut algorithm. While for large scale networks, we contributed a distributed QoS-aware greedy algorithm, which yields close to optimal solution. Our proposed schemes are evaluated via the extensive simulations considering practical scenarios, and the system sum rate results demonstrate an enhancement of $\sim$20% performance in comparison with several other practical strategies in literature, which validates our schemes' effectiveness.

INDEX TERMS Cooperative device-to-device communication, network coding, resource allocation, content delivery.

I. INTRODUCTION

Proliferation of mobile Internet connectivity via ubiquitous wireless access along with innovative applications and services has caused and will increase the mobile data traffic twice as fixed IP traffic between 2017 and 2022 as reported by Cisco Visual Networking Index [1]. Specifically, its compound annual growth rate will reach 46% by 2022 accomplishing 77.5 exabytes/month; and over two-thirds will be video contents [1]. Presently, conventional cellular and WiFi networks facilitate the mobile content downloading [2], and lacks in coping with the future needs. Indeed, the issue of limited bandwidth due to inadequate spectrum severly limit the applications of mobile content downloading, which include voice communication, video transmissions, and music streaming. To meet the ever-growing mobile cellular traffic, heterogeneous architecture combining cellular and device-to-device (D2D) communications supported by 5G network is a propitious solution [3].

With the rapid growth of demand for local area services, device-to-device (D2D) communication has been envisaged and integrated in the next generation mobile network to meet such demands [4]. There are several use-cases of D2D communications, which include cellular data offloading, content-distribution, and cellular data relaying [3]. In D2D communication, user equipments (UEs) in proximity

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transmit the sharing contents over direct links to the nearby devices bypassing cellular base station (BS) [5]. D2D communication comprises of two transmission modes: the direct D2D approach and cooperative D2D approach. The direct D2D mode not only saves energy consumption due to proximity but also improves spectral efficiency by directly sharing the contents of common interest [6]. Especially, local data services, such as contents sharing will benefit significantly [7]. The cooperative D2D scheme speeds up the content downloading between the BS and the end user by enabling the cellular user to act/work as the relay in the network. For this cooperation, they adopt dominant relay protocols known as decode-and-forward and amplify-and-forward [8]. Combined with the above two transmission modes, the system capacity of D2D communications is increased through local content sharing among proximity cellular users and cooperative content downloading from the BS.

Cooperative D2D communications cause complex interference to the existing cellular network due to reuse of spectrum, which may decrease the system performance seriously. Under cooperative D2D communications, the D2D nodes reuse the same spectral resources with relays and normal cellular UEs. Thus, mutual interference exists between the direct D2D pairs and cooperative D2D pairs. To achieve maximum system achievable rate, a robust cooperative D2D transmission scheme is designed by effectively allocating resource among relays, normal cellular users, D2D pairs, and relays.

More efficient collaboration among users can be achieved by network coding under the time-variant channel as the result of severe interference [9]–[11]. Osseiran *et al.* [9] reduced the frame error rate by combining cooperative transmission with network coding. Similarly, Frank *et al*. achieves efficient collaboration with network coding. In another work, Pahlevani *et al.* [11] mainly discussed the intra-session network coding applications' for D2D communication utilizing the random linear network coding (RLNC). This was an algebra coding scheme for reliable data transmission [12]. The authors also used RLNC as erased code for the block fading channel in [13], [14]. Similarly, for multi-hop wireless networks, Huang *et al.* [15] utilized RLNC as the intra-session network coding that used the recoding characteristic. The cooperative performance fast varying channel states can be improved with the help of rateless coded cooperative relay schemes [16]–[18]. Castura and Mao [16] established a rateless code based two-phase collaboration framework for wireless relay networks, and Nikjah and Beaulieuva [17] proposed a much simpler rateless coded relaying scheme. The performance of fountain codes was analyzed considering multi-hop cooperative relay networks [18]. Therefore, RLNC is suitable for cooperative D2D communications as the intra-session network coding due to the feature of rateless and recoding.

Resource allocation for cooperative D2D communications includes assignments for D2D pairs and cooperative relays of normal cellular users. Existing works mainly focused on the direct D2D issues such as interference management [23]–[25] and resource allocation [19]–[22]. For example, Xu *et al.* [21] allocated the downlink resources of cellular users to the D2Ds leveraging reverse iterative combinatorial auction method. Different from [21], Li *et al.* [22] considered a large scale cellular network and put forward a coalition formation game based approach assuming uplink scenario for allocating the cellular users' resources to D2D pairs. Apart from resource allocation discussed above, Min *et al.* [24] introduced innovative approach to tackle interference between cellular users and D2Ds, and increase the overall system capacity. Similarly, in cooperative D2D networks, the problem of relay selection in the scenario of multiple users and relays became significantly complicated [26]–[29]. In this regard, Kadloor and Adve [26] framed a relay selection problem as a convex optimization problem considering power allocation and achieved close-to-optimal solution. In another work, Pham *et al.* [27] put forward a mixed-integer linear programming problem for relay assignment and maximize the system capacity. Similarly, Zhang *et al.* [28] considered jointly the problem of subcarrier assignment and relay selection in OFDMA based relay networks. Zhou *et al.* [29] focused on two-hop relay networks with multiple source-destination pairs and proposed interference aware relay selection scheme .

However, few aforementioned works investigated the cooperative approach aided with network coding and the resource allocation scheme underlying cellular networks. As the same normal cellular UEs resources is shared by D2D pairs for cooperative D2D transmission, resource allocation among UEs and D2D pairs impacts cooperative relay selection. The cooperative D2D relaying influences D2D pairs sharing spectrum with cellular UEs due to the interference from both UEs and relays. Thus, we need to optimize the resource allocation of both relay and D2D pair to effectively manage the interference along with maximizing the cooperative D2D communications' gain. To get the fundamental performance bound achievable by cooperative D2D communications, it is imperative to determine the optimal resource allocation firstly under the network coding assisted scenario.

In this work, we mainly focus on the resource allocation problem in D2D communications consisting of two modes of transmission: termed as the direct D2D approach and cooperative approach. Taking into account the interference among cellular UEs, D2D pairs, and relay nodes, we frame an optimization problem for the resource allocation of network coding aided cooperative D2D communications. We consider different constraints such as cellular user's minimum rate requirement, restrict D2D pair to occupy only one resource block, and can get single relay assistance only. We obtain the optimal solutions through the proposed algorithms. We summarize our paper main contributions as follows:

- We introduce the RLNC to cooperative D2D communications that improves the system's achievable rate by tapping its rateless and recoding characteristics. To the authors' best knowledge, this is the first study to consider the resource allocation problem for cooperative D2D communication aided with network coding.

- We devise the resource allocation problem considering cooperative D2D communications as an achievable rate maximization problem. Moreover, we used D2D pairs' clustering method to further simplify the problem, and attain the optimal solutions via the branch-and-cut algorithm.
- We propose close optimal greedy and distributed algorithm to reduce the computational complexity for large scale networks. We evaluate how different networking environments influence our algorithms' performance. Our proposed algorithm performance is very close to optimal solution, and just lags behind 1.3%, when cellular users' number are varied assuming multiple D2D pairs and cooperative relays in a given scenario. In comparison to our previous work [22], we utilize smaller number of switching operations to ensure the same performance.

The remaining part of our paper is organized as follows. The system overview and models are introduced in Section II, followed by the optimization problem that is framed in Section III. Next, the optimal resource allocation is obtained by introducing the D2D pairs clustering's concept in Section IV, and then, we provide the near-optimal greedy and distributed algorithm in Section V. Performance evaluation and discussions are presented in Section VI, and finally Section VII concludes this work.

II. SYSTEM OVERVIEW AND MODELS

In this section, we first give a system overview for the cooperative D2D communications underlying cellular networks. Then we provide the system model and derive the achievable rate of the cellular user and D2D pairs.

A. SYSTEM DESCRIPTION AND PROBLEM OVERVIEW

This paper focuses on a single cell scenario considering relays and cellular UEs. We take into account the intra-cell interference only caused by the coexistence of cooperative D2D communications, with the assumption of the efficient inter-cell interference control mechanisms [4]. In our system, we assign appropriate resource blocks of cellular users to the D2D pairs and cooperative relays in the downlink scenario to get the maximum achievable transmission rate. It is noticed that in the same time slot, D2D pairs and the cooperative relays can share the same resources with the cellular UEs. Therefore, the interference among them needs to be limited for optimizing system performance. Thus, we allocate the resources of the cellular UEs appropriately to the cooperative relays and D2D pairs.

Our cooperative D2D communication system consists of multiple cellular users, D2D pairs, and cooperative relays, which contains direct D2D and cooperative D2D schemes. The cellular users cu_1 and cu_2 have the minimum rate due to QoS requirement as shown in Fig. 1. The D2D pairs (d_1^1, d_1^2) operate under direct D2D transmission mode to share the common interest contents by reusing the spectrum of cu_1, while D2D pairs, (d_2^1, d_2^2) and (d_3^1, d_3^2), occupy the spectrum

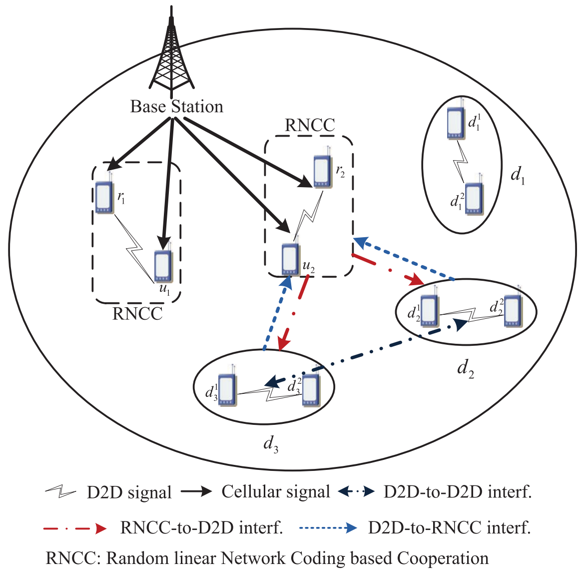

FIGURE 1. This figure shows the resource sharing relations assuming a cellular network based cooperative D2D communications, comprising of cellular users (i.e., cu_1 and cu_2), D2D pairs (i.e., d_1, d_2, & d_3), and cooperative relays (i.e., r_1 and r_2).

resource of cu_2 to exchange the same interested contents. Besides, cellular users cu_1 and cu_2 are assisted by two relays r_1 and r_2, respectively, through random linear network coding based cooperative relaying (RNCC). In this system, we adopt the rateless coded relaying protocol in [17] as the cooperative relay scheme to speed up the content downloading. r_1 and r_2 shares the same spectrum resource with cu_1 and cu_2, respectively.

Cooperative relays and direct D2D pairs may share the cellular users' downlink resources for communication. One relay is designed to support only one cooperative D2D transmission, while multiple D2D pairs are allowed to reuse the same cellular user's resource for maximizing system performance. Since different cellular users are allocated the different downlink resources, the cooperative D2D transmissions associated with one cellular user will not interfere another cellular user. Thus, the only signal interference to be considered is the one among the cellular user, its corresponding cooperative D2D and direct D2D pairs. Consider a cellular user cu shares the resource with the D2D pairs and cooperative relay. As illustrated in Fig. 1, the BS transmits signal s_u to the cellular user cu in the downlink scenario, and the D2D pair $d \in \mathcal{D}$ associated with cu transmits signal s_d. The received signals at the cellular user cu, relay r, and D2D receiver d are represented as y_{cu}, y_r and y_d, respectively, and are derived as follows:

$$y_{cu} = y_{b,cu} + \sum_{d\in\mathcal{D}} g_{du}\sqrt{p_{d,cu}}s_d + n_{cu}, \tag{1}$$

$$y_r = y_{b,r} + \sum_{d\in\mathcal{D}} g_{dr}\sqrt{p_{d,r}}s_d + n_r, \tag{2}$$

$$y_d = g_{dd}\sqrt{p_{d,d}}s_d + y_{b,d} + \sum_{d^0\in\mathcal{D}\setminus\{d\}} g_{d^0d}\sqrt{p_{d^0,d}}s_{d^0} + n_d, \tag{3}$$

where $y_{b,cu}$, $y_{b,r}$, and $y_{b,d}$ denote the received signals from BS at cu, r and d, respectively, determined by the cooperative D2D transmission scheme RNCC. Moreover, $g_{i,j}$ characterizes the channel coefficient for the $i-j$ link; where the transmitted power from i to j is represented by $p_{i,j}$, and n_j denotes the additive white Gaussian noise (AWGN) at receiver j with power spectral density N_0.

We consider a Rayleigh fading channel model for the transmission link between i to j, and there channel coefficients complies the independent complex Gaussian distribution [21]. The power received at node j from i can be derived as $p_{ij} = p_i \cdot |g_{ij}|^2 = p_i \cdot x_{ij}^{-\omega} \cdot |g_0|^2$ assuming path loss model. Here, x_{ij}, g_0, and ω represent the distance between i and j, and the channel coefficient that follows $\mathcal{CN}(0, 1)$ distribution, and the path-loss exponent, respectively.

In this cooperative D2D communications underlying cellular network, there exist two transmission schemes: direct D2D transmission via proximity users for content sharing and the cooperative relay scheme via relay nodes for content downloading. For example, cellular d_1^1 has the contents, which are interested by d_1^2. d_1^2 can obtain the contents from d_1^1 instead of the BS through direct D2D transmission. On the other hand, when r_1 does not have the contents for cu_1, it can act as the relay to assist cu_1 for content downloading through the cooperative D2D scheme. These two kinds of D2D communications cause severe interference due to spectrum sharing. Thus, we first design the robust cooperative D2D transmission, and then propose the effective interference management and resource allocation.

B. SYSTEM MODEL

We assume K cellular users, R relays, D D2D pairs in our proposed system denoted by the set $\mathcal{K} = \{cu_1, cu_2, \cdots, cu_K\}$, $\mathcal{R} = \{r_1, r_2, \cdots, r_R\}$ $\mathcal{D} = \{d_1, d_2, \cdots, d_D\}$, respectively. Each cellular user can select one cooperative relay r_i, $\forall r_i \in \mathcal{R}$, which assists the cellular user's transmission and shares the same cellular user's spectrum resource in different time slots. Also, the D2D pair d_i, $\forall d_i \in \mathcal{D}$ shares the same cellular user's spectral resource. For maximizing the cellular network's overall achievable transmission rate, the signal to interference plus noise ratio (SINR) needs to be considered. The SINR at any receiving terminal j can be derived and denoted by

$$\gamma_j = \frac{p_i x_{i,j}^{-\omega} |g_0|^2}{p_{int,j} + N_0}, \tag{4}$$

where $p_{int,j}$ and N_0 denote, respectively, the total interference power received by terminal j and the receiver's noise. We first derive the cellular user cu downlink achievable transmission rate according to the above interference model via RNCC cooperative D2D scheme. Then the D2D pair d achievable rate is obtained under the interference from RNCC transmission.

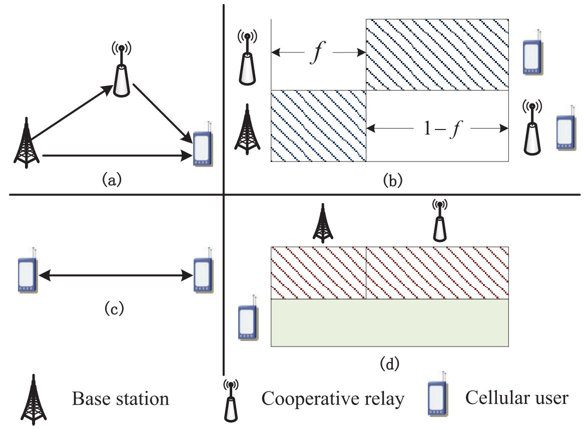

FIGURE 2. **(a) RNCC cooperative relay scheme. (b) Transmission and reception of RNCC. (c) Direct cooperative scheme. (d) Interference from RNCC scheme.**

1) RLNC CODED COOPERATIVE D2D SCHEME

As depicted in Figs. 2(a) and 2(b), RNCC comprises of two transmission phases. In the Phase 1, the BS transmits the coded packets by random linear network coding to cellular user cu. The relay r receives the coded packets because of wireless medium's inherent broadcasting nature. RNCC enters the Phase 2 as relay r receives adequate coded packets that are linear independent and used for source message decoding. During this phase the recoded packets r are send to cu without decoding owing to the random linear network coding's recoding feature. The BS does not transmit the coded packets to cu. Therefore, cu can recover the source's message correctly if it has received adequate linear independent coded packets. RLNC is suitable for the practical engineering implementation, as it has the rateless feature and can recode its received packets without decoding [13], [15].

Let maximum achievable rate at the cellular user cu is designated by R_{cu}^r with the cooperative relay r, and f denotes the ratio of Phase 1 to the whole RNCC transmission phase, which is mainly influenced by the channel state information (CSI) among the BS, cu and r. Under the RNCC scheme, any transmission rate R satisfies [16]

$$\begin{cases} R \le f \cdot I_{cu} + (1-f) \cdot I_{r,cu}; \\ R \le I_{b,r}; \\ R \le I_{r,cu}; \end{cases} \tag{5}$$

where $I_{b,r}$ represents the channel capacity between the BS and r. Moreover, $I_{r,u}$ and I_{cu} designate, respectively, the channel capacities from r to cu and when the BS communicates with cu directly. According to above constraints, R_{cu}^r and f can be obtained as follows:

$$\begin{cases} R_{cu}^r = \dfrac{I_{b,r} I_{r,cu}}{I_{b,r} + I_{r,cu} - I_{cu}}; \\ f = \dfrac{I_{r,cu}}{I_{b,r} + I_{r,cu} - I_{cu}}; \end{cases} \tag{6}$$

when $\min\{I_{r,cu}, I_{b,r}\} > I_{cu}$. When $\min\{I_{r,cu}, I_{b,r}\} < I_{cu}$, intuitively, the RNCC's 2nd phase transmission is not necessitated, therefore, $f = 1$ and $R^r_{cu} = I_{cu}$. Combining the above analysis, R^r_{cu} can be derived as:

$$R^r_{cu} = \frac{\max\{I_{b,r}, I_{cu}\}\max\{I_{r,cu}, I_{cu}\}}{\max\{I_{b,r}, I_{cu}\} + \max\{I_{r,cu}, I_{cu}\} - I_{cu}}. \quad (7)$$

2) ACHIEVABLE RATE (CELLULAR USER)

For obtaining the cellular user cu achievable rate, first, we define $\alpha^r_{cu,d}$ as the binary assignment variable to describe the resource allocation, where $\alpha^r_{cu,d} = 1$ entails that the UE cu resource blocks is used by D2D pair d, which is also assisted by relay r at the same time; otherwise, $\alpha^r_{cu,d} = 0$. And for direct communication, without cooperative D2D, between the BS and cellular users, we bring in a virtual relay r_{R+1} that incurs no interference for D2D pairs. $\alpha^{R+1}_{cu,d} = 1$ indicates that the BS transmits information to cu directly and cu shares its resource blocks with d. Adding r_{R+1} enlarges $\mathcal{R}$ to $\mathcal{R}^+ = \{r_1, r_2, \cdots, r_R, r_{R+1}\}$. We also define the virtual D2D pair d_0 and $\alpha^r_{cu,0} = 1$ means that no D2D pair is sharing the same resource blocks with the cellular user cu and relay r. Similarly, adding d_0 enlarges $\mathcal{D}$ to $\mathcal{D}^+ = \{d_0, d_1, d_2, \cdots, d_D\}$.

In the downlink, since cellular user, cooperative relay, and D2D pairs show the same spectrum, according to (1) and (2), therefore, the interference powers at the cellular user cu and the cooperative relay r are represented as:

$$\begin{cases} p_{int,cu} = \sum_{d\in\mathcal{D}} \alpha^r_{cu,d} p_d |g_{d,cu}|^2; \\ p_{int,r} = \sum_{d\in\mathcal{D}} \alpha^r_{cu,d} p_d |g_{d,r}|^2. \end{cases} \quad (8)$$

Thus, $I_{b,r}$, $I_{r,cu}$, and I_{cu} can be obtained as:

$$\begin{cases} I_{b,r} = \log_2(1 + \frac{p_b|g_{b,r}|^2}{\sum_{d\in\mathcal{D}} \alpha^r_{cu,d} p_d |g_{dr}|^2 + N_0}); \\ I_{r,cu} = \log_2(1 + \frac{p_r|g_{r,cu}|^2}{\sum_{d\in\mathcal{D}} \alpha^r_{cu,d} p_d |g_{d,cu}|^2 + N_0}); \\ I_{cu} = \log_2(1 + \frac{p_b|g_{b,cu}|^2}{\sum_{d\in\mathcal{D}} \alpha^r_{cu,d} p_d |g_{d,cu}|^2 + N_0}). \end{cases} \quad (9)$$

The achievable rate of cu can be derived by (8) with (9) as follows:

$$R^r_{cu} = \frac{\max\{I_{b,r}, I_{cu}\}\max\{I_{r,cu}, I_{cu}\}}{\max\{I_{b,r}, I_{cu}\} + \max\{I_{r,cu}, I_{cu}\} - I_{cu}}. \quad (10)$$

3) ACHIEVABLE RATE (D2D PAIR)

First, we find the interference power at the D2D receiver d, which is from the cellular user cu, cooperative r, and other D2D users utilizing the same spectrum. According to (3), the interference at the D2D receiver d can be derived as:

$$p_{int,d} = p_{nc,d} + \sum_{d^0\in\mathcal{D}\backslash\{d\}} z_{d^0,d} p_{d^0} |g_{d^0 d}|^2, \quad (11)$$

where $z_{d^0,d} = 1$ if and only if $\exists cu \in \mathcal{K} : \alpha^r_{cu,d} \cdot \alpha^r_{cu,d^0} = 1$; otherwise, $z_{d^0,d} = 0$. $p_{nc,d}$ refers the interference power incurred by the received signal $y_{b,d}$ of RNCC transmission scheme. As depicted in Fig. 2(d), in the cooperative Phase 1, the interference of the RNCC scheme, denoted by $p_{b1,d}$, is from the BS and can be expressed as:

$$p_{b1,d} = \sum_{cu\in\mathcal{K}} \alpha^r_{cu,d} p_b |g_{b,d}|^2. \quad (12)$$

The sum interference of first cooperative phase for d, represented by $p_{int1,d}$, is derived as:

$$p_{int1,d} = \sum_{cu\in\mathcal{K}} \alpha^r_{cu,d} p_b |g_{bd}|^2 + \sum_{d^0\in\mathcal{D}\backslash\{d\}} z_{d^0,d} p_{d^0} |g_{d^0 d}|^2. \quad (13)$$

In the second cooperative phase, the interference of the RNCC scheme, denoted by $p_{nc2,d}$, is from relay r and expressed as:

$$p_{nc2,d} = \sum_{r\in\mathcal{R}} \alpha^r_{cu,d} p_r |g_{rd}|^2. \quad (14)$$

The sum interference of the second cooperative phase for d, represented by $p_{int2,d}$, is derived as:

$$p_{int2,d} = \sum_{r\in\mathcal{R}} \alpha^r_{cu,d} p_r |g_{rd}|^2 + \sum_{d^0\in\mathcal{D}\backslash\{d\}} z_{d^0,d} p_{d^0} |g_{d^0 d}|^2. \quad (15)$$

From Fig. 2(b), it is noticed that the Phase 1 and 2 of cooperative RNCC happens in different time slots. Hence, the achievable rate of D2D pair d is derived as:

$$R_d = f \cdot \log_2\left(1 + \frac{p_d|g_{dd}|^2}{p_{int1,d} + N_0}\right) + (1-f) \cdot \log_2\left(1 + \frac{p_d|g_{dd}|^2}{p_{int2,d} + N_0}\right), \quad (16)$$

where f is determined accordingly as:

$$f = \begin{cases} \frac{I_{r,cu}}{I_{b,r} + I_{r,cu} - I_{cu}}, & \min\{I_{r,cu}, I_{b,r}\} > I_{cu}; \\ 1, & others, \end{cases} \quad (17)$$

which is given in (6).

III. PROBLEM FORMULATION

The previous analysis shows that R^r_{cu} and R_d rely upon the resource assignments for both cooperative D2D and direct D2D pairs, $\alpha^r_{cu,d}$, $cu \in \mathcal{K}$, $d \in \mathcal{D}^+$, $r \in \mathcal{R}^+$. In this paper, we focus on optimizing this assignment to maximize the sum rate of cellular user cu and the associated D2D pairs. Thus, $R_{sum}(X)$ represents the downlink system sum rate, where X represents the matrix of $\alpha^r_{cu,d}$, $cu \in \mathcal{K}$, $d \in \mathcal{D}^+$, $r \in \mathcal{R}^+$, and is computed as:

$$R_{sum}(X) = \sum_{cu\in\mathcal{K}} \left(\sum_{r\in\mathcal{R}^+} \alpha^r_{cu,d} R^r_{cu} + \sum_{d\in\mathcal{D}^+} \sum_{r\in\mathcal{R}^+} \alpha^r_{cu,d} R_d \right), \quad (18)$$

which depends on both the relay assignments for the cellular users and sharing relations of spectral resource between the cellular users and D2D pairs. In the downlink cellular network, each cellular user cu has the minimum rate requirements $\overline{R_{cu}}$, which needs to be guaranteed due to QoS requirements.

We limit that each cellular user can get only one relay for assistance, as multiple cooperative relays need the complex synchronization mechanism [26]. Thus, we have the constraint C. The equal-sign is due to the virtual relay r_{R+1}. It is assumed that one relay can cooperate with multiple cellular users. Since it is supposed that a D2D pair can reuse the resource of only one cellular user, therefore, the constraint is expressed as $\sum_{cu\in\mathcal{K}} cu, d^r \leq 1, \forall d \in \mathcal{D}, \forall r \in \mathcal{R}^+$. As multiple cellular users may not share their resource blocks, the virtual D2D pair d_0 is not in this constraint. In this resource allocation mode, since it enables more than one D2D pairs to occupy the cellular user's spectral resource, consequently, the spectrum resource reuse ratio can be enhanced. Thus, we can frame an optimization problem to get optimal resource allocation in the cooperative D2D underlying cellular network, which is given as:

$$\max_{\alpha^r_{cu,d}} R_{sum}(\alpha^r_{cu,d})$$
$$s.t. \begin{cases} \sum_{r\in\mathcal{R}^+} \alpha^r_{cu,d} = 1, \ \forall cu \in \mathcal{K}, \ d \in \mathcal{D}^+; \\ \sum_{cu\in\mathcal{K}} \alpha^r_{cu,d} \leq 1, \ \forall d \in \mathcal{D}, \ r \in \mathcal{R}^+; \\ \sum_{r\in\mathcal{R}^+} \alpha^r_{cu,d} R^r_{cu} \geq \overline{R_{cu}}, \ \forall cu \in \mathcal{K}; \\ \alpha^r_{cu,d} \in \{0, 1\}, \ \forall cu \in \mathcal{K}, \ r \in \mathcal{R}^+, \ d \in \mathcal{D}^+. \end{cases} \quad (19)$$

The first constraint guarantees that each cellular user is aided by only one cooperative relay; the second constraint limits the cellular user's resource block to one for each D2D transmitting node, and the final constraint guarantees each cellular user's minimum rate requirement.

As the aforementioned problem is clearly a non-linear and binary integer programming problem having $K(1 + R)(1 + D)$ variables, and such problems are NP-hard [30]. In this optimization framework, it is further observe that no concave properties are present in the objective function with $\alpha^r_{cu,d}$, even if we consider all the other constraints as linear. Thus, this framework not only head to a non-linear but also characterizes it as the non-convex optimization problem [30]. Next, we leverage the clustering concept for D2D pairs to transform the discussed problem to a binary linear integer programming problem, and further reduce the number of optimization variables by exploiting the property of optimum solutions.

IV. OPTIMAL RESOURCE ALLOCATION SCHEME

For simplifying the formulated problem (19), first of all, we need to identify the key factor that causes the characteristic of non-linear and non-convex in the formulated problem.

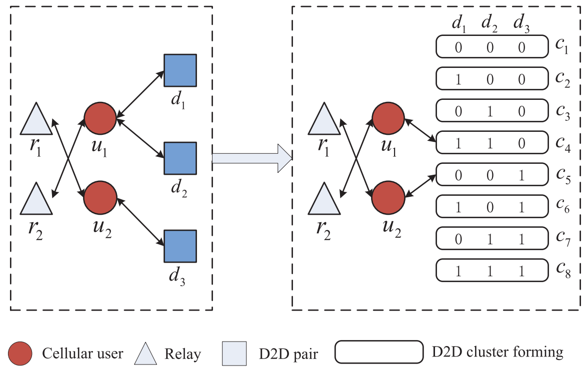

FIGURE 3. This figure has two parts, here, the left side shows the resource allocation model established on the relation $\alpha^r_{cu,d}$, while the right side depicts the resource allocation model based on $\omega^r_{cu,c}$ for the scenario shown in Fig. 1.

For the scenario showing in Fig. 1, we view our proposed resource allocation as the problem of maximizing weighted matching among cellular users $\mathcal{K}$, cooperative relays $\mathcal{R}$, and D2D pairs $\mathcal{D}$. In the Fig. 3, we show a matching graph in the left, where the squares, circles and triangles denote D2D pairs, cellular user, and relay terminal, respectively. The optimization variable $\alpha^r_{cu,d}$ determines the link relationship of the matching graph. The feasible resource allocation solution underlying cellular network is illustrated in the Fig. 3 (i.e., left side), where $\alpha^{r_2}_{cu_1,d_1} = 1$, $\alpha^{r_2}_{cu_1,d_2} = 1$ and $\alpha^{r_1}_{cu_2,d_3} = 1$. Furthermore, the edge values between the cellular user cu and the cooperative relay r and between cu and D2D pair d are defined, respectively, as R^r_{cu} and R_d. From (10) and (16), we can observe that R^r_{cu} is changing by the number of D2D pairs occupying the same cu resource. Similarly, R_d also changes by the number of D2D pairs that share or reuse the same resource. This is because of the other D2D pairs' interference sharing the same resource blocks with d. For example, d_1 and d_2 occupy the same resource block of cu_1. Although $\alpha^{r_2}_{cu_1,d_1} = 1$, $R^{r_2}_{cu_1}$ has two different values when $\alpha^{r_2}_{cu_1,d_2} = 0$ or $\alpha^{r_2}_{cu_1,d_2} = 1$. This changing value of the edges, incurred by mutual interference between d_1 and d_2, makes the formulated problem be non-linear and non-convex.

In order to eliminate the mutual interference among D2D pairs, we define one D2D pairs' combination i.e., $\mathcal{D} = \{d_1, d_2, \cdots, d_D\}$ as a cluster c. The cluster set is expressed as $\mathcal{C} = \{c_1, c_2, \cdots, c_C\}$, and the number of all possible clusters is computed as:

$$\binom{D}{0} + \binom{D}{1} + \cdots + \binom{D}{D} = 2^D. \quad (20)$$

Specifically, $c_i = \{v^1_i, v^2_i, \cdots, v^D_i\}$, $v^j_i \in \{0, 1\}$. $v^j_i = 0$ indicates that D2D pair d_j is not selected by cluster c_i; otherwise, $v^j_i = 1$. From the Fig. 3 (i.e., right side), $c_4 = \{1, 1, 0\}$ entails that c_4 has selected only d_1 and d_2. Here we conduct resource blocks allocation for cellular users cu, D2D clusters c, and cooperative relays r instead of D2D pairs d. We denote the assignment variable with $\beta^r_{cu,c}$. If cluster c

takes the already used spectral resource of cu and r, $\beta^r_{cu,c} = 1$, otherwise, $\beta^r_{cu,c} = 0$. It is worth noticing that as per setting each D2D cluster c (except c_0) only shares one cellular user cu spectrum, therefore, no interference emerges since no d gets the same spectrum as cu. This constraint eliminates the inter-cluster interference among the different D2D formed clusters. In other words, if $\beta^r_{cu,c} = 1$, the edge value between D2D cluster c and cellular user cu is not affected by other values of $\beta^r_{cu,c}$. Similarly, the edge value between cooperative relay r and cellular user cu is not changed.

The resource assignment founded on $\beta^r_{cu,c}$ is same as that established on $\alpha^r_{cu,d}$. Since each value of $\alpha^r_{cu,d}$ is equivalent to the value of $\beta^r_{cu,c}$. For example, in the left side of Fig. 3 the resource allocation is based on $\alpha^r_{cu,d}$, which is tantamount to the one located at the right side of the figure, where $\beta^{r2}_{cu_1,c_4} = 1$ and $\beta^{r1}_{cu_1,c_5} = 1$. The edge value between cooperative r and cellular user cu is denoted by R^r_{cu}. The edge value between D2D cluster c and cellular user cu is expressed by R_c. Based on the interference's previous analysis, R^r_{cu} can be computed on the basis of D2D clustering, which is given as follows:

$$\begin{cases} I_{b,r} = \log_2(1 + \dfrac{p_b|g_{b,r}|^2}{\sum\limits_{d\in c} p_d|g_{dr}|^2 + N_0}); \\ I_{r,cu} = \log_2(1 + \dfrac{p_r|g_{r,cu}|^2}{\sum\limits_{d\in c} p_d|g_{d,cu}|^2 + N_0}); \\ I_{cu} = \log_2(1 + \dfrac{p_b|g_{b,cu}|^2}{\sum\limits_{d\in c} p_d|g_{d,cu}|^2 + N_0}); \\ R^r_{cu} = \dfrac{\max\{I_{b,r}, I_{cu}\}\max\{I_{r,cu}, I_{cu}\}}{\max\{I_{b,r}, I_{cu}\} + \max\{I_{r,cu}, I_{cu}\} - I_{cu}}. \end{cases} \tag{21}$$

R_c based on D2D cluster can be obtained as:

$$\begin{cases} p_{int1,d} = p_b|g_{bd}|^2 + \sum\limits_{d^0\in c\setminus\{d\}} p_{d^0}|g_{d^0d}|^2; \\ p_{int2,d} = p_r|g_{rd}|^2 + \sum\limits_{d^0\in c\setminus\{d\}} p_{d^0}|g_{d^0d}|^2; \\ R_d = f\cdot R_{d1} + (1-f)\cdot R_{d2}; \\ R_c = \sum\limits_{d\in c} R_d. \end{cases} \tag{22}$$

For brevity, we define R_{d1} and R_{d2} as:

$$R_{d1} = \log_2\left(1 + \frac{p_d|g_{dd}|^2}{p_{int1,d} + N_0}\right), \tag{23}$$

$$R_{d2} = \log_2\left(1 + \frac{p_d|g_{dd}|^2}{p_{int2,d} + N_0}\right). \tag{24}$$

For each value of $\beta^r_{cu,c}$, we have the sum rate $R_{sum} = R^r_{cu} + R_c$, and each cellular user allows using its resources with just one D2D cluster (except c_0). Besides, $\sum_{c\in\mathcal{C}\setminus c_0} \beta^r_{cu,c} \leq 1, \forall cu \in K, \forall r \in \mathcal{R}^+$. Moreover, D2D pairs can't be apportioned more than once. Therefore, we limit that $\sum_{c\in\mathcal{C}\setminus c_0} \beta^r_{cu,c} c \leq \bar{c}, \forall cu \in \mathcal{K}, \forall r \in \mathcal{R}^+$, where the vector $\bar{c}$ entries are all ones $[11\cdots 1]$. Based on optimization variables $\beta^r_{cu,c}$, we reformulate the problem in (19) accordingly as:

$$\max \sum_{cu\in\mathcal{K}}\sum_{r\in\mathcal{R}^+}\sum_{c\in\mathcal{C}} \beta^r_{cu,c}\left(R^r_{cu} + R_c\right)$$
$$s.t. \begin{cases} \sum\limits_{r\in\mathcal{R}^+} \beta^r_{cu,c} = 1,\ \forall cu \in \mathcal{K},\ c \in \mathcal{C};\ \sum\limits_{cu\in\mathcal{K}} \beta^r_{cu,c} = 1, \\ \forall c \in \mathcal{C},\ r \in \mathcal{R}^+; \\ \sum\limits_{cu\in K}\sum\limits_{c\in\mathcal{C}} \beta^r_{cu,\,c} c \leq \bar{c},\ \forall r \in \mathcal{R}^+; \\ \sum\limits_{r\in\mathcal{R}^+} \beta^r_{cu,\,c} R^r_{cu} \geq \overline{R_{cu}},\ \forall u \in \mathcal{K}; \\ \beta^r_{cu,\,c} \in \{0, 1\},\ \forall cu \in \mathcal{K},\ r \in \mathcal{R}^+,\ c \in \mathcal{C}. \end{cases} \tag{25}$$

As the aforementioned problem is a binary integer linear programming (BILP) and is already proven to be NP-complete [30]. Therefore, for obtaining optimal solution, we can use optimization tools, such as CPLEX [31]. However, long running time is needed due to $K(R+1)C$ optimization variables. Thus, we need to exploit the property of (25) to further reduce the number of optimization variables. Let's take an assumption that $(\beta^r_{cu,c})^*$ characterizes the optimal solution to (25), and $(\beta^{r_s}_{cu,c})^* = 1$, where r_s refers the selected relay. Hence, we can have the following:

$$(R^{r_s}_{cu} + R_c) = \max_r (R^r_{cu} + R_c),\ R^{r_s}_{cu} \geq \overline{R_{cu}}, \tag{26}$$

which implies that the cooperative relay selection can be determined by each link from cellular user to cooperative cluster. For instance, if the Equation (26) is not satisfied, then the cooperative relay r_t can be found as the feasible solution that guarantees $(R^{r_t}_{cu} + R_c) = \max_r(R^r_{cu} + R_c)$. The outcome of feasible solution $(\beta^{r_t}_{cu,c})^* = 1$ is larger in comparison to that of $(\beta^{r_s}_{cu,c})^* = 1$, and the cooperative relay r_s can be substituted by r_t to attain enhanced sum rate. Thus, (26) is valid for all optimal solutions and the optimization problem in (25) can be reformed as follows:

$$\max \sum_{cu\in\mathcal{K}}\sum_{c\in\mathcal{C}} \beta^{r_s}_{cu,c}\left(R^{r_s}_{cu} + R_c\right)$$
$$s.t. \begin{cases} \sum\limits_{c\in\mathcal{C}} \beta^{r_s}_{cu,c} = 1, & \forall cu \in \mathcal{K}; \\ \sum\limits_{cu\in\mathcal{K}}\sum\limits_{c\in\mathcal{C}} \beta_{cu}, & c^{r_s} c \leq \bar{c}; \\ \beta^{r_s}_{cu,c} \in \{0, 1\}, & \forall u \in \mathcal{K}, c \in \mathcal{C}; \end{cases} \tag{27}$$

where

$$\begin{cases} r_s = \arg\max_r \left(R^r_{cu} + R_c\right), & \forall cu \in \mathcal{K},\ \forall c \in \mathcal{C}, \\ R^{r_s}_{cu} \geq \overline{R_{cu}}. \end{cases} \tag{28}$$

Now the BILP problem of (25) with $K(R+1)C$ variables is reduced to UC variables, hence, it became possible to be solved optimally by leveraging the method known as branch-and-cut, whose computational complexity is exponential in

Algorithm 1 QoS-Aware Greedy Algorithm for Relay Selection and D2D Pair Assignment

Initialization:
  Initialize the position information of cellular users $\mathcal{K}$, $\mathcal{R}$ and relays $\mathcal{D}$;
  Initialize required minimum rates $\overline{R_{cu}}$;
Calculate achievable rate R^r_{cu} of cu;
while $\mathcal{D} \neq \emptyset$ **do**
  Step 1: Calculate w_d with (34);
  Select $d^s = \arg\max_{d \in \mathcal{D}} \omega_d$;
  Set $\mathcal{E} = K$, $d^s_u = \emptyset$;
  Step 2: Assign d^s to each cu, $cu_m = \arg\max_{u \in \mathcal{E}} R_{cu}, \mathcal{D}^r_{cu}$;
  $R_{cu_m,\delta} = R^r_{cu_m,\mathcal{D}_{cu}} - R_{cu_m,bak}$;
  Draw a random variable ψ is uniform distribution (0,1], and set $\exp(R_{cu_m,\delta}/R_\delta)$;
  Step 3: Calculate the QoS requirement;
  if $(R^r_{cu_m} > \overline{R_{cu}})$ & $(\eta_{cum} > \psi)$ **then**
    $d^s_{cu} = d^s_{cu} \cup cu_m$, $R_{cu_m,bak} = R^r_{cu_m,\mathcal{D}_{cu}}$;
  else
    $\mathcal{E} = \mathcal{E} \backslash cu_m$;
    if $\mathcal{E} \neq \emptyset$ **then**
      Return to Step 2;
    end if
  end if
  $\mathcal{D} = \mathcal{D} \backslash d^s$;
end while
Output the resource allocation $\alpha^r_{cu,d}$.

general [30]. However, recent proposed techniques, such as primal heuristics and balance maintaining, can locate an optimal solution efficiently [32]. The computation complexity of modified method is exponential in the worst case.

V. QOS-AWARE GREEDY AND DISTRIBUTED ALGORITHMS

In this section, we depict the greedy and distributed algorithm for resource allocations for large scale networks. The first step is to get the initial solutions through our proposed greedy algorithm, and the second step is to obtain the close optimum solutions through the distributed algorithm based on the above initial solutions. Therefore, our designed scheme consists of two algorithms: QoS-aware greedy algorithm and distributed algorithm.

A. QOS-AWARE GREEDY ALGORITHM

The branch-and-cut algorithm needs long running time to get an optimal solution when the number of variables in a optimization problem is a few hundred variables [32]. From the definition of D2D cluster $\mathcal{C}$, we note that the number of $\mathcal{C}$ grows exponentially with the number of D2D pairs. The computation complexity of the branch-and-cut algorithm for a large number of D2D pairs increases exponentially. Thus, we need to design the more efficient algorithm to decrease the running time. On the other hand, each cellular user has its minimum transmission rate, which needs to be guaranteed for QoS requirement. From the above analysis, the aim of cooperative relay is to increase the capacity of cellular user u through the RNCC scheme, and D2D pairs working in the same spectrum increase the overall capacity of the cellular system. Thus, we propose the QoS-aware greedy algorithm, which reduces the computation complexity significantly.

The key of our proposed algorithm is to identify the D2D pair $d's$ priority, which selects the cellular user cu at each iteration. Due to interference from D2D pairs, the achievable rate of cu is decreased. Intuitively, we note that the D2D pair, which is furthest to its associated cellular user cu, incurs the smallest interference for cu. Conversely, the other D2D pairs also suffered from interference of d, which are assigned the spectrum of cu. We construct the distance matrix $\mathcal{Z}[z_{d,cu}]_{D\times K}$ accordingly as:

$$z_{d,cu} = \sqrt{(x_d - x_{cu})^2 + (y_d - y_{cu})^2} + \sum_{d_{cu} \in \mathcal{D}_{cu}} \sqrt{(x_d - x_{d_{cu}})^2 + (y_d - y_{d_{cu}})^2}, \ \forall d \in \mathcal{D}, \ \forall cu \in \mathcal{K}, \tag{29}$$

where $x_d, y_d, x_{d_{cu}}, y_{d_{cu}}, x_{cu}$ and y_{cu} are the location information of D2D pair d, d_{cu} and cellular user cu, and BS can compute such information. $\mathcal{D}_{cu}$ denotes the D2D pairs collection that is assigned to the cellular user cu. The weighted value of d is denoted by ρ_d and is calculated as follows:

$$\rho_d = \frac{\sum_{cu \in \mathcal{K}} z_{d,cu}}{\sum_{d \in \mathcal{D}} \sum_{cu \in \mathcal{K}} z_{d,cu}}, \tag{30}$$

which determines the probability value to select d.

Next, the QoS matrix $\mathcal{Q}[q_{cu,r}]_{K\times(R+1)}$ is defined as

$$q_{cu,r} = \begin{cases} 1, & R^r_{cu} \geq \overline{R_{cu}}; \\ 0, & otherwise. \end{cases} \tag{31}$$

When the sum value of each row is larger than 0, the QoS constraints can be guaranteed. Besides, we define the accept probability of cellular user cu_m that is $\eta_{cu_m} = \min\{\exp(R_{cu_m,\delta}/R_\delta), 1\}$, R_{cu_m}, δ is the changing achievable rate of $R_{cu_m}, \mathcal{D}_{cu}{}^r$, when d is assigned to cu_m and R_δ is the predefined threshold value. When $R_{cu_m,\delta} > 0$, we have $\eta_{cu_m} = 1$ and accept cu_m. Otherwise, cu_m is accepted with the probability η_{cu_m}. When QoS constraints are not guaranteed or the accept probability is not fulfilled, cellular user cu is removed from the candidates for D2D pairs d.

Our proposed scheme is described via Algorithm 1. We initialize the physical distance matrix in Step 1. From which we can derive the weighted selection probability of each D2D pair d from (30) and use d_s with the maximum weighted probability for each iteration. In Step 2, we select the cellular user cu in the candidates collection $\mathcal{E}$, which shares its resource block with d to get the maximum capacity $R^r_{cu_m,\mathcal{D}_{cu}}$. In Step 3, when the QoS constrains and acceptance probability of each cellular user can both be satisfied with the cooperative relay, d is assigned to cu_m. Otherwise, the candidates for d is updated for the next iteration. The allocation process stops when all cellular users is searched completely. When $\mathcal{D}$ is empty, the algorithm terminates and outputs the assignment result.

As an example in Fig. 1, in Step 1, distance matrix $\mathcal{Z}[z_{d,cu}]_{3\times 2}$ and ρ_d is calculated by (29) and (30). We note that d_1 has the maximum weighted value and is selected in the first iteration. In Step 2, when d_1 utilizes the cellular users cu_1 and cu_2 frequency resourceblocks, then, we can have the sum achievable rate $R^r_{cu_1,\mathcal{D}_{cu_1}}$ and $R^r_{cu_2,\mathcal{D}_{cu_2}}$ respectively. In Step 3, we note that $R^r_{cu_1,\mathcal{D}_{cu_1}} > R^r_{cu_2,\mathcal{D}_{cu_2}}$ and $R^r_{cu_1,\mathcal{D}_{cu_1}} > \overline{R_{cu_1}}$, d_1 are assigned to cu_1. $\mathcal{D}$ is updated and the process enters the next iteration. From the above example and analysis, we have the computational complexity of aforementioned QoS-aware greedy algorithm i.e., $O(DKR)$, which is polynomial-time.

B. QOS-AWARE DISTRIBUTED SOLUTION

In our proposed system, we introduce D2D pairs cluster $\mathcal{C}$ for getting optimal resource allocation solutions among cellular users, cooperative relays, and D2D pairs. More importantly, the formulated problem (27) exploits the property of optimal solution about the relay selection and D2D pairs assignment, which simplifies the optimization problem significantly. However, with the rise in the number of $\mathcal{D}$, the number of cluster $\mathcal{C}$ also increases exponentially. Centralized greedy algorithm needs gathering the global information for all cellular users, which raises the complexity for large scale network scenario. Moreover, the greedy algorithm maximizes the achievable rate gain without considering the future impact of the resource allocations, however, for large number of D2D pairs its performance decreases. Therefore, in this subsection, we put forward a cluster based distributed algorithm. Some of the distributed resource allocation algorithms are analyzed in [22], [33], [34]. Our formal work investigated uplink resource allocation problem using coalition formation game. Vatsikas et al. [33] also leveraged coalition game for subcarrier allocation in OFDMA system. Specifically, we framed a distributed algorithm considering coalition formation as in [22], and take into account each cellular user's QoS constraint.

First the coalitions $\mathcal{T} = \{\mathcal{T}_1, \mathcal{T}_2, \cdots, \mathcal{T}_{cu}\}$ are defined, where $\mathcal{T}_i \cap \mathcal{T}_j = \varnothing$ for any $i \neq j$, and also $\cup_{i=1}^{U} \mathcal{T}_i = \mathcal{D}$. Moreover, U designates the total coalitions in the structure $\mathcal{T}$. We assume that the coalition of $\mathcal{T}_{cu}$ shares the cellular user $cu \in \mathcal{K}$ resource, and its rate $\mathcal{R}(\mathcal{T}_{cu})$ is derived as:

$$\begin{cases} R(\mathcal{T}_{cu}) = R^{\bar{r}}_{cu} + \sum\limits_{d \in \mathcal{T}_{cu} R_d}; \\ \bar{r} = \arg\max\limits_{r} (R^{\bar{r}}_{cu} + \sum\limits_{d \in \mathcal{T}_{cu}} R_d); \\ R^{\bar{r}}_{cu} \geq \overline{R_{cu}}, \end{cases} \tag{32}$$

which represents the coalition $\mathcal{T}_{cu}$ total achievable rate. Next, we define the first condition for switch operation, and is expressed as:

$$\mathcal{R}_d(\mathcal{T}_{cu}) > \mathcal{R}_d(\mathcal{T}_{cu^s}), \tag{33}$$

where $\mathcal{R}_d(\mathcal{T}_{cu})$ and $\mathcal{R}_d(\mathcal{T}_{cu^s})$ represent the achievable rates for coalitions $\mathcal{T}_{cu}$ and $\mathcal{T}^s_{cu}$, respectively. In addition, $\overline{R_{cu}}$ shows the cellular user cu minimum rate requirement. The value $\overline{R_{cu}}$ demands to be guaranteed against each switch operation for the cellular user associated with the coalition. Like the assumption in [22], we also specify the acceptance probability conditional to the unsatisfied constraint, which is defined as follows:

$$\phi_{cu,cu^s} = \exp\left(\frac{R(T_{cu^s}) - R(T_{cu})}{T_n}\right), \tag{34}$$

where $T_n = \frac{T_0}{\log(n-1)}$, in which the value of T_0 is considered constant, while n designates the current count of switch operations. We also define the second necessary condition for switching, which is given as:

$$\lambda < \phi_{cu,cu^s}, \tag{35}$$

where λ represents the uniform distribution in (0, 1].

According to the previous analysis, as shown in Algorithm 2, we design our algorithm in 3 steps. In the first step, we select D2D pair d randomly with its associated coalition. Next, the coalition $\mathcal{T}_{cu^s}$ switching is also randomly done . While in the Step 2, our algorithm chooses a relay r_s to maximize each coalition's achievable rate considering their QoS constraint. In Step 3, we execute switch operation conditional to the satisfaction of (33) and (35). Furthermore, the coalition structure $\mathcal{T}_{cur}$ is also updated accordingly. Algorithm 2 is demonstrated to converge in finite number of switch operations to the optimal solutions [22].

For computational complexity analysis in terms of cellular users K, D2D pairs D, and cooperative relays R number, we investigate two algorithms' complexity i.e., QoS-aware greedy and distributed algorithm. For computation time, we further focus on its two different parts. The greedy algorithm complexity i.e., Algorithm 1,is $O(DKR)$, while the complexity of distributed algorithm is decided by some predefined maximum iterations' number, and that is proportional to the D2D pairs' D number. For large scale networks, each switch operation complexity is $O(R)$ and the Algorithm 2 overall complexity is $O(DR)$. Based on the aforementioned analysis, our proposed algorithms' (i.e., greedy and distributed algorithm) computation complexity is obtained as $O(DKR)$, and their performance are close to the optimal solutions.

VI. PERFORMANCE EVALUATION

A. SIMULATION SETUP

For performance evaluation of our proposed algorithms, we perform extensive simulations in this section. We assume a single cell scenario for simulations, and further captured the path-loss and shadowing effect against all cellular users, D2D links, and cooperative relays. Our network simulation takes the urban microcell scenario for the cellular and relay

Algorithm 2 QoS-Aware Distributed Algorithm

Initialization:
System is initialized with one feasible partition $\mathcal{T}_{greedy}$ from above greedy algorithm;
Initialize $\mathcal{T}_{cur} = \mathcal{T}_{greedy}$;
Repeat
Step 1: Select d and its related coalition;
Select $d \in \mathcal{D}$ randomly, and treat this coalition as $\mathcal{T}_{cu}$;
Select another coalition randomly $\mathcal{T}_{cu}^{s}$;
Step 2: Requirement for minimum rate;
$\overline{r} = \arg\max_{r}(R_{cu}^{\overline{r}} + \sum_{d \in \mathcal{T}_{cu} \setminus \{k\}} R_d)$;
$\overline{r^s} = \arg\max_{r}(R_{cu}^{\overline{r_s}} + \sum_{d \in \mathcal{T}_{cu^s} \cup \{k\}} R_d)$;
if $R_{cu}^{\overline{r}} \geq \overline{R_{cu}}$ & $R_{cu}^{\overline{r^s}} \geq \overline{R_{cu}}$ **then**
  Go to the Step 3;
else
  Return to the Step 2, $n = n + 1$;
end if
Step 3: Switch operation
if (37) and (39) is satisfied **then**
  k joins $\mathcal{T}_{u^s}$, and updates the current $\mathcal{T}_{cur}$ as
  $(\mathcal{T}_{cur} \setminus \{\mathcal{T}_{cu}, \mathcal{T}_{cu^s}\}) \cup (\{\mathcal{T}_{cu} \setminus \{k\}, \mathcal{T}_{cu^s} \cup \{k\}\})$;
end if
Until approaching the iterations' maximum number (predefined) .
Output the final converged coalition structure.

TABLE 1. Parameters settings for simulation.

Parameter	value
Area of cell	Coverage radius (500 m)
D2D maximum distance	5m
Transmit power	BS: 46 dBm; Device: 23 dBm
Bandwidth of sub-carrier	15 kHz
Spectral-density of noise	-174 dBm/Hz
Relay deployment	Circle radius (250 m)
Path loss exponent	3.5

communication channel and takes two proximal UEs communicating for the D2D communication channel [21].

In out setting, BS is considered in the center of the circle at 500m radius, and the same system parameters are considered as in [21]. In TABLE 1, the main simulation parameters are illustrated. Moreover, the cooperative relays are deployed in the same cell with 250m radius at an equal angule $2\pi/R$, $R = 6$, unlike the randomly located cellular users at $[(0.5 + 0.5\eta_k)cos(2\pi\theta_k), (0.5 + 0.5\eta_k)sin(2\pi\theta_k)]$, $k = 1, \cdots, K$, and uniformly distributed η_k and θ_k in (0, 1]. Also, the D2D pairs are distributed randomly in the allocated area. The BS can obtain the position information of all the users, D2D pairs, and cooperative relays. In addition, for each simulation scenario the number of D2D pairs are fixed. Therefore, the simulations are repeated 100 times, and each

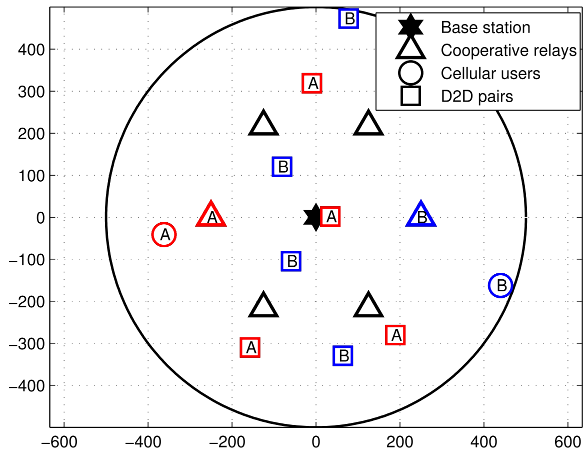

FIGURE 4. An optimal resource allocation snapshot obtained via the proposed algorithm considering 2 cellular users, 8 D2D pairs, and 6 cooperative relays in the network.

time their locations are updated. For better exemplification and understanding that how cellular users, D2D pairs, and cooperative relays are positioned in the simulation, we plot their locations in Fig. 4 and represented by circle, triangle, and square, respectively. In addition, we also show the snapshot considering our proposed algorithm regarding optimal resource allocations assuming cellular users (2 Nos.), D2D pairs (8 Nos.), and cooperative relays (6 Nos.) marked by A and B, respectively.

We use OS to denote the optimal solution via proposed D2D pair clustering method, QGREEDY to denote our proposed QoS-aware greedy algorithm and QDIS-GDY to denote the proposed QoS-aware distributed algorithm with the initial solutions from the QGREEDY algorithm. For evaluating the proposed solutions' efficiency, we consider the achievable sum rate along with the fraction of D2D transmissions as the performance metrics. For aggregation of system achievable rate, which includes all the entities' communication rates such as cellular users, D2D pairs, and cooperative relays through RNCC.

In order to evaluate the effectiveness of OS, QGREEDY, and QDIS-GDY, we compare our proposed schemes' performance with the following approaches:

a) Random Selection and Greedy Relaying (RSGR): This approach allocates the resources to D2D pairs by randomly selecting the cooperative relays. In other words, the D2D pair shares resource with a randomly selected cellular user. While a cellular user selects one cooperative relay to be cooperated to get the maximum gain of the system sum rate. For D2D pairs, random selection is considered as the baseline algorithm in [21], [22].

b) Furthest First and Greedy Relaying (FFGR): In this approach, first, D2D pairs occupy the cellular user's spectral resource having the utmost distance to this D2D pair, known as the greedy algorithm in [20]. Next, each cellular user selects the cooperative relay to get the maximum achievable rate. Though furthest first concept reduces the unnecessary interference; but, the system sum rate can't be optimized.

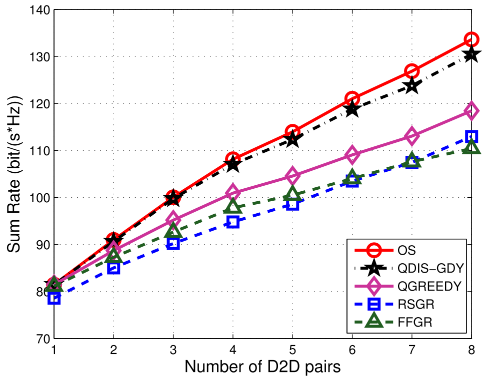

FIGURE 5. System sum rate against different algorithms considering D2D pairs (varying in number) and 4 cellular users.

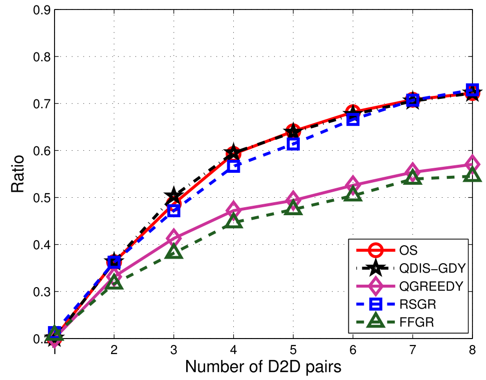

FIGURE 6. D2D transmission performance against different algorithms with 4 cellular users and D2D pairs (varying in number).

c) Decode-and-Forward Cooperative D2D Protocol (DF): As its name implies, DF protocol first decodes and then forwards data. In this regard, the RLNC aided cooperative relay performance is compared with that of the DF cooperative protocol [8].

B. RESULTS ANALYSIS

To show the optimal solutions of our formulated BILP problem and evaluate our proposed algorithms' performance i.e., QGREEDY and QDIS-GDY. As shown in Figs. 5 and 6, we show the system sum rate and the fraction of D2D communication, respectively, by varying D2D pairs' number. From Fig. 5, it is observed that QDIS-GDY's sum rate is more prominent than that of QGREEDY, RSGR and FFGR. QGREEDY outperforms RSGR and FFGR by about 30%, and provides the initial solutions for QDIS-GDY. The furthest first and greedy relaying algorithm even performs worse than random selection and greedy relaying, as the cooperative relays also incur interference for D2D pairs. We notice that the smallest number of D2D pairs lead to smallest D2D transmission fraction value. In the given system, the D2D transmission fraction arrives at ~ 70% when there are 6 D2D pairs.

To further investigate our proposed algorithm (QDIS-GDY) optimal convergence, the average deviation is defined between the QDIS-GDY and OS results, which is given as follows:

$$\Delta_{ad} = \frac{1}{v}\sum_{v=1}^{8}\frac{R^{(OS)}(v) - R^{(QDIS-GDY)}(v)}{R^{(OS)}(v)} \tag{36}$$

where the system sum rate achieved is represented as $R^{(OS)}$ and $R^{(QDIS-GDY)}$, respectively, by the OS and QDIS-GDY schemes. Moreover, the value v designates the number of $\mathcal{U}$ or $\mathcal{D}$. Similarly, the average deviation as shown in Fig. 5 is about 2.3% between QDIS-GDY and OS. From aforementioned results, it is concluded that our approach QDIS-GDY performance is close to the optimal value compared with other schemes.

For further performance analysis of our proposed QDIS-GDY approach, we obtain the system sum rate and the fraction of D2D communications as shown in Figs. 7 and 8 by varying the cellular users' number, respectively. Similarly, from the Fig. 7, we notice that FFGR performs worst among all algorithms due to interference from the cooperative relays. ~ 1.3% average deviation is observed between QDIS-GDY and OS. From the Fig. 8, it is noticed that increase in cellular users' number can decrease the percentage of the D2D transmission rate. This is because of cellular users' increasing number in the system, and the D2D transmission opportunities are decreased due to the increase of the direct cellular transmission. For a large scale network, we utilize QDIS-GDY to get the near optimal result. As depicted in Fig. 9, we simulate with 10 cellular users and vary D2D pairs from 8 to 15. It is noticed that the system sum rate of QDIS-GDY scheme raises around 20% when 15 D2D pairs are considered . Combining with Fig. 6, these results demonstrate the significant role of D2D communications in the underlay cellular network.

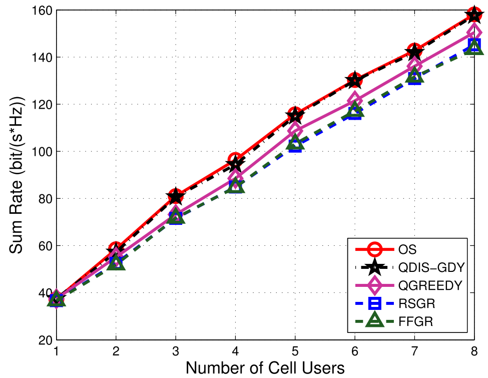

FIGURE 7. System sum rate versus cellular users with 4 D2D pairs against different resource allocation algorithms.

Now, we examine the important role of the cooperative relays through RNCC as shown in the Fig. 10, where the system sum rate is observed versus cooperative relays. From the Fig. 10, it is quite obvious that increase in the cooperative relays will further ameliorate system sum rate. This improvement in the cellular user's achievable rate is due to the random linear network coding cooperative scheme, even when the number of cellular users and D2D pairs are

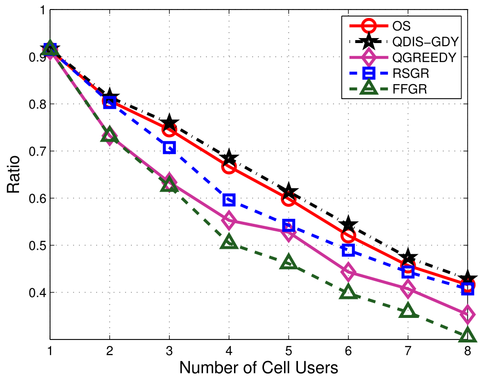

FIGURE 8. Fraction of D2D transmission performance versus cellular users (varying in number) with 4 D2D pairs against different resource allocation algorithms.

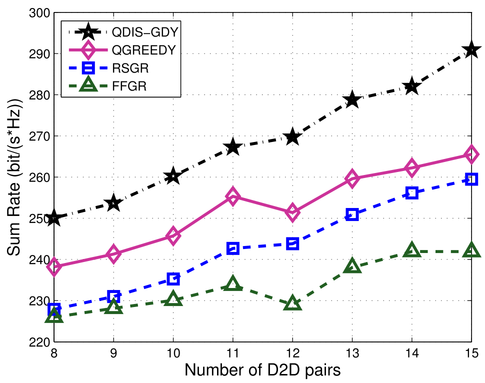

FIGURE 9. System sum rate considering large networks with 10 cellular users for different resource allocation algorithms.

keep constant. Also, it is observed that with 3 fixed relays the system sum rate can ameliorate about 5%. These result comparisons reveal that cooperative relays mainly increase the cellular user's achievable rate.

For measuring the influence of cellular users' minimum rate requirement on overall performances of all schemes, we show the system sum rate and fraction of D2D transmission, respectively, by varying the value of minimum rate in Fig. 11 and Fig. 12. We note that the system sum rate decreases significantly among all transmission schemes when the minimum rate is increased. This is simply because of smaller number of D2D pairs and cellular users due to the enlarged QoS requirements, and hence causes decrease in the system sum rate. From Fig. 12, the results are quite obvious, which indicates the decreasing of D2D pairs in the system. For example, when minimum rate is 9 $bits/(sHz)$, the fraction of D2D pairs transmission decreases about 85%. This clearly demonstrates that the system performance is significantly influenced by the cellular user's QoS.

At last, we compare the performance of our schemes, i.e., RNCC cooperative relay and DF cooperative protocol. Considering the DF cooperative protocol, the cellular user u rate with cooperative relay r is expressed as: [8]

$$R_u^r = \frac{1}{2} \min\{\log(1 + \gamma_{b,r}), \quad \log(1 + \gamma_{b,cu} + \gamma_{r,cu})\}, \qquad (37)$$

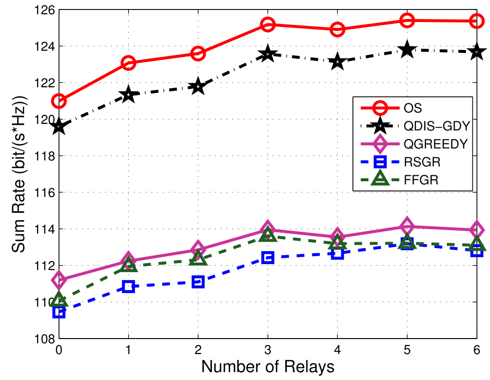

FIGURE 10. System sum rate of D2D communications against different resource allocation algorithms versus different number of cooperative relays considering 6 cellular users and 4 D2D pairs.

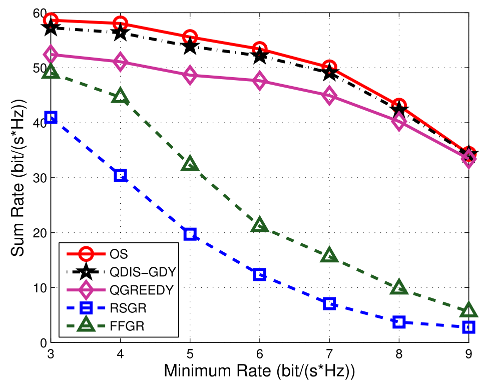

FIGURE 11. System sum rate with different minimum rate requirement of cellular user from different resource allocation algorithms.

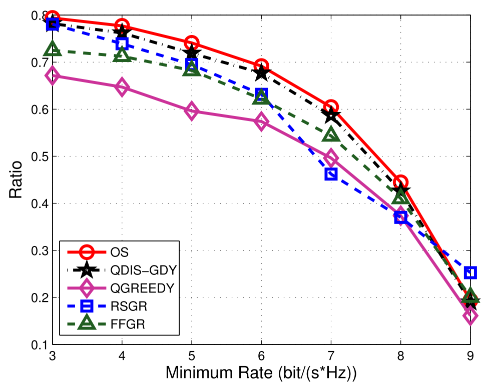

FIGURE 12. Performance of fraction of D2D transmission with different minimum rate requirement of cellular user from different resource allocation algorithms.

where $\gamma_{b,r}$, $\gamma_{b,cu}$, and $\gamma_{r,cu}$ are the SINRs obtained, respectively, against the links between the BS and the cooperative relay, between the BS and cellular user, and between cooperative relay and cellular user. We plot the system sum rate under different cooperative relay numbers with no direct D2D pair in Fig. 13 and existing direct cooperative transmissions in Fig. 14. We notice $\sim$ 45% improvement on the system sum rate with the RNCC cooperative scheme in Fig. 13. We observe $\sim$ 12% average improvement on system sum rate with RNCC cooperative scheme in Fig. 14. DF does not adapt

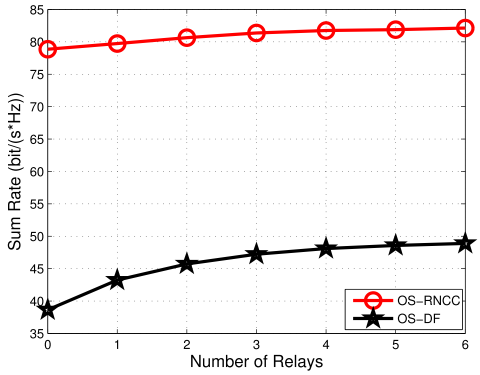

FIGURE 13. System sum rate of different cooperative relay schemes with 6 cellular users in the case of no direct cooperative transmission among the D2D pairs.

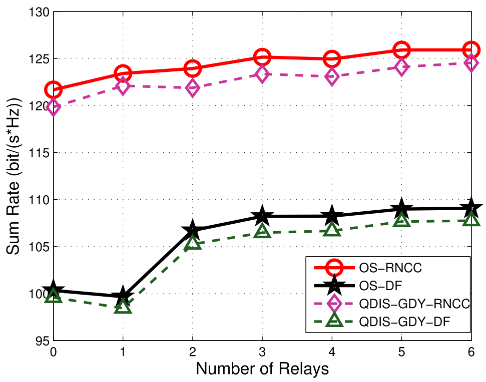

FIGURE 14. System sum rate versus different cooperative relay schemes in case of existing direct cooperative transmissions with 4 D2D pairs and 6 cellular users.

to the severe channel varying and achieve the low system sum rate. The RNCC cooperative scheme is robust to varying channel statistics. Therefore, it achieves the maximum system sum rate.

VII. CONCLUSION AND FUTURE WORK

We investigated the resource allocation problem for network coding assisted D2D communications underlay cellular network. The system comprises of multiple cellular users, D2D pairs, and cooperative relays. We first proposed the robust random linear network coding assisted cooperation and formulated the resource allocation problem for system sum rate maximization, which was NP-hard. Therefore, we reformulated it as a binary integer linear programming problem and achieved the optimal solution via introducing the D2D pair clustering. The exponential number of cooperative clusters leads to significantly complicated computation with increasing number of D2D pairs $\mathcal{D}$. Thus, we further proposed QoS-aware greedy algorithm and distributed algorithm to get near optimal solution, which reduces the complexity dramatically. Evaluation with extensive simulations showed that the random linear network coding aided cooperative scheme achieved system sum rate improvement of $\sim$ 12% compared to the decode-and-forward cooperative scheme. Potential future works can study the multiple hops model based resource allocation problem for the network coding assisted D2D communications.

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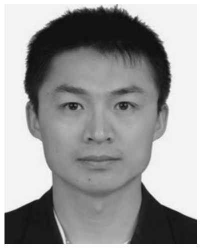

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