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Improving quality of service for cell-edge user in D2D-relay networks

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Abstract: In this paper, we investigate a scenario of D2D-relay communications where one D2D user may help cell-edge user to exchange information for improving its quality of service (QoS). We formulate a resource allocation problem, which aims at maximizing the data rate of the cell-edge user. In particular, we propose an iterative power allocation algorithm and derive the optimal closed-form power allocation expressions by Lagrangian dual method. Simulation results verify the theoretical solution and show that our D2D-relay scheme achieves higher spectrum efficiency than the traditional cellular-relay communication scheme.

Keywords: Quality of service; cell-edge user; D2D-relay; Data rate

I. INTRODUCTION

In accordance with the 5G requirement, terrible network traffic is caused by massive growth of mobile services and application. Challenges are coming for traditional cellular networks including scarce spectrum resources, poor coverage and etc. It is a better choice to use user equipment which closes to BS and itself to forward data when UE with bad coverage communications with an application server in the core network. Some researches have been done in this field. Liu et al. [1] investigated relay control on simultaneous wireless information and power transfer in full-duplex relay networks. They have developed a greedy search (GS) algorithm to enhance outage performance. The paper [2] investigated utility function minimum maximization issue of bidirectional amplify and forward relaying systems from relay deployment and chose unified utility function rather the separated optimization goals. Fahd et al. [3] improved relay selection and transmit power at the relay to maximize the sum-throughput of the network subject to a minimum throughput requirement of each hop and transmit power constraint. The work [4] proposes an energy-saving and optimal RN placement (EEORNP) algorithm, maximizing the network coverage and keeping signal-to-interference ratio with constrained energy.

With more and more intelligent devices performing multi-functions, making sure the application keep up with the trend of technology. Device-to-device (D2D) communication, as a solution with bright future to reduce delay and improve throughput, obtains a bright future, allowing UEs in close proximity to communicate in direct[5]. However, this is at the cost of generating interference to cellular users (CUs). To reduce the interference level of the D2D system, many a algorithms has been brought out in the literature [6-8]. To optimize the maximize links for supporting the network is defined by the paper [9], and D2D resource allocation and power control (DRAPC) framework can be noticed. The search algorithm in [10] and matching algorithm in [11] are used to solve the resource allocation problem in underlaying D2D communications. And graph-coloring theory has been introduced to provide modeling and solutions for resource allocation of D2D communication [12]. Hassan et al. [13] use a weighted bipartite matching algorithm to minimize the interference. Generalized Benders Decomposition was used for solving optimal Mode Selection by Cross-Layer Decomposition in D2D Cellular Networks[14]. The paper [15] investigated the DRAPC communication underlaying networks, providing the optimal conditions for resource allocation of D2D pairs, power control of CUs, and

an iterative algorithm for sum rate maximization. The low-complexity iterative algorithm[16] help maximize the energy efficiency of the D2D pair and guarantees the CUs service. Guaranteeing the KKT conditions can achieve the maximization of energy efficiency.

The D2D relay technology, with D2D communication as its basis, is been mentioned in recent time[17]. D2D-enabled UE help cellular transmission which act like a relay between BS and some other UEs. Unlike typical cellular relays, a much high flexibility for networking can be found in this technology which answers the traffic by dynamic deployment and resource allocation. Zeng et al. [18] analyze the pairing stability in the D2D-relay networks. A positive association of the proposed metric and the system performance was figured out by them. Using stochastic geometry, Wang et al. [19] found out the downlink coverage probability of relay-assisted mmWave cellular networks. They studied the spectral efficiency enhancement in the cellular downlink and the influence of D2D transmissions on the cellular uplink. The paper [20] studies the coverage in D2D relay networks with theoretical derivation and experimental simulation by stochastic geometry. The coverage which optimizes the overall system downlink rate is built and an algorithm is advanced for getting the best solution. Some relevant studied can be found. But it still need to be further explore. D2D relays majorly concentrate on the user pairing [18] and coverage[19], [20]. Few study on the resource allocation and transmission rate analysis, which is primarily significant on network management.

This paper investigates a D2D-relay communication scenario. The goal of the scheme is to obtain the maximization data rate of the cell-edge user. The main contributions of this paper are as follows.

- To solve the problem of relative scarcity of spectrum resources, we use D2D user as a relay to forward data instead of the traditional cellular-relay, which undoubtedly improves the spectrum efficiency greatly and guarantees the transmission performance of cell-edge users.
- Considering the optimal power allocation of UEs and transmission rate of the user, we formulate a mixed-integer nonlinear programming (MINLP) problem to maximize the data rate of the cell-edge user. An efficient iterative algorithm is developed to solve this problem. By using Lagrangian dual method, we derive the optimal closed-form power allocation expressions.
- Theoretical analyses and extensive simulations are provided to reveal the rationale of the proposed algorithms, and the results demonstrate that our D2D-relay scheme outperforms traditional cellular-relay communication scheme.

The rest of this paper is organized as follows. The system model and problem formulation are presented in Section II. the proposed algorithm is derived in Section III. Simulation results are presented in Section IV and the paper is concluded in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first introduce the system model of the network and then formulate data rate maximization and resource allocation problems.

A. System Model

In order to improve the coverage quality for cell-edge users (CEUs), we need to consider the optimization problem of downward data rates in such a scenario which shown by Fig. 1. We consider a base station (BS) which is located at the center of the cell, the set of cellular users (CUEs) and D2D users are denoted by $C=\{1,2,...,C\}$ and $D=\{1,2,...,D\}$, respectively. The system bandwidth is divided into N orthogonal Resource Blocks (RBs) denoted by $N=\{1,2,...,N\}$ which are used by all the CUEs underlay fashion. In this paper, we assume that the CEUs to communicate with BS using either direct or relay mode. When the link condition is good, the CEUs receive datas from BS directly. However,

when the CEUs are outside the coverage region of the BS or having bad channel condition, the communications need to be supported by the relays. We assume that the Decode and Forward (DF) relaying strategy is employed. In this mode, each communication period is divided into two intervals corresponding to BS-Relay phase (cellular communication) and Relay-CEUs phase (D2D communication). Relays communicate with CEUs by reusing the uplink resources together with the existing cellular users which is shown by Fig. 2. However, to avoid further co-channel interference, we assume that one channel can be reused by at most one D2D pair, and each D2D pair can only reuse one channel.

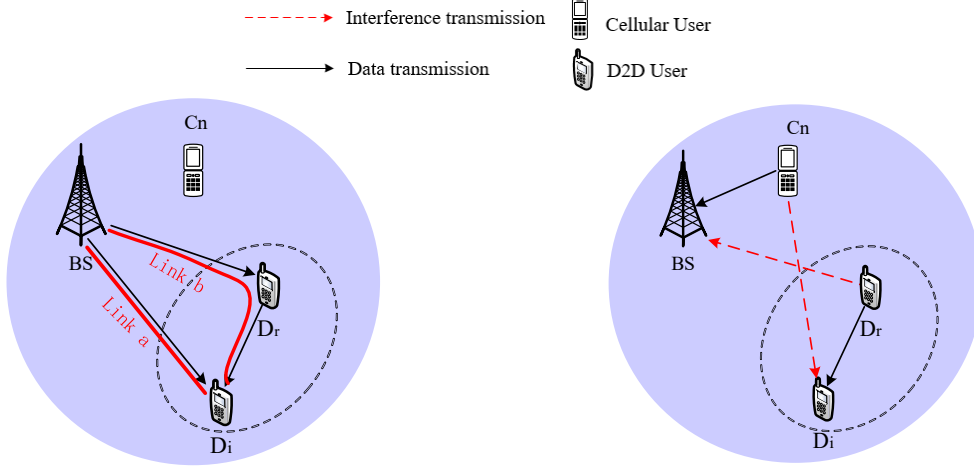


Fig.1. System model

Fig.2. Reuse model

1) Direct mode

When a cell-edge user D_i is directly communicating with BS, the communication link a is built (seen in Fig.1), the maximum achievable data rate can be calculated by the Shannon formula as

$$R_{bi} = \log_2 \left(1 + \frac{P_b H_{bi}}{N_0} \right) \quad (1)$$

where P_b is the power of BS, H_{bi} is the channel gain from BS to the cell-edge user D_i , and N_0 is the Gaussian white noise.

2) Relay mode

However, when the cell-edge user is far apart from BS or the quality of link is not good enough for direct communication, D_i may choose D_r as its D2D relay and link b is built (seen in Fig.1). D2D pairs (D_r and D_i) communicate by reusing the uplink channel of a cellular user C_n . And similarly, the maximum achievable data rate can be expressed as

$$R_{ri} = \log_2 \left(1 + \frac{P_r H_{ri}}{P_c H_{ci} + N_0} \right) \quad (2)$$

where P_r and P_c denote the transmit power of the relay user and cellular user, H_{ri} is the channel gain between D_r and D_i , H_{ci} is the channel gain between C_n and D_i .

B. Problem Formulation

Our goal is to find the theoretical maximum downlink rate of the cell-edge user, firstly, a binary variable is defined to indicate whether the cell-edge user D_i chooses relay user D_r as its serving relay

$$\alpha = \begin{cases} 1 & \text{uses relay mode} \\ 0 & \text{otherwise} \end{cases}, \forall i \in D, \forall r \in D \quad (3)$$

then, the optimization problem can be formulated as follow

$$\mathbf{P1:} \quad \max \left\{ (1-\alpha) \log_2 \left(1 + \frac{P_b H_{bi}}{N_0} \right) + \alpha \log_2 \left(1 + \frac{P_r H_{ri}}{P_c H_{ci} + N_0} \right) \right\} \quad (4)$$

$$\text{s.t.} \quad 0 < P_c \leq P_{\max} \quad \forall c \in C \quad (5)$$

$$0 < P_r \leq P_{\max} \quad \forall r \in D \quad (6)$$

$$\alpha \in \{0, 1\} \quad (7)$$

$$\log_2 \left(1 + \frac{P_c H_{cb}}{P_r H_{rb} + N_0} \right) \geq R_{\min} \quad \forall c \in C \quad (8)$$

where P_{\max} denotes the maximum transmit power of the UEs. R_{\min} denotes the data rate threshold of the UEs. Constrains (5)-(6) guarantee that the transmit powers of the UEs are adjusted within the desired range. The constrains (8) guarantees the quality of service of cellular users.

III. THE PROPOSED RESOURCE ALLOCATION SCHEME

A. Optimization Problem Transformation

In our proposed system model, we employ the full duplex DF protocol under which the relay will get rid of the interference before forwarding the received information. Then the transmitting information from BS to the cell-edge user via relay user D_r can be divided into two phases: in the first phase, BS transmits its signals while the relay user D_r listens; in the second phase, relay user D_r decodes the information received in the first phase and then forwards it to the cell-edge user D_i . Assume cell-edge user D_i only receives information in the second phase in every transmission cycle, and then we can get the joint received SINR at cell-edge user side.

$$\gamma_i = \min \{ \gamma_{br}, \gamma_{ri} \} \quad (9)$$

The instantaneous data rate of the cell-edge user i can thus be expressed by

$$R_i = \log_2 (1 + \gamma_i) \quad (10)$$

Following [21], we can get the following conclusion, only when

$$\gamma_{br} = \gamma_{ri} \quad (11)$$

R_i can be maximized. Substituting $\gamma_{br} = \frac{P_b H_{br}}{N_0}$ and $\gamma_{ri} = \frac{P_r H_{ri}}{P_c H_{ci} + N_0}$ into Eq. (11), P_b can be expressed as

$$P_b = \frac{H_{ri} N_0 P_r}{(P_c H_{ci} + N_0) H_{br}} \quad (12)$$

Substituting (12) into **P1**, we can transform the optimization problem as

$$\mathbf{P2:} \quad \max \left\{ (1-\alpha) \log_2 \left(1 + \frac{H_{ri} P_r H_{ib}}{(P_c H_{ci} + N_0) H_{br}} \right) + \alpha \log_2 \left(1 + \frac{P_r H_{ri}}{P_c H_{ci} + N_0} \right) \right\} \quad (13)$$

$$\text{s.t. (5), (6), (7), (8)}$$

By observing problem **P2**, we can draw a conclusion that the objective function is a reduction function with respect to P_c . So if we want to get the maximum of the optimization problem, P_c needs to be minimized. From constrain (8), we can obtain the minimum value of P_c as

$$P_c = \frac{(2^{R_{\min}} - 1)(P_r H_{rb} + N_0)}{H_{cb}} \quad (14)$$

Also, constrain (6) can be rewritten as

$$0 < \frac{(2^{R_{\min}} - 1)(P_r H_{rb} + N_0)}{H_{cb}} \leq P_{\max} \quad \forall r \in D \quad (15)$$

Substituting Eq. (14) into Eq. (13), we can transform the optimization problem as **P3**.

$$\begin{aligned} \mathbf{P3}: \quad & \max \left\{ (1 - \alpha) \log_2 \left(1 + \frac{P_r H_{ri} H_{cb} H_{bi}}{(2^{R_{\min}} - 1) H_{rb} H_{ci} H_{br} P_r + ((2^{R_{\min}} - 1) H_{ci} + H_{cb}) H_{br} N_0} \right) \right. \\ & \left. + \alpha \log_2 \left(1 + \frac{P_r H_{ri} H_{cb}}{(2^{R_{\min}} - 1) H_{rb} H_{ci} P_r + ((2^{R_{\min}} - 1) H_{ci} + H_{cb}) N_0} \right) \right\} \\ & \text{s.t. } (6), (7), (15) \end{aligned} \quad (16)$$

B. Power Allocation Expression Derivation

We can note that, the problem **P3** is a non-linear mixed-integer problem. To solve this problem, essential relaxation is introduced in this part. The binary variable α in the objective function, and the constrain (7) is relaxed to continuous variable.

$$\alpha \in [0, 1] \quad (17)$$

It can be easily proved the optimization problem **P3** is a concave maximization problem with respect to power allocation variable P_r . So it can be solved by its dual problem and the difference between the primal and dual solution is zero when strong duality holds [22], [23]. In this section, we solve the problem **P3** by solving its associated dual problem. The Lagrangian function can be written by

$$L(P, \lambda) = (1 - \alpha) \log_2 \left(1 + \frac{taP_r}{bP_r + c} \right) + \alpha \log_2 \left(1 + \frac{aP_r}{bP_r + c} \right) + \lambda_1 (P_{\max} - P_r) + \lambda_2 \left(P_{\max} - dP_r - \frac{N_0}{H_{cb}} \right) \quad (18)$$

where

$$a = H_{ri} H_{cb} \quad (19)$$

$$b = (2^{R_{\min}} - 1) H_{rb} H_{ci} \quad (20)$$

$$c = [(2^{R_{\min}} - 1) H_{ci} + H_{cb}] N_0 \quad (21)$$

$$d = \frac{(2^{R_{\min}} - 1) H_{rb}}{H_{cb}} \quad (22)$$

$$t = \frac{H_{bi}}{H_{rb}} \quad (23)$$

λ_1 and λ_2 are the non-negative Lagrangian multipliers corresponding to the power constraints (6) and (15). The constraints are KKT conditions for optimizing power allocation, thus the dual function is given by

$$H(\lambda) = \max L(P, \lambda) \quad (24)$$

$$\text{s.t. } \lambda_1, \lambda_2 \geq 0$$

the dual problem is

$$\min_{\lambda > 0} H(\lambda) \quad (25)$$

For a fixed Lagrange multiplier and a given α , the problem is a standard optimization problem with the KKT conditions. Specifically, the partial derivative of the Lagrangian $L(P, \lambda)$ respect to P_r can be expressed as

$$\frac{\partial L}{\partial P_r} = \frac{(1-\alpha)}{\ln 2} \cdot \frac{act}{atP_r + bP_r + c} \cdot \frac{1}{bP_r + c} + \frac{\alpha}{\ln 2} \cdot \frac{ac}{aP_r + bP_r + c} \cdot \frac{1}{bP_r + c} - \lambda_1 - d\lambda_2 \quad (26)$$

To obtain the optimal solution, we set the partial derivative equal to 0, the optimal solution to (27) falls into two cases:

1) $\alpha=0$; 2) $\alpha=1$.

1) **Case** $\alpha=0$ (direct mode)

The optimal power value for P_r can be derived as

$$P_r = \frac{-(act + 2bc) \pm \sqrt{a^2 c^2 t^2 + \frac{4abct(at+b)}{(\lambda_1 + d\lambda_2)\ln 2}}}{2b(at+b)} \quad (27)$$

We can note that, the value of power cannot be a negative number, so we get rid of the negative value and get the value for P_r as follow

$$P_r = \frac{-(act + 2bc) + \sqrt{a^2 c^2 t^2 + \frac{4abct(at+b)}{(\lambda_1 + d\lambda_2)\ln 2}}}{2b(at+b)} \quad (28)$$

2) **Case** $\alpha=1$ (relay mode)

Similarly, when $\alpha=1$, the optimal power value for P_r can be derived as

$$P_r = \frac{-(ac + 2bc) + \sqrt{a^2 c^2 + \frac{4abc(a+b)}{(\lambda_1 + d\lambda_2)\ln 2}}}{2b(a+b)} \quad (29)$$

The dual variables primal calculation problem can be solved by the gradient method since the objective function is differentiable. Therefore, the dual variables can be updated as follows

$$\lambda_1^{K+1} = [\lambda_1^K - \sigma_1 (P_{\max} - P_r)]^+ \quad (30)$$

$$\lambda_2^{K+1} = \left[\lambda_2^K - \sigma_2 \left(P_{\max} - \frac{(2^{R_{\min}} - 1)H_{rb}}{H_{cb}} P_r - \frac{N_0}{H_{cb}} \right) \right]^+ \quad (31)$$

where K is the iteration index. σ_1 and σ_2 are positive step sizes at iteration K .

The following Algorithm 1 gives an iterative algorithm in order to get the optimal solutions of problem **P3** (as well as **P1** and **P2**). At the beginning, we initialize the related variables (see line 1). And then, we update the Lagrangian multipliers (see line 4). The power resources of relay users P_r is allocated in line 5-6. After updating Lagrangian function (see line 8), we obtain the optimal P_r value as P_r^* .

```

1: Set maximum iteration number  $J_{\max}$  and maximum
   tolerance  $\varepsilon_1$  ;
2: Set  $P_r^{(1)}$ ,  $\lambda_1^{(1)}$  and  $\lambda_2^{(1)}$ ;
3: while  $|L^{(j)} - L^{(j-1)}| > \varepsilon_1$  or  $j \leq J_{\max}$  do
4:   Update  $\lambda_1^{(K)} \square \lambda_2^{(K)}$  with (25)~(26);
5:   if  $\alpha=0$ , Update  $P_r^{(n)}$  with (23);
6:   else Update  $P_r^{(n)}$  with (24);
7:   Set  $n = n + 1$ 
8:   Update  $L^{(j)}$  by (13);
9:   Set  $j = j + 1$ ;
10:  Set  $K = K + 1$ ;
11: end while
12: Output  $P_r^*$ 

```

IV. SIMULATION RESULTS

In this section, we evaluate and compare the performances of our proposed DRPA scheme and the typical cellular-relay method. For simplicity, we consider a single-cell scenario with scarce spectrum resources. Assuming that the BS is situated at its center, cellular users and relay users are uniformly distributed in the cell. And the BS and the cell-edge user communication link are randomly chosen. The distance is given less than the maximum communication distance 150m. The simulation results are presented to evaluate the performance of the DRPA scheme. The specific simulation parameters are shown in Table 1.

Table 1 Simulation Parameters

Parameters	Value
The radius of the cellular network	150m
Number of Base station	1
Number of CUS	12
Number of Relays	15
Number of Cell-edge Users	11
Maximum transmission power for UE P_{\max}	23dbm
Additive noise power N_0	-110dbm
Minimum Rate R_{\min}	0.8
Path loss exponent	3.7
Accuracy $\varepsilon_1, \varepsilon_2$	10^{-5}

The convergence performance of our proposed DRPA algorithm can be observed in Fig. 3. It can be seen that the DRPA algorithm converges with 2 iterations and tends to stabilize for the rest of the iterations. This shows that our algorithm converges at a fast time and the proposed algorithm has lower computation complexity.

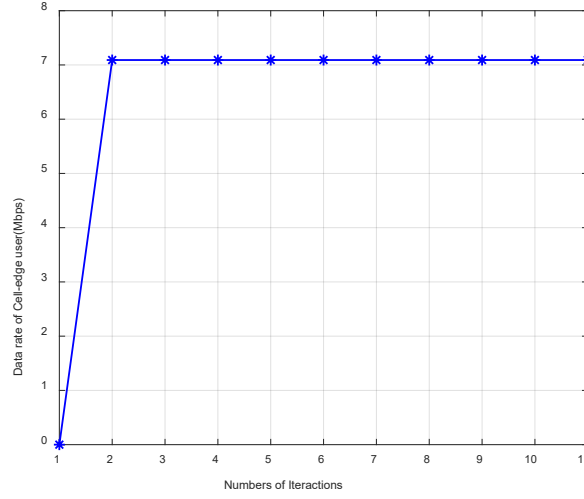


Fig. 3. The convergence of the proposed algorithm

To understand the interplay between data rate of the cell-edge user and the distance in direct transmission mode, we set the minimum data rate requirement with 1Mbps, 0.8Mbps, and 0.6Mbps. And the distance between BS and the cell-edge user is set from 50m to 150m with 10m interval identically. As can be seen from the Fig.4, with the increasing of the distance, all the data rates are monotonically decreased. This is because, with the distance increasing, the quality of link is less and less suitable for communication. And we should choose some relay users to forward data to improve the quality of communication.

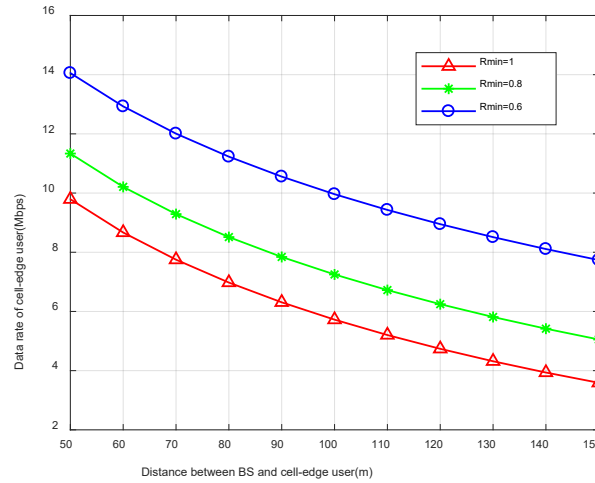


Fig. 4. The data rate of cell-edge user under different distance

In Fig.5, we compare direct communication ($\alpha=0$) and relay communication ($\alpha=1$) to further illustrate the transmission performance of the cell-edge user. In the case of the same parameters setting, the data rate decreases with the distance increases in direct mode. On the contrary, in the relay mode, with the increasing of the distance, the data rate is monotonically increased. And the two modes share the same data rate at the distance of 66m. This is coincident the relay communication is more suitable for long-distance (more than 70m) communication.

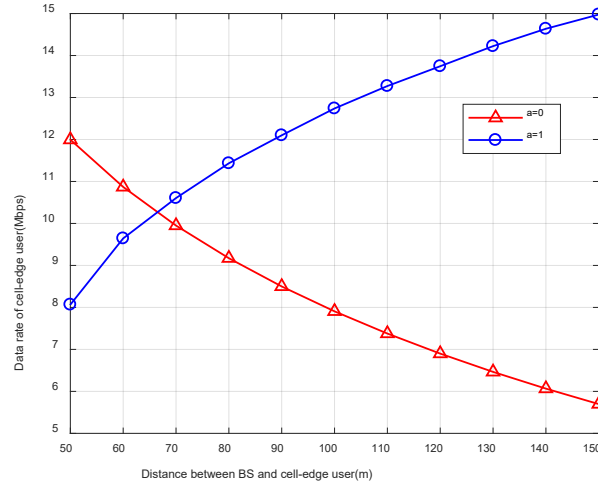


Fig. 5. Data rate of cell-edge user under different transmission mode

Furthermore, Fig.6 presents that the data rate of cell-edge user versus the distance between relay and cell-edge user on the condition of different maximum power. The distance is set from 20m to 90m with 10m interval identically. The maximum transmits power is set to be 20dbm, 30dbm, and 40dbm. It can be seen from Fig. 6 that with the increase of the distance, the data rate is decreased. This is because the fading increases when the distance increases, which has a great influence on the transmission link. So the distance between the cell-edge user and the relay user should not be too large.

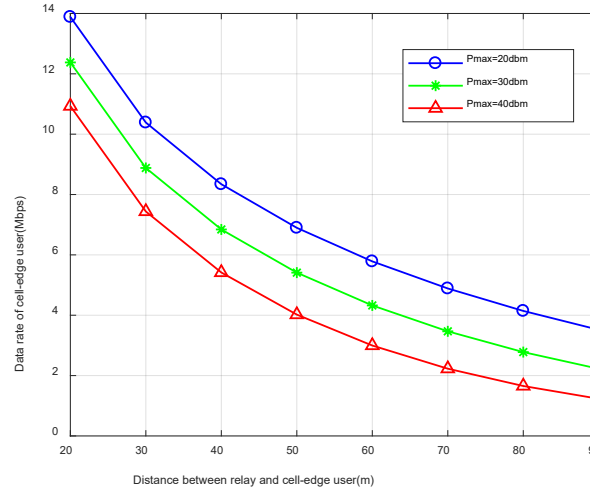
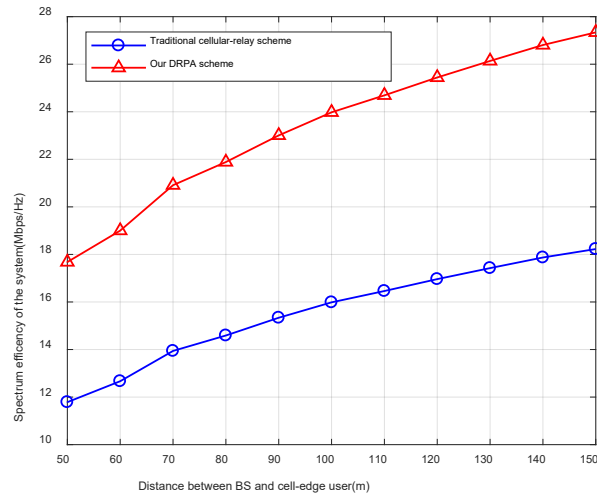


Fig. 6. Data rate of cell-edge user under different distance between relay and cell-edge user

For examining the advantage of the proposed algorithm, we compare our DRPA scheme with the traditional cellular-relay scheme, which is shown in Fig.7. It is observed that as the distance increases from 50m to 150m, the data rates of the cell-edge user increase for all schemes. And our proposed scheme performs better compared with the traditional scheme. The reason is that D2D communication is adopted in the data forwarding process, which improves the spectral efficiency.



V. CONCLUSIONS

In this paper, we improve cell-edge user coverage quality by designing a D2D-relay communication mechanism for underlay cellular networks. The problem of maximizing data rate is formulated as a non-linear mixed-integer problem. An iterative power allocation algorithm which based on Lagrangian dual method is developed to allocate powers to the UEs. We derive the optimal closed-form solution and demonstrated that the proposed algorithm converges within a reasonable time. Simulation results illustrated that the proposed scheme and DRPA algorithm significantly improve the data rate of the cell-edge in comparison to the traditional cellular-relay scheme.

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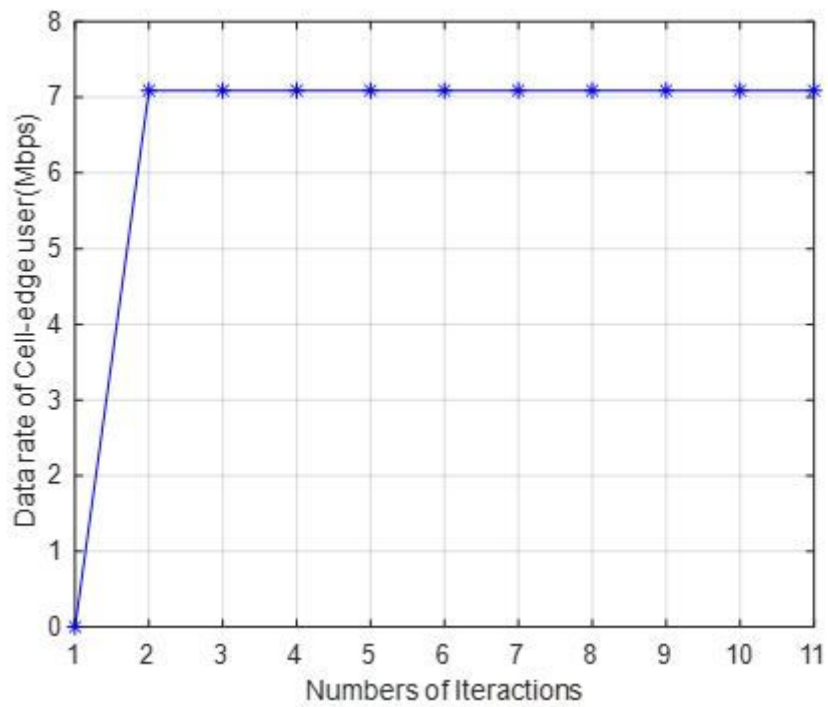


Figure 3

The convergence of the proposed algorithm

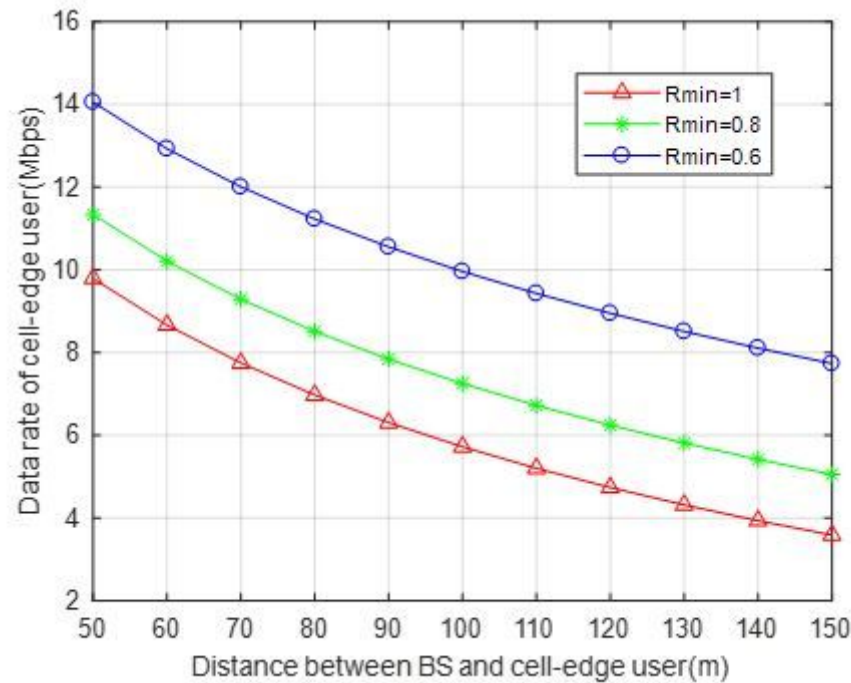


Figure 4

The data rate of cell-edge user under different distance

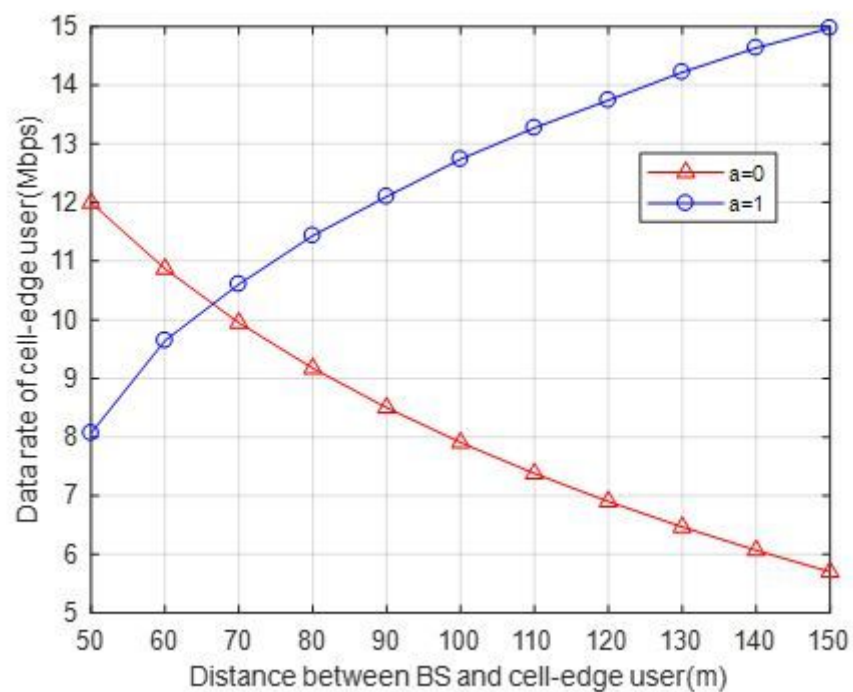


Figure 5

Data rate of cell-edge user under different transmission mode

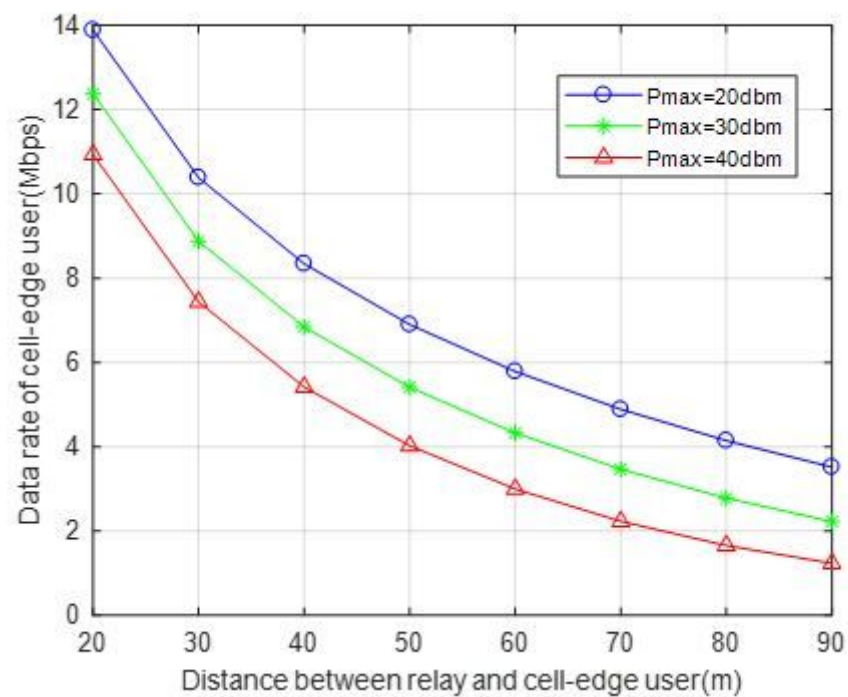


Figure 6

Data rate of cell-edge user under different distance between relay and cell-edge user

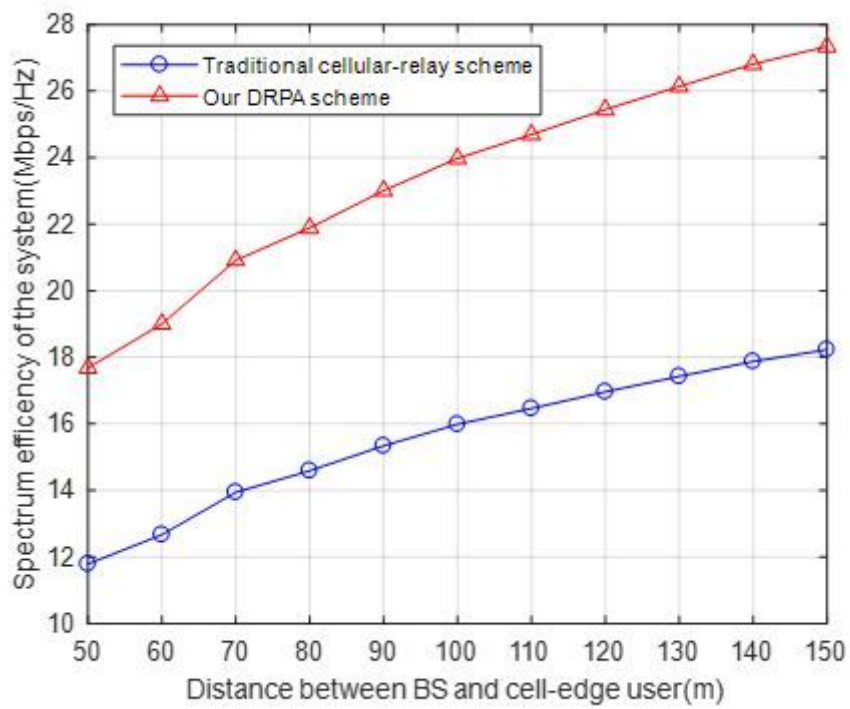


Figure 7

For examining the advantage of the proposed algorithm, we compare our DRPA scheme with the traditional cellular-relay scheme, which is shown in Fig.7.