Power Control for Two-Way AF Relay Assisted D2D Communications Underlaying Cellular Networks

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ABSTRACT As a key technology of the 5G communication system, device-to-device (D2D) communications have drawn significant research interests. However, the advantage of D2D communications may be limited when D2D users are far away from each other or the communication environments are harsh. In order to extend the range of D2D communications, a promising way is to use relaying technique to assist the communications. In this paper, we use a two-way amplify-and-forward (AF) relay to assist the underlay D2D communications and investigate the power control problem. Specifically, we formulate the power control problem as the optimization of the performance of the D2D link while fulfilling the quality-of-service (QoS) requirement of the cellular link. Two optimization objectives are considered for the D2D link, i.e., maximization of the minimum SINR at D2D users and maximization of the sum-rate of D2D users. For the first optimization objective, we can compare the possible optimal solutions for the three boundary conditions and obtain the optimal solutions. For the second optimization objective, we can convert the objective function into a concave function based on difference of convex (D. C.) structure, and use an iterative algorithm to solve the optimization problem. The simulation results show that the proposed power control scheme can improve the performance of the D2D link.

INDEX TERMS D2D communications, two-way AF relay, power control.

I. INTRODUCTION

In recent years, the fifth-generation (5G) mobile communication system has attracted worldwide research interests and begun to be deployed all over the world [1]–[6]. With the rapid development of the 5G mobile communications, people's lives and society will change dramatically.

As one of the most important techniques for the 5G mobile communication system, device-to-device (D2D) communications have been studied widely [7]–[9]. Unlike traditional cellular communication where all the communication signals must pass through the base station (BS), D2D communications can offload traffic from cellular networks by enabling mobile devices in proximity to communicate directly with each other. As such, D2D communications can increase

spectral efficiency, improve cellular coverage, reduce transmission delay, and decrease energy consumption of mobile devices. According to whether the licensed cellular spectrum is exploited, D2D communications can be divided into two categories, i.e., inband D2D and outband D2D. So far, most of the literature on D2D communications focuses on inband D2D because the spectrum can be fully controlled by the BS and user quality-of-service (QoS) requirements can be fulfilled. Inband D2D can be further divided into underlay mode and overlay mode [8], [9]. In underlay D2D mode, the cellular and D2D users can share the same spectrum resources, while in overlay D2D mode, the D2D users are allocated dedicated cellular spectrum resources. Underlay D2D communications can improve the spectrum efficiency by reusing spectrum resources, but it will cause interference between D2D and cellular users. This interference can be mitigated by power control and resource allocation [11]–[13].

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So far, most of the studies on D2D communications consider the scenarios where D2D users can establish a direct link. However, in practice, the advantage of D2D communications may be limited when D2D users are far away from each other or the communication environments are harsh. In order to substantially extend the range of D2D communications, a promising way is to use relaying technique to assist the communications. In [14], the authors investigated the resource allocation under channel gain uncertainty for relay-assisted D2D communication in LTE-A cellular networks where D2D pairs are served by the relay nodes. In [15], relay-assisted D2D communication was proposed as a supplement to direct D2D communications for enhancing traffic offloading capacity in LTE-A systems. The proposed relay selection schemes can improve D2D communication performance significantly. In [16], the authors investigated the performance trade-off between spectral efficiency and energy efficiency in relay-assisted D2D-cellular networks, where D2D users reuse the resource of cellular uplink transmissions. It is worth noting that all these works are limited to half-duplex one-way relaying (OWR), which suffers from a spectral efficiency loss since additional resources are required for relaying transmission.

To compensate spectral efficiency loss in one-way relaying system, two-way relaying (TWR) using an amplify-and-forward (AF) or a decode-and-forward (DF) protocol has been proposed [17]–[19]. Generally, TWR comprises two source nodes and one relay node. The two source nodes simultaneously send their information to the relay node in the first phase and the relay node forwards the combined signal to the two source nodes in the second phase. To complete one-round of information exchange between two source nodes, OWR requires four time-slots while TWR only needs two time-slots. As such, some papers have begun to integrate TWR into D2D communications. References [20] and [21] investigated the outage probability of underlay D2D communications assisted by two-way DF relaying and AF relaying, respectively. However, the authors only consider the performance of D2D link and ignore the cellular link. In [22], the authors investigated the linear precoder-decoder schemes for a multiple-input multiple-output (MIMO) underlay D2D communication system. Two transmit modes for D2D communications were considered: two-way relaying based D2D and direct D2D. In the two-way relaying based D2D mode, physical layer network coding (PNC) was used. In [23], the authors investigated the average energy efficiency and spectral efficiency of multihop D2D communications where one user may help the other two users to exchange information with PNC scheme. In [24], Huang and Gharavi presented an analytical approach to evaluate the performance of two-way asymmetric D2D communications with and without network coding. In [25], the authors investigated the performance of D2D communication assisted by two-way DF relaying. The analytical results showed that D2D communication assisted by two-way DF relaying provides better performance

in terms of maximum achievable sum-rate as compared to cellular communication mode.

In this paper, we propose a two-way AF relaying scheme to assist the underlay D2D communications and investigate the power control problems, which are formulated as the optimization of the performance of the D2D link while fulfilling the QoS requirement of the cellular link. Two optimization objectives are considered for the D2D link, i.e., maximization of the minimum SINR at D2D users and maximization of the sum-rate of D2D users. Simulation results show that the performance can be improved by using power control.

The rest of the paper is organized as follows. In section II, the system model is introduced. The power control algorithms are investigated in section III. Afterward, in section IV, some simulation results are given. Finally, section V concludes this paper.

II. SYSTEM MODEL

Consider a single-cell scenario with two types of communication, i.e., traditional cellular communication and D2D communication aided by two-way AF relaying. Underlay D2D mode is assumed, i.e., the cellular link and D2D link share the same spectrum resources. The cellular link consists of a cellular user (CU) and a BS, while the D2D link consists of a pair of D2D users (DU_1 and DU_2) and an assisted relay user (RU). We assume the direct link between DU_1 and DU_2 does not exist due to the large separation or obstacles. DU_1 and DU_2 communicate with each other via RU which uses two-way AF relaying protocol.

We assume time division duplex (TDD) mode is used, then the first phase and second phase of the two-way D2D communication can share the uplink or downlink resource of the cellular communications. Therefore, there are four possible transmission schemes according to the relationship between the uplink and downlink phases of cellular communication and the two phases of the two-way D2D communication. Since the power control algorithms are similar for all the possible transmission schemes, this paper focuses on one specific transmission scheme, as shown in Fig. 1, where the first phase of the two-way D2D communication shares the downlink resource of the cellular communications, while the second phase of the two-way D2D communication shares the uplink resource of the cellular communications.

We assume all the channels are reciprocal and time-invariant over two phases, i.e., the channel from node A to node B, and the channel from node B to node A are the same. For the cellular link, the desired channel between BS and CU is denoted as h_0. For the D2D link, the desired channels between DU_1, DU_2 and RU are denoted as h_1 and h_2, respectively. We denote the interference channel between BS and RU as f_0, and the interference channel between DU_1, DU_2 and CU as f_1 and f_2, respectively. Furthermore, we assume that perfect channel state information (CSI) is available at both the transmitter and the receiver, and the BS can obtain all the CSI.
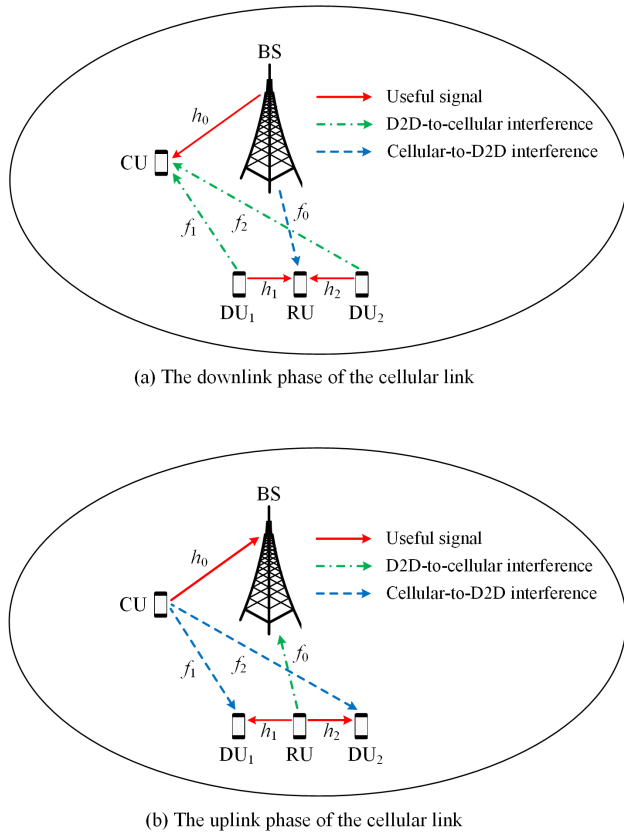
(a) The downlink phase of the cellular link

(b) The uplink phase of the cellular link

FIGURE 1. System model of two-way AF relay assisted D2D communications underlaying cellular networks.

We denote the unit-power transmitted symbol of the BS, CU, DU_1, and DU_2 as x_b, x_c, x_1, and x_2, respectively. The transmit power of BS, CU, RU, DU_1, and DU_2 are denoted as P_b, P_c, P_r, P_1, and P_2, respectively. We assume the maximum transmit power of BS and CU are $P_b^{\max}$ and $P_c^{\max}$, respectively, and the maximum transmit power of RU, DU_1, and DU_2 are the same and denoted as $P_d^{\max}$. The complex additive white Gaussian noise (AWGN) at the BS, CU, RU, DU_1, and DU_2 are denoted by n_b, n_c, n_r, n_1, and n_2, respectively, which have zero mean and variance N_0.

During the first phase, the received signals at the CU and the RU are given as

$$y_c = \sqrt{P_b}h_0x_b + \sqrt{P_1}f_1x_1 + \sqrt{P_2}f_2x_2 + n_c, \quad (1)$$
$$y_r = \sqrt{P_1}h_1x_1 + \sqrt{P_2}h_2x_2 + \sqrt{P_b}f_0x_b + n_r. \quad (2)$$

During the second phase, the RU multiplies its received signal in the first phase by a scaling factor β which is chosen

to satisfy the power constraint at the RU, i.e.,

$$\beta = \frac{\sqrt{P_r}}{\sqrt{P_1|h_1|^2 + P_2|h_2|^2 + P_b|f_0|^2 + N_0}}. \quad (3)$$

Then, the RU forwards the amplified signal $x_r = \beta y_r$ to DU_1 and DU_2, and the received signal at the BS, DU_1 and DU_2 are given as

$$y_b = \sqrt{P_c}h_0x_c + f_0x_r + n_b, \quad (4)$$
$$\begin{aligned} y_1 &= h_1\beta y_r + \sqrt{P_c}f_1x_c + n_1 \\ &= \sqrt{P_1}\beta h_1h_1x_1 + \sqrt{P_2}\beta h_1h_2x_2 + \sqrt{P_b}\beta h_1f_0x_b \\ &\quad + \beta h_1n_r + \sqrt{P_c}f_1x_c + n_1, \end{aligned} \quad (5)$$
$$\begin{aligned} y_2 &= h_2\beta y_r + \sqrt{P_c}f_2x_c + n_2 \\ &= \sqrt{P_1}\beta h_1h_2x_1 + \sqrt{P_2}\beta h_2h_2x_2 + \sqrt{P_b}\beta h_2f_0x_b \\ &\quad + \beta h_2n_r + \sqrt{P_c}f_2x_c + n_2. \end{aligned} \quad (6)$$

Since both DU_1 and DU_2 know their own transmitted symbols and the knowledge of the CSI, the self-interference can be removed from the received signal. After the self-interference cancellation, the signal-to-interference-and-noise ratios (SINRs) at DU_1 and DU_2 can be expressed as

$$SINR_1 = \frac{P_2|\beta|^2|h_1|^2|h_2|^2}{P_b|\beta|^2|h_1|^2|f_0|^2 + |\beta|^2|h_1|^2N_0 + P_c|f_1|^2 + N_0}, \quad (7)$$
$$SINR_2 = \frac{P_1|\beta|^2|h_1|^2|h_2|^2}{P_b|\beta|^2|h_2|^2|f_0|^2 + |\beta|^2|h_2|^2N_0 + P_c|f_2|^2 + N_0}. \quad (8)$$

By substituting (3) into (7) and (8) and after some manipulations, the SINRs can be rewritten as in (9) and (10), shown at the bottom of the page.

III. POWER CONTROL ALGORITHMS
In this section, we formulate the power control problem as the optimization of the performance of the D2D link while fulfilling the QoS requirement of the cellular link. Two optimization objectives are considered for the D2D link: (1) Maximization of the minimum SINR at DU_1 and DU_2, and (2) Maximization of the sum-rate of DU_1 and DU_2. We denote the uplink and downlink SINR requirement of the cellular link as τ_u and τ_d, respectively. Then the QoS requirement of the cellular link can be given as

$$\frac{P_b|h_0|^2}{P_1|f_1|^2 + P_2|f_2|^2 + N_0} \ge \tau_d, \quad \frac{P_c|h_0|^2}{P_r|f_0|^2 + N_0} \ge \tau_u. \quad (11)$$

$$SINR_1 = \frac{P_2P_r|h_1|^2|h_2|^2}{(P_b|f_0|^2 + N_0)(P_c|f_1|^2 + P_r|h_1|^2 + N_0) + (P_c|f_1|^2 + N_0)(P_1|h_1|^2 + P_2|h_2|^2)} \quad (9)$$

$$SINR_2 = \frac{P_1P_r|h_1|^2|h_2|^2}{(P_b|f_0|^2 + N_0)(P_c|f_2|^2 + P_r|h_2|^2 + N_0) + (P_c|f_2|^2 + N_0)(P_1|h_1|^2 + P_2|h_2|^2)} \quad (10)$$

Obviously, feasible solution exists under the condition $\frac{P_b^{\max}|h_0|^2}{N_0} > \tau_d$ and $\frac{P_c^{\max}|h_0|^2}{N_0} > \tau_u$. In this paper, we assume this condition is always satisfied.

From (9) and (10), we can see both $SINR_1$ and $SINR_2$ are monotonic decreasing functions respect to P_b and P_c, so the inequality constraints in (11) should be equality constraints. Otherwise, we can decrease the values of P_b and P_c till the equality constraints are satisfied while increasing the minimum SINR at DU_1 and DU_2 or the sum-rate of DU_1 and DU_2. Therefore, we have

$$P_b = \frac{\left(P_1|f_1|^2 + P_2|f_2|^2 + N_0\right)\tau_d}{|h_0|^2}, \tag{12}$$

$$P_c = \frac{\left(P_r|f_0|^2 + N_0\right)\tau_u}{|h_0|^2}. \tag{13}$$

Substituting (13) into (9) and (10), it is easy to see that both $SINR_1$ and $SINR_2$ are monotonically increasing functions of the transmit power of RU. Considering the constraints $P_c \leq P_c^{\max}$ and $P_r \leq P_d^{\max}$, the optimal value of P_r is given as

$$P_r^* = \min\left(P_d^{\max}, \frac{P_c^{\max}|h_0|^2}{|f_0|^2\tau_u} - \frac{N_0}{|f_0|^2}\right). \tag{14}$$

Substituting (12), (13) and (14) into (9) and (10) and after some manipulations, we can obtain

$$SINR_1 = \frac{P_2 P_r^*}{A_1 P_1 + A_2 P_2 + A_3}, \tag{15}$$

$$SINR_2 = \frac{P_1 P_r^*}{B_1 P_1 + B_2 P_2 + B_3}, \tag{16}$$

where

$$A_1 = \left(\frac{\left(P_r^*|f_0|^2 + N_0\right)|f_1|^2\tau_u}{|h_0|^2} + N_0\right)$$
$$\times \left(\frac{|f_0|^2|f_1|^2\tau_d}{|h_0|^2|h_1|^2|h_2|^2} + \frac{1}{|h_2|^2}\right) + \frac{P_r^*|f_0|^2|f_1|^2\tau_d}{|h_0|^2|h_2|^2},$$

$$A_2 = \left(\frac{\left(P_r^*|f_0|^2 + N_0\right)|f_1|^2\tau_u}{|h_0|^2} + N_0\right)$$
$$\times \left(\frac{|f_0|^2|f_2|^2\tau_d}{|h_0|^2|h_1|^2|h_2|^2} + \frac{1}{|h_1|^2}\right) + \frac{P_r^*|f_0|^2|f_2|^2\tau_d}{|h_0|^2|h_2|^2},$$

$$A_3 = \left(\frac{\left(P_r^*|f_0|^2 + N_0\right)|f_1|^2\tau_u}{|h_0|^2|h_1|^2|h_2|^2} + \frac{P_r^*}{|h_2|^2} + \frac{N_0}{|h_1|^2|h_2|^2}\right)$$
$$\times \left(\frac{|f_0|^2\tau_d}{|h_0|^2} + 1\right)N_0,$$

$$B_1 = \left(\frac{\left(P_r^*|f_0|^2 + N_0\right)|f_2|^2\tau_u}{|h_0|^2} + N_0\right)$$
$$\times \left(\frac{|f_0|^2|f_1|^2\tau_d}{|h_0|^2|h_1|^2|h_2|^2} + \frac{1}{|h_2|^2}\right) + \frac{P_r^*|f_0|^2|f_1|^2\tau_d}{|h_0|^2|h_1|^2},$$

$$B_2 = \left(\frac{\left(P_r^*|f_0|^2 + N_0\right)|f_2|^2\tau_u}{|h_0|^2} + N_0\right)$$

$$\times \left(\frac{|f_0|^2|f_2|^2\tau_d}{|h_0|^2|h_1|^2|h_2|^2} + \frac{1}{|h_1|^2}\right) + \frac{P_r^*|f_0|^2|f_2|^2\tau_d}{|h_0|^2|h_1|^2},$$

$$B_3 = \left(\frac{\left(P_r^*|f_0|^2 + N_0\right)|f_2|^2\tau_u}{|h_0|^2|h_1|^2|h_2|^2} + \frac{P_r^*}{|h_1|^2} + \frac{N_0}{|h_1|^2|h_2|^2}\right)$$
$$\times \left(\frac{|f_0|^2\tau_d}{|h_0|^2} + 1\right)N_0.$$

A. MAXIMIZATION OF THE MINIMUM SINR

In this subsection, we formulate the power control problem as the maximization of the minimum SINR at DU_1 and DU_2. The optimization problem can be formulated as

$$\max_{P_1, P_2} \min\left(SINR_1, SINR_2\right)$$
$$\text{s.t. } 0 < P_1|f_1|^2 + P_2|f_2|^2 \leq \eta,$$
$$0 < P_1, P_2 \leq P_d^{\max}. \tag{17}$$

where $\eta = \frac{P_b^{\max}|h_0|^2}{\tau_d} - N_0$. To solve this optimization problem, we first introduce the following two propositions.

Proposition 1: The optimal solution to problem (17) must satisfy $SINR_1 = SINR_2$.

Proof: We can prove this assertion by the following argument. Note that $SINR_1$ is a monotonic decreasing function with respect to P_1 and a monotonic increasing function with respect to P_2, and $SINR_2$ is a monotonic increasing function with respect to P_1 and a monotonic decreasing function with respect to P_2. Suppose that at the optimal solution, $SINR_1 > SINR_2$, then we can decrease the value of P_2 to decrease $SINR_1$ and increase $SINR_2$ till $SINR_1 = SINR_2$ while increasing the smaller SINR. Suppose that at the optimal solution, $SINR_1 < SINR_2$, then we can decrease the value of P_1 to increase $SINR_1$ and decrease $SINR_2$ till $SINR_1 = SINR_2$ while also increasing the smaller SINR. As such, we can conclude that $SINR_1 = SINR_2$ at the optimal solution.

Proposition 2: The optimal solution to problem (17) must be on the boundary of the feasible region.

Proof: This can be proved by contradiction. Suppose the optimal solution of (23) is $\left(P_1^*, P_2^*\right)$, which is in the interior of the feasible region. Then there exist a constant $\lambda = \min\left(\frac{P_d^{\max}}{P_1^*}, \frac{P_d^{\max}}{P_2^*}, \frac{\eta}{P_1^*|f_1|^2 + P_2^*|f_2|^2}\right) > 1$ such that $\left(\lambda P_1^*, \lambda P_2^*\right)$ is on the boundary of the feasible region. It is easy to see that the new solution satisfy

$$\frac{\lambda P_2^* P_r^*}{A_1 \lambda P_1^* + A_2 \lambda P_2^* + A_3} = \frac{P_2^* P_r^*}{A_1 P_1^* + A_2 P_2^* + \frac{A_3}{\lambda}}$$
$$> \frac{P_2^* P_r^*}{A_1 P_1^* + A_2 P_2^* + A_3} \quad \text{as } \lambda > 1, \tag{18}$$

$$\frac{\lambda P_1^* P_r^*}{B_1 \lambda P_1^* + B_2 \lambda P_2^* + B_3} = \frac{P_1^* P_r^*}{B_1 P_1^* + B_2 P_2^* + \frac{B_3}{\lambda}}$$
$$> \frac{P_1^* P_r^*}{B_1 P_1^* + B_2 P_2^* + B_3} \quad \text{as } \lambda > 1, \tag{19}$$

Since both SINRs are improved, the smaller SINR is improved. This contradictions the assumption that $\left(P_1^*, P_2^*\right)$ is the optimal solution. Therefore, we can conclude the optimal solution must be on the boundary of the feasible region.

Since the boundary of the feasible region can be divided into three cases, we need to investigate each case separately.

CASE A: $P_1 = P_d^{\max}$. In this case, substituting $P_1 = P_d^{\max}$ into SINR_1 and SINR_2 and using $\text{SINR}_1 = \text{SINR}_2$, we can obtain

$$B_2 P_2^2 + \left[(B_1 - A_2) P_d^{\max} + B_3\right] P_2 - P_d^{\max}\left(A_1 P_d^{\max} + A_3\right) = 0. \quad (20)$$

It is easy to ascertain that this quadratic equation has only one positive solution. If this positive solution is less than or equal to $P_d^{\max}$ and $\frac{\eta - P_d^{\max}|f_1|^2}{|f_2|^2}$, the optimal solution may be on this boundary. Otherwise, the optimal solution must not be on this boundary.

CASE B: $P_2 = P_d^{\max}$. In this case, substituting $P_2 = P_d^{\max}$ into SINR_1 and SINR_2 and using $\text{SINR}_1 = \text{SINR}_2$, we can obtain

$$A_1 P_1^2 + \left[(A_2 - B_1) P_d^{\max} + A_3\right] P_1 - P_d^{\max}\left(B_2 P_d^{\max} + B_3\right) = 0. \quad (21)$$

Similar to case A, this quadratic equation has only one positive solution. If this positive solution is less than or equal to $P_d^{\max}$ and $\frac{\eta - P_d^{\max}|f_2|^2}{|f_1|^2}$, the optimal solution may be on this boundary. Otherwise, the optimal solution must not be on this boundary.

CASE C: $P_1|f_1|^2 + P_2|f_2|^2 = \eta$. In this case, substituting $P_1 = \frac{\eta - P_2|f_2|^2}{|f_1|^2}$ into SINR_1 and SINR_2 and using $\text{SINR}_1 = \text{SINR}_2$, we can obtain

$$\left(A_1|f_2|^4 - B_2|f_1|^4 - A_2|f_1|^2|f_2|^2 + B_1|f_1|^2|f_2|^2\right) P_2^2$$
$$- \left(2A_1|f_2|^2\eta + A_3|f_1|^2|f_2|^2 + B_3|f_1|^4 - A_2|f_1|^2\eta + B_1|f_1|^2\eta\right) P_2 + A_1\eta^2 + A_3|f_1|^2\eta = 0. \quad (22)$$

By solving this quadratic equation, we can get one or two positive solutions for P_2. For each positive solution of P_2, we can obtain the corresponding P_1. If the obtained P_1 is positive and both the obtained P_1 and P_2 are less than or equal to $P_d^{\max}$, the optimal solution may be on this boundary. Otherwise, the optimal solution must not be on this boundary.

Finally, we compare the obtained possible optimal solutions for the three boundary conditions. The solution that maximizes the objective function is the optimal solution.

B. MAXIMIZATION OF THE SUM-RATE

In this subsection, we formulate the power control problem as the maximization of the sum-rate of DU_1 and DU_2. The optimization problem can be formulated as

$$\max_{P_1, P_2} \quad \log_2\left(1 + \text{SINR}_1\right) + \log_2\left(1 + \text{SINR}_2\right)$$
$$\text{s.t.} \quad 0 < P_1|f_1|^2 + P_2|f_2|^2 \leq \eta,$$
$$0 < P_1, P_2 \leq P_d^{\max}. \quad (23)$$

Since the objective function is non-convex, the standard convex optimization methods cannot directly be used to solve this problem. Note that the objective function has a difference of convex (D. C.) structure, we can use an efficient iterative algorithm to solve this problem. We denote $\boldsymbol{P} = [P_1, P_2]^T$, where superscript $(\cdot)^T$ denotes the transpose, and the objective function can be written as

$$\log_2\left(1 + \text{SINR}_1\right) + \log_2\left(1 + \text{SINR}_2\right) = f_1\left(\boldsymbol{P}\right) - f_2\left(\boldsymbol{P}\right), \quad (24)$$

where

$$f_1\left(\boldsymbol{P}\right) = \log_2\left(A_1 P_1 + \left(A_2 + P_r^*\right) P_2 + A_3\right) + \log_2\left(\left(B_1 + P_r^*\right) P_1 + B_2 P_2 + B_3\right),$$

and

$$f_2\left(\boldsymbol{P}\right) = \log_2\left(A_1 P_1 + A_2 P_2 + A_3\right) + \log_2\left(B_1 P_1 + B_2 P_2 + B_3\right).$$

It is easy to verify that $f_1\left(\boldsymbol{P}\right)$ and $f_2\left(\boldsymbol{P}\right)$ are concave on $\boldsymbol{P}$, thus (24) is a D. C. function. Besides, the constraints in (23) are all linear. Thus, we can solve (23) based on D. C. programming.

Based on [30], the term $f_2\left(\boldsymbol{P}\right)$ can be approximated by $f_2\left(\boldsymbol{P}^{(k)}\right) + \left\langle \nabla f_2\left(\boldsymbol{P}^{(k)}\right), \boldsymbol{P} - \boldsymbol{P}^{(k)} \right\rangle$ at point $\boldsymbol{P}^{(k)}$ by using the first order Taylor expansion, where $\langle \boldsymbol{x}, \boldsymbol{y} \rangle = \boldsymbol{x}^T \boldsymbol{y}$ denotes the inner product between vectors $\boldsymbol{x}$ and $\boldsymbol{y}$, and $\nabla f_2\left(\boldsymbol{P}^{(k)}\right)$ denotes the gradient of $f_2\left(\boldsymbol{P}\right)$ at $\boldsymbol{P}^{(k)} = \left[P_1^{(k)}, P_2^{(k)}\right]^T$. Since the term $f_2\left(\boldsymbol{P}\right)$ is linearized, the D. C. function (24) can be converted into a concave function. Then, we can select a feasible initial value $\boldsymbol{P}^{(0)}$ and obtain $\boldsymbol{P}^{(k+1)}$ at k-th iteration by the optimal solution of the following convex optimization problem:

$$\max_{\boldsymbol{P}} \quad \left\{ f_1\left(\boldsymbol{P}\right) - f_2\left(\boldsymbol{P}^{(k)}\right) - \left\langle \nabla f_2\left(\boldsymbol{P}^{(k)}\right), \boldsymbol{P} - \boldsymbol{P}^{(k)} \right\rangle \right\},$$
$$\text{s.t.} \quad 0 < P_1|f_1|^2 + P_2|f_2|^2 \leq \eta,$$
$$0 < P_1, P_2 \leq P_d^{\max}. \quad (25)$$

This optimization problem can be solved by using standard convex optimization techniques, such as the interior-point method [28], [29]. The iterative algorithm is summarized in Algorithm 1.

Algorithm 1 Iterative Algorithm

1: Set $k = 0$, choose a feasible $\boldsymbol{P}^{(0)}$, $\varepsilon > 0$.
2: **repeat**
3:     Solve convex optimization problem (25) to obtain
4:     the solution $\boldsymbol{P}^*$;
5:     Set $k = k + 1$;
6:     Set $\boldsymbol{P}^{(k)} = \boldsymbol{P}^*$;
7: **until** $\left\| \boldsymbol{P}^{(k)} - \boldsymbol{P}^{(k-1)} \right\| < \varepsilon$.

According to [30], the non-convex optimization problem (23) is well approximated by the convex optimization problem (25). Besides, the improved solutions always converge so that the iterative process stops after limited iterations.

IV. NUMERICAL AND SIMULATION RESULTS

In this section, we present some numerical and simulation results to validate our analysis. The simulation scenario is shown in Fig. 2, where the BS is located at the origin, CU and RU are located on the y-axis, and DU_1, RU and DU_2 are located in a straight line. The coordinates of CU, RU, DU_1, and DU_2 are given as $(0, 200)$, $(0, -d_{br})$, $(-d_{1r}, -d_{br})$, and $(d_{2r}, -d_{br})$, respectively, where d_{br}, d_{1r}, and d_{2r} denote the distances between BS and RU, DU_1 and RU, and DU_2 and RU, respectively. Other basic simulation parameters are given as follows: $N_0 = -100$ dBm, $P_b^{max} = 26$ dBm, $P_c^{max} = P_d^{max} = 20$ dBm, and $\tau_u = 10$ dB.
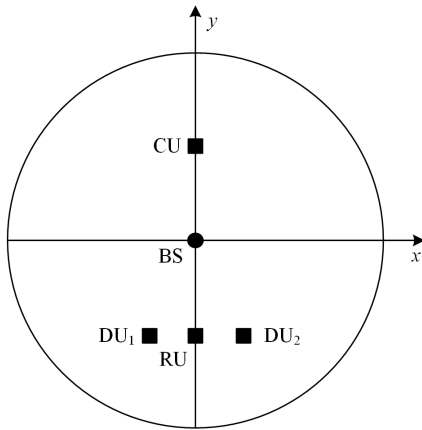

FIGURE 2. The simulation scenario.

We assume the channels comprise both Rayleigh fading and path loss, and the path loss exponent is assumed to be 4. We use Monte-Carlo simulations to get the average of the performance metric. For comparison, we also simulate the performance of equal transmit power scheme, i.e.,

$$P_1 = P_2 = \frac{\eta}{|f_1|^2 + |f_2|^2}. \tag{26}$$

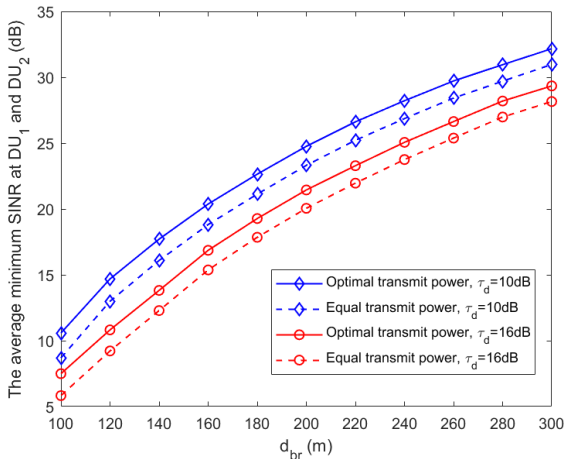Fig. 3 and Fig. 4 show the average minimum SINR at DU_1 and DU_2 with different locations of RU, DU_1 and DU_2.
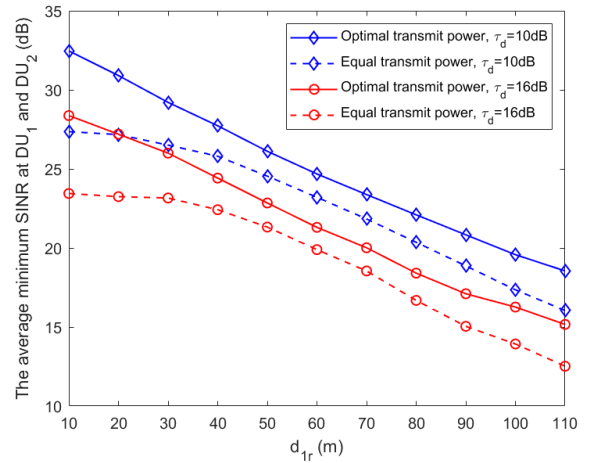

FIGURE 4. The average minimum SINR at DU_1 and DU_2 with $d_{br} = 200$ m and $d_{2r} = 60$ m.

In Fig. 3, we assume $d_{1r} = d_{2r} = 60$ m, and plot the average minimum SINR at DU_1 and DU_2 versus d_{br} for $\tau_d = 10$ dB and 16 dB, respectively. From Fig. 3, we can see that the proposed optimal transmit power scheme performs about 1.5 dB better than the equal transmit power scheme. In Fig. 4, we assume $d_{br} = 200$ m and $d_{2r} = 60$ m, and plot the average minimum SINR at DU_1 and DU_2 versus d_{1r} for $\tau_d = 10$ dB and 16 dB, respectively. From Fig. 4, we can see that the gap between the optimal transmit power scheme and the equal transmit power scheme becomes bigger and bigger as the difference between d_{1r} and d_{2r} increases. For example, when $d_{1r} = 10$ m, the proposed optimal transmit power scheme performs about 5 dB better than the equal transmit power scheme. Both Fig. 3 and Fig. 4 show that the proposed power control scheme can improve the performance of the minimum SINR at DU_1 and DU_2.

Fig. 5 and Fig. 6 illustrate the average sum-rate of DU_1 and DU_2 with different locations of RU, DU_1 and DU_2. In Fig. 5, we assume $d_{1r} = d_{2r} = 60$ m, and plot the average sum-rate

FIGURE 3. The average minimum SINR at DU_1 and DU_2 with $d_{1r} = d_{2r} = 60$ m.
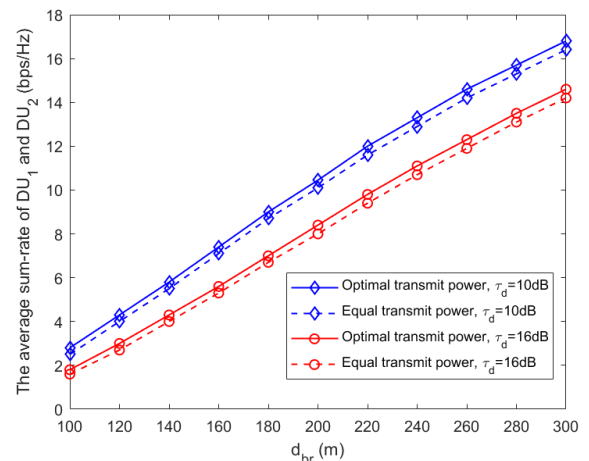

FIGURE 5. The average sum-rate of DU_1 and DU_2 with $d_{1r} = d_{2r} = 60$ m.
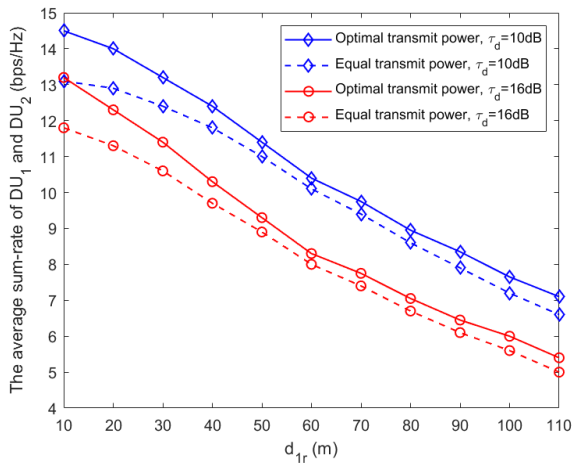
FIGURE 6. The average sum-rate of DU_1 and DU_2 with $d_{br} = 200$ m and $d_{2r} = 60$ m.

at DU_1 and DU_2 versus d_{br} for $\tau_d = 10$ dB and 16 dB, respectively. Fig. 5 shows that the proposed optimal transmit power scheme performs better than the equal transmit power scheme, but the benefits are not that great. In Fig. 6, we assume $d_{br} = 200$ m and $d_{2r} = 60$ m, and plot the average sum-rate at DU_1 and DU_2 versus d_{1r} for $\tau_d = 10$ dB and 16 dB, respectively. Fig. 6 shows that the gap between the optimal transmit power scheme and the equal transmit power scheme becomes bigger and bigger as the difference between d_{1r} and d_{2r} increases. For example, when $d_{1r} = 10$ m, the proposed optimal transmit power scheme performs more than 1 bps/Hz better than the equal transmit power scheme. Both Fig. 5 and Fig. 6 show that the proposed power control scheme can improve the performance of the sum-rate of DU_1 and DU_2.

V. CONCLUSION

In this paper, we proposed a two-way AF relaying scheme to extend the range of D2D communications and investigated its power control problems, which were formulated as the maximization of the minimum SINR at D2D users or maximization of the sum-rate of D2D users while fulfilling the QoS requirement of the cellular link. For each optimization objective, we proposed the corresponding power control algorithm. It was shown by the simulation results that the proposed power control schemes present a better performance than the equal transmit power scheme. Note that this paper focuses on two-way AF relay assisted D2D communications, and we will extend this research to two-way DF relay in the future.

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