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SPECIAL SECTION ON NEW WAVEFORM DESIGN AND AIR-INTERFACE FOR FUTURE HETEROGENEOUS NETWORK TOWARDS 5G

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Power Control for Full-Duplex D2D Communications Underlaying Cellular Networks

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ABSTRACT As two promising candidate techniques for the 5G mobile communication system, device-to-device (D2D) communications and full-duplex communications have drawn significant research interests. Since full-duplex communications are suitable for use in low transmit power scenarios to lower the residual self-interference (SI), while D2D communications work in short distance scenarios which result in low transmit power, it is natural to integrate full-duplex into D2D communications. In this paper, we investigate the power control for full-duplex D2D communications underlaying cellular networks. Specifically, we formulate the power control problem by maximizing the achievable sum-rate of the full-duplex D2D link while fulfilling the minimum rate requirement of the cellular link under the maximum transmit power constraint of the cellular user and D2D users. Two algorithms are proposed to solve the optimization problem. For the first algorithm, we convert the objective function into a concave function based on difference of convex (D. C.) structure and propose an iterative algorithm to solve the optimization problem. For the second algorithm, we consider the received signal-to-interference-plus-noise ratios (SINRs) at the D2D users are high. Based on high-SINR approximation, closed-form optimal solutions are obtained for different boundaries of the feasible region. Numerical results are presented to illustrate the effect of the channel gains and SI cancellation ability on the optimal transmit power and the achievable sum-rate of the full-duplex D2D link.

INDEX TERMS D2D communications, full-duplex, power control, underlaying cellular networks.

I. INTRODUCTION

The fifth-generation (5G) mobile communication system, which is expected to be large-scale deployed in the future, has attracted worldwide research interests in recent years [1]–[5]. Currently, many novel techniques are being studied for future 5G systems, among which device-to-device (D2D) communications and full-duplex communications have been regarded as two promising candidate techniques [3], [4].

As one of the most important techniques for the 5G mobile communication system, D2D communications have drawn significant research interests [6]–[8]. Different from traditional cellular communication where all the communications must go through the base station (BS), D2D communications enable nearby mobile devices to communicate directly with each other, thereby improving spectral efficiency, reducing packet delay, and introducing new peer-to-peer and location-aware applications, such as content distribution and multi-player gaming. In general, D2D communications can be divided into two categories, i.e., overlay D2D communications and underlay D2D communications [8]. In overlay D2D communications, cellular resources are dedicated to D2D users. In contrast, underlay D2D communications allow cellular and D2D communications to share the same resources, which can improve spectrum efficiency but cause interference between D2D and cellular communication. This interference can be mitigated through power control and resource allocation. In [9], the authors formulated a resource allocation problem for D2D communications underlaying cellular uplink to maximize the overall network throughput while meeting the quality-of-service (QoS) requirements for both D2D users and cellular users. Based on stochastic geometry, reference [10] proposed a random network model

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for underlay D2D communications and developed both centralized and distributed power control algorithms. In [11], the authors investigated joint resource allocation and power control for maximization of the energy efficiency of D2D communications underlaying cellular networks.

So far, most of the studies on communications focused on half-duplex mode, which means the devices could either receive or transmit. It has long been regarded as impractical to use full-duplex mode, which allows the devices to transmit and receive at the same time and over the same frequency, due to strong self-interference (SI). Recently, encouraged by the progress in SI cancellation techniques, the SI can be effectively eliminated by using various techniques, such as physical separation of the transmit and receive antennas, analog domain cancellation and digital domain cancellation [12]–[16]. Therefore, the full-duplex mode has attracted a lot of research interests. Although there have been many works on SI cancellation techniques, the SI cannot be completely cancelled in practice. In [15], analog and digital techniques can cancel 110 dB of SI with transmit power of 20 dBm. In [16], the SI has been cancelled to only 3 dB higher than the noise level using the all-digital SI cancellation technique. As such, the residual SI will consequently limit the performance gain introduced by the full-duplex mode.

According to the measurements in the practical experiments, the residual SI is related to the transmit power and it is better to use full-duplex mode for low transmit power. Since D2D communications work in short distance scenarios, which result in low transmit power and thus low residual SI, it is natural to integrate full-duplex into D2D communications [17]. Compared to half-duplex D2D communications, full-duplex D2D communications have many advantages. First, full-duplex D2D communications can further improve the spectral efficiency and, in the best case, double the spectral efficiency. Besides, full-duplex D2D communications can further reduce the delay, which is suitable for 5G ultra-reliable low-latency communications (URLLC) services, such as vehicle-to-everything (V2X) communications.

Recently, some papers have begun to investigate the full-duplex D2D communications. In [18], the authors proposed a stochastic geometry-based framework for large-scale cellular networks overlaid with full-duplex D2D users that have residual SI and a tunable D2D link distance distribution. In [19], the authors analyzed the impact of activating D2D users on the throughput of full-duplex based D2D aided underlaying network by considering residual SI at the full-duplex devices. Reference [20] investigated the power control problem and coverage probability performance for full-duplex relay-assisted D2D communication. In [21], the authors investigated the resource allocation problem for multi-user full-duplex underlay D2D communication, considering both perfect channel state information (CSI) and statistical CSI. In [22], the capacity improvement of full-duplex D2D underlaying cellular networks was analyzed, and the numerical results showed that the capacity improvement of the full-duplex D2D communications is much greater than the half-duplex D2D communication if sufficient SI cancellation is achieved. In the cognitive network, reference [23] investigated the optimal mode selection (half-duplex, full-duplex, or silent) for full-duplex enabled D2D secondary users to protect the primary user transmission.

In this paper, we investigate the power control for full-duplex D2D communications underlaying cellular networks. Specifically, we formulate the power control problem by maximizing the achievable sum-rate of the full-duplex D2D link while fulfilling the minimum rate requirement of the cellular link under the maximum transmit power constraint of the cellular user and D2D users. Two algorithms are proposed to solve the optimization problem. For the first algorithm, we rewrite the objective function as a difference of convex (D. C.) structure, which can be converted into a concave function by using the first-order Taylor expansion, then we propose an iterative algorithm to solve this problem. For the second algorithm, we consider the received signal-to-interference-plus-noise ratios (SINRs) at the D2D users are high. Based on high-SINR approximation, closed-form optimal solutions are obtained for possible boundaries of the feasible region.

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 numerical results are given. Finally, section V concludes this paper.

II. SYSTEM MODEL

In this section, we introduce the system model of full-duplex D2D communications underlaying cellular networks, as shown in Fig. 1. We consider a single-cell scenario with two types of communication, i.e., traditional cellular communication and D2D communication. 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). The uplink resource sharing is considered, i.e., the D2D transmission occupies the uplink resources allocated to the CU. For simplicity, we assume one cellular link can only share its uplink resource with one D2D link. When there are multiple CUs and D2D pairs, resource allocation or channel assignment can be done to ensure one CU has a suitable D2D pair as partner [9], [11], [21].

We denote the channels of the CU-BS, CU-DU_1, CU-DU_2, DU_1-BS, DU_2-BS, DU_1-DU_2 and DU_2-DU_1 links as h_{cb}, h_{c1}, h_{c2}, h_{1b}, h_{2b}, h_{12}, and h_{21}, respectively. All the channels are assumed to be frequency-flat and quasi-static. We further assume that all the CSI, is perfectly known at the BS. The transmit power of the CU, DU_1, and DU_2 are denoted by P_c, P_1, and P_2, respectively. We assume the maximum transmit power of the CU, DU_1 and DU_2 are the same and denoted as $P_{\max}$.

We assume each device is equipped with two antennas, one for receiving and the other for transmitting. Similar to the previous works, we assume the residual SI is subject to the complex Gaussian distribution. This assumption can

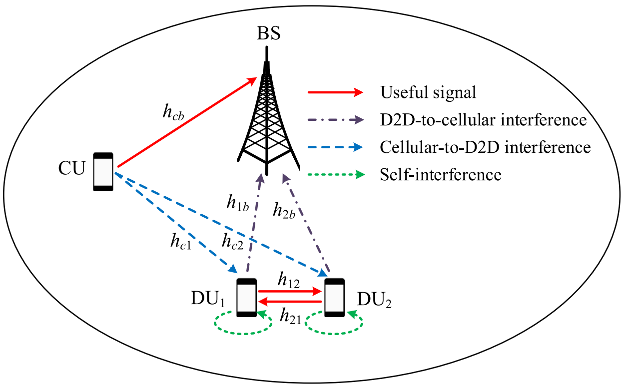

FIGURE 1. System model of full-duplex D2D communications underlaying cellular networks.

be considered as the worst-case assumption about the interference. Furthermore, according to the measurements in the practical experiments, the residual SI at DU_1 and DU_1 were modelled as zero-mean complex Gaussian random variables with variance βP_1 and βP_2, respectively, where β is a constant that reflects the SI cancellation ability [16], [22], [24].

Then the received SINRs at BS, DU_1 and DU_2 are given as

$$\gamma_b = \frac{P_c|h_{cb}|^2}{P_1|h_{1b}|^2 + P_2|h_{2b}|^2 + N_0}, \quad (1)$$

$$\gamma_1 = \frac{P_2|h_{21}|^2}{P_c|h_{c1}|^2 + \beta P_1 + N_0}, \quad (2)$$

and

$$\gamma_2 = \frac{P_1|h_{12}|^2}{P_c|h_{c2}|^2 + \beta P_2 + N_0}, \quad (3)$$

respectively, where N_0 denotes the noise power.

III. POWER CONTROL ALGORITHM

A. PROBLEM FORMULATION

In this paper, we investigate the power control problem by maximizing the achievable sum-rate of the full-duplex D2D link while fulfilling the minimum rate requirement of the cellular link [25].

Based on (1), the achievable rate of the cellular link is given as

$$R_C = \log_2\left(1 + \frac{P_c|h_{cb}|^2}{P_1|h_{1b}|^2 + P_2|h_{2b}|^2 + N_0}\right). \quad (4)$$

We assume the cellular link has a minimum rate requirement, which is denoted by R_T.

Based on (2) and (3), the achievable sum-rate of the full-duplex D2D link is given as

$$R_D = \log_2\left(1 + \frac{P_2|h_{21}|^2}{P_c|h_{c1}|^2 + \beta P_1 + N_0}\right) + \log_2\left(1 + \frac{P_1|h_{12}|^2}{P_c|h_{c2}|^2 + \beta P_2 + N_0}\right). \quad (5)$$

Then, we can formulate the following optimization problem

$$\max_{P_c,P_1,P_2} \; R_D \quad s.t. \;\; R_C \ge R_T, \; 0 < P_c, P_1, \; P_2 \le P_{\max}. \quad (6)$$

We first convert the minimum rate constraint of the CU as

$$P_c \ge \frac{\eta\left(P_1|h_{1b}|^2 + P_2|h_{2b}|^2 + N_0\right)}{|h_{cb}|^2}, \quad (7)$$

where $\eta = 2^{R_T} - 1$. In order to get the maximum of the objective function, the lower bound of P_c has to be achieved. We can prove this assertion by the following argument. For given P_1 and P_2, if the lower bound of P_c has not be achieved, we can always decrease P_c to increase the objective function. Therefore, we have

$$P_c = \frac{\eta\left(P_1|h_{1b}|^2 + P_2|h_{2b}|^2 + N_0\right)}{|h_{cb}|^2}. \quad (8)$$

Substituting (8) into (5) and using two simple variable substitutions, i.e., $P_1 = \frac{x}{|h_{1b}|^2}$ and $P_2 = \frac{y}{|h_{2b}|^2}$, we have

$$R_D(x,y) = \log_2\left(1 + \frac{y}{a_1x + b_1y + c_1}\right) + \log_2\left(1 + \frac{x}{a_2x + b_2y + c_2}\right), \quad (9)$$

where

$$a_1 = \frac{\eta|h_{c1}|^2|h_{2b}|^2}{|h_{cb}|^2|h_{21}|^2} + \frac{\beta|h_{2b}|^2}{|h_{1b}|^2|h_{21}|^2}, \quad a_2 = \frac{\eta|h_{c2}|^2|h_{1b}|^2}{|h_{cb}|^2|h_{12}|^2},$$
$$b_1 = \frac{\eta|h_{c1}|^2|h_{2b}|^2}{|h_{cb}|^2|h_{21}|^2}, \quad b_2 = \frac{\eta|h_{c2}|^2|h_{1b}|^2}{|h_{cb}|^2|h_{12}|^2} + \frac{\beta|h_{1b}|^2}{|h_{2b}|^2|h_{12}|^2},$$
$$c_1 = \left(1 + \frac{\eta|h_{c1}|^2}{|h_{cb}|^2}\right)\frac{|h_{2b}|^2N_0}{|h_{21}|^2},$$
$$c_2 = \left(1 + \frac{\eta|h_{c2}|^2}{|h_{cb}|^2}\right)\frac{|h_{1b}|^2N_0}{|h_{12}|^2}.$$

Then, the optimization problem (6) can be written as

$$\max_{x,y} \; R_D(x,y) \quad s.t. \; 0 < x \le \tau_1, \quad 0 < y \le \tau_2, \; x + y \le \tau_0, \quad (10)$$

where $\tau_1 = P_{\max}|h_{1b}|^2$, $\tau_2 = P_{\max}|h_{2b}|^2$, and $\tau_0 = \frac{P_{\max}|h_{cb}|^2}{\eta} - N_0$. Obviously, feasible solutions exist when $\tau_0 > 0$. In this paper, we assume this condition is always satisfied.

B. ITERATIVE ALGORITHM

Due to the non-convexity of the objective function, we cannot solve it directly. Note that the objective function has a D. C. structure, an efficient iterative algorithm can be used to solve this problem. First, we denote $z = [x, y]^T$ where superscript $(\cdot)^T$ denotes the transpose operator, and rewrite the objective function as

$$R_D(z) = g_1(z) - g_2(z), \quad (11)$$

where

$$g_1(z) = \log_2(a_1x + (b_1+1)y + c_1) + \log_2((a_2+1)x + b_2y + c_2), \quad (12)$$

and

$$g_2(z) = \log_2(a_1x + b_1y + c_1) + \log_2(a_2x + b_2y + c_2). \quad (13)$$

Obviously, $g_1(z)$ and $g_2(z)$ are concave on z, thus (11) is a D. C. function. Moreover, the constraint set in (10) is convex since the constraints are all linear. Thus, we can solve this problem based on D. C. programming.

According to [28], the term $g_2(z)$ can be approximated as $g_2(z^{(k)}) + \langle \nabla g_2(z^{(k)}), z - z^{(k)} \rangle$ at point $z^{(k)}$ 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 $\nabla g_2(z^{(k)})$ denotes the gradient of g_2 at $z^{(k)}$. Then, the D. C. function can be converted into a concave function. Starting from a feasible initial value $z^{(0)}$, $z^{(k+1)}$ at k-th iteration can be obtained as the optimal solution of the following convex optimization problem:

$$\begin{aligned} &\max_{z} \; g_1(z) - g_2(z^{(k)}) - \langle \nabla g_2(z^{(k)}), z - z^{(k)} \rangle \\ &s.t.\; 0 < x \le \tau_1, \quad 0 < y \le \tau_2, \; x + y \le \tau_0, \end{aligned} \quad (14)$$

which can be solved efficiently by using standard convex optimization techniques, e.g., the interior-point method [26], [27]. The iterative algorithm can be summarized in Algorithm 1.

Algorithm 1 Iterative Algorithm

1: Initialization: Set $k = 0$, choose a feasible $z^{(0)}$, $\varepsilon > 0$
2: **repeat**
3: Solve convex optimization problem $z^{(k+1)} = \max_{z} \; g_1(z) - g_2(z^{(k)}) - \langle \nabla g_2(z^{(k)}), z - z^{(k)} \rangle$ to obtain the solution z^*;
4: Set $k = k + 1$;
5: Set $z^{(k)} = z^*$;
6: **until** $\| z^{(k)} - z^{(k-1)} \| < \varepsilon$

According to [28], the non-convex optimization problem (10) is well approximated by the convex optimization problem (14). Moreover, the $\{z^{(k)}\}$ of improved solutions always converges so that the iterative process terminates after finite iterations.

C. POWER CONTROL ALGORITHM FOR HIGH SINR

To make the optimization problem (10) tractable, we assume the received SINRs at DU_1 and DU_2 are high, which is reasonable since the D2D users are usually very close to each other and require high data-rate. Then the objective function is given as

$$R_D(x, y) \approx \log_2 \left(\frac{y}{a_1x + b_1y + c_1} \right) \left(\frac{x}{a_2x + b_2y + c_2} \right). \quad (15)$$

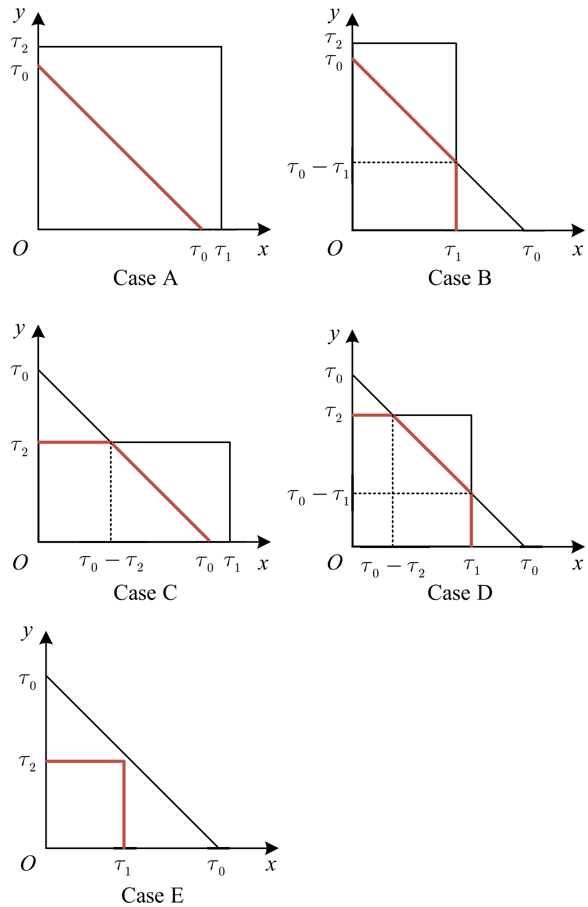

FIGURE 2. Possible cases for the boundary of the feasible region.

Furthermore, the optimization problem (10) can be written as

$$\begin{aligned} &\min_{x,y} f(x, y) \\ &s.t.\; 0 < x \le \tau_1, \quad 0 < y \le \tau_2, \; x + y \le \tau_0, \end{aligned} \quad (16)$$

where $f(x, y) = \frac{(a_1x+b_1y+c_1)(a_2x+b_2y+c_2)}{xy}$. To solve this optimization problem, we first introduce the following proposition.

Proposition 1: The optimal solution of the optimization problem (16) must be on the boundary of the feasible region.

Proof: This can be proved by contradiction. Suppose the optimal solution of (16) is (x^*, y^*), which is in the interior of the feasible region. Then there exist a constant $\lambda = \min\left(\frac{\tau_1}{x^*}, \frac{\tau_2}{y^*}, \frac{\tau_0}{x^*+y^*}\right) > 1$ such that

$$\begin{aligned} &f(\lambda x^*, \lambda y^*) \\ &= \frac{(a_1x^* + b_1y^* + \frac{c_1}{\lambda})(a_2x^* + b_2y^* + \frac{c_2}{\lambda})}{x^*y^*} \\ &< \frac{(a_1x^* + b_1y^* + c_1)(a_2x^* + b_2y^* + c_2)}{x^*y^*} = f(x^*, y^*). \end{aligned} \quad (17)$$

Therefore, we can conclude the optimal solution must be on the boundary of the feasible region.

For different values of τ_0, τ_1 and τ_2, the boundary of the feasible region is different. Fig. 2 shows five possible cases for the boundary of the feasible region. For each case, we can obtain the optimal solution separately.

CASE A: $\tau_0 \leq \tau_1$ and $\tau_0 \leq \tau_2$

In this case, the optimal solution should be on the boundary $\{(x, y)| x + y = \tau_0, 0 < x < \tau_0\}$. Substituting $y = \tau_0 - x$ into the objective function $f(x, y)$ and after some manipulations, we can get

$$f(x) = \frac{Ax+B}{\tau_0 - x} + \frac{C}{x} + \frac{D}{x(\tau_0 - x)} + E, \tag{18}$$

where $A = a_1a_2, B = a_1c_2+c_1a_2, C = b_1b_2\tau_0+b_1c_2+c_1b_2$, $D = c_1c_2$, and $E = a_1b_2+b_1a_2-b_1b_2$. Taking the derivative of $f(x)$ with respect to x, we have

$$\frac{\partial f(x)}{\partial x} = \frac{(A\tau_0+B-C)x^2 + 2(C\tau_0 + D)x - C\tau_0^2 - D\tau_0}{x^2(\tau_0 - x)^2}. \tag{19}$$

Since the denominator is greater than 0, $\frac{\partial f(x)}{\partial x} = 0$ is equivalent to the numerator equals to 0. If $A\tau_0 + B - C \neq 0$, we can get two possible solutions by solving this quadratic equation

$$x_1 = \frac{-(C\tau_0 + D) + \sqrt{(C\tau_0 + D)\left(A\tau_0^2 + B\tau_0 + D\right)}}{A\tau_0 + B - C},$$
$$x_2 = \frac{-(C\tau_0 + D) - \sqrt{(C\tau_0 + D)\left(A\tau_0^2 + B\tau_0 + D\right)}}{A\tau_0 + B - C}. \tag{20}$$

It is easy to check $\frac{\partial f(x)}{\partial x}|_{x\to 0^+} < 0$ and $\frac{\partial f(x)}{\partial x}|_{x\to\tau_0^-} > 0$, which means the quadratic equation has only one solution in the feasible region. We denote this solution as x^*, and this solution indeed gives a minimum. As such, the optimal solution is given as $(x, y) = (x^*, \tau_0 - x^*)$. If $A\tau_0+B-C = 0$, we can easily obtain the optimal solution as $(x, y) = \left(\frac{\tau_0}{2}, \frac{\tau_0}{2}\right)$.

CASE B: $\tau_0 > \tau_1$ and $\tau_0 < \tau_2$

In this case, the optimal solution should be on the boundary $\{(x, y)| x + y = \tau_0, 0 < x \leq \tau_1\}$ or the boundary $\{(x, y)| x = \tau_1, 0 < y \leq \tau_0 - \tau_1\}$.

For boundary condition $\{(x, y)| x + y = \tau_0, 0 < x \leq \tau_1\}$, as in case A, we can substitute $y = \tau_0 - x$ into the objective function $f(x, y)$ and find the solution x^*. If $0 < x^* \leq \tau_1$, the optimal solution is given as $(x, y) = (x^*, \tau_0 - x^*)$; otherwise, the optimal value of x is τ_1 because the objective function decreases with the increase of x for $x \leq \tau_1$, so the optimal solution is given as $(x, y) = (\tau_1, \tau_0 - \tau_1)$.

For boundary condition $\{(x, y)| x = \tau_1, 0 < y \leq \tau_0 - \tau_1\}$, the objective function becomes

$$f(y) = \frac{b_1b_2y}{\tau_1} + \frac{(a_1\tau_1 + c_1)(a_2\tau_1 + c_2)}{\tau_1 y} + a_2b_1 + a_1b_2 + \frac{b_1c_2 + b_2c_1}{\tau_1}. \tag{21}$$

Obviously, for $0 < y \leq \sqrt{\frac{(a_1\tau_1+c_1)(a_2\tau_1+c_2)}{b_1b_2}}$, the objective function decreases with the increase of y; for $y > \sqrt{\frac{(a_1\tau_1+c_1)(a_2\tau_1+c_2)}{b_1b_2}}$, the objective function increases with the increase of y. Therefore, the optimal solution is given as $(x, y) = \left(\tau_1, \sqrt{\frac{(a_1\tau_1+c_1)(a_2\tau_1+c_2)}{b_1b_2}}\right)$ if $\sqrt{\frac{(a_1\tau_1+c_1)(a_2\tau_1+c_2)}{b_1b_2}} < \tau_0 - \tau_1$; otherwise the optimal solution is given as $(x, y) = (\tau_1, \tau_0 - \tau_1)$.

Comparing the optimal solutions for the two boundary conditions, we can obtain the optimal solution for this case.

CASE C: $\tau_0 < \tau_1$ and $\tau_0 > \tau_2$

In this case, the optimal solution should be on the boundary $\{(x, y)| x + y = \tau_0, \tau_0 - \tau_2 \leq x < \tau_0\}$ or the boundary $\{(x, y)| y = \tau_2, 0 < x \leq \tau_0 - \tau_2\}$.

As in case A and case B, for boundary condition $\{(x, y)| x + y = \tau_0, \tau_0 - \tau_2 \leq x < \tau_0\}$, we can substitute $y = \tau_0 - x$ into the objective function $f(x, y)$ and find the solution x^*. If $\tau_0 - \tau_2 \leq x^* < \tau_0$, the optimal solution is given as $(x, y) = (x^*, \tau_0 - x^*)$; otherwise, the optimal value of x is $\tau_0 - \tau_2$ because the objective function increases with the increase of x for $\tau_0 - \tau_2 \leq x < \tau_0$, so the optimal solution is given as $(x, y) = (\tau_0 - \tau_2, \tau_2)$.

For boundary condition $\{(x, y)| y = \tau_2, 0 < x \leq \tau_0 - \tau_2\}$, the objective function becomes

$$f(x) = \frac{a_1a_2x}{\tau_2} + \frac{(b_1\tau_2 + c_1)(b_2\tau_2 + c_2)}{\tau_2 x} + a_1b_2 + a_2b_1 + \frac{a_1c_2 + a_2c_1}{\tau_2}. \tag{22}$$

Obviously, for $0 < x \leq \sqrt{\frac{(b_1\tau_2+c_1)(b_2\tau_2+c_2)}{a_1a_2}}$, the objective function decreases with the increase of x; for $x > \sqrt{\frac{(b_1\tau_2+c_1)(b_2\tau_2+c_2)}{a_1a_2}}$, the objective function increases with the increase of x. Therefore, the optimal solution is given as $(x, y) = \left(\sqrt{\frac{(b_1\tau_2+c_1)(b_2\tau_2+c_2)}{a_1a_2}}, \tau_2\right)$ if $\sqrt{\frac{(b_1\tau_2+c_1)(b_2\tau_2+c_2)}{a_1a_2}} < \tau_0 - \tau_2$; otherwise the optimal solution is given as $(x, y) = (\tau_0 - \tau_2, \tau_2)$.

Similar to case B, we can compare the optimal solutions for the two boundary conditions and obtain the optimal solution for this case.

CASE D: $\tau_0 > \tau_1$, $\tau_0 > \tau_2$, and $\tau_1 + \tau_2 > \tau_0$

In this case, the optimal solution should be on the boundary $\{(x, y)| x + y = \tau_0, \tau_0 - \tau_2 \leq x \leq \tau_1\}$, the boundary $\{(x, y)| x = \tau_1, 0 < y \leq \tau_0 - \tau_1\}$, or the boundary $\{(x, y)| y = \tau_2, 0 < x \leq \tau_0 - \tau_2\}$.

Similar to the previous cases, for boundary condition $\{(x, y)| x + y = \tau_0, \tau_0 - \tau_2 \leq x \leq \tau_1\}$, we can substitute $y = \tau_0 - x$ into the objective function $f(x, y)$ and find the solution x^*. If $\tau_0 - \tau_2 < x^* < \tau_1$, the optimal solution is given as $(x, y) = (x^*, \tau_0 - x^*)$. If $0 < x^* < \tau_0 - \tau_2$, the optimal value of x is $\tau_0 - \tau_2$ because the objective function increases with the increase of x for $\tau_0 - \tau_2 \leq x \leq \tau_1$, so the optimal solution is given as $(x, y) = (\tau_0 - \tau_2, \tau_2)$. If $\tau_1 < x^* < \tau_0$, the optimal value of x is τ_1 because the objective function decreases with the increase of x for $\tau_0 - \tau_2 \leq x \leq \tau_1$, so the optimal solution is given as $(x, y) = (\tau_1, \tau_0 - \tau_1)$.

For boundary condition $\{(x, y)| x = \tau_1, 0 < y \leq \tau_0 - \tau_1\}$, we can use the same procedure as in case B to obtain the optimal solution. For boundary condition

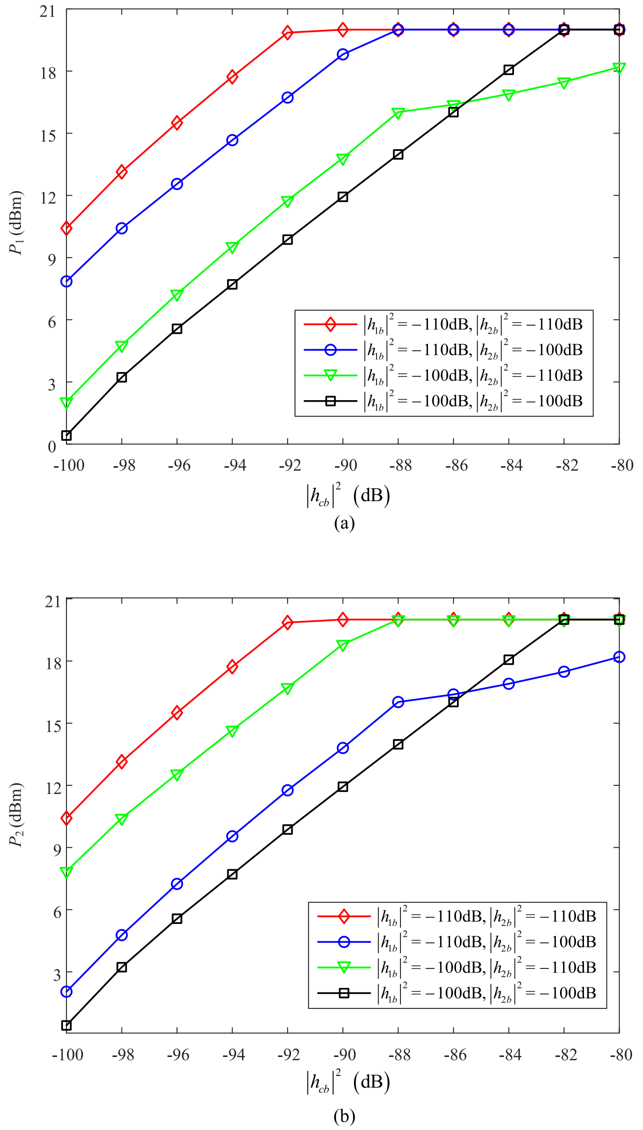

FIGURE 3. The effects of channel gains $|h_{cb}|^2$, $|h_{1b}|^2$, and $|h_{2b}|^2$ on the optimal transmit power of the D2D users, where $R_T = 5$ bit/s/Hz, $P_{\max} = 20$ dBm, $\beta = -90$ dB, $N_0 = -100$ dBm, $|h_{c1}|^2 = |h_{c2}|^2 = -110$ dB and $|h_{12}|^2 = |h_{21}|^2 = -60$ dB. (a) The optimal transmit power of DU_1; (b)The optimal transmit power of DU_2.

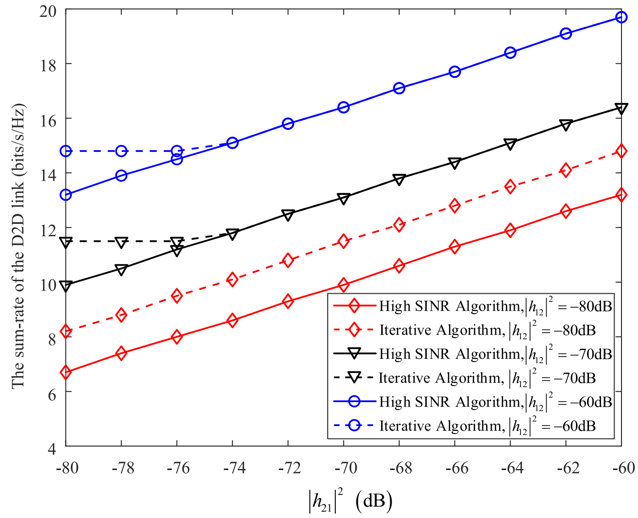

FIGURE 4. The effects of channel gains $|h_{12}|^2$ and $|h_{21}|^2$ on the achievable sum-rate of the full-duplex D2D link, where $R_T = 5$ bit/s/Hz, $P_{\max} = 20$ dBm, $\beta = -90$ dB, $N_0 = -100$ dBm, $|h_{cb}|^2 = -90$ dB, $|h_{c1}|^2 = |h_{c2}|^2 = -110$ dB and $|h_{1b}|^2 = |h_{2b}|^2 = -100$ dB.

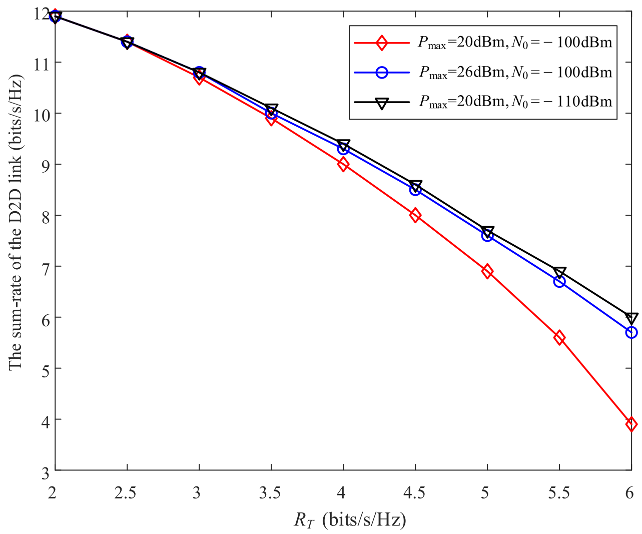

FIGURE 5. The relationship between the minimum rate requirement of CU and the achievable sum-rate of the full-duplex D2D link, where $\beta = -90$ dB, $|h_{cb}|^2 = -100$ dB, $|h_{c1}|^2 = |h_{c2}|^2 = -100$ dB, $|h_{12}|^2 = |h_{21}|^2 = -70$ dB and $|h_{1b}|^2 = |h_{2b}|^2 = -100$ dB.

$\{(x, y)| y = \tau_2, 0 < x \leq \tau_0 - \tau_2\}$, we can use the same procedure as in case C to obtain the optimal solution.

Finally, we can obtain the optimal solution for this case by comparing the optimal solutions for the three boundary conditions,

CASE E: $\tau_0 > \tau_1$, $\tau_0 > \tau_2$, and $\tau_1 + \tau_2 \leq \tau_0$

In this case, the optimal solution should be on the boundary $\{(x, y)| x = \tau_1, 0 < y \leq \tau_2\}$ or the boundary $\{(x, y)| y = \tau_2, 0 < x \leq \tau_1\}$.

For boundary condition $\{(x, y)| x = \tau_1, 0 < y \leq \tau_2\}$, the optimal solution is given as $(x, y) = \left(\tau_1, \sqrt{\frac{(a_1\tau_1+c_1)(a_2\tau_1+c_2)}{b_1b_2}}\right)$ if $\sqrt{\frac{(a_1\tau_1+c_1)(a_2\tau_1+c_2)}{b_1b_2}} < \tau_2$; otherwise the optimal solution is given as $(x, y) = (\tau_1, \tau_2)$.

For boundary condition $\{(x, y)| y = \tau_2, 0 < x \leq \tau_1\}$, the optimal solution is given as $(x, y) = \left(\sqrt{\frac{(b_1\tau_2+c_1)(b_2\tau_2+c_2)}{a_1a_2}}, \tau_2\right)$ if $\sqrt{\frac{(b_1\tau_2+c_1)(b_2\tau_2+c_2)}{a_1a_2}} < \tau_1$; otherwise the optimal solution is given as $(x, y) = (\tau_1, \tau_2)$.

IV. NUMERICAL RESULTS

In this section, we present some numerical results to illustrate the effect different parameters, such as the channel gains and SI cancellation ability, on the optimal transmit power and the achievable sum-rate of the full-duplex D2D link.

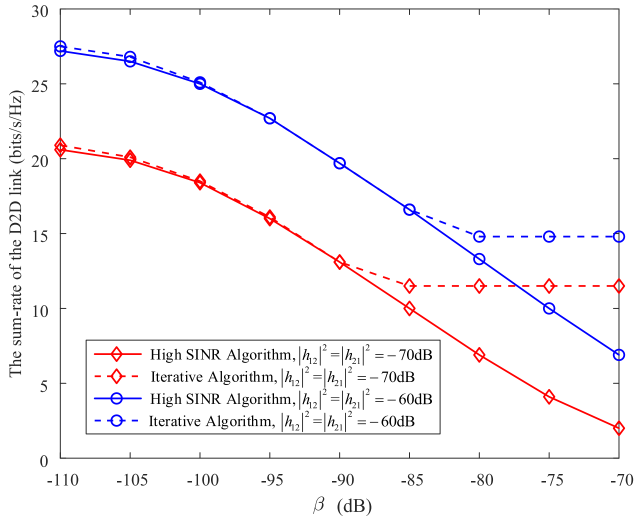

FIGURE 6. The effect of SI cancellation ability on the achievable sum-rate of the full-duplex D2D link, where $R_T = 5$ bit/s/Hz, $P_{\max} = 20$ dBm, $N_0 = -100$ dBm, $|h_{cb}|^2 = -90$ dB, $|h_{c1}|^2 = |h_{c2}|^2 = -110$ dB and $|h_{1b}|^2 = |h_{2b}|^2 = -100$ dB.

Fig. 3 illustrates the effects of channel gains $|h_{cb}|^2$, $|h_{1b}|^2$, and $|h_{2b}|^2$ on the optimal transmit power of the D2D users. For the given parameters, note that the five possible cases for the boundary of the feasible region are covered. As shown in Fig. 2 (a) and (b), the optimal transmit power of DU_1 and DU_2 increase with the increase of $|h_{cb}|^2$ until the maximum transmit power of DU_1 and DU_2 are reached. When $|h_{1b}|^2 = -110$ dB and $|h_{2b}|^2 = -100$ dB, the optimal transmit power of DU_1 is larger than the optimal transmit power of DU_2. When $|h_{1b}|^2 = -100$ dB and $|h_{2b}|^2 = -110$ dB, the optimal transmit power of DU_1 is smaller than the optimal transmit power of DU_2. Since $|h_{1b}|^2$ and $|h_{2b}|^2$ denote the interference link gain to the cellular link, we can conclude that the D2D user with smaller interference link gain will transmit more power. Using the optimal transmit power, we can calculate the corresponding achievable sum-rate of the full-duplex D2D link, based on which we find the sum-rate of the full-duplex D2D link is around 19.5 bits/s/Hz.

Fig. 4 shows the effects of channel gains $|h_{12}|^2$ and $|h_{21}|^2$ on the sum-rate of the full-duplex D2D link for both iterative algorithm and high SINR algorithm. From Fig. 4, we can see that the sum-rate of the full-duplex D2D link increases with the increase of $|h_{12}|^2$ or $|h_{21}|^2$. When $|h_{12}|^2 = -80$ dB or $|h_{21}|^2 = -80$ dB, the iterative algorithm can obtain better performance than the high SINR algorithm. This is because the high SINR assumption is no longer satisfied. When $|h_{12}|^2 = -70$ dB or $|h_{12}|^2 = -60$ dB, as $|h_{21}|^2$ increases, the iterative algorithm and the high SINR algorithm obtain almost the same performance.

Fig. 5 shows the relationship between the minimum rate requirement of CU and the achievable sum-rate of the full-duplex D2D link. From Fig. 5, we can see that the sum-rate of the full-duplex D2D link decreases with the increase of the minimum rate requirement of CU. Moreover, as the noise power N_0 decreases or the maximum transmit power $P_{\max}$ increases, the sum-rate of the D2D link can be further improved.

Fig. 6 illustrates the effect of SI cancellation ability on the sum-rate of the full-duplex D2D link. Form Fig. 6, we can observe that the SI cancellation ability has a large impact on the sum-rate of the full-duplex D2D link. When β is small (i.e., the SI can be effectively eliminated), the iterative algorithm and the high SINR algorithm obtain almost the same performance. With the increase of β, the iterative algorithm can obtain better performance than the high SINR algorithm. The reason is the same as in Fig. 4, i.e., the high SINR assumption is no longer satisfied. Note that when $\beta \geq -80$ dB, the sum-rate of the full-duplex D2D link becomes a constant for the iterative algorithm. This is because when β is large, the SI cannot be effectively eliminated. Therefore, it is better to use half-duplex mode for D2D users and the SI cancellation ability has no effect on the sum-rate of the D2D link.

V. CONCLUSION

In this paper, we investigated the power control for full-duplex D2D communications underlaying cellular networks. The power control problem was formulated by maximizing the achievable sum-rate of the full-duplex D2D link while fulfilling the minimum rate requirement of the cellular link under the maximum transmit power constraint of the cellular user and D2D users. We proposed two algorithms to solve the optimization problem. For the first algorithm, we proposed an iterative algorithm based on D. C. programming. For the second algorithm, we used a high-SINR approximation and obtained the closed-form optimal solutions for different boundaries of the feasible region. Numerical results showed the effect of the channel gains and SI cancellation ability on the optimal transmit power and the achievable sum-rate of the full-duplex D2D link.

Note that in this paper we assume one cellular link can only share its uplink resource with one D2D link. If the uplink resource of one cellular link is shared by multiple D2D pairs, the power control problem becomes more challenging and will be our future work. Besides, the power control algorithms in this paper were limited to the case of perfect CSI. Therefore, power control in the case of imperfect and statistical CSI is also the future research direction.

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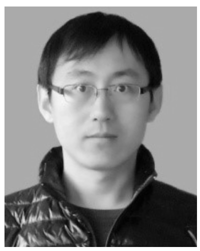

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