Power allocation for full-duplex NOMA relaying based underlay D2D communications

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Received May 30, 2018; revised August 18, 2018; accepted September 5, 2018;
published January 31, 2019

Abstract

In this paper, a full-duplex NOMA relaying based underlay device-to-device (D2D) communication scheme is proposed, in which D2D transmitter assists cellular downlink transmission as a full-duplex relay. Specifically, D2D transmitter receives signals from base station and transmits the superposition signals to D2D receiver and cellular user in NOMA scheme simultaneously. Furthermore, we investigate the power allocation under the proposed scheme, aiming to maximize D2D link's achievable transmit rate under cellular link's transmit rate constraint and total power constraint. To tackle the power allocation problem, we first propose a power allocation method based on linear fractional programming. In addition, we derive closed-form expressions of the optimal transmit power for base station and D2D transmitter. Simulation results show that the performance of two solutions matches well and the proposed full-duplex NOMA relaying based underlay D2D communication scheme outperforms existing full-duplex relaying based D2D communication scheme.

Keywords: device-to-device, full-duplex, NOMA, power allocation

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This research was supported by the National Natural Science Foundation of China under Grant 51504255, 51504214, 61771417, 51734009. the Fundamental Research and Development Foundation of Jiangsu Province (BE2015040) and National Key Research and Development Program (2016YFC0801403),

http://doi.org/10.3837/tiis.2019.01.002 **ISSN : 1976-7277**

1. Introduction

The explosive growth of mobile devices and wireless services results in unprecedented increase of traffic load in cellular system [1]. To cope with this challenging problem, device-to-device communications (D2D) and NOMA are considered as two promising technologies in the fifth generation (5G) wireless communication to improve spectrum efficiency [2].

D2D communications enable two adjacent users can communicate with each other, thus can provide flexible mobile local service, and offload the heavy traffic of base station [3]-[4]. By D2D communication, one mobile user can be directly served by one nearby user who stores his requested contents, instead of by the base station. Through direct communications between mobile users, the heavy traffic of base station can be offloaded, especially for the services in which a group of people request some popular contents they are all interested with, such as live football match or web conference [5]. D2D communications can be implemented as an underlay network to the cellular network, and the transmission power of cellular links and D2D links should be coordinated efficiently to avoid harmful interference to cellular users [6][7]. However, despite of all the benefits brought by D2D communication, the performance of cellular link is not benefited.

To tackle this problem, relaying based D2D communications have been explored in recent years, in which a D2D transmitter also acts as a relay to assist cellular transmission [8]. The benefits of relaying based D2D communication include the following three folds. Firstly, the base station can offload its heavy traffic. Secondly and D2D link can achieve a high spectral efficiency. Thirdly, the performance of cellular link can be improved because of the relaying of D2D transmitter. In short, both D2D links and cellular links can be benefited in this scheme. A half-duplex relaying based D2D communication scheme is proposed in [9], and a power allocation problem is investigated to maximize the achievable rates of D2D link under the constraints on rate requirement of cellular link. In [10], a full-duplex relaying based D2D communication scheme is proposed and the optimal power allocation at the base station and D2D transmitter are derived in closed-form to maximize the achievable transmit rate of D2D link while guaranteeing the QoS of cellular user. In [9] and [10], D2D transmitter forward signals to cellular user and transmit its own signals to D2D receiver simultaneously. Cellular user and D2D receiver access the channel at the same time and each receives its desired signals while treats other user’s signal as interference.

NOMA is considered as promising radio access technology for future cellular system and can achieve significant improvement in spectral efficiency by allowing multiple users to share the same spectrum resource in power domain [11][12]. To avoid the inter-user interference in NOMA network, successive interference cancellation (SIC) technique is applied to decode the received signals. Inspired by the potential benefits of NOMA, many researchers have explored NOMA schemes in different kinds of communications, such as cooperation communications [13], machine-to-machine communications [14] and wireless powered communication network [15]. Several works have been carried out to the performance analysis and optimization of NOMA, including spectral efficiency [16], energy efficiency [17] and physical layer security [18]. Recently, few works have been done so far to explore NOMA in D2D communications. In [19], NOMA transmission is utilized in a D2D group in which one D2D transmitter communicate with multiple D2D receivers simultaneously, and resource allocation problem is investigated. A full-duplex device-to-device aided cooperative NOMA scheme is proposed in [20], in which the NOMA-strong user forwards signals to NOMA-weak user, and the outage probability is derived under the proposed scheme.

Considering performance improvement achieved by NOMA, in this paper we exploit NOMA technique in full-duplex relaying based D2D communications and propose a novel full-duplex NOMA relaying based D2D communication scheme, in which a full-duplex D2D transmitter not only performs direct communication with D2D receiver, but also acts as a full-duplex relay for cellular user. Different from schemes proposed in [9] and [10], the D2D transmitter sends signals to D2D receiver and cellular user in NOMA scheme. Different from [20], the D2D transmitter not only forward data to cellular user, but also has its own data to send. Comparing with above works, the main contributions of this paper are as follows:

1) We propose a novel full-duplex NOMA relaying based D2D underlay communication scheme, by assigning D2D transmitter as full-duplex relay to assist cellular downlink transmission. Specifically, D2D transmitter sends superposition signals to D2D receiver and cellular user in NOMA scheme.

2) Furthermore, we formulate the power allocation problem as maximizing achievable rate of D2D link under the cellular user's transmit rate constraint and aggregate power constraint. To tackle the power allocation problem, the orignal problem is transformed into a linear fractional programming by variable replacements and solved by linear fractional programming method. Furthermore, we derive the closed-form solution of optimal transmit power on the BS and the D2D transmitter, as well as the optimal power fraction on D2D transmitter.

2. System Model and Problem Formulation

2.1 System Model

We consider a cellular system with one base station (BS), one cellular user (CU) and one D2D pair, which is composed of one D2D transmitter (DT) and one D2D receiver (DR), as illustrated in **Fig. 1**. Assume DT is equipped with isolated transmit and receive antennas to facilitate full-duplex transmission.

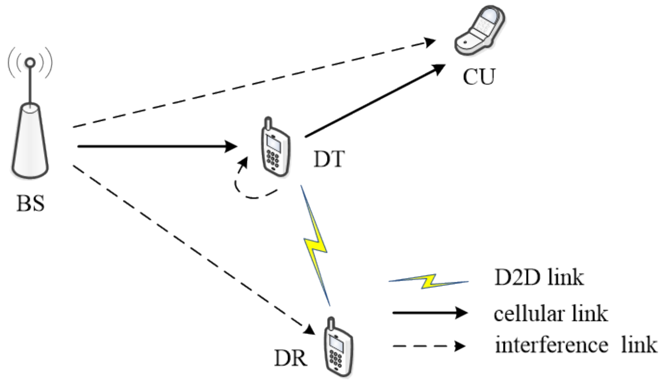

Fig. 1. System Model

During the transmission, DT transmits signals to DR by underlying spectral frequency of CU. Meanwhile, DT acts as a full-duplex relay for cellular downlink transmission and forwards signals to CU. In each timeslot, DT receives cellular signals from BS, while suffers the self-interference from its transmit antenna. Meanwhile DT transmits a superposition signal composed by the regenerated signal which is received from BS and requested by CU, and its own signal which is requested by DR. CU receives the forwarded signal which is originally transmit by the base station and regards the DT's own signals as interference. DR receives its desired signal from DT and regards the CU's signals as interference.

To improve the spectral efficiency, DT transmits the superposition signal to CU and DT in NOMA scheme. Successive interference cancellation technique is applied at CU and DR to cope with the multi-user interference.

$h_{B,T}$ denotes the channel coefficient between BS and DT. $h_{T,C}$ and $h_{T,R}$ denote the channel coefficients between DT and CU, DT and DR respectively. $h_{B,C}$, $h_{B,R}$ denote channel coefficient from BS to CU and DR respectively. Assume DT operates in full-duplex mode with resident self-interference. h_{LI} denotes the equivalent channel coefficient between DT's transmit antenna to receive antenna after self-interference cancellation. All the channels are modeled as narrow-band quasi-static and frequency-flat-fading channels. Assume the BS and DT can acquire all the channel state information.

In a practical cellular system, the CSI of each channel can be derived as follows. $h_{B,C}$, $h_{B,R}$ and $h_{B,T}$ are measured by CU, DR and DT respectively and feedback to the BS. h_{LI} which is determined by the physical channel between the transmit antenna and receive antenna of DT as well as the self-interference cancellation technology, can be measured by the DT and feedback to BS. $h_{T,C}$ and $h_{T,R}$ are measured by CU and DR respectively and feedback to the BS.

Denote P_B and P_T as the transmit power of BS and DT. When DT receives the signal from BS, the signal to interference and noise (SINR) can be represented as

$$\gamma_{B,T} = \frac{P_B g_{B,T}}{P_T g_{LI} + 1}, \tag{1}$$

where $g_{B,T}$ and g_{LI} denote the channel to noise ratio (CNR) of channel $h_{B,T}$ and h_{LI} respectively, $g_{B,T} = |h_{B,T}|^2/\sigma^2$, $g_{LI} = |h_{LI}|^2/\sigma^2$. σ^2 denote the covariance of the noise at DT.

We assume that the DT operates as a full-duplex decode and forward (DF) relay for CU. DT receives the signals transmitted by BS, superposes it with its own signals requested by DR and then broadcasts the superposition signals to CU and DR. Thus the superimposed signal transmitted by DT is composed of two parts. The first part is the regenerated signal received from the BS and forwarded to the CU. The second part is signal requested by DR from DT.

The superposition signal transmitted by DT can be represented as

$$x_T = \sqrt{\alpha P_T}\, x_C + \sqrt{(1-\alpha) P_T}\, x_R\,, \tag{2}$$

where x_C and x_R denote the signals required by CU and DR respectively, $(1-\alpha)P_T$ denotes the power allocated to D2D link, and αP_T denotes the power allocation to CU. We denote α as power partition factor, $0 \le \alpha \le 1$.

The the achievable transmission rate received by DR and CU can be respectively derived as

$$R_{DR} = W \log_2(1+\gamma_{T,R})\,, \tag{3}$$

$$R_{CU} = W \log_2(1+\gamma_{B,C})\,, \tag{4}$$

where $\gamma_{T,R}$ denote the SINR received by DR, $\gamma_{B,C}$ denote the equivalent end-to-end SINR received by CU, which is dependent on the worse SINR between two hops, $\gamma_{B,C} = \min(\gamma_{B,T}, \gamma_{T,C})$, where $\gamma_{B,T}$ and $\gamma_{T,C}$ are the received SINR of DT and CU respectively. The expressions of $\gamma_{T,C}$ and $\gamma_{T,R}$ are discussed in the following.

2.2 Problem Formulation

We aim to maximize the achievable transmit rate of D2D link, while guarantee the QoS requirement of CU, in terms of minimum transmit rate. The optimization problem can be formulated as

$$\max_{P_B, P_T, \alpha} R_{DR} \tag{5a}$$

$$\text{s.t.} \quad R_{CU} \geq R_{\min}^{C} \tag{5b}$$

$$P_B + P_T \leq P_{\max} \tag{5c}$$

$$P_B \geq 0, P_T \geq 0 \tag{5d}$$

$$0 \leq \alpha \leq 1 \tag{5e}$$

Constraint (5b) represent the minimum transmit rate requirement of CU and constraints (5c) represent the total power limit.

Since DT transmit signals to DR and CU simultaneously by applying NOMA transmission protocol, the successive interference cancellation (SIC) can be carried out at the user (DR or CU) with stronger channel, which is usually termed as NOMA-strong user. Thus we analyze the optimization problem (5) in the following two cases considering the relationship of DR's and CU's channels.

Case 1: $g_{T,R} \geq g_{T,C}$, where $g_{T,R}$ and $g_{T,C}$ denote the CNR of channel $h_{T,R}$ and $h_{T,C}$, $g_{T,R} = |h_{T,R}|^2/\sigma^2$, $g_{T,C} = |h_{T,C}|^2/\sigma^2$. In this case, since the CNR of DR is better than that of CU, we term DR as NOMA-strong user. Correspondingly, the CU is termed as NOMA-weak user. According to the decode sequence of NOMA system, DR can cancel the interference caused by CU's data. According to the decode sequence of NOMA system, NOMA-strong user (DR in case 1) can first decodes the signals of NOMA-weak user (CU in case 1) and subtracts the interference caused by signal of NOMA-weak user (CU in case 1) from the superimposed signal. Then the NOMA-strong user (DR in case 1) decodes the signals of itself. After successive cancellation, the received SINR of DR (NOMA-strong user) can be represented as

$$\gamma_{T,R}^{1} = \frac{(1-\alpha) P_T g_{T,R}}{P_B g_{B,R} + 1}, \tag{6}$$

where $g_{B,R}$ denote the CNR of channel $h_{B,R}$, $g_{B,R} = |h_{B,R}|^2/\sigma^2$. The NOMA-weak user decodes its signal directly and regards signal of NOMA-strong user as interference. Thus the received SINR of CU (NOMA-weak user) is given by

$$\gamma_{T,C}^{1} = \frac{\alpha P_T g_{T,C}}{P_B g_{B,C} + (1-\alpha) P_T g_{T,C} + 1}, \tag{7}$$

where $g_{B,C} = |h_{B,C}|^2/\sigma^2$. Since the equivalent end-to-end received SINR of CU is dependent on the worse SINR of two hops, the constraint (5b) can be rewritten as

$$\gamma_{B,C} = \min(\gamma_{B,T}, \gamma_{T,C}^{1}) \geq \varphi, \tag{8}$$

where $\varphi = 2^{R_{\min}^{C}/W} - 1$ denote the minimum SINR that satisfy the rate requirement of CU.

Also, since the DR is NOMA-strong user, DR need to cancel the interference caused by CU's signal. To ensure this, the achievable rate when DR decodes the signals for CU would no less than the achievable rate that DR received,

$$R_R^{(C)} \geq R_{CU}, \tag{9}$$

where $R_R^{(C)}$ denotes the achievable rate of DR to decode the signal of CU, $R_R^{(C)} = \log_2(1 + \gamma_R^{(C)})$. $\gamma_R^{(C)}$ denotes the SINR of DR when decoding CU's signal,

$$\gamma_R^{(C)} = \frac{\alpha P_T g_{T,R}}{(1-\alpha)P_T g_{T,R} + P_B g_{B,R} + 1}. \tag{10}$$

Since log(•) is an increasing function, (9) can be rewritten as

$$\gamma_R^{(C)} \geq \gamma_{T,C}^1. \tag{11}$$

Thus, in this case when DR is NOMA-strong user, optimization problem (5) can be transformed into

$$\begin{aligned} &\max_{P_B, P_T, \alpha} \ \gamma_{T,R}^1 \\ &s.t. \quad (8), (11), (5c), (5d), (5e) \end{aligned} \tag{12}$$

Case 2: When $g_{T,C} \geq g_{T,R}$, which means that the CNR of CU is better than that of DR, we term CU as NOMA-strong user. Correspondingly, the DR is termed as NOMA-weak user. According to the decode sequence of NOMA system, NOMA-strong user can cancel the interference caused by NOMA-weak user. Accroding to the decode sequence of NOMA system, the received SINR of CU and DR can be respectively represented as

$$\gamma_{T,C}^2 = \frac{\alpha P_T g_{T,C}}{P_B g_{B,C} + 1}, \tag{13}$$

$$\gamma_{T,R}^2 = \frac{(1-\alpha) P_T g_{T,R}}{P_B g_{B,R} + \alpha P_T g_{T,R} + 1}. \tag{14}$$

Since the equivalent end-to-end received SINR of CU is determined by the worse SINR between two hops, constraint (5b) can be transformed into

$$\gamma_{B,C} = \min(\gamma_{B,T}, \gamma_{T,C}^2) \geq \varphi, \tag{15}$$

where $\varphi = 2^{R_{\min}^C / W} - 1$ denote the minimum SINR that satisfy the rate requirement of CU.

Also, since CU is NOMA-strong user, CU needs to cancel the interference caused by DR's signals. To ensure this, the achievable rate when CU decodes the signals for DR would be no less than the achievable rate that DR received.

$$R_C^{(R)} \geq R_{DR}, \tag{16}$$

where $R_C^{(R)}$ denotes the achievable rate when CU decodes the DR's signal, $R_C^{(R)} = \log_2(1 + \gamma_C^{(R)})$. $\gamma_C^{(R)}$ denotes the SINR when CU decodes DR's signal.

$$\gamma_C^{(R)} = \frac{(1-\alpha) P_T g_{T,C}}{\alpha P_T g_{T,C} + P_B g_{B,C} + 1}, \tag{17}$$

Since log(•) is an increasing function, (16) can be converted into

$$\gamma_C^{(R)} \geq \gamma_{T,R}^2, \tag{18}$$

Then in this case, the optimization (5) can be transformed into

$$\begin{aligned} &\max_{P_B, P_T, \alpha} \ \gamma_{T,R}^2 \\ &s.t. \quad (15), (18), (5c), (5d), (5e) \end{aligned} \tag{19}$$

In the following section, we try to solve problem (12) and (19) respectively.

3. Optimal power solution

3.1 Linear Fractional Programming Method

In this section, we propose a linear fraction programming method (LFPM) for problem (12) and problem (15) respectively, by converting the orginal problems into linear fraction program.

Case 1: DR is NOMA-strong user

In this case, power allocation in full-duplex NOMA relaying based D2D communications is formulated as optimization problem (12), which is a non-linear fractional programming and is difficult to solve directly. Fortunately, it can be transformed into a linear fractional programming problem by variables replacement. Let $\alpha P_T = P_{T,C}$, $(1-\alpha)P_T = P_{T,R}$, $P_T = P_{T,C} + P_{T,R}$, constraints (5c) and (5d) can be rewritten as

$$P_B + P_{T,C} + P_{T,R} - P_{\max} \leq 0\,, \tag{20}$$

$$P_B \geq 0,\ P_{T,C} \geq 0,\ P_{T,R} \geq 0\,. \tag{21}$$

Considering equation (1) and (6), constraint (8) can be equivalent transformed into:

$$\varphi\left((P_{T,C} + P_{T,R})g_{LI} + 1\right) - P_B g_{B,R} \leq 0\,, \tag{22}$$

$$\varphi\left(P_B g_{B,C} + P_{T,R} g_{T,C} + 1\right) - P_{T,C} g_{T,C} \leq 0\,. \tag{23}$$

Considering (7) and (10), constraint (11) can be transformed as:

$$P_B(g_{T,C}g_{B,R} - g_{T,R}g_{B,C}) - (g_{T,R} - g_{T,C}) \leq 0\,. \tag{24}$$

After transformation of constraint (5c) (5d) (15) and (18), then the optimization problem (12) can be transformed into

$$\begin{aligned} &\max_{P_B, P_{T,C}, P_{T,R}} \frac{P_{T,R} g_{T,R}}{P_B g_{B,R} + 1} \\ &s.t. \quad (22), (23), (24), (20), (21) \end{aligned} \tag{25}$$

The constraints in optimization (25) are all linear constraints and the objective function is a linear factional function. Thus the optimization problem (25) is a linear fractional programming. According linear fractional programming method [21], problem (25) can be transformed into

$$\begin{aligned} &\min_{P_B', P_{T,C}', P_{T,R}', z} \quad -P_{T,R}' g_{T,R} \\ &s.t.\ C1:\ P_{T,C}' g_{LI}\varphi + P_{T,R}' g_{LI}\varphi - P_B' g_{B,R} + \varphi z \leq 0 \\ &\qquad C2:\ P_B' g_{B,C}\varphi + P_{T,R}' g_{T,C}\varphi - P_{T,C}' g_{T,C} + \varphi z \leq 0 \\ &\qquad C3:\ P_B'(g_{T,C}g_{B,R} - g_{T,R}g_{B,C}) - (g_{T,R} - g_{T,C})z \leq 0 \\ &\qquad C4:\ P_B' + P_{T,C}' + P_{T,R}' - P_{\max} z \leq 0 \\ &\qquad C5:\ P_B' g_{B,R} + z = 1 \\ &\qquad C6:\ P_B' \geq 0,\ P_{T,C}' \geq 0,\ P_{T,R}' \geq 0,\ z \geq 0 \end{aligned} \tag{26}$$

Optimization problem (26) can be proved equivalent to optimization problem (25) by variables transform, $t = P_B g_{B,R} + 1$, $P_B' = P_B/t$, $P_{T,C}' = P_{T,C}/t$, $P_{T,R}' = P_{T,R}/t$, $z = 1/t$. We can observe that problem (26) is a linear programming problem, which can be easily solved by convex optimization method [22]. After deriving the optimal solution $P_B'^{*}$, $P_{T,C}'^{*}$, $P_{T,R}'^{*}$, z^* of problem (26), we can calculate the optimal solution of problem (25), $P_B^* = P_B'^{*}/z^*$, $P_{T,C}^* = P_{T,C}'^{*}/z^*$, $P_{T,R}^* = P_{T,R}'^{*}/z^*$. Then the optimal solution of problem (12) can be derived $P_B^* = P_B^*$,

$P_T^* = P_{T,C}^* + P_{T,R}^*$, $\alpha^* = P_{T,C}^*/P_T^*$.

Case 2: CU is NOMA-strong user

In this case, power allocation in full-duplex NOMA relaying based D2D communications is formulated as optimization problem (19). Since the form of (19) is similar to that of (12), the solution to (19) can be solved similar to problem (12). The details of solution are omitted due to space limitation.

3.2 Closed-form solution

We further derive a closed-form solution to optimization problem (5) in this section. Similarly, we consider two cases: CU as NOMA-strong user and DR as NOMA-strong user.

Case 1: DR is NOMA-strong user

When DR is NOMA-strong user, we aim to derive a closed-form solution of problem (12). To analyze the problem (12) further, we first introduce Lemma 1 and Lemma 2.

Lemma 1: The optimal solution to problem (12) satisfies $\gamma_{B,T} = \gamma_{T,C}^1$

Proof: Suppose (P_B^*, P_T^*, α^*) is the optimal solution of problem (12), which satisfy all constraints in problem (12), and R_{DR}^* is the correspondence value of objective function. Assume $\gamma_{B,T} > \gamma_{T,C}^2$. Then there exists a sufficient small constant ε, such that $P_B' = P_B^* - \varepsilon$, $P_T' = P_T^* + \varepsilon$, $\alpha' = \alpha^*$ also satisfy constraints (8) (5c) (5d) and (5e). Since P_B' is smaller than P_B, constraint (11) also holds. Then we can observe that (P_B', P_T', α') is also feasible and $R_{DR}'(P_B', P_T', \alpha') > R_{DR}^*(P_B^*, P_R^*, \alpha^*)$. Thus this contradicts with the assumption that (P_B^*, P_T^*, α^*) is the optimal solution to problem (12).

Assume $\gamma_{B,T} < \gamma_{T,C}^1$. Then there exists a sufficient small constant ε, $P_B' = P_B^*$, $P_T' = P_T^*$, $\alpha' = \alpha^* - \varepsilon$, which satisfies that ($P_B'$, P_T', α') is also feasible and $R_{DR}'(P_B', P_T', \alpha') > R_{DR}^*(P_B^*, P_R^*, \alpha^*)$. Also, this contradicts with the assumption that (P_B^*, P_T^*, α^*) is optimal solution.

From analysis above, we can derive $\gamma_{B,T} = \gamma_{T,C}^1$.

Lemma 2: The optimal solution to problem (12) satisfies $R_{CU} = R_{\min}^C$ and $\gamma_{B,C} = \varphi$.

Proof: From (3), (4), (6) and (7), R_{CU} is a decreasing function of α, while R_{DR} is an increasing function of α with fixed P_B and P_T. Assume (P_B^*, P_T^*, α^*) is the optimal solution of problem (12), which satisfies all constraints. The correspondence optimal value of problem (12) is denoted as R_{RX}^*. Suppose $R_{CU}(P_B^*, P_R^*, \alpha^*) > R_{\min}^C$. Then there exists a sufficient small positive constant ε, which satisfies that $P_B' = P_B^*$, $P_T' = P_T^*$, $\alpha' = \alpha^* - \varepsilon$ is also feasible and $R_{RX}'(P_B', P_T', \alpha') > R_{RX}^*(P_B^*, P_R^*, \alpha^*)$. This contradicts with the assumption that P_B^*, P_R^*, α^* is optimal solution.

Considering Lemma 1 and Lemma 2, constraint (8) in optimization problem (12) can be converted as

$$\gamma_{B,T} = \gamma_{T,C}^1 = \varphi. \tag{27}$$

Substituting (1) and (6) into equation (27), we have

$$P_B^* = \frac{\alpha g_{T,C}\varphi(\varphi+1) + \varphi^2(g_{LI} - g_{T,C})}{\alpha g_{B,T} g_{T,C}(\varphi+1) - \varphi(g_{B,C} g_{LI}\varphi + g_{B,T} g_{T,C})}, \tag{28}$$

$$P_T^* = \frac{\varphi(g_{B,T} + g_{B,C}\varphi)}{\alpha g_{B,T} g_{T,C}(\varphi+1) - \varphi(g_{B,C} g_{LI}\varphi + g_{B,T} g_{T,C})}. \tag{29}$$

Thus the P_B and P_T can be expressed as two functions of α. Then we convert the constraints (5d) (5c) and (11) of optimization problem (12) into constraints on α considering (28) and (29). Substituting (28) and (29) into constraint (5d), we can derive two constraints on α as follows

$$\alpha \geq \alpha_1 = \frac{\varphi\,(g_{T,C} - g_{LI})}{g_{T,C}\,(\varphi + 1)}, \tag{30}$$

$$\alpha \geq \alpha_2 = \frac{\varphi\,(g_{B,C}g_{LI}\varphi + g_{B,T}g_{T,C})}{g_{B,T}g_{T,C}\,(\varphi + 1)}. \tag{31}$$

To simplify the feasible domain of α, we analyze the relationship of α_1 and α_2, by analyzing the difference between α_1 and α_2

$$\alpha_2 - \alpha_1 = \frac{g_{LI}\varphi(g_{B,C}\varphi + g_{B,T})}{g_{B,T}g_{T,C}\,(\varphi + 1)} > 0. \tag{32}$$

According to (30), (31) and (32), the feasible region of α can be represented as

$$\alpha > \alpha_2. \tag{33}$$

Substituting (28) and (29) into constraint (5c), we can derive

$$\alpha \geq \alpha_3 = \frac{\varphi\,[g_{T,C}(P_{\max}g_{B,T} - \varphi) + \varphi(P_{\max}g_{B,C}g_{LI} + g_{LI} + g_{B,C}) + g_{B,T}]}{g_{T,C}\,(P_{\max}g_{B,T} - \varphi)(\varphi + 1)}. \tag{34}$$

Also, we analyze the relationship of α_2 and α_3 by analyzing the difference between α_2 and α_3

$$\alpha_3 - \alpha_2 = \frac{\varphi\,(g_{B,C}\varphi + g_{B,T})(g_{LI}\varphi + g_{B,T})}{g_{B,T}g_{T,C}\,(\varphi + 1)(P_{\max}g_{B,T} - \varphi)}.$$

To figure out the relationship between α_2 and α_3, we introduce Lemma 3.

Lemma 3：It always holds that $P_{\max}g_{B,T} - \varphi > 0$.

Proof：Since $\gamma_{B,C} = \min(\gamma_{B,T}, \gamma_{T,C}) > \varphi$, we have $\gamma_{B,T} > \gamma_{B,C} > \varphi$. Also considering $\sigma^2/(P_R h_{LI} + \sigma^2) \leq 1$, we have

$$\begin{aligned} P_{\max}g_{B,T} - \varphi &\geq P_{\max}g_{B,T} - \gamma_{B,T} \\ &= P_{\max}g_{B,T} - \frac{P_B g_{B,T}}{P_T g_{LI} + 1} \\ &\geq P_{\max}g_{B,T} - \frac{(P_{\max} - P_T)g_{B,T}}{P_T g_{LI} + 1} \\ &\geq P_{\max}g_{B,T} - (P_{\max} - P_T)g_{B,T} = P_T g_{B,T} > 0 \end{aligned}$$

According to Lemma 3, we shall have $\alpha_3 - \alpha_2 > 0$. Constraints (33) and (34) on α can be simplified as

$$\alpha > \alpha_3. \tag{35}$$

Then we focus on constraint (11). Substituting (7) and (10) into constraint (11), we have

$$\frac{g_{T,R}}{P_B g_{B,R} + 1} \geq \frac{g_{T,C}}{P_B g_{B,C} + 1}. \tag{36}$$

From (36), to guarantee DR can perform SIC successfully, the CINR of DR needs to be better than that of CU. (36) can be further rewritten as

$$P_B(g_{B,R}g_{T,C} - g_{B,C}g_{T,R}) \leq (g_{T,R} - g_{T,C}). \tag{37}$$

Substituting (28) into (37), we have

$$g_{T,C}\,(\varphi + 1)(\varphi\phi_B - g_{B,T}\phi_A)\alpha \leq \varphi[\varphi(g_{T,C} - g_{LI})\phi_B - (g_{B,C}g_{LI}\varphi + g_{B,T}g_{T,C})\phi_A], \tag{38}$$

where $\phi_A = g_{T,R} - g_{T,C}$, $\phi_B = g_{B,R}g_{T,C} - g_{B,C}g_{T,R}$. Then we derive the feasible domain α of in two conditions as

$$\begin{cases} \alpha \geq \alpha_4 = \dfrac{\varphi[\varphi(g_{T,C} - g_{LI})\phi_B - (g_{B,C}g_{LI}\varphi + g_{B,T}g_{T,C})\phi_A]}{g_{T,C}(\varphi+1)(\varphi\phi_B - g_{B,T}\phi_C)} & if\ \varphi\phi_B - g_{B,T}\phi_A < 0 \\ \alpha \leq \alpha_5 = \dfrac{\varphi[\varphi(g_{T,C} - g_{LI})\phi_B - (g_{B,C}g_{LI}\varphi + g_{B,T}g_{T,C})\phi_A]}{g_{T,C}(\varphi+1)(\varphi\phi_B - g_{B,T}\phi_A)} & if\ \varphi\phi_B - g_{B,T}\phi_A > 0 \end{cases} \tag{39}$$

Then joint considering the constraints of α in (5e) (34) (39), we can obtained the feasible domain of α as follows

$$\begin{cases} \max(\alpha_3, \alpha_4) \leq \alpha \leq 1 & if\ \varphi\phi_B - g_{B,T}\phi_A < 0 \\ \alpha_3 \leq \alpha \leq \min(\alpha_5, 1) & if\ \varphi\phi_B - g_{B,T}\phi_A > 0 \end{cases} \tag{40}$$

After deriving the feasible domain of α, by substituting (28) and (29) into (7), we can derived another expression of the objective function of (12)

$$\gamma_{T,R}^1 = \frac{(1-\alpha)\varphi(g_{B,T} + g_{B,C}\varphi)g_{T,R}}{[\alpha g_{T,C}\varphi(\varphi+1) + \varphi^2(g_{LI} - g_{T,C})]g_{B,R} + \alpha g_{B,T}g_{T,C}(\varphi+1) - \varphi(g_{B,C}g_{LI}\varphi + g_{B,T}g_{T,C})}. \tag{41}$$

Note that equation (41) only include one variable α. Also we can observe that $\gamma_{T,R}^1$ is a decreasing function of α. Thus the optimal solution of α can be derived as

$$\alpha^* = \begin{cases} \max(\alpha_3, \alpha_4) & if\ \varphi\phi_B - g_{B,T}\phi_A < 0 \\ \alpha_3 & if\ \varphi\phi_B - g_{B,T}\phi_A > 0 \end{cases}. \tag{42}$$

After deriving the optimal value of α, by substituting equation (42) into equation (28) and (29), we can derive the optimal value of P_B and P_T, denoted as P_B^* and P_T^*.

Case 2: CU is NOMA-strong user

When CU is NOMA-strong user, we aim to derive a closed-form solution of problem (19). In this case, we can observe that Lemma 1 and Lemma 2 also hold.

Considering Lemma1 and Lemma 2, constraint (15) in optimization problem (19) can be converted as

$$\gamma_{B,T} = \gamma_{T,C}^2 = \varphi. \tag{43}$$

Substituting (1) and (13) into equation (43), we have

$$P_B^* = \frac{\varphi(\alpha g_{T,C} + g_{LI}\varphi)}{\alpha g_{B,T}g_{T,C} - g_{B,C}g_{LI}\varphi^2}, \tag{44}$$

$$P_T^* = \frac{\varphi(g_{B,T} + g_{B,C}\varphi)}{\alpha g_{B,T}g_{T,C} - g_{B,C}g_{LI}\varphi^2}. \tag{45}$$

Thus the P_B and P_T can be expressed as two functions of α. Then we transform the constraints (5d) (5c) and (18) of optimization problem (12) considering (44) and (45).

Then substituting (44) and (45) into constraint (5d) and (5c), we can derive the feasible region of α as follows

$$\alpha \geq \alpha_1^{'} = \frac{g_{B,C}g_{LI}\varphi^2}{g_{B,T}g_{T,C}}, \tag{46}$$

$$\alpha \geq \alpha_2^{'} = \frac{g_{LI}\varphi^2(P_{\max}g_{B,C} + 1) + \varphi(g_{B,C}\varphi + g_{B,T})}{g_{T,C}(P_{\max}g_{B,T} - \varphi)}. \tag{47}$$

From (46) and (47), we have two conditions on α. To simplify the feasible domain of α, we analyze the relationship of α_1 and α_2, by analyzing the difference between α_1 and α_2

$$\alpha_2^{'} - \alpha_1^{'} = \frac{\varphi(g_{LI}\varphi + g_{B,T})(g_{B,C}\varphi + g_{B,T})}{g_{T,C}(P_{\max} g_{B,T} - \varphi)}. \tag{48}$$

According to Lemma 3, $P_{max} g_{B,T} - \varphi > 0$. Then we shall have $\alpha_2' > \alpha_1'$. According to (46) and (47), the feasible region of α is

$$\alpha > \alpha_2'. \tag{49}$$

Then we focus on constraint (18). Substituting (14) and (17) into constraint (18), we have

$$\frac{g_{T,C}}{P_B g_{B,C} + 1} \geq \frac{g_{T,R}}{P_B g_{B,R} + 1}. \tag{50}$$

Equation (50) means that to guarantee CU can perform SIC successfully, the CINR of CU needs to be better than that of DR. Equation (50) can be further rewritten as

$$P_B(g_{B,C} g_{T,R} - g_{B,R} g_{T,C}) \leq (g_{T,C} - g_{T,R}). \tag{51}$$

Substituting (44) into (51), we have

$$(\varphi\phi_D - g_{B,T}\phi_C)\alpha \leq g_{LI}\varphi^2 (g_{B,R} - g_{B,C}). \tag{52}$$

where $\phi_C = g_{T,C} - g_{T,R}$, $\phi_D = g_{B,C} g_{T,R} - g_{B,R} g_{T,C}$. Then we derive the feasible domain α of in two conditions as

$$\begin{cases} \alpha \geq \alpha_3^{'} = \dfrac{g_{LI}\varphi^2 (g_{B,R} - g_{B,C})}{\varphi\phi_D - g_{B,T}\phi_C} & if \ \varphi\phi_D - g_{B,T}\phi_C < 0 \\ \alpha \leq \alpha_4^{'} = \dfrac{g_{LI}\varphi^2 (g_{B,R} - g_{B,C})}{\varphi\phi_D - g_{B,T}\phi_C} & if \ \varphi\phi_D - g_{B,T}\phi_C > 0 \end{cases}. \tag{53}$$

Then joint considering the constraints of α in (5e) (49) (53), we can obtained the feasible domain of α as follows

$$\begin{cases} \max(\alpha_2^{'}, \alpha_3^{'}) \leq \alpha \leq 1 & if \ \varphi\phi_D - g_{B,T}\phi_C < 0 \\ \alpha_2^{'} \leq \alpha \leq \min(\alpha_4^{'}, 1) & if \ \varphi\phi_D - g_{B,T}\phi_C > 0 \end{cases}. \tag{54}$$

After deriving the feasible domain of α, by substituting (44) and (45) into (14), we can derived another expression of the objective function of (19)

$$\gamma_{T,R} = \gamma_{T,R}^2 = \frac{(1-\alpha)\varphi(g_{B,T} + g_{B,C}\varphi) g_{T,R}}{\varphi(\alpha g_{T,C} + g_{LI}\varphi) g_{B,R} + \alpha\varphi(g_{B,T} + g_{B,C}\varphi) g_{T,R} + \alpha g_{B,T} g_{T,C} - g_{B,C} g_{LI}\varphi^2}. \tag{55}$$

From (55), we can observe that $\gamma_{T,R}$ is a decreasing function of α. Thus the optimal solution of α can be derived as

$$\alpha^* = \begin{cases} \max(\alpha_2^{'}, \alpha_3^{'}) & if \ \varphi\phi_D - g_{B,T}\phi_C < 0 \\ \alpha_2^{'} & if \ \varphi\phi_D - g_{B,T}\phi_C > 0 \end{cases}. \tag{56}$$

After deriving the optimal value of α, by substituting equation (56) into equation (44) and (45), we can derive the optimal value of P_B and P_T, denoted as P_B^* and P_T^*.

To implement the algorithms (LFPM and the closed-form solution) in a practical cellular system, the algorithms are executed in the BS to caculate the optimal power of BS and DT, and then the optimal power (P_B, P_T, α) is transmitted to the DT to facilitate the full-duplex NOMA relaying based D2D communication.

4. Simulation Results

In this section, we evaluate the performance of the proposed two power allocation methods in the full-duplex NOMA relaying based D2D communications. We compare the performance of LFPM and closed-form solution with that of optimal power allocation in full-duplex relaying based D2D [10], termed as FD D2D relaying (OMA).

According to FD D2D relaying (OMA), the D2D links is allowed to underlay cellular downlink by assigning D2D transmitter (DT) as FD relay to assist cellular downlink transmissions. The DT transmit the integrated signal composed by the regenerated signal that will forward to CU and the signals to be transmitted to DR directly. Both CU and DR suffer from the co-channel interference. While in the proposed scheme (FD NOMA relaying based D2D), the DR and CU received signals from DT according to NOMA communication. Thus, the NOMA-strong user can perform successive interference cancellation and only the NOMA-weak user suffers from the co-channel interference.

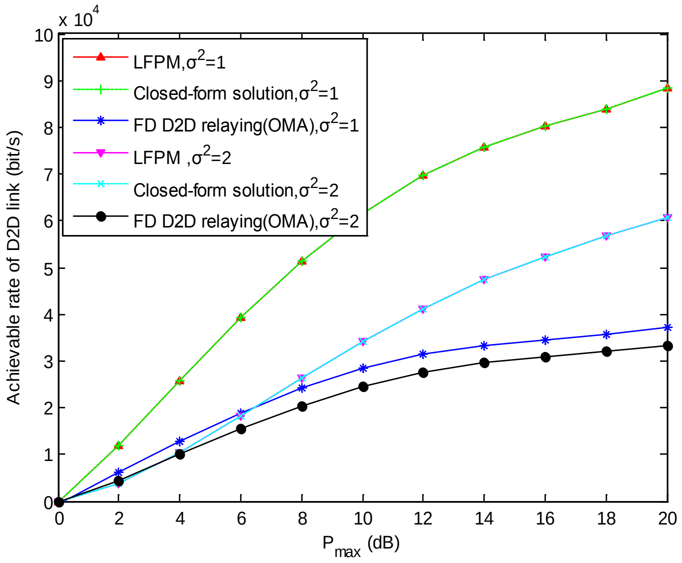

Fig. 2. Achievable rate of D2D link versus $P_{\max}$

In **Fig. 2** and **Fig. 3**, the achievable rate of D2D link is simulated via Monte Carlo method. All the channels are modeled as Rayleigh fading channels. **Fig. 2** illustrates the achievable transmit rate of D2D link versus the total transmit power with $R_{\min}^{C}$= 70 Kbps, W = 0.1 MHz. We find that the performance of our derived closed-form solution matches that of LFPM perfectly, which verifies the accuracy of the closed-form solution. With the increasing of total power, the achievable transmit rates of D2D link under different power allocation schemes all increase. Both LFPM and closed-form solution outperforms the power allocation solution in [10] and the achievable rate of D2D link of LFPM and closed-form solution is 2.4 times that of power allocation scheme in [10]. This is due to the fact that in [10], both cellular user and D2D receiver suffer the interference of the partner's signal, while in the proposed scheme in this paper, NOMA-strong user (CU or DR) can perform successive interference cancellation. Also, D2D link can achieve a higher rate with a lower noise variance.

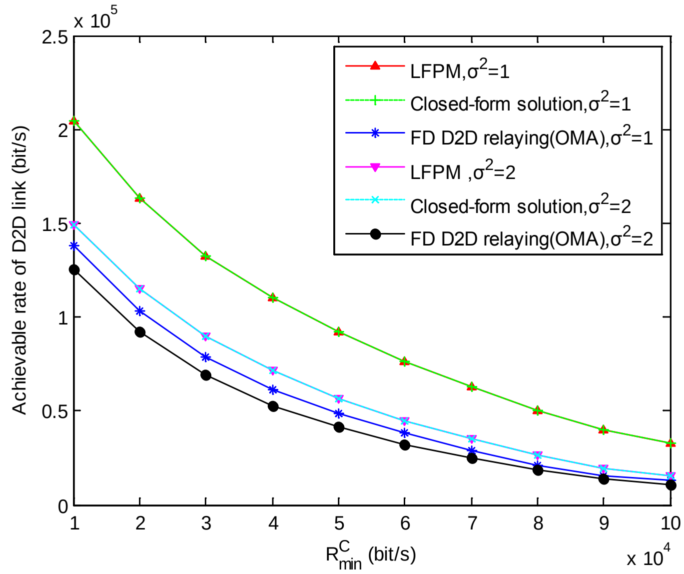

Fig. 3. Achievable rate of D2D link versus $R^C_{\min}$

Fig. 3 illustrates the achievable transmit rate of D2D link versus CU’s minimum transmit rate $R^C_{\min}$ with $P_{\max} = 10$, $W = 0.1$ MHz, considering different power allocation scheme. As we can see from Fig. 3, the achievable rate of D2D like decrease with the increase of $R^C_{\min}$. This is due to the fact that when CU requires a higher rate, more power should be allocated on CU and less power is reserved for D2D link. Also the performance of LFPM matches that based on closed-form solution well and both can achieve a better performance than power allocation scheme in [10].

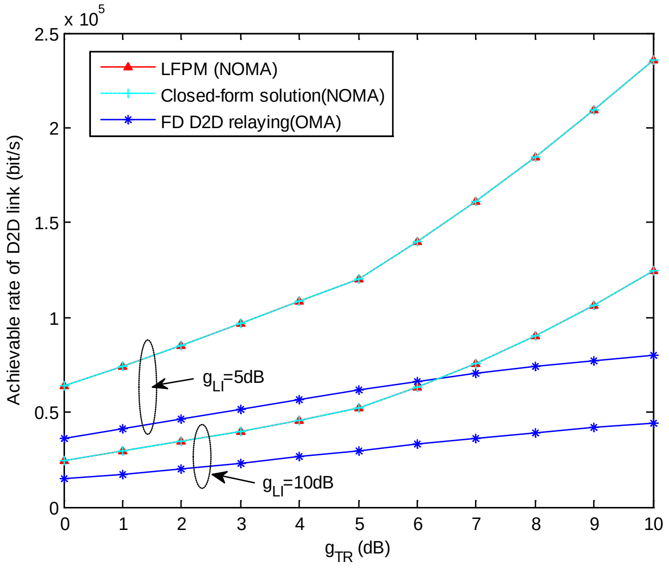

Fig. 4. Achievable rate of D2D link versus g_{TR}

Fig. 4 illustrates the achievable rate of D2D link versus the CNR of D2D link $g_{T,R}$, considering different power allocation schemes, with $g_{B,T} = g_{T,C}$= 5 dB, $g_{B,C} = g_{B,R}$= -5 dB, $R^{C}_{\min}$= 70 Kbps, $P_{\max}$= 2, W = 0.1 MHz. With the increasing of g_{TR}, the achievable rate of all power allocation scheme increase. Also, the performance of LFPM and closed-form solution increase much faster than that of power allocation scheme in [10] which again verifies our theoretical analysis. We note that as for LFPM and closed-form solution, the performance increases much faster when $g_{T,R}$>5dB. This is due to the fact that when $g_{T,R}$<5dB, the CNR of DT-DR link is worse of DT-CU link and thus DR is NOMA-weak user. In this condition, DR suffers the interference of CU's signal. When $g_{T,R}$>5dB, DR become NOMA-strong user, and it can cancel the co-channel interference by SIC. The impact of self-interference channel is also illustrated in **Fig. 4**. We can observe that a lower self-interference channel gain will cause higher performance. This happens due to the fact that with lower self-interference channel gain, less power is needed to achieve the same received SINR at DT. Thus more power is reserved for DT to transmit signals to DR and CU.

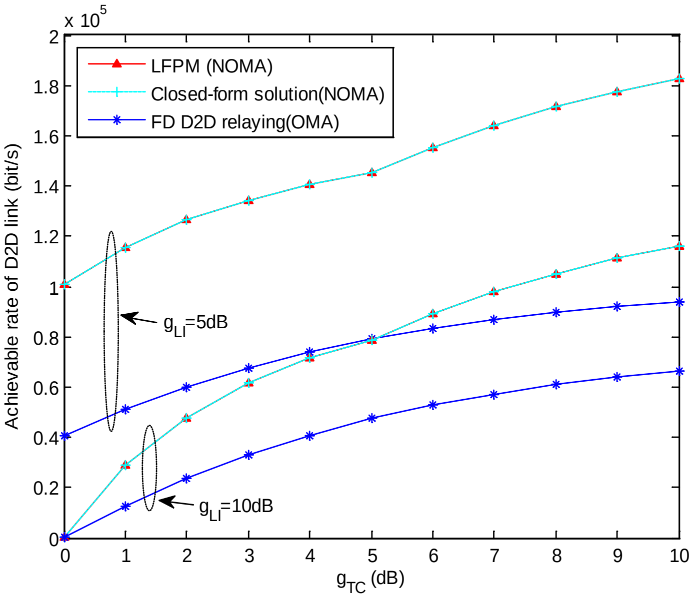

Fig. 5. Achievable rate of D2D link versus g_{TC}

The performance of the achievable rate of D2D link versus channel-noise ratio $g_{T,C}$ is illustrated in **Fig. 5** with $g_{T,R}$= 5 dB, $R^{C}_{\min}$= 60 Kbps. With the increasing of $g_{T,C}$, the D2D link can achieve a higher rate with all schemes. This is due to the fact that when the CU has a good channel with DT, lower power needs to be used on DT to accomplish the communication with cellular link. Thus more power can be reserved for the D2D link. Specifically, the achievable rate of D2D link is 0 with $g_{TLI} =$ 10dB, $g_{T,C} =$ 0dB. In another word, DT needs to allocate all power on CU's signal to satisfy its minimum rate requirement and the D2D link fails to communicate.

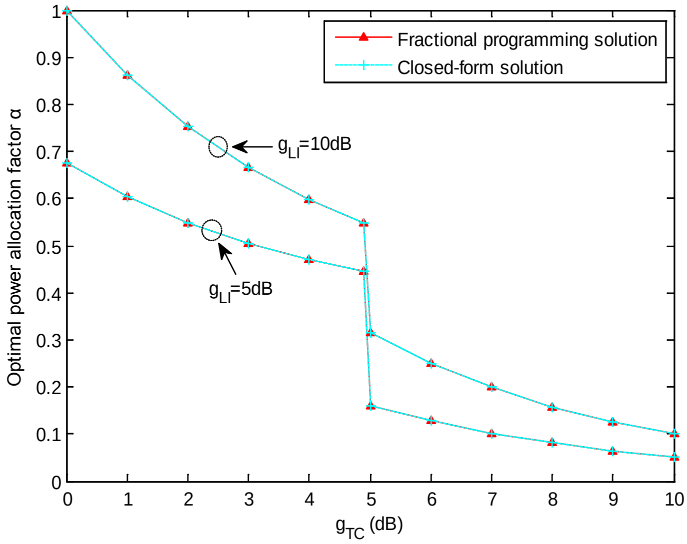

Fig. 6. Optimal solution of α versus $g_{T,C}$

Fig. 6 illustrates the optimal power allocation fraction α vesus the channel to noise ratio of the channel between DT and CU for the fraction programming method and closed-form solution. The optimal solution of α decreases with the increasing of $g_{T,C}$. This happens due to the fact that when DT transmit signals to CU with a better channel, less power is needed to achieve the required rate of CU. Thus the power allocation fraction α become small. We can also observe that the optimal solution of decrease sharply at $g_{T,C}$= 5dB. This is due to the fact, when $g_{T,C}$ increases to more than 5dB, CU turns from NOMA-weak user to NOMA-strong user. As NOMA-strong user, less power is allocated because it can cancel the interference caused by NOMA-weak user. At g_{LI} = 10dB, g_{TC} = 0dB, the optimal solution α of is 1, which means all the power at DT is used to transmit signals to CU and the achievable rate of D2D link decrease to 0. This can be verified by the simulation result in **Fig. 5**.

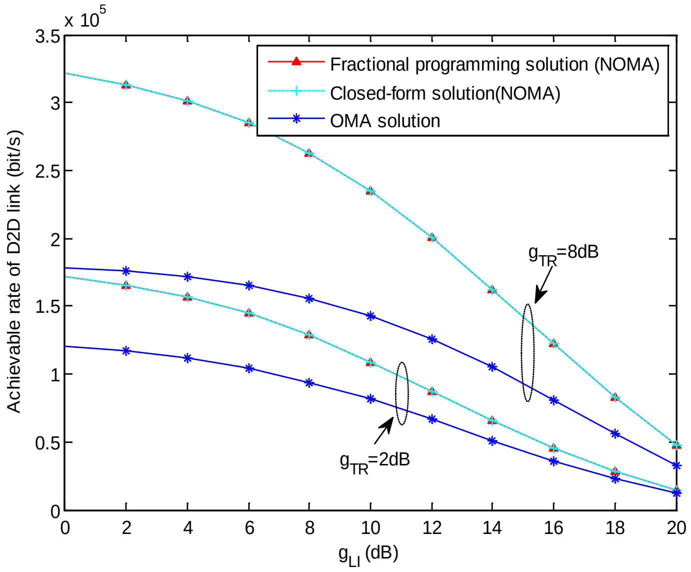

Fig. 7. Achievable rate of D2D link versus g_{LI}

Fig. 7 illustrates the achievable rate of D2D link considering different self interference cancellation ability with $g_{B,T} = g_{T,C}$= 5 dB, $g_{B,C} = g_{B,R}$= -5 dB, $R_{\min}^{C}$= 30 Kbps, $P_{\max}$= 2. With the increasing of g_{LI}, which means the full-duplex DT has a bad self-interference cancellation performance, the achievable rate of D2D link decrease for all power allocation schemes. This happens due to the fact that when the DT suffers a larger self-interference, the base station needs to transmit signals with larger power to satisfy the rate requirement of cellular user, causing the power allocated on DT decreased. Compare with figures with $g_{T,R}$=2dB, when DR is NOMA-weak user, a higher rate of D2D link can be achieved with $g_{T,R}$=8dB, when DR is termed as NOMA-strong user.

5. Conclusion

In this paper, we propose a novel full-duplex NOMA relaying based device-to-device scheme, which allows D2D transmitter to underlay a cellular network by acting a full-duplex NOMA relay simultaneously. To maximize the achievable rate of D2D link, a power allocation method based on fractional programming is proposed. Furthermore, we derive the closed-form solution of optimal transmit power at the BS and DT as well as the optimal power allocation factor. The simulation results show that the performance of the fractional programming based method matches the close-form solution perfectly and both the proposed schemes outperform the full-duplex relaying based D2D scheme significantly.

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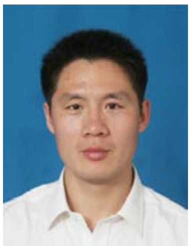

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