Binary Power Control for Full-Duplex Networks

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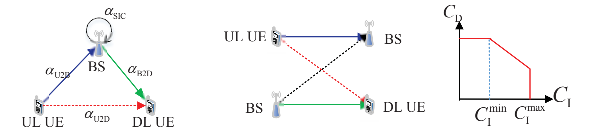
***Abstract*—Full-duplex (FD) communications benefit from recent breakthroughs in analog and digital signal processing and demonstrate nearly doubled spectrum efficiency for point-to-point links with beyond 100 dB self-interference cancellation capability. However, FD cellular networks with base stations (BSs) in FD mode and user terminals (UEs) in half-duplex mode also introduce intra-cell inter-UE interference and other kinds of interference, which might even eat up the potential gain. In this paper, we propose to take advantage of power control and inter-UE interference cancellation (IC) techniques to cope with the bothersome intra-cell inter-UE interference. We verify that the power control solution for single-cell FD network with a given user pair exhibits an interesting binary feature, that is, either both the BS and the uplink UE transmit at the maximum power or one of them completely mutes to achieve the optimal sum rate. Moreover, the binary feature holds even when inter-UE IC is applied, thus showing appealing computational efficiency. We also demonstrate significant performance improvement by applying binary power control with inter-UE IC to both single-cell and multi-cell FD networks.**

I. Introduction

To satisfy the surging traffic demand and to solve the accompanied spectrum scarcity, mobile networks in conventional half-duplex (HD) mode are facing unprecedented challenges to further improve the efficiency of spectrum usage. On the other hand, bidirectional transmission at the same time and frequency resource, also known as full-duplex (FD) communication, has long been dreamed but was hindered by strong self-interference from a node's transmitter to its receiver. However, recent breakthroughs in analog and digital signal processing bring positive news to the real application of FD communications. It is now feasible to have up to 110dB self-interference cancellation (SIC) capability [1], making it practical to cancel the self-interfering signal and decode the signal of interest [1]–[3].

While roughly doubled throughput has been reported for single link FD transmission [3], putting FD communication into networks is not that straightforward, as lack of synchronization in transmission direction leads to complicated interference issues. Compared to HD network, single-cell FD cellular network with only a BS work in FD mode and user terminals (UEs) in HD mode newly experiences intra-cell inter-UE interference, as well as the residual self-interference after SIC. Multi-cell FD networks suffer from even worse interference situation, which might lead to a severe performance deterioration, even eating up the potential gain of FD networks [4]. In order to mitigate the negative impact of the annoying interference, there has emerged a substantial body of works including power control [5]–[8] and user scheduling [5], [9], [10].

In this paper, we first dive into the power control problem in single-cell FD network with only one given pair of uplink (UL, i.e., from UE to BS) and downlink (DL, i.e., from BS to UE) UEs. Specifically, in Section II, an optimization problem is formulated to maximize the sum rate with transmission power of the BS and the UL UE as control variables. In Section III, we shall first show a surprising observation from the analytical solution that the optimal power control for both the BS and the UL UE has binary features, i.e., either transmitting at its full power level or completely muting. Afterwards, we extend the power control problem to scenarios where UEs are equipped with stronger receivers that can jointly detect interference or at least suppress them to some level, motivated by the fact that with the evolution of the Moore's Law, nowadays's digital processing capability at UE shall become strong enough to perform joint detection of multiple signals [11]. Once again, we shall prove that the binary feature in sum rate-optimized power control solution holds, even when we apply inter-UE interference cancellation (IC) techniques to the DL UE. Hence, the sum rate-optimization problem could be significantly simplified with apparent improvement in computational efficiency. Moreover, to our best knowledge, though researchers [8], [12] have already obtained some similar observations for binary power control solutions under scenarios without inter-UE IC, our work should be the first to consider the case with inter-UE IC technique. Next, in Section IV, we give insight into multi-cell FD networks. Instead of theoretically analyzing the related performance, we demonstrate the performance of multi-cell FD networks with single-cell based binary power control and inter-



(a) Single-Cell Full Duplex with a User Pair (b) Equivalent Channels (c) Capacity Region

Fig. 1. Scenario description and system models in single-cell FD networks.

UE IC technique in system-level simulations. Finally, we conclude this paper in Section V.

II. System Model and Problem Formulation

We primarily consider single-cell FD network with a given pair of UL and DL UEs, as depicted in Fig. 1(a). Compared with traditional HD network, the increased interference in FD networks is the intra-cell interference from the UL UE to the DL UE, as well as the residual self-interference after SIC in the BS.

Generally, the UL rate can be calculated by applying the Shannon capacity formula to the channels in Fig. 1(b), that is

$$R_{\mathrm{U}} = B \log_2 \left(1 + \frac{\alpha_{\mathrm{U2B}} P_{\mathrm{u}}}{\alpha_{\mathrm{SIC}} P_{\mathrm{b}} + N_0}\right), \tag{1}$$

where P_{u} denotes the transmission power of the UL UE. α_{U2B} characterizes the channel from the UL UE to the BS and α_{SIC} reflects the SIC capability of the BS. B stands for the allocated bandwidth for UL/DL transmission and N_0 is the noise power. Meanwhile, if the DL UE treats this interfering signal from the UL UE as noise, the DL rate can be formulated as

$$R_{\mathrm{D}}^{0} = B \log_2 \left(1 + \frac{\alpha_{\mathrm{B2D}} P_{\mathrm{b}}}{\alpha_{\mathrm{U2D}} P_{\mathrm{u}} + N_0}\right), \tag{2}$$

where P_{b} denotes the transmission power of the BS. α_{B2D} and α_{U2D} characterize the channel from the BS to the DL UE and from the UL UE to the DL UE, respectively. Therefore, the problem to maximize the total system throughput of both UL and DL can be formulated in the following manner:

$$\begin{aligned} \max_{P_{\mathrm{b}}, P_{\mathrm{u}}} \quad & C_0 \left(P_{\mathrm{b}}, P_{\mathrm{u}}\right) = R_{\mathrm{U}} + R_{\mathrm{D}}^{0} \\ s.t. \quad & 0 < P_{\mathrm{b}} \leq P_{\mathrm{b}}^{\max},\ 0 < P_{\mathrm{u}} \leq P_{\mathrm{u}}^{\max}. \end{aligned} \tag{3}$$

On the other hand, with the inter-UE IC applied, the DL UE could boost its DL rate under some conditions, by firstly decoding the interfering signal from the UL UE. Hence, inter-UE IC could potentially increase the system sum rate. For example, if intra-cell inter-UE interference is perfectly canceled, the downlink rate could be improved to

$$R_{\mathrm{D}}^{1\text{-}1} = B \log_2 \left(1 + \frac{\alpha_{\mathrm{B2D}} P_{\mathrm{b}}}{N_0}\right). \tag{4}$$

Here, as the DL rate becomes relevant with the degree of inter-UE interference cancellation, the required power control solution needs a re-investigation.

III. Binary Power Control in Single-Cell Network

A. Power Control Without Inter-UE IC

In this part, we discuss the power control solution for the optimization problem in Eq. (3). Mathematically, the manipulation of Eq. (3) leads to the following results:

Theorem 1. For the sum rate optimization problem (i.e., Eq. (3)) in single-cell FD network with a given user pair, where the transmission power of the BS and the UL UE P_{b} and P_{u} are subject to constraints $0 < P_{\mathrm{b}} \leq P_{\mathrm{b}}^{\max}$ and $0 < P_{\mathrm{u}} \leq P_{\mathrm{u}}^{\max}$, the optimal power pair $(P_{\mathrm{b}}^{\mathrm{opt}}, P_{\mathrm{u}}^{\mathrm{opt}})$ should satisfy

$$(P_{\mathrm{b}}^{\mathrm{opt}}, P_{\mathrm{u}}^{\mathrm{opt}}) \in \left\{(0, P_{\mathrm{u}}^{\max}), (P_{\mathrm{b}}^{\max}, 0), (P_{\mathrm{b}}^{\max}, P_{\mathrm{u}}^{\max})\right\}. \tag{5}$$

Proof. Firstly, the optimization issue in Eq. (3) is equivalent to

$$\begin{aligned} \max_{P_{\mathrm{b}}, P_{\mathrm{u}}} C_0' = & \left(1 + \frac{\alpha_{\mathrm{U2B}} P_{\mathrm{u}}}{\alpha_{\mathrm{SIC}} P_{\mathrm{b}} + N_0}\right) \left(1 + \frac{\alpha_{\mathrm{B2D}} P_{\mathrm{b}}}{\alpha_{\mathrm{U2D}} P_{\mathrm{u}} + N_0}\right) \\ s.t. \quad & 0 < P_{\mathrm{b}} \leq P_{\mathrm{b}}^{\max},\ 0 < P_{\mathrm{u}} \leq P_{\mathrm{u}}^{\max}. \end{aligned} \tag{9}$$

For a given P_{u}, taking the derivative C_0' over P_{b}, we can obtain Eq. (6) at the top of Page 3. Consequently, $\frac{\partial C_0'}{\partial P_{\mathrm{b}}}$ might be always larger than 0. Meanwhile, if there exists some P_{b} to make $\frac{\partial C_0'}{\partial P_{\mathrm{b}}} = 0$, there exists at most one such stationary point $P_{\mathrm{b}}^{\mathrm{S0}} = -\frac{N_0}{\alpha_{\mathrm{SIC}}} + \frac{\sqrt{(\alpha_{\mathrm{U2B}}\alpha_{\mathrm{SIC}}P_{\mathrm{u}}N_0 + \alpha_{\mathrm{U2D}}\alpha_{\mathrm{U2B}}\alpha_{\mathrm{SIC}}P_{\mathrm{u}}^2 - \alpha_{\mathrm{B2D}}\alpha_{\mathrm{U2B}}P_{\mathrm{u}}N_0)/\alpha_{\mathrm{B2D}}}}{\alpha_{\mathrm{SIC}}}$ in the interval $[0, P_{\mathrm{b}}]$, which corresponds to a local minimum of C_0' or C_0. Therefore, for a given P_{u}, the optimal BS transmission power $P_{\mathrm{b}}^{\mathrm{opt}}$ for C_0 is

$$P_{\mathrm{b}}^{\mathrm{opt}} = \begin{cases} 0 & P_{\mathrm{b}}^{\mathrm{S0}} > P_{\mathrm{b}}^{\max}; \\ P_{\mathrm{b}}^{\max} & P_{\mathrm{b}}^{\mathrm{S0}} < 0; \\ 0 \text{ or } P_{\mathrm{b}}^{\max} & \text{otherwise}. \end{cases} \tag{10}$$

In other words, for a given P_{u}, the optimal BS transmission power has binary feature. Similarly, for a given P_{b}, the optimal transmission power of the UL UE also exhibits binary property. Hence, it comes the conclusion. □

According to Theorem 1, the optimal transmission power without inter-UE IC has binary feature, that is, either

$$\frac{\partial C_0'}{\partial P_b} = \frac{\alpha_{B2D}(N_0+\alpha_{SIC}P_b)^2+\alpha_{B2D}\alpha_{U2B}P_uN_0-\alpha_{U2B}\alpha_{SIC}P_uN_0-\alpha_{U2D}\alpha_{U2B}\alpha_{SIC}P_u^2}{(N_0+\alpha_{U2D}P_u)(N_0+\alpha_{SIC}P_b)^2}. \tag{6}$$

$$(P_b^{subopt1}, P_u^{subopt1}) \in \mathscr{P}^1 = \begin{cases} (\min(P_b^{I1}, P_b^{max}), P_u^{max}), & \text{Cond. } 1^a \text{ holds;} \\ (P_b^{max}, P_u^{max}), & \text{Cond. } 2^a \text{ holds;} \\ \{(0, P_u^{max}), (P_b^{max}, P_u^{max})\}, & \text{Cond. } 2^b \text{ holds;} \\ \emptyset, & \text{otherwise.} \end{cases} \tag{7}$$

$$(P_b^{subopt3}, P_u^{subopt3}) \in \mathscr{P}^3 = \begin{cases} \{(\min(P_b^{I2}, P_b^{max}), P_u^{max}), (0, P_u^{max}), (\min(P_b^{I2}, P_b^{max}), 0)\}, & \text{Cond.} 1^b,\ 1^c,\ 2^a, \text{ and } 2^c \text{ hold;} \\ \emptyset, & \text{otherwise.} \end{cases} \tag{8}$$

the BS and the UL UE transmit at their maximum power level or one of them just mutes to fall back to HD mode. To understand this binary feature more clearly, we plot the power control results for a set of different relative UE locations in Fig. 2(a). Specifically, we configure a single-cell FD network scenario where the BS and the UL UE are located at (0,0) and (-25,0), respectively, and set other parameters as Table II. By moving the DL UE along the horizontal axis from (-40,0) to (40,0), we obtain the corresponding optimal power control solutions for both the UL UE and the BS by exhaustive search, which yield Fig. 2(a) and are consistent with our analytical observation. Moreover, Fig. 3 shows, compared to the case without power control, the pure binary control could significantly improve the sum rate of FD network by adding the transmission direction (i.e., UL and DL) as another dimension of diversity, and bring up to 60% performance gain over HD network.

B. Power Control With Inter-UE IC

In this part, we investigate the power control issue with inter-UE IC technique. Assume that the signals received by the DL UE from the BS and the UL UE are synchronized, the channel from the BS and the UL UE to the DL UE can be regarded as a two-user multiple access channel (MAC) [6], as depicted in Fig. 1(b). Therefore, the rate pair (R_D, R_U) should be within the two-user MAC rate region, so that the DL UE could reliably decode signals from both the BS and the UL UE and successfully perform inter-UE IC. As depicted in Fig. 1(c), the interfering channel (from the UL UE to the DL UE) capacity at two corners are $C_I^{min} = B\log_2\left(1+\frac{\alpha_{U2D}P_u}{\alpha_{B2D}P_b+N_0}\right)$ and $C_I^{max} = B\log_2\left(1+\frac{\alpha_{U2D}P_u}{N_0}\right)$, respectively. Hence, the power control problem could be divided into three cases, depending on the relationship between R_U and C_I^{min} or C_I^{max}.

TABLE I
Description of the conditions in Section III-B.

Cond.	Constraints
1^a	$\alpha_{U2B}\alpha_{B2D} > \alpha_{SIC}\alpha_{U2D}$, $\alpha_{U2D} \geq \alpha_{U2B}$
1^b	$\alpha_{U2B}\alpha_{B2D} > \alpha_{SIC}\alpha_{U2D}$, $\alpha_{U2D} \leq \alpha_{U2B}$, $P_b^{I2} <= P_b^{max}$
1^c	$\alpha_{U2B}\alpha_{B2D} > \alpha_{SIC}\alpha_{U2D}$, $\alpha_{U2D} \leq \alpha_{U2B}$, $P_b^{I2} > P_b^{max}$
2^a	$\alpha_{U2B}\alpha_{B2D} < \alpha_{SIC}\alpha_{U2D}$, $\alpha_{U2D} \leq \alpha_{U2B}$, $P_b^{I1} \leq P_b^{max}$
2^b	$\alpha_{U2B}\alpha_{B2D} < \alpha_{SIC}\alpha_{U2D}$, $\alpha_{U2D} > \alpha_{U2B}$
2^c	$\alpha_{U2B}\alpha_{B2D} < \alpha_{SIC}\alpha_{U2D}$, $\alpha_{U2D} \leq \alpha_{U2B}$, $P_b^{I1} > P_b^{max}$

Case 1: $R_U \leq C_I^{min}$ and $R_U \leq C_I^{max}$. In this case, the DL UE can perfectly cancel all the interference from the UL UE, and obtain the downlink rate in Eq. (4). Therefore, the optimization problem could be written as

$$\begin{aligned} \max_{P_b, P_u} \quad & C_{1\text{-}1}(P_b, P_u) = R_U + R_D^{1\text{-}1} \\ s.t. \quad & 0 < P_b \leq P_b^{max},\ 0 < P_u \leq P_u^{max} \\ & R_U \leq C_I^{min}, R_U \leq C_I^{max}. \end{aligned} \tag{11}$$

Lemma 1. For the optimization of the sub-problem defined in Eq. (11), the optimal power pair $(P_b^{subopt1}, P_u^{subopt1})$ should satisfy Eq. (7) at the top of Page 3, where $P_b^{I1} = \frac{(\alpha_{U2D}-\alpha_{U2B})N_0}{\alpha_{U2B}\alpha_{B2D}-\alpha_{SIC}\alpha_{U2D}}$ and $P_b^{I2} = \frac{\alpha_{U2B}-\alpha_{U2D}}{\alpha_{U2D}\alpha_{SIC}}N_0$, Cond. 1^a, 2^a and 2^b are given in Table I.

Proof. For $R_U \leq C_I^{min}$ and $R_U \leq C_I^{max}$, we have the interval of P_b and P_u as follows

$$P_b \in \begin{cases} \left[0, \min(P_b^{I1}, P_b^{max})\right] & \text{Cond. } 1^a \text{ holds;} \\ \left[P_b^{I1}, P_b^{max}\right] & \text{Cond. } 2^a \text{ holds;} \\ [0, P_b^{max}] & \text{Cond. } 2^b \text{ holds;} \\ \emptyset & \text{otherwise,} \end{cases} \tag{12}$$

where we utilize the facts that when Cond. 2^a holds, $P_b^{I1} > P_b^{I2}$. When Cond. 2^b holds, $P_b^{I1} < 0$ and $P_b^{I2} < 0$.

Firstly, $C_{1\text{-}1}$ is monotonically increasing along with P_u. Meanwhile, by denoting the $\exp(C_{1\text{-}1}/B)$ as $C_{1\text{-}1}'$, we

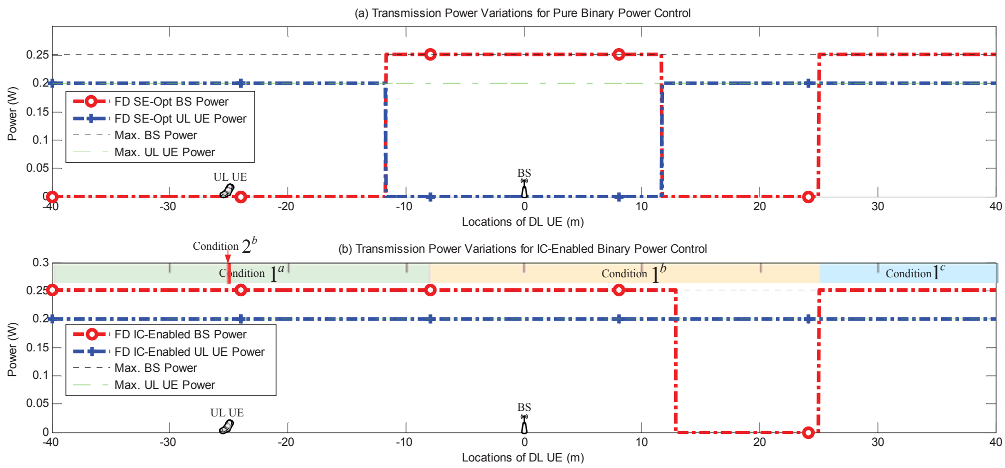


Fig. 2. Binary power control in single-cell FD network with and without IC: The optimal transmission power of the BS and the UL UE in terms of sum rate maximization. The color bars at the top of subfigure (b) depict different conditions in Table I for the MAC channel in Fig. 1(c).

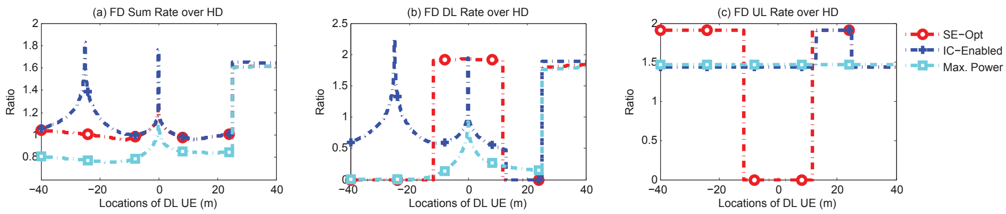


Fig. 3. Binary power control in single-cell FD network with and without IC: The optimal transmission power of the BS and the UL UE in terms of SE maximization.

can have $\frac{\partial C'_{1\text{-}1}}{\partial P_{\text{b}}} \propto \alpha_{\text{B2D}}\left(\alpha_{\text{SIC}}P_{\text{b}}+N_0\right)^2+\alpha_{\text{U2B}}(\alpha_{\text{B2D}}-\alpha_{\text{SIC}})P_{\text{u}}N_0$. Similar to the proof of Theorem 1, it can be derived that the optimal transmission power of the BS has binary feature. Specifically, when Cond. 1^a holds, $\alpha_{\text{B2D}} > \alpha_{\text{SIC}}$, which gives $\frac{\partial C'_{1\text{-}1}}{\partial P_{\text{b}}} > 0$. Meanwhile, when Cond. 2^a holds, $C_{1\text{-}1}(P_{\text{b}}^{\max}, P_{\text{u}}^{\max}) = R_{\text{D}}^{1\text{-}1} + B\log_2(1+\frac{\alpha_{\text{U2B}}P_{\text{u}}^{\max}}{\alpha_{\text{SIC}}P_{\text{b}}^{\max}+N_0}) \geq R_{\text{D}}^{1\text{-}1} + B\log_2(1+\frac{\alpha_{\text{U2D}}P_{\text{u}}^{\max}}{\alpha_{\text{B2D}}P_{\text{b}}^{\max}+N_0}) = B\log_2(1+\frac{\alpha_{\text{B2D}}P_{\text{b}}^{\max}+\alpha_{\text{U2D}}P_{\text{u}}^{\max}}{N_0}) > B\log_2(1+\frac{\alpha_{\text{B2D}}P_{\text{b}}^{\text{I1}}+\alpha_{\text{U2D}}P_{\text{u}}^{\max}}{N_0}) = C_{1\text{-}1}(P_{\text{b}}^{\text{I1}}, P_{\text{u}}^{\max})$. Thus, the optimal BS transmission powers for Cond. 1^a and 2^a are $\min(P_{\text{b}}^{\text{I1}}, P_{\text{b}}^{\max})$ and $P_{\text{b}}^{\max}$, respectively. It comes the conclusion. □

Case 2: $C_{\text{I}}^{\min} \leq R_{\text{U}} \leq C_{\text{I}}^{\max}$. In this case, the DL UE can not totally cancel the interference from the UL UE, but still glean some gain by applying inter-UE IC technique. Meanwhile, the maximum achievable sum rate is

$$\begin{aligned} C_{1\text{-}2} &= B\log_2(1+\frac{\alpha_{\text{B2D}}P_{\text{b}}+\alpha_{\text{U2D}}P_{\text{u}}}{N_0}) \\ s.t.\quad & 0<P_{\text{b}}\leq P_{\text{b}}^{\max},\ 0<P_{\text{u}}\leq P_{\text{u}}^{\max} \\ & C_{\text{I}}^{\min}\leq C_{\text{U}}\leq C_{\text{I}}^{\max}. \end{aligned} \tag{13}$$

Apparently, $C_{1\text{-}2}$ is monotonically increasing with the transmission power of the BS and the UL UE. Meanwhile, the interval of P_{b} and P_{u} under Cond. 1^a, 1^b, 2^a, and 2^c is as follows,

$$P_{\text{b}} \in \begin{cases} \left[\max(P_{\text{b}}^{\text{I1}}, P_{\text{b}}^{\text{I2}}), P_{\text{b}}^{\max}\right] & \text{Cond. } 1^a \text{ and } 1^b \text{ hold;} \\ \left[P_{\text{b}}^{\text{I2}}, \min(P_{\text{b}}^{\text{I1}}, P_{\text{b}}^{\max})\right] & \text{Cond. } 2^a \text{ and } 2^c \text{ hold;} \\ \emptyset, & \text{otherwise.} \end{cases} \tag{14}$$

So, we have

Lemma 2. The optimal power pair $(P_{\text{b}}^{\text{subopt2}}, P_{\text{u}}^{\text{subopt2}})$ for the sub-problem of optimizing $C_{1\text{-}2}$ in Eq. (13) should be

$$\begin{aligned} &(P_{\text{b}}^{\text{subopt2}}, P_{\text{u}}^{\text{subopt2}}) \in \mathscr{P}^2 \\ &= \begin{cases} (P_{\text{b}}^{\max}, P_{\text{u}}^{\max}), & \text{Cond. } 1^a \text{ and } 1^b \text{ hold;} \\ (\min(P_{\text{b}}^{\text{I1}}, P_{\text{b}}^{\max}), P_{\text{u}}^{\max}), & \text{Cond. } 2^a \text{ and } 2^c \text{ hold;} \\ \emptyset, & \text{otherwise,} \end{cases} \end{aligned} \tag{15}$$

where Cond. 1^b and 2^c are given in Table I.

Case 3: $R_{\text{U}} \leq C_{\text{I}}^{\min}$ and $R_{\text{U}} \geq C_{\text{I}}^{\max}$. In this case, it is impossible to perform inter-UE IC before the DL UE decodes information from the BS. Therefore, it is the same

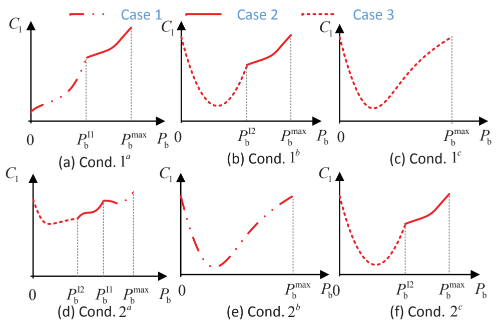


Fig. 4. The variations of C_1 with respect to P_b when P_u is fixed.

as the scenario without inter-UE IC, except that P_b should be in the interval

$$P_\mathrm{b} \in \begin{cases} \left[0, \min(P_\mathrm{b}^{\mathrm{I2}}, P_\mathrm{b}^{\max})\right], \\ \qquad \text{Cond. } 1^b,\ 1^c,\ 2^a,\ \text{and } 2^c \text{ hold;} \\ \emptyset, \qquad\qquad\qquad \text{otherwise,} \end{cases} \tag{16}$$

where Cond. 1^c is given in Table I. Then, following the lines in Theorem 1, we can have the lemma below.

Lemma 3. When $R_\mathrm{U} \leq C_\mathrm{I}^{\min}$ and $R_\mathrm{U} \geq C_\mathrm{I}^{\max}$, the sub-optimal power pair $(P_\mathrm{b}^{\mathrm{subopt3}}, P_\mathrm{u}^{\mathrm{subopt3}})$ satisfies Eq. (8) at the top of Page 3.

In summarization, with the aid of inter-IE IC technique, we can have the following theorem:

Theorem 2. With inter-UE IC technique, the power pair $(P_\mathrm{b}^{\mathrm{opt}}, P_\mathrm{u}^{\mathrm{opt}})$ that achieves the maximum sum rate, should satisfy

$$(P_\mathrm{b}^{\mathrm{opt}}, P_\mathrm{u}^{\mathrm{opt}}) \in \begin{cases} (P_\mathrm{b}^{\max}, P_\mathrm{u}^{\max}), \qquad \text{Cond. } 1^a \text{ holds;} \\ \{(P_\mathrm{b}^{\max}, P_\mathrm{u}^{\max}), (0, P_\mathrm{u}^{\max})\}, \ \text{Cond. } 2^b \text{ holds;} \\ \{(P_\mathrm{b}^{\max}, P_\mathrm{u}^{\max}), (P_\mathrm{b}^{\max}, 0), (0, P_\mathrm{u}^{\max})\}, \\ \qquad \text{Cond. } 1^b,\ 1^c,\ 2^a, \text{and } 2^c \text{ holds.} \end{cases} \tag{17}$$

Proof. Combining the results in Lemma 1, 2, and 3, we have

$$(P_\mathrm{b}^{\mathrm{opt}}, P_\mathrm{u}^{\mathrm{opt}}) \in \bigcup \left(\mathscr{P}^1, \mathscr{P}^2, \mathscr{P}^3\right). \tag{18}$$

Firstly, $P_\mathrm{u}^{\mathrm{opt}}$ possesses binary feature in all cases. Hence, we only need to verify the binary feature for $P_\mathrm{b}^{\mathrm{opt}}$. For Cond. 1^a, we have shown the sum rate increases from 0 to $\min(P_\mathrm{b}^{\mathrm{I1}}, P_\mathrm{b}^{\max})$ in Lemma 1 and keeps increasing from $\min(P_\mathrm{b}^{\mathrm{I1}}, P_\mathrm{b}^{\max})$ to $P_\mathrm{b}^{\max}$ in Lemma 2. Hence, $P_\mathrm{b}^{\mathrm{opt}}$ has binary feature for Cond. 1^a. Similarly, for other conditions, Fig. 4 shows the variations of C_1 with respect to P_b when P_u is fixed. Accordingly, the binary feature of $P_\mathrm{b}^{\mathrm{opt}}$ holds for all conditions. It comes the conclusion. □

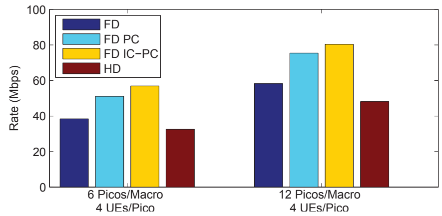


Fig. 5. The performance comparison in multi-cell FD networks with and without IC-enabled power control.

Theorem 2 implies that power control with inter-UE IC still keeps the binary feature. Fig. 2(b) visually demonstrates the binary results with the same configuration scenario as Fig. 2(a). Specifically, for the region where Cond. 1^a holds, the DL UE is closer to the UL UE than the BS, and suffers from strong inter-UE interference Therefore, FD networks without the inter-UE IC technique should fall back to HD mode as depicted in Fig. 2(a). Instead, benefiting from the inter-UE IC technique, FD networks are able to allow the BS and the UL UE simultaneously transmit, so as to obtain higher sum rate as in Fig. 3.

IV. Simulation Results

In this section, we extend our investigation and evaluation to multi-cell FD networks with multiple pairs of UEs, which suffer from more complicated interference problems. We consider non-cochannel heterogeneous networks with macro BSs working in HD mode on one frequency band and pico BSs working in FD mode on another. We set main parameters according to Table II, as specified in 3GPP TR 36.828 [13]. Specifically, the deployment of macro BSs and pico BSs follows the regular way, that is, 7 macro BSs in total are located at vertices or center of a hexagon and pico BSs are randomly scattered in each sector of macro BSs. We drop UEs clustered around pico BSs and select one pair of DL and UL UEs by applying the proportional fairness (PF) method to UL and DL independently. Moreover, we will investigate how the power control schemes (with and without inter-UE IC) in single-cell FD network could contribute to improving the multi-cell performance in terms of system sum rate. Without loss of generality, the baseline HD networks in our simulation is assumed to work in FDD mode, i.e., each transmission direction (UL or DL) uses $1/2$ of the total bandwidth.

As can be observed from Fig. 5, under the assumption of 110 dB SIC capability, positive gain (18%) of FD networks in system sum rate can be available even when no extra power control strategy is used. This is because in FD case, all the bandwidth could be used for both UL and

TABLE II
Main parameters in the system-level simulator, which are compatible with 3GPP TR 36.828 [13].

Category	Sub-Cat	Configuration
TTI		1ms
Bandwidth		Half Duplex: 10 MHz; Full Duplex: 20 MHz
Topology	Macro	500m-ISD at static positions with 3 sectors
	Pico	6 or 12 picos uniformly distribted in 500m-ISD macro's region
	UE	2 or 4 users uniformly distributed in 40m-radius picocell's region
Propagation Model	Pathloss	Table A. 1-3 in 3GPP TR 36.828 [13]
	Shadowing	Pico to UE: 10 dB; UE to UE: 12 dB; Pico to Pico: 6 dB
	Noise Figure	Pico: 13 dB; UE: 9 dB
Transmission Power		Pico: 24 dBm; UE: 23 dBm
SIC Capability		50 dB to 110 dB, 110 dB by default
Cell Range Extension (bias)		6 dB
Proportional Fairness		Window length: 500; Exponent factor: 0.05

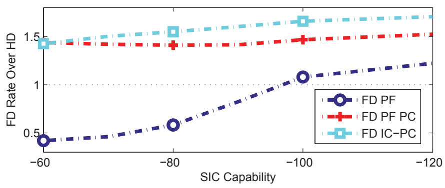


Fig. 6. The rate gain of FD networks over HD networks versus the SIC capability.

DL UEs, so user diversity improves system throughput. Meanwhile, single-cell based pure power control leads to extra 38% rate gain and inter-UE IC could further boost the extra gain to 57%. On the other hand, when the number of pico BSs per macro BS increases from 6 to 12, it also yields an increase in sum rate in both HD networks and FD networks, since it adds to the higher frequency reuse ratio. Meanwhile, inter-UE IC-enabled power control always provides highest sum rate.

Fig. 6 demonstrates FD networks without power control need around 100 dB SIC capabilityto mitigate the negative impact of other kinds of interference, such as the intra-cell inter-UE interference. Moreover, with the aid of power control schemes, FD networks could fall back to HD mode whenever necessary to reap a larger SE at some transmission direction (i.e., UL and DL). Hence, even when the SIC capability is not so effective, FD networks with power control always exhibit performance improvement.

V. Conclusion

In this paper, we first discussed the power control solution for optimizing the sum rate of a user pair in single-cell FD network. We proved a binary feature for the optimal power control results, that is, either both the BS and the UL UE transmit at the maximum power or one of them mutes to achieve the optimal sum rate. Moreover, for scenarios with intra-cell inter-UE IC technique, the binary feature remains valid for power control. Hence, the power control solution simplifies the sum rate-optimization problem with significant computational efficiency improvement. We also verified that the combination of binary power control and intra-cell inter-UE IC technique could significantly contribute to the performance improvement in FD networks, with a 58% sum rate increase in multi-cell scenarios.

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