

Interference Coordination for Small Cell Networks with Full-Duplex Base Stations

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Abstract—In this paper, an inter-cell interference coordination (ICIC) scheme for small cell networks with full-duplex (FD) base stations is proposed to maximize the overall system throughput. To be compatible with existing enhanced ICIC (eICIC) and further enhanced ICIC (FeICIC) techniques, the proposed ICIC scheme adopts cell range expansion and almost blank subframe to coordinate various kinds of interference caused by FD communications. In detail, the novel scheme includes four steps, namely, choosing the serving base station, pairing users for FD communication, resource block allocation, and power control of FD users. Numerical simulation results show that our proposed ICIC scheme can effectively harvest the FD gain for small cell networks.

I. INTRODUCTION

According to the prediction, nearly 50 billion mobile devices will be accessed to the wireless network by 2020, which poses a rigorous challenge to the network capacity improvement. To deal with it, the cellular industry has deployed various small base stations (SBSs) to fully reuse the limited frequency spectrum. On the other hand, the full-duplex (FD) communication technique has also gained growing research interests as a promising means to improve the spectrum efficiency recently [1], [2]. The FD communication can potentially double the wireless link capacity by allowing a device to transmit and receive simultaneously on the same frequency band. However, self-interference which is caused by the FD device itself is the main obstacle to implement the FD communication. Fortunately, with the current advanced analog, digital, and antenna domain interference cancellation techniques [3]–[6], the residual self-interference (RSI) can be mitigated to a sufficiently low level, i.e., up to -110dB, which paves the way for the implementation of the FD communication.

Since self-interference cancellation demands sophisticated circuits, user equipments (UEs) may not have the capability of the FD communication whereas base stations (BSs) could have. Therefore, we consider a three-node model where two UEs, an uplink one and a downlink one, transmit with an FD BS on the same wireless channel simultaneously. In such a system, there still exist many challenges, especially the uplink-to-downlink interference (UDI) that the downlink

UE suffers from the co-channel uplink UE. There have been several recent studies investigating the performance analysis and UDI cancellation in single-cell FD cellular systems. The asymptotic study in [7] shows that the FD communication can improve the system throughput by 80% as compared against the conventional HD communication. Leveraging the stochastic geometry approach, it is analyzed that about 30% of system throughput gain can be achieved by the FD communication in a heterogeneous cellular network [8]. In [9], four distributed UDI cancellation schemes by leveraging the channel state information have been proposed in the scenario of an FD BS with two HD mobile devices. In [10], a sub-optimal user pairing and resource allocation algorithm has been proposed for time-division cellular networks, which maximizes the overall system throughput while guaranteeing users' quality-of-service (QoS). In [11], a joint assignment and fairness maximization algorithm has been developed to solve the problem of uplink/downlink channel pairing and power allocation in consideration of user fairness. Moreover, the energy- and spectral- efficiency tradeoff in single-cell FD cellular networks has been investigated in [12].

The above studies have demonstrated that the FD communication could improve the cellular system throughput of the single-cell scenario to a certain extent. However, it is still an open issue that how much performance gain could be achieved by the FD communication in the multi-cell scenario due to complicated inter-cell interference. In addition to self-interference and UDI, there also exists inter-cell interference from co-channel small cell users. Therefore, in this paper, we further investigate the inter-cell interference coordination in HetNets with FD small cell base stations. We propose a novel full-duplex inter-cell interference coordination (FdICIC) to maximize the minimum throughput of users in a HetNet with FD SBSs. Our proposal consists of four steps: choosing serving BS for each user, pairing users for FD communications, allocating resource block (RB) among MBS and SBSs, and determining the transmit power of each FD user. The effectiveness of our proposed FdICIC scheme is validated by numerical results.

The rest of this paper is organized as follows. In Section 2, the system model is described. The detail procedures of the proposed FdICIC are presented in Section 3. Numerical results are provided in Section 4 and the paper is finally concluded in Section 5.

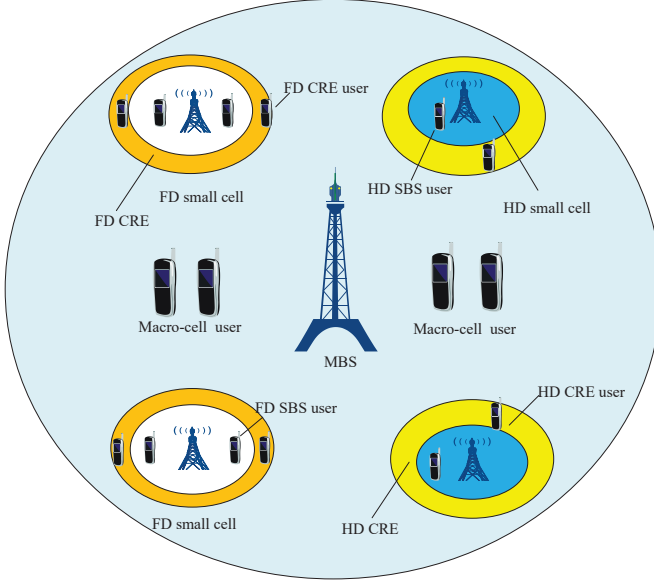


Fig. 1: System model.

II. SYSTEM MODEL

As shown in Fig. 1, the MBS is located at the center of the network to provide coverage and several SBSs are randomly located to offload traffic from the MBS. We further assume that the MBS only works in the HD mode while some SBSs have the ability of the FD communication. There are two kinds of SBSs: SBSs with the FD communication capability, denoted by the set ψ_{SBS}^{FD} , SBSs with the conventional HD communication, denoted by the set ψ_{SBS}^{HD} . User devices are randomly distributed in the network, which can only work in the HD mode due to their hardware limitation and backward compatibility.

In the LTE system, a frame with a bandwidth of W ($W = 20\text{MHz}$) can be divided into K ($K = 100$) RBs, each has f_0 ($f_0 = 180\text{kHz}$) bandwidth and T_0 ($T_0 = 0.5\text{ms}$) time length. We further assume that both uplink and downlink users can utilize the sounding reference signal (SRS) to estimate their channel qualities. Therefore, the MBS and SBSs can know the perfect channel state information (CSI) of all uplink and downlink users.

We denote ϕ_U and ϕ_D as the uplink user set and downlink user set, respectively, and N_i and N_j as the number of RBs occupied by uplink user i and downlink user j , respectively. Therefore, the throughput of each uplink user i and downlink user j in the system can be respectively expressed as

$$T_i^U = N_i f_0 \log_2(1 + SINR_i^U), \quad \forall i \in \phi_U, \quad (1)$$

$$T_j^D = N_j f_0 \log_2(1 + SINR_j^D), \quad \forall j \in \phi_D, \quad (2)$$

where $SINR_i^U$ and $SINR_j^D$ are the signal-to-interference-plus-noise ratio (SINR) of uplink user i and downlink user j , respectively, which can be written as

$$SINR_i^U = \begin{cases} \frac{p_i^U h_i^U}{\sigma_0^2 + p_j^D \eta + \sum_{a \in \psi_{SBS}^{HD}} p_a^U h_a^U + \sum_{b \in \psi_{SBS}^{FD}} p_b^U h_b^U + p_M^U h_M^U}, & \forall i \in \phi_{SBS}^{FD}, \\ \frac{p_i^U h_i^U}{\sigma_0^2 + \sum_{a \in \psi_{SBS}^{HD}} p_a^U h_a^U + \sum_{b \in \psi_{SBS}^{FD}} p_b^U h_b^U + p_M^U h_M^U}, & \forall i \in \phi_{SBS}^{HD}, \\ \frac{p_i^U h_i^U}{\sigma_0^2 + \sum_{a \in \psi_{SBS}^{HD}} p_a^U h_a^U + \sum_{b \in \psi_{SBS}^{FD}} p_b^U h_b^U}, & \forall i \in \phi_{MBS}, \end{cases} \quad (3)$$

$$SINR_j^D = \begin{cases} \frac{p_j^D h_j^D}{\sigma_0^2 + p_i^U h_{i,j}^U + \sum_{a \in \psi_{SBS}^{HD}} p_a^D h_a^D + \sum_{b \in \psi_{SBS}^{FD}} p_b^D h_b^D + p_M^D h_M^D}, & \forall j \in \phi_{SBS}^{FD}, \\ \frac{p_j^D h_j^D}{\sigma_0^2 + \sum_{a \in \psi_{SBS}^{HD}} p_a^D h_a^D + \sum_{b \in \psi_{SBS}^{FD}} p_b^D h_b^D + p_M^D h_M^D}, & \forall j \in \phi_{SBS}^{HD}, \\ \frac{p_j^D h_j^D}{\sigma_0^2 + \sum_{a \in \psi_{SBS}^{HD}} p_a^D h_a^D + \sum_{b \in \psi_{SBS}^{FD}} p_b^D h_b^D}, & \forall j \in \phi_{MBS}. \end{cases} \quad (4)$$

In such a system, there exist five kinds of interference. The first type of interference is self-interference, denoted by $p_j^D \eta$, which is caused by the downlink transmission of the same FD SBS. The second type of interference is co-channel interference, denoted by $p_i^U h_{i,j}^U$, which is caused by the uplink transmission of the same FD SBS. The third type of interference is from adjacent HD small cells, denoted by $\sum_{a \in \psi_{SBS}^{HD}} p_a^D h_a^D$ and $\sum_{a \in \psi_{SBS}^{HD}} p_a^U h_a^U$, respectively. The fourth type of interference is from adjacent FD small cells, denoted by $\sum_{b \in \psi_{SBS}^{FD}} p_b^D h_b^D$ and $\sum_{b \in \psi_{SBS}^{FD}} p_b^U h_b^U$, respectively. The last type of interference is from the macro cell, denoted by $p_M^D h_M^D$ and $p_M^U h_M^U$, respectively. Table 1 summarizes all notations that are used in this paper.

III. THE PROPOSED INTERFERENCE COORDINATION SCHEME

The proposed FdICIC algorithm consists of the following four steps: choosing serving BS, user pairing, RB allocation, and power control.

A. Choosing serving BS

As the first step, it is important to choose the appropriate serving BS for each user. The MBS and each SBS will periodically broadcast reference signals, user i can choose its serving BS by the reference signal received power (RSRP),

TABLE I: NOTATION TABLE

Variables	Meanings
p_i^U	Uplink user transmission power
p_j^D	Downlink user transmission power
η	Residual self-interference power
$h_{i,j}$	Co-channel interference
p_a^U, p_a^D	Uplink and downlink power in HD SBS
h_a^U, h_a^D	Co-channel interference from HD SBSs
p_b^U, p_b^D	Uplink and downlink power in FD SBS
h_b^U, h_b^D	Co-channel interference from FD SBSs
p_M^U, p_M^D	Uplink and downlink power in the MBS
h_M^U, h_M^D	Co-channel interference from the MBS
σ_0^2	Power of the AWGN
h_i^U	Uplink channel gain of user i
h_j^D	Downlink channel gain of user j
$p_{i,k}^U$	Uplink transmit power of user i on RB k
$p_{j,k}^D$	Downlink transmit power of user j on RB k
ψ_{SBS}^{FD}	Set of FD SBSs
ψ_{SBS}^{HD}	Set of HD SBSs
ϕ_{SBS}^{FD}	Set of users in FD SBSs
ϕ_{SBS}^{HD}	Set of users in HD SBSs
ϕ_{MBS}	Set of users in the MBS

denoted as θ_i . To offload more users from the MBS to SBSs, we adopt the CRE technique in this step. The RSRP that user i receives from the MBS, FD SBS, and HD SBS can be denoted as $\theta_{i,MBS}$, $\theta_{i,SBS}^{FD}$, and $\theta_{i,SBS}^{HD}$, respectively. The detailed procedures for choosing the appropriate serving BS can be presented in Algorithm 1.

In Algorithm 1, Δ_{CRE}^{FD} and Δ_{CRE}^{HD} are the CRE biases for FD and HD SBSs, respectively. These values should be carefully determined to maximize the overall system performance, as will be elaborated in Section IV. The main idea of Algorithm 1 is to choose the maximum RSRP for each user i . According to the CRE technique, we should first compare the RSRPs from the MBS, the HD SBS, and the FD SBS, as $\theta_{i,MBS}$, $\theta_{i,SBS}^{FD}$, and $\theta_{i,SBS}^{HD}$, respectively. If the maximum RSRP is $\theta_{i,SBS}^{HD}$ or $\theta_{i,SBS}^{FD}$, then user i will be associated to the HD SBS or the FD SBS. Otherwise, we should compare $\theta_{i,MBS}$, $\theta_{i,SBS}^{FD} + \Delta_{CRE}^{FD}$, and $\theta_{i,SBS}^{HD} + \Delta_{CRE}^{HD}$. If $\theta_{i,MBS}$ is the maximum one, then user i will be associated to the MBS. Otherwise, the maximum RSRP is $\theta_{i,SBS}^{FD} + \Delta_{CRE}^{FD}$ or $\theta_{i,SBS}^{HD} + \Delta_{CRE}^{HD}$, and the user i is FD CRE user (those users are in the CRE area while it is connected to a FD SBS) or HD CRE user (those users are in the CRE area while it is connected to a HD SBS).

B. Suboptimal user pairing

After the serving BS is determined, users in the FD SBSs should be appropriately paired to conduct the FD communication. Here, we assume that each FD SBS independently performs the user pairing to avoid signalling exchange among different SBSs. Therefore, the inter-cell interference is neglected. For the k -th RB, the uplink data rate of user i and downlink data rate of user j can be denoted

Algorithm 1 The algorithm for choosing the serving BS

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1: All users receive RSRP from the MBS and SBSs.
2: If  $\theta_{i,SBS}^{HD} \geq \max\{\theta_{i,MBS}, \theta_{i,SBS}^{FD} + \Delta_{CRE}^{FD}\}$ .
   User  $i$  is HD SBS user.
3: Else if  $\theta_{i,SBS}^{FD} \geq \max\{\theta_{i,MBS}, \theta_{i,SBS}^{HD} + \Delta_{CRE}^{HD}\}$ .
   User  $i$  is FD SBS user.
4: Else
5:    $\theta_i = \max\{\theta_{i,MBS}, \theta_{i,SBS}^{FD} + \Delta_{CRE}^{FD}, \theta_{i,SBS}^{HD} + \Delta_{CRE}^{HD}\}$ .
6:   If  $\theta_i = \theta_{i,SBS}^{FD} + \Delta_{CRE}^{FD}$ .
     User  $i$  is HD CRE user.
7:   Else if  $\theta_i = \theta_{i,SBS}^{HD} + \Delta_{CRE}^{HD}$ .
     User  $i$  is FD CRE user.
8:   Else
     User  $i$  is macro-cell user.
9:   End If
10: End If

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as $R_{i,k}^U$ and $R_{j,k}^D$, respectively, which can be expressed as

$$R_{i,k}^U = \log_2 \left(1 + \frac{p_{i,k}^U h_i^U}{\sigma_0^2 + p_{j,k}^D \eta} \right), \quad (5)$$

$$R_{j,k}^D = \log_2 \left(1 + \frac{p_{j,k}^D h_j^D}{\sigma_0^2 + p_{i,k}^U h_{i,j}} \right). \quad (6)$$

We denote $\gamma_{i,j}$ as the matching factor, that is, $\gamma_{i,j} = 1$ if uplink user i is paired with downlink user j ; $\gamma_{i,j} = 0$ otherwise. In this step, we assume that each user transmits at its maximum power. We will refine the power control procedure in the fourth step. Therefore, the user pairing problem can be formulated as

$$\max \sum_{i \in \phi_U} \sum_{j \in \phi_D} \gamma_{i,j} (R_{i,k}^U + R_{j,k}^D), \quad (7)$$

subject to

$$\gamma_{i,j} \in \{0, 1\}, \quad \forall i, j, \quad (7a)$$

$$p_{i,k}^U = P_{MAX}^U, \quad \forall i, k, \quad (7b)$$

$$p_{j,k}^D = P_{MAX}^D, \quad \forall j, k. \quad (7c)$$

The above optimization problem has only one variable: $\gamma_{i,j}$, which can be solved by the Hungarian algorithm with a polynomial complexity. After user pairing, those unpaired users may transmit in the conventional HD mode.

C. RB allocation

After choosing the serving BS and pairing the FD users, all users can be classified into five categories: macro-cell users, FD SBS users, HD SBS users, FD CRE users, and HD CRE users.

There are two objectives for the RB allocation: maximizing the overall system throughput and ensuring certain fairness among different users. To meet both objectives simultaneously, we utilize the NBS for the optimization criterion, which has been widely used to achieve good balance between individual fairness and global performance.

To formulate the NBS-based optimization problem, we shall first define the utility function for each user.

We first treat all CRE users as a whole, denoted as ϕ_{CRE} . Let l denote the number of RBs for the whole CRE users and Q_l denote the minimum number of RBs for the whole CRE users, as

$$Q_l = \sum_{i \in \phi_{CRE}} \frac{B_{\min}}{f_0 R_i}, \quad \forall i, \quad (8)$$

where $B_{\min}$ denotes the QoS requirement of user i ($B_{\min}$ is either $B_{\min}^U$ or $B_{\min}^D$), R_i denotes the data rate of user i that transmits at the maximum power. Therefore, the utility gain of CRE users can be defined as

$$z^W = l - Q_l, \quad (9)$$

which denotes the additional number of RBs those users can occupy.

We denote the FD user pair set and the HD user set as ϕ_M and ϕ_J , respectively, the minimum number of RBs to satisfy the QoS of the FD user pair m and the HD user j as Q_m^F and Q_j^H , respectively, and the data rates that transmit at the maximum power of FD user pair m and HD user j as R_m^U , R_m^D and R_j , respectively. In a similar way, we can have

$$Q_m^F = \max\left\{\frac{B_{\min}^U}{f_0 R_m^U}, \frac{B_{\min}^D}{f_0 R_m^D}\right\}, \quad \forall m \in \phi_M, \quad (10)$$

$$Q_j^H = \frac{B_{\min}}{f_0 R_j}, \quad \forall j \in \phi_J. \quad (11)$$

Moreover, the numbers of RBs allocated to the FD user m and the HD user j can be denoted by β_m and ϕ_j , respectively. Therefore, the utility gain of the FD user m can be expressed as

$$z_m^F = \beta_m - Q_m^F. \quad (12)$$

Similarly, the utility gain of the HD user j can be defined as

$$z_j^H = \phi_j - Q_j^H. \quad (13)$$

Based on the definition of NBS, we can formulate the optimization problem as

$$z^{NBS} = \max_{\{l, \beta, \phi\}} z^W \prod_{m=1}^M z_m^F \prod_{j=1}^J z_j^H, \quad (14)$$

$$\text{subject to} \quad \sum_{m=1}^M \beta_m + \sum_{j=1}^J \phi_j + l = K, \quad (14a)$$

$$\beta_m \geq Q_m^F, \quad \forall m \in \phi_M, \quad (14b)$$

$$\phi_j \geq Q_j^H, \quad \forall j \in \phi_J, \quad (14c)$$

$$l \geq Q_l. \quad (14d)$$

where M and J are the numbers of FD users and HD users, respectively. The above problem can be solved in closed-

form, as presented in the following theorem.

Theorem 1 The optimal RB allocation of l , β , and ϕ can be expressed as

$$l^* = \frac{K + (M + J)Q_l - \sum_{j=1}^J Q_j^H - \sum_{m=1}^M Q_m^F}{M + J + 1}, \quad (15)$$

$$\beta_m^* = \frac{1}{M + J + 1} \left(K - Q_l - \sum_{m=1}^M Q_m^F - \sum_{j=1}^J Q_j^H \right) + Q_m^F, \quad (16)$$

$$\phi_j^* = \frac{1}{M + J + 1} \left(K - Q_l - \sum_{m=1}^M Q_m^F - \sum_{j=1}^J Q_j^H \right) + Q_j^H. \quad (17)$$

According to Theorem 1, the optimal RB allocation for each FD user and HD user has been obtained. Meanwhile, the whole number of RBs allocated to all CRE users has also been determined as l^* . By using the same method, the optimal number of RBs allocated for each CRE user can also be calculated as

$$\beta_{m, CRE}^* = \frac{1}{M_0 + J_0} \left(l^* - \sum_{m=1}^{M_0} Q_m^F - \sum_{j=1}^{J_0} Q_j^H \right) + Q_m^F, \quad (18)$$

$$\phi_{j, CRE}^* = \frac{1}{M_0 + J_0} \left(l^* - \sum_{m=1}^{M_0} Q_m^F - \sum_{j=1}^{J_0} Q_j^H \right) + Q_j^H, \quad (19)$$

where M_0 and J_0 are the numbers of FD CRE users and HD CRE users, respectively.

D. Optimal power control

After the above three steps, the inter-cell interference can be effectively mitigated due to orthogonal RB allocation. However, the co-channel interference between the user pair within the same FD cell still exists.

We now need to determine the optimal transmit power of the uplink and downlink users. All users in the HD mode can transmit at the maximum power, P_{MAX} (P_{MAX} is either P_{MAX}^U or P_{MAX}^D). The optimization problem can be formulated as

$$\max_{(p_{i,k}^U, p_{j,k}^D)} \sum_{k=1}^{N_{i,j}} f_0 (R_{i,k}^U + R_{j,k}^D), \quad (20)$$

subject to

$$\sum_{k=1}^{N_{i,j}} p_{i,k}^U \leq P_{MAX}^U, \quad \forall i, k, \quad (20a)$$

$$\sum_{k=1}^{N_{i,j}} p_{j,k}^D \leq P_{MAX}^D, \quad \forall j, k, \quad (20b)$$

$$\sum_{k=1}^{N_{i,j}} f_0 R_{i,k}^U \geq B_{\min}^U, \quad \forall i, k, \quad (20c)$$

$$\sum_{k=1}^{N_{i,j}} f_0 R_{j,k}^D \geq B_{\min}^D, \quad \forall j, k. \quad (20d)$$

$$(p_{i,k}^{U*}, p_{j,k}^{D*}) = \begin{cases} \arg \max_{(p_{i,k}^U, p_{j,k}^D) \in \psi_1} f(p_{i,k}^U, p_{j,k}^D), & \text{if } \frac{P_{MAX}^U h_i^U}{\sigma_0^2 + P_{MAX}^D \eta} \leq \xi_{i,\min}^U, \\ \arg \max_{(p_{i,k}^U, p_{j,k}^D) \in \psi_2} f(p_{i,k}^U, p_{j,k}^D), & \text{if } \frac{P_{MAX}^U h_i^U}{\sigma_0^2 + P_{MAX}^D \eta} > \xi_{i,\min}^U, \frac{P_{MAX}^D h_j^D}{\sigma_0^2 + P_{MAX}^U h_{i,j}} \leq \xi_{j,\min}^D, \\ \arg \max_{(p_{i,k}^U, p_{j,k}^D) \in \psi_3} f(p_{i,k}^U, p_{j,k}^D), & \text{if } \frac{P_{MAX}^U h_i^U}{\sigma_0^2 + P_{MAX}^D \eta} > \xi_{i,\min}^U, \frac{P_{MAX}^D h_j^D}{\sigma_0^2 + P_{MAX}^U h_{i,j}} > \xi_{j,\min}^D, \end{cases} \quad (21)$$

In the above, $N_{i,j}$ is the number of RBs that the FD user pair (i, j) occupies.

We can see that power allocation for each RB k can be determined independently. There are only two variables need to be optimized in the above problem, i.e., $p_{i,k}^U$ and $p_{j,k}^D$. Therefore, the optimal power allocation for FD user pair $(p_{i,k}^{U*}, p_{j,k}^{D*})$ can be found by following a similar method in [13]. The optimal power solution $(p_{i,k}^{U*}, p_{j,k}^{D*})$ must lay in the boundary of the admissible power area, which can be expressed as (21), where

$$\begin{cases} \psi_1 = \{(P_{MAX}^U, P_1), (P_{MAX}^U, P_2)\}, \\ \psi_2 = \{(P_3, P_{MAX}^D), (P_4, P_{MAX}^D)\}, \\ \psi_3 = \{(P_{MAX}^U, P_1), (P_4, P_{MAX}^D), (P_{MAX}^U, P_{MAX}^D)\}, \\ P_1 = \frac{(P_{MAX}^U h_{i,j} + \sigma_0^2) \xi_{j,\min}^D}{h_j^D}, \\ P_2 = \frac{(P_{MAX}^U h_i^U - \xi_{i,\min}^U \sigma_0^2)}{\xi_{i,\min}^U \eta}, \\ P_3 = \frac{(P_{MAX}^D h_j^D - \xi_{j,\min}^D \sigma_0^2)}{\xi_{j,\min}^D h_{i,j}}, \\ P_4 = \frac{(P_{MAX}^D \eta + \sigma_0^2) \xi_{i,\min}^U}{h_i^U}. \end{cases} \quad (22)$$

IV. NUMERICAL RESULTS

In this section, we will present numerical results for the proposed FdICIC. We consider the MBS is located at the center and four SBSs are uniformly distributed around the MBS. Among them, F ($F \in \{0, 1, 2, 3, 4\}$) SBSs are working in the FD mode while H ($H = 4 - F$) SBSs are working in the traditional HD mode. We further assume there are A users randomly located in the system. The user density in small cell coverage is twice higher than that in the macro cell coverage. The major simulation parameters are summarized in Table 2.

Fig. 2 depicts the overall system throughput for different RSI powers. It can be observed from the figure that the RSI power has a great impact on the performance of the proposed FdICIC. That is, the overall system throughput decreases as the RSI power increases. When the RSI power is too large, the FD communication even has a worse performance than the HD communication. Therefore, the self-interference cancellation is essential for the practical implementation of the FD communications. Our simulation results show that the FD communication can improve the system throughput by about 10% - 20% with four FD SBSs when the RSI

TABLE II: SIMULATION PARAMETERS

Parameter	Value
The macro cell radius	0.5 km
The small cell radius	0.1 km
Noise spectral density	-174 dBm/Hz
Path loss between users and MBS	$128.1 + 37.6 \log(d(\text{km}))$
Path loss between users and SBS	$140.7 + 36.7 \log(d(\text{km}))$
Path loss between users	$148 + 40 \log(d(\text{km}))$
The number of RBs, K	100
Bandwidth, W	20 MHz
Shadowing standard deviation	10 dB
Time slot length, T	0.5ms
Max Tx power, P_{MAX}^U, P_{MAX}^D	24 dBm
Tx power of the MBS	43 dBm
Tx power of the SBS	33 dBm

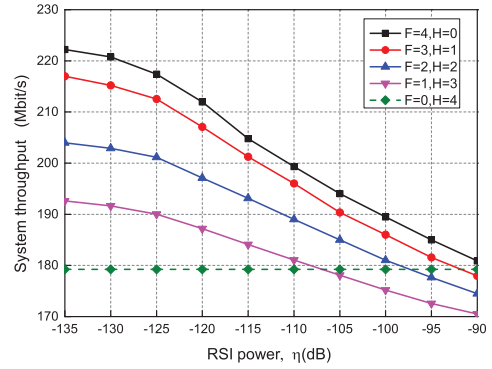


Fig. 2: System throughput of different F and H . CRE=15dB. $A=60$. $B_{\min}^U = B_{\min}^D = 0.2 \text{ Mbit/s}$.

power is -130dB to -110dB. From the figure, it can be also observed that the system throughput can be improved as more SBSs are capable of the FD communication.

Fig. 3 shows the system throughput versus the CRE bias. As the CRE increases, the overall system throughput first increases and then decreases. The reason can be explained as follows. When the CRE bias is small, increasing CRE can offload more users from the MBS to SBSs to increase the throughput. Also, more users can potentially work in the FD communication mode, leading to more FD gains. However, when the CRE bias is already large enough, increasing CRE would cause more interference from the MBS to CRE users. From our study, it is rather important to determine the optimal CRE bias for given RSI power and the number of

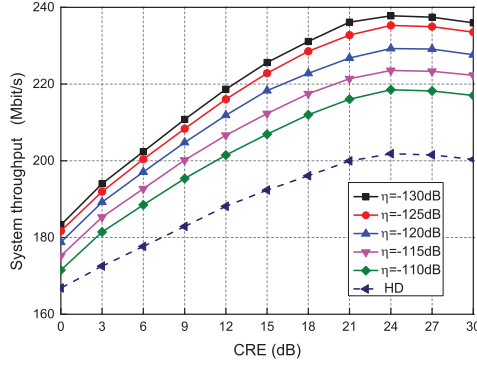


Fig. 3: System throughput of different CRE. $F=4$. $A=60$.
 $B_{\min}^U = B_{\min}^D = 0.1\text{Mbit/s}$.

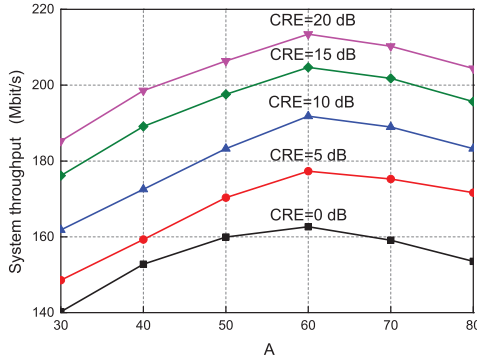


Fig. 4: System throughput of different A . $F=4$. $\eta=-130\text{dB}$.
 $B_{\min}^U = B_{\min}^D = 0.3\text{Mbit/s}$.

FD SBSs, which could be an important future direction of this work.

Fig. 4 illustrates the overall system throughput for different user numbers, A . It is interesting that the overall system throughput first increases and then decreases with the user number. When A is small, increasing it can bring about more multi-user diversity gain and FD gain, i.e., more users can be paired to transmit in the FD mode. However, when A is large enough, more RBs should be assigned to those users with bad channel quality to guarantee their minimum data rate requirements, resulting in the degradation of the overall system throughput. This result suggests that it is important for the admission control to admit an appropriate number of users for system throughput maximization.

V. CONCLUSION

In this paper, we aim to propose the FdICIC scheme for heterogeneous small cell networks with FD communication enabled SBSs. Our objective is to maximize the minimum throughput of users by coordinating various types of interference, including self-interference, inter-cell interference,

and UDI. The novel FdICIC scheme includes four steps. First, each user is properly associated to the MBS, FD SBS, or HD SBS based on the optimized CRE biases. Then, users in FD SBSs are carefully paired to perform the FD communication according to a proposed approach based on the Hungarian algorithm. After that, the RB resources are allocated to each user to maximize the system performance while guaranteeing the QoS requirement by solving an NBS based optimization problem. Finally, a closed-form power control expression is derived to determine the optimal transmit power of each user working in the FD mode. Our extensive simulation results demonstrate that significant system throughput gain can be obtained by utilizing the FD SBS with the proposed FdICIC scheme.

REFERENCE

- [1] D. Kim, H. Lee, and D. Hong, "A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2017 - 2046, 4th quarter, 2015.
- [2] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637 - 1652, Sep. 2014.
- [3] T. Riihonen, S. Werner, and R. Wichman, "Residual self-interference in full-duplex MIMO relays after null-space projection and cancellation," in *Proc. Asilomar Conf. Signals, Syst. Comput.*, 2010, pp. 653-657.
- [4] B. Day, A. Margetts, D. Bliss, and P. Schniter, "Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range," *IEEE Trans. Signal Process.*, vol. 60, no. 7, pp. 3702-3713, Jul. 2012.
- [5] E. Everett, A. Sahai, and A. Sabharwal, "Passive self-interference suppression for full-duplex infrastructure nodes," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 680-694, Feb. 2014.
- [6] S. Goyal, P. Liu, S. Panwar, R. Difazio, R. Yang, and E. Bala, "Full duplex cellular systems: Will doubling interference prevent doubling capacity?" *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 121 - 127, May 2015.
- [7] X. Xie and X. Zhang, "Does full-duplex double the capacity of wireless networks?" *IEEE INFOCOM*, pp. 253 - 261, Apr. 2014.
- [8] J. Lee and T. Quek, "Hybrid full-/half-duplex system analysis in heterogeneous wireless networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 5, pp. 2883 - 2895, May 2015.
- [9] J. Bai and A. Sabharwal, "Distributed full-duplex via wireless side-channels: Bounds and protocols," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 4162 - 4173, Aug. 2012.
- [10] D. Wen and G. Yu, "Time-division cellular networks with full-duplex base stations," *IEEE Commun. Lett.*, vol. 20, no. 2, pp. 392 - 395, Feb. 2016.
- [11] J. M. B. da Silva, G. Fodor, and C. Fischione, "Spectral efficient and fair user pairing for full-duplex communication in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 16, pp. 7578 - 7593, Nov. 2016.
- [12] D. Wen, G. Yu, R. Li, Y. Chen, and G. Y. Li, "Results on energy- and spectral- efficiency tradeoff in cellular networks with full-duplex enabled base stations," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1 - 14, Mar. 2017.
- [13] D. Feng, L. Lu, Y. Wu, G. Li, G. Feng, and S. Li, "Device-to-device communications underlying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541 - 3551, Aug. 2013.