Duplex Mode Selection and Channel Allocation for Full-Duplex Cognitive Femtocell Networks

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Abstract—**In this paper, we investigate the problem of incorporating full-duplex (FD) transmission in cognitive femtocell networks (CFN) to achieve higher spectrum utilization. We aim to maximize the sum rate of a full-duplex cognitive femtocell network (FDCFN) as well as guaranteeing the quality of service (QoS) of users in the form of a required signal to interference plus noise ratios (SINR). We propose a duplex mode selection strategy based on stable roommate matching, as well as a greedy channel allocation algorithm with a proven performance bound. Numerical results show that the proposed schemes effectively improve the sum rate of the FDCFN.**

I. INTRODUCTION

The femtocell technology has been recognized as a key technology by Qualcomm for meeting the 1000x data challenge, i.e., the predicted astounding 1000x increase in mobile data in the near future [1]. However, due to the current spectrum scarcity problem, femtocells are more likely to operate on the same spectrum band with the existing macrocells, resulting in cross-tier interference (between femtocells and macrocells) and inter-femtocell interference (among femtocells). Interference management is critical for the success of this technology.

The cognitive femtocell network (CFN) is proposed as a solution to the interference problem [2], [3]. In general, the macrocell users (MU) are regarded as primary users (PU) and the femtocell users (FU) are regarded as secondary users (SU); the FBS's periodically senses the spectrum usage of MUs and allocates the unoccupied channels to FUs. The previous research works aim to improve the performance (such as throughput, capacity, energy efficiency, etc.) of CFN as well as guaranteeing the QoS of both MUs and FUs. In [4], [5], spectrum and power allocation in a CFN is formulated as optimization problems, with the objectives to maximize capacity and energy efficiency, respectively. In [6], a strategic game model was introduced by setting the payoff of a femtocell as the expected number of resource blocks (RB) without interference. With this mechanism, each femtocell makes rational decisions on the spectrum usage pattern and the interference between femtocells is mitigated. Another game theoretic mode was proposed in [7], where the penalty of a femtocell is determined by excessive usage of RBs and transmission power. The femtocells are thus discouraged to occupy excessive RBs and transmit with high power, resulting in mitigated interference.

With the recent development of self-interference suppression technology, a wireless transceiver is able to simultaneously transmit and receive signals on the same channel, yielding a full-duplex (FD) transmission pattern [8]. In [9], an FD OFDMA based multi-cell network was analyzed, where the FD empowered BS simultaneously serves two cellular users on the same channel. Despite the presence of inter-cell and intra-cell interference, the results show that the capacity can be enhanced by 86% in the uplink and 99% in the downlink.

The successful use of FD in cellular networks motivates us to integrate this technology into the CFN. This is a more challenging case due to the more complicate interference scenarios. Similar to the cellular network, an FBS in the CFN can simultaneously serve a pair of FUs on the same channel, resulting in improved spectrum utilization. However, due to the limited processing capability and battery capacity of mobile devices, self-interference suppression may not be applicable to femtocell user equipments (FUE). For the two FUEs using the same channel, the uplink signal of one FUE causes interference to the downlink of the other. To control such intra-femtocell interference, it is necessary to carefully pair the FUs for FD transmission. When the intra-femtocell interference is strong, half-duplex (HD) would be a better choice. Therefore, the duplex mode selection strategy and channel allocation should be carefully designed to mitigate intra-femtocell interference and achieve high capacity.

In this paper, we consider a CFN integrated with FD functionality. In such a full-duplex cognitive femtocell network (FDCFN), we aim to maximize the sum rate of FUs as well as guaranteeing the QoS of both FUs and MUs in the form of a minimum SINR requirement. The goals are achieved through duplex mode selection and channel allocation. The main contributions of this paper are summarized as follows.

- We incorporate the FD and CR techniques into femtocell networks, and formulate the duplex mode selection and channel allocation problem in an FDCFN.
- We propose a duplex mode selection strategy for FDCFN. The FUE pairing is formulated as a roommate matching problem, and we develop an effective algorithm to solve the matching problem. Duplex mode selection is based on pairing results to achieve high capacity gains.
- We propose a greedy channel allocation algorithm for the FDCFN based on pairing results and derive a performance lower bound.
- The proposed schemes are evaluated with simulations and comparison with several benchmark schemes, where su-

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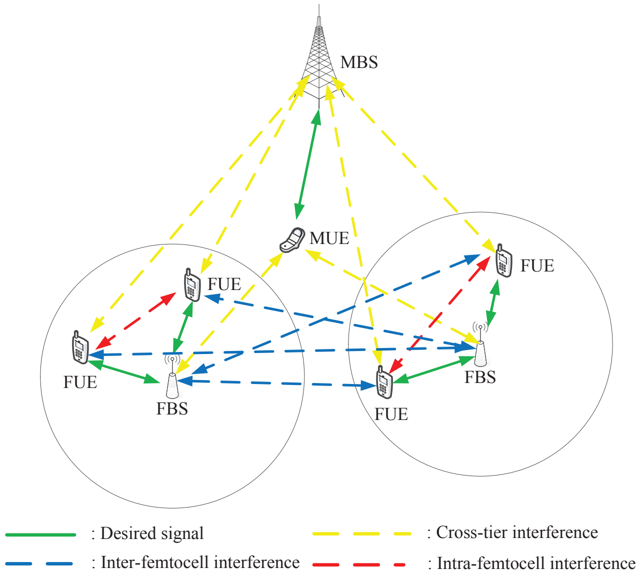

Fig. 1. The system model for a full-duplex cognitive femtocell network.

perior performance of the proposed schemes is observed.

The remainder of this paper is organized as follows. The problem formulation is described in Section II. The proposed duplex mode selection strategy is discussed in Section III and a greedy channel allocation algorithm is presented in Section IV. The performance evaluation is presented in Section V and Section VI concludes this paper.

II. PROBLEM FORMULATION

We consider a CFN with one MBS and F femtocells, as shown in Fig. 1. The FUs are treated as SUs while the MUs as PUs. All the femtocells operate on the same spectrum band as the macrocell, and both the macrocell and femtocells are based on OFDMA, where a channel consists of several subcarriers with bandwidth W. Without loss of generality, we assume that only the FBS's can operate in the FD mode, while the FUEs cannot. The macrocell adopts frequency division duplexing (FDD), i.e., the MBS assigns two channels for an MUE for uplink and downlink transmissions, respectively.

A. SINR Analysis

Let binary variables $a^u_{f,i}(n)$, $a^d_{f,i}(n) \in \{0,1\}$ be the channel allocation indicators: $a^u_{f,i}(n), a^d_{f,i}(n) = 1$ indicates that channel n is allocated to FUE i in femtocell f for uplink and downlink transmissions, respectively; and $a^u_{f,i}(n), a^d_{f,i}(n) = 0$ otherwise. The transmit powers of the FUEs and FBS's on each channel are denoted as p_u and p_d, respectively. Due to lack of space, we do not consider power control in this paper, and thus p_u and p_d are assumed to be constant.

Let $\gamma_{MUE}(n)$ denote the received SINR of an MUE on channel n, which is given by

$$\gamma_{MUE}(n) = \frac{p_b H_{b,m}(n)}{I_f(n) + N_0}, \tag{1}$$

where p_b is the MBS transmit power on the channel, $H_{b,m}(n)$ is the channel gain between the MBS and the MUE on channel n, and N_0 is the noise power. Let π_f be the set of FUEs in femtocell f. Let $H^u_{f,i,m}(n)$ be the channel gain between FUE i in femtocell f and MUE m on channel n, $H^d_{f,i,m}(n)$ the channel gain between FBS f and MUE m on channel n (when transmitting to FUE i). Denote $I_f(n)$ as the interference caused by all the femtocell transmissions on channel n, which can be expressed as

$$I_f(n) = \sum_{f=1}^{F}\sum_{i\in\pi_f}\{a^u_{f,i}(n)p_u H^u_{f,i,m}(n) + a^d_{f,i}(n)p_d H^d_{f,i,m}(n)\}. \tag{2}$$

Similarly, let p_m be the transmit power of the MUE. Assuming channel reciprocity, the SINR at the MBS on channel n, denoted as $\gamma_{MBS}(n)$, is given by

$$\gamma_{MBS}(n) = \frac{p_m H_{b,m}(n)}{I_f(n) + N_0}. \tag{3}$$

As shown in Fig. 1, there are three types of interference in an FDCFN, namely the cross-tier interference, inter-femtocell interference, and intra-femtocell interference. The SINR at FUE i in femtocell f on channel n is given by

$$\gamma^{FUE}_{f,i}(n) = \frac{p_d H^d_{f,i}(n)}{I_{of}(n) + I_{ff}(n) + I_{pf}(n) + N_0}, \tag{4}$$

where $H^d_{f,i}(n)$ is channel gain between FUE i and FBS f on channel n. $I_{of}(n)$ is the interference caused by FUEs and FBS's in other femtocells operating on channel n, which can be derived as

$$I_{of}(n) = \sum_{k=1,k\neq f}^{F}\ \sum_{l\in\pi_k}\{a^u_{k,l}(n)p_u H^u_{f,i,k,l}(n) + \\ a^d_{k,l}(n)p_d H^d_{f,i,k}(n)\}, \tag{5}$$

where $H^u_{f,i,k,l}(n)$ is the channel gain between FUE l in femtocell k and FUE i in femtocell f on channel n, and $H^d_{f,i,k}(n)$ is the channel gain between FBS k and FUE i in femtocell f on channel n. Denote $I_{ff}(n)$ as the intra-femtocell interference caused by FUE j to FUE i. Assuming that FUE j and FUE i are paired to operate in the FD mode, $I_{ff}(n)$ can be written as

$$I_{ff}(n) = a^u_{f,j}(n)p_u H_{f,i,j}(n), \tag{6}$$

where $H_{f,i,j}$ is the channel gain between FUE i and FUE j on channel n. $I_{pf}(n)$ is the cross-tier interference caused by the MUE or MBS using channel n, which can be written as

$$I_{pf}(n) = p_m H^u_{f,i,m}(n) \quad \text{or} \quad I_{pf}(n) = p_b H^u_{f,i,b}(n), \tag{7}$$

where $H^u_{f,i,m}$ and $H^u_{f,i,b}$ are the channel gains between FUE i in femtocell f and MUE m, and the MBS on channel n, respectively.

The SINR at FBS f on channel n is given by

$$\gamma^{FBS}_{f,i}(n) = \frac{p_u H^u_{f,i}(n)}{I_{of}(n) + I_{sf}(n) + I_{pf}(n) + N_0}. \tag{8}$$

$I_{sf}(n)$ is the residual self-interference on channel n at the FBS. Here, the self-interference suppression coefficient $0 <$

$\kappa < 1$ is defined as the ratio of residual self-interference power to the original self-interference power. $I_{sf}(n)$ is given as

$$I_{sf}(n) = \kappa \cdot p_d. \tag{9}$$

B. Sum Rate Maximization

Based on the SINR analysis, the sums of the achievable rates for the uplink and downlink are given by

$$\begin{cases} \mathcal{C}_{FUE} = \sum_{f=1}^{F} \sum_{n=1}^{N} a_{f,i}^{d}(n) W \log_2(1 + \gamma_{f,i}^{FUE}(n)), \\ \mathcal{C}_{FBS} = \sum_{f=1}^{F} \sum_{n=1}^{N} a_{f,i}^{u}(n) W \log_2(1 + \gamma_{f,i}^{FBS}(n)), \end{cases}$$

respectively. We then formulate the sum rate maximization problem for the FD cognitive femtocell network as follows.

$$\underset{\{a_{f,i}^{u}(n), a_{f,i}^{d}(n)\}}{\arg\max} \quad \{\mathcal{C}_{FBS} + \mathcal{C}_{FUE}\} \tag{10}$$

subject to:

$$\gamma_{MUE}(n) \geq \Gamma_1, \gamma_{MBS}(n) \geq \Gamma_1, \ \forall\, n, \tag{11}$$

$$\gamma_{f,i}^{FUE}(n) \geq \Gamma_2, \gamma_{f,i}^{FBS}(n) \geq \Gamma_2, \ \forall\, n, f, i \in \pi_f, \tag{12}$$

$$a_{f,i}^{u}(n) + a_{f,j}^{u}(n) \leq 1, \ \forall\, n, f, i, j \in \pi_f, \tag{13}$$

$$a_{f,i}^{d}(n) + a_{f,j}^{d}(n) \leq 1, \ \forall\, n, f, i, j \in \pi_f, \tag{14}$$

$$a_{f,i}^{u}(n) + a_{f,j}^{d}(n) \leq 2, \ \forall\, n, f, \forall\, i, j \in \pi_f. \tag{15}$$

In (11) and (12), Γ_1 and Γ_2 are the minimal SINRs to satisfy the QoS requirements of the macrocell and femtocell operations, respectively. Inequalities (13) and (14) are due to the fact that a channel cannot be shared by two FUEs for uplink or downlink transmissions. Inequality (15) is because in the best case, a channel can be shared by two FUs: one FU uses the channel for uplink transmission and the other FU uses the channel for downlink transmission.

III. DUPLEX MODE SELECTION AND FUE PAIRING

To achieve FD transmission, an FBS needs to schedule a pair of FUEs to simultaneously operate on the same channel: with one FUE using the channel for uplink transmission and the other FUE using the channel for downlink transmission [9]. Although the FBS can adopt effective self-interference cancellation, the intra-femtocell interference caused by the uplink of one FUE to the downlink of the other FUE remains a critical problem. Under some circumstances, such intra-femtocell interference can severely degrade the QoS of the FUs. As a result of the low data rates, the FD mode would be inefficient compared to the traditional HD mode.

To fully harvest the potential of FD transmission in the presence of intra-femtocell interference, a desirable approach is to schedule two FUs who are relatively far from each other to use the same channel. With multiple FUEs in a femtocell, it is necessary to design a pairing strategy to find a pair of FUEs for FD transmissions. From the perspective of an FUE, there are preferred and undesired FUEs, since pairing with different FUEs results in different interference and QoS. This observation motivates us to use stable roommate matching to characterize the FUE pairing problem [10].

In the stable roommate matching problem, we consider a group of people who wish to find a satisfactory roommate. Each person has a preference list selected from all other people in the group. The preference list indicates the willingness of a person to choose other people as roommate. Then, a stable matching is defined as follows [10].

Definition 1: In a stable matching, there is no such pair of people who are not matched as roommates, while both of them prefer each other to their current partners. In other words, there is no such a pair of people that both of them have a better choice than their current partners.

By definition, a stable matching offers a desirable pairing strategy for a group of people. In our model, we regard each FUE in a femtocell as a person to pick another person in the same femtocell as roommate. The preference list of an FUE is determined by the level of interference caused by other FUEs. We then employ the effective algorithm proposed in [10] to solve the matching problem, and use the pairing result to select the duplex mode for the FUEs. The proposed FUE paring strategy consists of three stages, which are described in the following. The proofs are omitted due to lack of space.

A. First Stage

First, each FUE establishes its preference list according to the interference power received from other FUEs. To implement this procedure, all FUEs send out pilot signals using a specific time slot. Then, the FUEs identify and measure the signal powers from other FUEs. Afterwards, each FUE sorts the other FUEs in descending order of the received powers and insert them into the preference list in the same order.

Initially, each FUE proposes to other FUEs following the order of the preference list. When an FUE i receives a proposal from another FUE j, the following strategy is adopted.

- FUE i rejects FUE j if it already holds a better proposal from another FUE.
- FUE i holds FUE j for consideration if FUE j is better than the one that it currently holds. Then, FUE i rejects the FUE that it currently holds.

An FUE stops to propose until a promise of consideration is received. If it receives a rejection, it will continue to propose to other FUEs following the order of its preference list.

The propose and reject actions terminate when either of these two conditions are satisfied.

- Every FUE holds a proposal.
- One FUE has been rejected by every other FUE.

In the second case, every FUE but the rejected FUE holds a proposal. This is because they all rejected him as they already have a better choice. Then, the following lemma can be applied to reduce the preference lists of the FUEs.

Lemma 1: If FUE i rejects FUE j in the proposal sequence described above, then FUE i and FUE j cannot be partners in a stable matching.

From Lemma 1, we derive the following useful corollary.

Corollary 1: At any stage of the proposal process, if FUE i proposes to FUE j, we have that in a stable matching (i) FUE

i cannot have a better partner than FUE j; (ii) FUE j cannot have a worse partner than FUE i.

According to Lemma 1, for the case that one FUE is rejected by everyone else, there is no stable matching exits since this FUE does not have a partner. To deal with this case, we set this FUE to work in the HD mode, i.e. it does not pair with any other FUEs for FD transmission. Then, the reduced problem can be solved as earlier discussed. With every FUE holds a proposal, the following corollary is derived to reduce the preference lists.

Corollary 2: The preference list of FUE i, who holds a proposal from FUE j, can be reduced by deleting

- All those to whom FUE i prefers FUE j;
- All those who hold a proposal from a person whom they prefer to FUE i (including all those who have rejected FUE i).

The purpose of reducing the preference lists is based on the following lemma.

Lemma 2: If the preference list of every FUE contains just one FUE, then the lists specify a stable matching.

Although the preference lists are reduced in the first stage, some lists may still contain more than one person. This brings us to the second stage of the algorithm.

B. Second Stage

In the second stage, we further reduce the preference lists until each FUE holds only one proposal. The key is to find a cyclic sequence and initiate more rejections based on the sequence. We can prove that, with such rejections, a stable matching can be achieved.

An *all-or-nothing* cyclic sequence is defined as follows.

Definition 2: Let $\{a_1, \cdots, a_r\}$ be a set of FUEs satisfying the following conditions.

- For $i = 1, \cdots, r-1$, the second person in a_i's current reduced preference list is the first person in a_{i+1}'s, denote this person as b_{i+1};
- The second person in a_r's current reduced preference list is the first in a_1's, denote this person as b_1.

Then, we adopt the algorithm presented in Algorithm 1 to find an all-or-nothing cyclic sequence. With the all-or-nothing sequence, we force each b_i to reject the proposal from a_i. Thus, each a_i turns to propose to b_{i+1}, the second favored FUE for a_i. With these rejections and proposals, all successors (those who rank after) of a_i can be deleted from the list of b_{i+1}, and b_{i+1} can be deleted from their lists. We continue the search of all-or-nothing circles and force rejections until each FUE holds only one proposal. However, whether these rejections cause instability to a stable matching remains uncertain. Next, we show that the rejections within an all-or-nothing circle would not cause instability to a matching that derived from reduced preference lists.

In a stable matching, if every FUE is partnered by someone on its reduced list, we say that such a matching is *contained* in the reduced lists. We first present the following lemma.

Algorithm 1: Find an All-or-Nothing Cyclic Sequence

```
do
    Let $p_1$ be an arbitrary FUE with preference list contains more than one FUE ;
    do
        $q_i \leftarrow$ the second FUE in $p_i$'s current list ;
        $p_{i+1} \leftarrow$ the last person on $q_i$'s current list (so that $q_i$ is the first in $p_{i+1}$'s list) ;
    while (the p sequence is not cyclic);
while (there is at least one FUE whose perference list contains more than one FUE);
Denote $p_s$ as the first element in the $p$ sequence to be repeated, $r = s - 1$ ;
for $i = 1 : r$ do
    $a_i = p_{s+i-1}$ ;
end
Then $\{a_1, \cdots, a_r\}$ is an all-or-nothing sequence ;
```

Lemma 3: Let $\{a_1, \cdots, a_r\}$ be an all-or-nothing circle, and b_i be the first person in a_i's reduced list, $1 \le i \le r$. Then, in any stable matching contained in these reduced lists, either a_i and b_i are partners for all values of i or for no value of i.

To show that the rejection within an all-or-nothing circle does not cause instability to a stable matching matching contained in the reduced lists, we need to consider the case that a_i and b_i are partners for all values of i in the circle.

Lemma 4: Let $\mathcal{A} = \{a_1, \cdots, a_r\}$ and $\mathcal{B} = \{b_1, \cdots, b_r\}$. Suppose M is a stable matching contained in the reduced lists, with a_i and b_i as partners for all $1 \le i \le r$. Denote M' as the matching in which each a_i is partnered by b_{i+1}, and any FUE not in $\mathcal{A} \cup \mathcal{B}$ has the same partner as in M. Then, M' is stable.

Lemma 4 demonstrates that the rejections and proposals introduced in Stage 2 maintain the stability of a matching contained in reduced lists. Thus, we can find a stable matching by adopting the procedure described earlier in Stage 2.

C. Third Stage

Based on the matching results, we determine the FD/HD mode selection for the FUEs in Stage 3. Note that, the mode selection discussed in this part is regarded as an initial solution that does not consider the effect of inter-femtocell interference and cross-tier interference. The duplex modes may be refined due to inter-femtocell and cross-tier interferences in the greedy channel allocation algorithm described in Section IV.

For two paired FUEs, denoted as FUE 1 and FUE 2, let H_{11} and H_{22} be the channel gains between the FBS and the two FUEs, respectively, and H_{12} the channel gain between the two FUEs. The sum capacity of this pair of users with FD and HD modes can be derived as in (16). For each FUE pair, we compare the sum capacities of FD and HD as given in (16). We then select the duplex mode that achieves a higher capacity for the pair of FUEs.

IV. GREEDY CHANNEL ALLOCATION ALGORITHM

The formulated channel allocation problem in (10)–(15) is an integer programming problem. Solving it through exhaus-

$$\begin{cases} \mathcal{C}(FD)=\log_2\left(1+\frac{p_dH_{11}}{p_uH_{12}+N_0}\right)+\log_2\left(1+\frac{p_dH_{22}}{p_uH_{12}+N_0}\right)+\log_2\left(1+\frac{p_uH_{11}}{p_d\kappa+N_0}\right)+\log_2\left(1+\frac{p_uH_{22}}{p_d\kappa+N_0}\right) \\ \mathcal{C}(HD)=\frac{1}{2}\left\{\log_2\left(1+\frac{p_dH_{11}}{N_0}\right)+\log_2\left(1+\frac{p_dH_{22}}{N_0}\right)+\log_2\left(1+\frac{p_uH_{11}}{N_0}\right)+\log_2\left(1+\frac{p_uH_{22}}{N_0}\right)\right\}. \end{cases} \tag{16}$$

Algorithm 2: Greedy Channel Allocation Algorithm

```
Initialize: $\eta(n)=\emptyset$ , $\varepsilon(n)=\{1,2,\cdots,s,\cdots\}$, $a_{s'}(n)=0$, for all $s',n$ ;
for $n=1:N$ do
    while $(\varepsilon(n)\neq\emptyset)$ & $(\Delta(\eta(n)+s,\eta(n))>0)$ do
        $s'\leftarrow\arg\max_{s\in\varepsilon(n)}\{\Delta(\eta(n)+s,\eta(n))\}$ ;
        Suppose $a_{s'}(n)=1$ ;
        Update SINRs of MUs and FUs ;
        if (the SINR requirements of MUs and FUs are satisfied) then
            Set $a_{s'}(n)=1$ ;
            $\eta(n)\leftarrow\eta(n)+s',\varepsilon(n)\leftarrow\varepsilon(n)-s'$ ;
        else
            if ($s'$ is in the FD mode) then
                $s''_{\min}\leftarrow\arg\min_{s'(u),s'(d)}\{\Delta(\eta(n)+s'(u),\eta(n)),\Delta(\eta(n)+s'(d),\eta(n))\}$ ;
                $s''_{\max}\leftarrow\arg\max_{s'(u),s'(d)}\{\Delta(\eta(n)+s'(u),\eta(n)),\Delta(\eta(n)+s'(d),\eta(n))\}$ ;
                Set $a_{s''_{\min}}(n)=0$ ;
                Update SINRs of MUs and FUs ;
                if (the SINR requirements of MUs and FUs are satisfied) then
                    $\varepsilon(n)\leftarrow\varepsilon(n)-s',\varepsilon(n)\leftarrow\varepsilon(n)+s''_{\max}$ ;
                else
                    Set $a_{s''_{\max}}(n)=0$ ;
                    $\varepsilon(n)\leftarrow\varepsilon(n)-s'$ ;
                end
            else
                $a_{s'}(n)=0$ ;
                $\varepsilon(n)\leftarrow\varepsilon(n)-s'$ ;
            end
        end
    end
end
```

tive search incurs prohibitive high complexity. In this section, we propose a greedy algorithm to allocate channels to FBS-FUE links. First, for each femtocell, we select the link with maximal capacity, and denote $\{1,2,\cdots,s,\cdots\}$ as the set of selected links. If link s is in the FD mode, we denote $s(u)$ and $s(d)$ as the paired uplink and downlink that compose link s. Denote $\eta(n)$ as the set of FBS-FUE links that are allocated with channel n, $\varepsilon(n)$ as the set of links that are not allocated with channel n. Let $R(\eta(n)+s)$ and $R(\eta(n))$ be the sum rates of link sets $\eta(n)+s$ and $\eta(n)$ operate on channel n, respectively. Then, we define $\Delta(\eta(n)+s,\eta(n))=R(\eta(n)+s)-R(\eta(n))$. Thus $\Delta(\eta(n)+s,\eta(n))$ is the increment of objective value by allocating channel n to link s.

The procedure of the greedy channel allocation algorithm is given in Algorithm 2. For each channel, the FBS-FUE link that achieves the largest performance gain is chosen. If allocating the channel to such a link does not result in violation of the QoS requirements for all FUs and MUs, the channel is allocated to the link and we continue to search the link with the largest performance gain in the remaining links. If the allocation violates the QoS requirement of an MU or FU, we consider two cases depending on the duplex mode of the link. If the link is in the HD mode, the link cannot access the channel. If the link is in the FD mode, we first compare the performance gains of the two links that form the FD link, and forbidden the one with the lower gain to access the channel. Then, we update the SINRs of FUs and MUs. If the QoS requirements are satisfied, we move to the next round to find the link with the largest capacity gain. If the QoS requirements are not satisfied, both links that form the FD link cannot access the channel. This process terminates when all the links are examined or the allocation cannot achieve a positive performance gain.

Let G_I be the interference graph for the femtocell network: each link is represented as a vertex and there is an edge between two vertices when the two links cannot simultaneously utilize the same channel due to inter-femtocell interference. We can derive a lower performance bound for the proposed greedy channel allocation algorithm, which is summarized in the following theorem.

Theorem 1: The objective value achieved by the greedy channel allocation algorithm is at least $\frac{1}{1+D_{\max}}$ of the global optimum, where $D_{\max}$ is the maximum node degree in the interference graph G_I.

V. SIMULATION STUDY

In this section, we validate the performances of the proposed duplex mode selection strategy and channel allocation algorithm with Matlab simulations. We consider a macrocell overlaid with multiple femtocells, as shown in Fig. 1, and evaluate the sum rate of all the femtocells. The radii of the macrocell and a femtocell are 500 m and 20 m, respectively. We consider a total bandwidth of 4 MHz that are divided into 160 channels. The transmit power of the MBS is set as 35 dBm, while the transmit power of the MUEs has five levels ranging from 10 dBm to 30 dBm according to the distance between the MUE and MBS. The transmit power of an FBS and an FUE on each channel is set to 10 dBm. The noise power spectrum density is assumed to be -174 dBm/Hz. We employ the ITU path loss model for both indoor and outdoor environments [12]. All channels experience Rayleigh fading. The self-interference cancellation coefficient κ is set to 0.1.

We first present the performance of the proposed duplex mode selection strategy in Figs. 2 and 3. In Fig. 2, we compare with three alternative schemes: (i) all FD with the proposed pairing strategy, (ii) all FD with a random pairing strategy, and (iii) all HD. In the first scheme, all pairs of FUEs that are matched with the proposed strategy adopt FD transmission. In the second scheme, FUEs are randomly paired, and all the paired FUEs adopt FD transmission. In the third scheme,

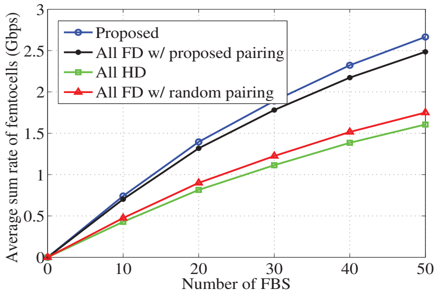

Fig. 2. Average sum capacity versus the number of FBS under different duplex modes. The average number of FUE is five.

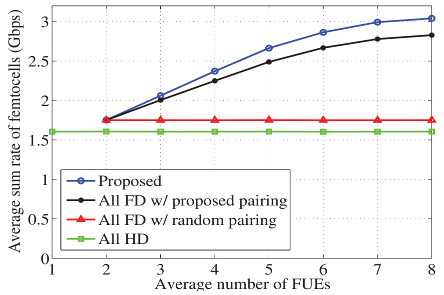

Fig. 3. Average sum capacity versus the average number of FUEs under different duplex modes. The number of FBS is 50.

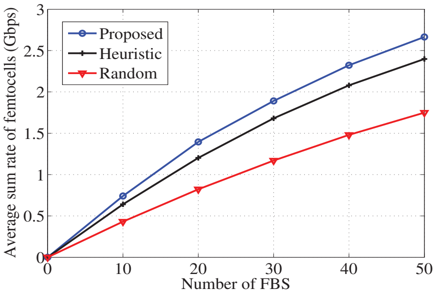

Fig. 4. Average sum capacity versus the number of FBS's under different channel allocation schemes.

all FUEs adopt HD transmission. It can be observed that the FD transmission achieves higher sum rates than HD transmission due to the improved spectrum utilization. The proposed scheme achieves better performance than the all FD and all HD schemes, since we dynamically adjust the duplex mode for each pair of FUEs by choosing the mode that offers a higher rate. It can also be observed that the pairing strategy based on stable roommate matching outperforms the random pairing strategy, indicating that the stable matching provides a relatively better solution by pairing the FUEs with small interference to each other.

In Fig. 3, we compared the performances under different numbers of FUEs. With the same reasons discussed above, the proposed scheme outperforms all the other schemes. With random pairing strategy, the performance of FD transmission is only slightly better than the HD transmission, since the intra-femtocell interference degrades the data rates of FUEs. Actually, if the self-interference cancellation coefficient κ is larger or the size of femtocell is smaller, the performance of FD with random pairing can be even worse than HD transmission. The FD transmission with proposed pairing strategy achieves better performance than the one with random pairing, since the intra-femtocell interference is mitigated by properly pairing the FUEs for FD transmission. As the average number of FUE increases, the performance gain of the proposed pairing strategy becomes significant, since more pairs of FUEs benefit from the reduced intra-femtocell interference.

Fig. 4 compares the performance of different channel allocation schemes. We employ a heuristic algorithm with the idea proposed in [13] as a benchmark. In this heuristic algorithm, the FBS-FUE link that causes the smallest interference to the MUE or MBS on a channel is firstly chosen to access to the channel, and such process is continued until the QoS requirement of an MU or FU is violated. For the random allocation scheme, we randomly choose an FBS-FUE link at each step until the QoS requirement of an MU or FU is violated. It can be seen that the proposed scheme outperforms the other two schemes, since the links with higher channel gains are always firstly chosen, and whenever the QoS requirements are not satisfied, we continue to search for the link with the maximal gain among the other possible links.

VI. CONCLUSION

In this paper, we investigated the problem of duplex mode selection and channel allocation for FDCFNs. We employed stable roommate matching to model the FUE pairing problem, and proposed a duplex selection strategy based on the pairing result. We also developed a greedy algorithm for channel allocation and derive a performance bound. The proposed algorithms are validated with simulations.

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