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Fractional Frequency Donation for Cognitive Interference Management among Femtocells

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***Abstract*— In this paper, we propose a cognitive interference management approach, called fractional frequency donation, to alleviate co-channel interference among selfish femtocells. In such networks, our approach allows each femtocell to access all available bands but requires good femtocells with high throughput to "donate" some bands to poor ones. When the donors and the corresponding donated bands are properly selected, both good performance on average- and 5% edge-throughputs can be achieved. Simulation results show that in femtocell networks, the proposed fractional frequency donation approach is more suitable than the conventional fractional frequency reuse ones.**

***Index Terms*— Femtocells, interference management, selfish spectrum access, cognitive radio, spectrum sensing.**

I. Introduction

Femtocell is one of the most competitive candidates for future mobile systems since it can provide high-speed indoor wireless access with low-cost infrastructure [1]. Different from conventional cellular BSs, whose locations and frequency bands are carefully planned to avoid *co-channel interference* (CCI), femtocell BSs are randomly deployed and may inevitably work in the same frequency bands. This incurs severe CCI not only between femtocells and macrocells, i.e., two-tier interference, but also among femtocells, i.e., inter-cell interference. Thus, *interference management* (IM) is critical for femtocell networks [2].

Recently, there are lots of contributions on IM in femtocell networks. Comprehensive overviews have been provided in [3][4], including power control [5] and frequency assignment [6]. More recently, cognitive radio techniques have been introduced into femtocells in [7][8], where macrocells and femtocells are regarded as primary and secondary systems, respectively. The performance of femtocells is enhanced by spectrum sensing and sharing techniques.

Most of the above contributions minimize the power consumption or maximize the number of simultaneous communication links for a given constant throughput at each femtocell. However, it is more desirable to maximize each femtocell's throughput because they are located inside private houses/apartments and maintained by subscribers. It is reasonable for femtocells to work in a selfish manner, i.e., using all available resources, such as transmit power, frequency bands, and time slots, to maximize their own throughputs.

In this paper, we will propose a cognitive IM approach called *fractional frequency donation* (FFD) to alleviate CCI among femtocells when each femtocell intends to access all available frequency bands by *selfish frequency access* (SFA). Here, the available bands can be obtained from either a neighbor list or a spectrum database when cellular or TV white bands are used*, respectively. In principle, FFD manages CCI by asking the good femtocells† to "donate" some available bands to the poor ones. Then the throughput of the poor femtocells can be significantly improved due to less CCI on the donated bands. Furthermore, FFD encourages those poor femtocells to allocate more power on the donated bands while less on the un-donated ones. As a result, CCI on the un-donated bands can be reduced, which compensates throughput loss of the good femtocells. Therefore, FFD can provide both high average-throughput and good edge-throughput.

The rest of this paper is organized as follows. In Section II, we present system setup. In Section III, we first introduce SFA and then propose FFD to deal with CCI. Consequently, in Section IV, we develop a proactive spectrum sensing algorithm for donated band identification in FFD. In Section V, we first determine the FFD parameters through simulation and then compare its performance with some existing methods. Finally, we conclude the paper in Section VI.

II. System Setup

As shown in Fig. 1, we consider a network consisting of a macro *base station* (BS) (or a TV tower) and N femtocells, where all femtocells are inside the coverage of the macro BS (or the TV tower) and have the same available frequency

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*TV white bands are the unused TV bands, which are also considered for femtocells, e.g., FARAMIR project in Europe [9].

†Throughout this paper, good and poor femtocells represent the femtocells with high and low throughput, which are determined by their locations in femtocell networks.

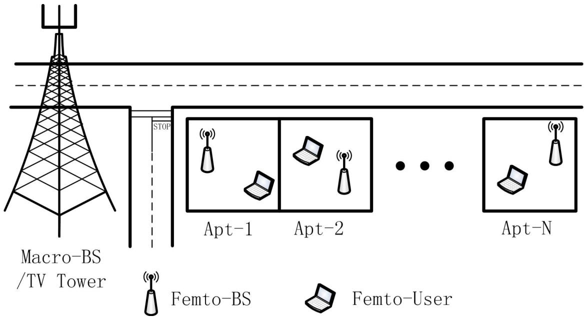

Fig. 1. Femtocell system setup.

bands. No backhaul is available between any BSs. Before accessing the network, each femtocell inquiries a neighbor list to find unused frequency bands when a macro BS is considered, or checks a spectrum database to find TV white bands when a TV tower is considered. Here, both the neighbor list and the spectrum database are assumed to be error free. Consequently, the femtocells will cause no interference to the users in the macrocell or the TV tower.

In Fig. 1, N apartments with the size of $a \times a$ square meters (m^2) are built along with the road, where each apartment has a Femto BS and an active Femto user[‡]. Downlink closed-access is considered, where femtocells are installed for private use and only serve the registered users. Let g_{ij} denote the channel gain from Femto BS i to Femto user j. It consists of large scale path-loss g_{ij}^{pl} and small scale fading g_{ij}^{fd}, i.e.,

$$g_{ij} = g_{ij}^{pl} g_{ij}^{fd}, \quad 1 \le i \le N, 1 \le j \le N, \tag{1}$$

where $i = j$ indicates transmission channel inside an apartment and $i \neq j$ is for interference channel between two apartments. In our scenario, small scale fading follows independent Rayleigh distribution while large scale path-loss follows "ITU-R p1238" channel model [10], i.e.,

$$g_{ij}^{pl}(dB) = 20\log_{10} f_c + 10\varsigma\log_{10}(d) + L_{f_c}(n) + 28, \tag{2}$$

where f_c represents the carrier frequency, ς is the path loss coefficient, d is the distance between a Femto BS and a Femto user, and $L_{f_c}(n)$ is the floor penetration loss factor.

Let $\vec{P}_i = [p_i(1), p_i(2), \ldots, p_i(f), \ldots, p_i(F)]^T$ denote a transmit power vector at Femto BS i, where $p_i(f)$ is the power allocated on the fth frequency band, $1 \le f \le F$, F is the number of available bands, and $[\cdot]^T$ denotes transpose operation. Then the throughput of Femtocell i can be obtained from Shannon's Law as follows,

$$T_i = \sum_{f=1}^{F} \log_2\left(1 + \frac{g_{ii}(f)p_i(f)}{p_n + \sum_{j=1,i\neq j}^{N} g_{ij}(f)p_j(f)}\right), \tag{3}$$

where p_n denotes the noise power at Femto users.

[‡]This paper is to develop the basic idea of FFD. Thus, for simplicity, we assume one active user in each femtocell to avoid scheduling in multiple user cases.

III. Fractional Frequency Donation

We will first introduce SFA to greedily use all available resources, including transmit power and frequency band. This enables some femtocells to achieve high throughput when they are in good locations with less CCI. However, for the rest of femtocells, SFA may cause severe CCI when they are in bad locations. To deal with the issue, we will propose FFD to alleviate CCI. It first finds proper femtocells as donors and then identifies proper bands to donate. In particular, for the band identification, both interference from and to existing femtocells needs to be sensed distributively. Thus, it will need a proactive spectrum sensing method obtaining the bands to be donated, which will be developed in Section IV.

A. Selfish Frequency Access

Denote P_m as the maximum transmit power, then the throughput at each femtocell can be maximized by

$$J_i = \max_{\vec{P}_i}\{T_i\}, \tag{4}$$

$$= \max_{\vec{P}_i}\left\{\sum_{f=1}^{F}\log_2\left(1+\frac{g_{ii}(f)p_i(f)}{p_n+\sum_{j=1,i\neq j}^{N} g_{ij}(f)p_j(f)}\right)\right\} \tag{5}$$

$$\text{s.t.} \quad \sum_{f=1}^{F} p_i(f) \le P_m, p_i(f) \ge 0, \tag{6}$$

where $1 \le i \le N$ and no IM is considered. According to [11], the power allocation to maximize the individual throughput can be obtained by a water filling solution, i.e.,

$$p_i(f) = \left[\frac{1}{v_*} - \frac{p_n + \sum_{j=1,i\neq j}^{N} g_{ij}(f)p_j(f)}{g_{ii}(f)p_i(f)}\right]^+ \text{for } 1 \le f \le F, \tag{7}$$

where $1/v_*$ represents the "water-level". From (7), the maximum individual throughput can be achieved by accessing all available frequency bands with water filling power allocation, which is called *selfish frequency access*.

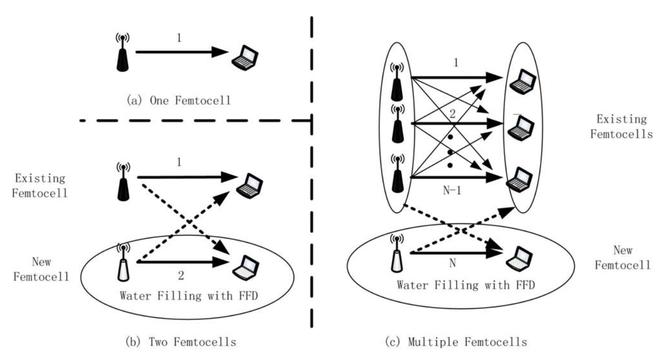

Fig. 2. Selfish frequency access.

Obviously, SFA is optimal when there is only one femtocell as shown in Fig. 2-(a). As the number of femtocells grows, the new femtocell's admission will result in CCI, including interference both from and to existing femtocells as shown in Fig. 2-(b). In this case, the power allocation and the corresponding performance of different femtocells interact with each other. As a result, iteration algorithm is required [2], which takes time to converge to good performance. However, it may not be suitable for femtocell networks with a dynamic topology due to turning on of unexpected Femto BSs. Furthermore, its convergence is not guaranteed and may lead to failure of iteration algorithms.

In fact, when SFA in (7) is applied, the iteration is unnecessary. As shown in Fig. 2-(b) again, the existing femtocell performs water filling power allocation across all available bands while a new one intends to access the same available bands as well. In this case, CCI can be managed by designing only the new femtocell rather than both. This is because the existing femtocell is able to automatically adjust its power allocation when interference power changes. Similarly, for the multiple femtocell case in Fig. 2-(c), all existing femtocells can be regarded as one. Then it reduces to the two femtocell case. As a result, CCI can be managed without iteration, where each femtocell manages the interference with the existing ones when it turns on as a new one. Once accessed to the network with data transmission, the femtocell becomes an existing one and does not need to manage the interference caused by other new femtocells. Next, we will propose FFD for the interference management of each new femtocell.

B. Frequency Donation

In SFA, high throughput can be achieved for the good femtocells, but they bring severe CCI to the poor ones. Then the overall system performance is considerably degraded by a high outage probability. FFD is to reduce the CCI by asking good femtocells to "donate" some frequency bands to the poor ones. When the denoted bands have less value to the good ones but much value to the poor ones, the throughput of the poor femtocells can be significantly improved with minor performance loss of the good ones. In particular, FFD encourages the poor femtocells to allocate more power on the donated bands and less power on the un-donated ones. This alleviates the CCI of the good femtocells as well and high average-throughput can still be obtained.

To realize FFD, we need to first find proper donors, i.e., the femtocells with high throughput, and then identify proper frequency bands to donate. In practice, the channel gain from Femto BS i to Femto user i on the fth bands, i.e., $g_{ii}(f)$, can be obtained by channel estimation. The noise power plus interference power, i.e., $p_n + \sum_{j=1,i\neq j}^{N} g_{ij}(f)p_j(f)$, can be measured at each Femto user. Then the equivalent channel gain on the fth band can be expressed as

$$\tilde{g}_{ii}(f) = \frac{g_{ii}(f)}{p_n + \sum_{j=1,i\neq j}^{N} g_{ij}(f)p_j(f)}. \tag{8}$$

Take an average on (8), we have

$$G_{ii} = \frac{1}{F}\sum_{f=1}^{F} \tilde{g}_{ii}(f). \tag{9}$$

If the average equivalent channel gain is above a threshold η, i.e., $G_{ii} > \eta$, then the femtocell is selected as a donor. Otherwise, it is not.

Next, we identify proper bands for donation. In principle, two kinds of interference will be considered in band identification, interference from and to the existing femtocells. If a donor receives strong interference from others on a certain frequency band, then the band is called *polluted band* and can be regarded as a candidate for donation. On the other hand, if a donor generates severe interference to others through a certain frequency band, then the band is called *polluting band* and can also be regarded as a candidate for donation. Thus, FFD can be realized by asking donors to perform SFA without using polluted, polluting, or both bands. In the following section, we will develop a method to identify polluted and polluting bands.

IV. Polluted and Polluting Band Identification

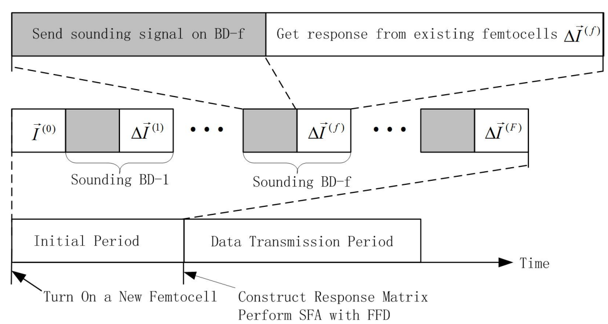

Fig. 3. Frame structure for polluted and polluting band identification.

Polluted and polluting bands reflect the interference from and to the existing femtocells, respectively. Conventional spectrum sensing [12] can only obtain the interference from the existing femtocells since no backhaul is available among femtocells. In order to obtain both interference, proactive spectrum sensing [13] is required. In proactive spectrum sensing, before accessing frequency bands, a new femtocell first transmits some sounding signals and then gets both interference information by observing the response of the existing femtocells. Here, the response refers to the transmit power variation of the existing femtocells, caused by the sounding signals and measured by the new Femto user.

Fig. 3 provides a frame structure to obtain polluted and polluting bands. Before SFA for data transmission, an initial period is needed, composed of an initial interference measurement slot and F sounding slots. In the initial interference measurement slot, the new Femto user gets the interference power $\vec{I}^{(0)}$ from existing femtocells. In each sounding slot, the new Femto BS first sends a sounding signal and then the new Femto user observes the interference power variation of the existing Femto BSs, i.e., $\Delta\vec{I}^{(f)}$. After F sounding slots, a response matrix can be constructed by $\Delta\vec{I}^{(f)}, 1 \leq f \leq F$, which contains interference information both from and to the existing femtocells. In the following, we will first obtain the response matrix during the initial period in Fig. 3 and then identify polluted and polluting bands, respectively. Finally, we will summarize the proposed FFD in the third subsection.

A. Obtain Response Matrix

The response matrix is measured at the new Femto user and represents interference power variation caused by sounding signals. Before sounding, the initial interference power, i.e., $\vec{I}^{(0)}$, is measured as a baseline. Then the power variation can be calculated by comparing the interference power before and after sounding.

1) Before Sounding: Even through we develop our method in a two femtocell case as in Fig 2-(b) for simplicity, it can be directly applied to the case of multiple femtocells. In Fig. 2-(b), before the new femtocell's turning on, there is only one existing femtocell and then its channel gain becomes

$$\tilde{g}_{11}^{(0)}(f) = \frac{g_{11(f)}}{p_n}. \quad (10)$$

When using SFA in (7), the transmit power of the existing Femto BS can be expressed as

$$p^{(0)}(f) = \left[\frac{1}{v_*^{(0)}} - \frac{1}{\tilde{g}_{11}^{(0)}(f)}\right]^+, \quad (11)$$

where $1/v_*^{(0)}$ denotes the "water level" before the new femtocell's sounding. In particular, $v_*^{(0)}$ can be obtained by

$$v_*^{(0)} = \frac{L'}{1 + \sum_{f\in\Omega}\left(\frac{1}{\tilde{g}_{11}^{(0)}(f)}\right)}, \quad (12)$$

where Ω is an index set of L' positive power.

Based on (11), the interference power measured by the new Femto user can be expressed as

$$\vec{I}^{(0)} = [g_{12}(1)p^{(0)}(1),\ g_{12}(2)p^{(0)}(2),\ \ldots,\ g_{12}(F)p^{(0)}(F)]^T, \quad (13)$$

where $g_{12}(f)$ represents the interference channel gain from the existing Femto BS to the new Femto user.

2) After Sounding: In the lth sounding slot, the new Femto BS will send a sounding signal, i.e.,

$$\vec{X}_l = [x(1),\ x(2),\ \ldots,\ x(f),\ \ldots,\ x(F)]^T, \quad (14)$$

where

$$x(f) = \begin{cases} 0, & f \neq l, \\ P_m, & f = l. \end{cases} \quad (15)$$

It will cause interference to the existing Femto user. Then the equivalent channel gain[§] on the lth frequency band varies from (10) to (16), i.e.,

$$\tilde{g}_{11}^{(l)}(f) = \frac{g_{11}(f)}{p_n + g_{21}(f)x(f)}, \quad (16)$$

where $g_{21}(f)$ indicates the channel gain from the new Femto BS to the existing Femto user.

[§]Here, the equivalent channel gain refers to the channel gain of the existing femtocell considering the interference power from the new femtocell and its own noise power.

The existing Femto BS will automatically adjust its power allocation based on the new channel gain in (16). From (12) and (16), we can obtain

$$\frac{1}{v_*^{(l)}} \geq \frac{1}{v_*^{(0)}}, \quad (17)$$

where $1/v_*^{(l)}$ represents the new "water level" in the lth sounding slot. This shows that the sounding signal actually raises the "water level" of the existing Femto BS's power allocation. Then the power allocated to any band $f \neq l$ grows whereas the power allocated to the band $f = l$ decreases, i.e.,

$$\begin{cases} p^{(l)}(f) \geq p^{(0)}(f), & f \neq l, \\ p^{(0)}(f) \leq p^{(0)}(f), & f = l. \end{cases} \quad (18)$$

Similar to (13), the interference power from the existing femtocells in the lth sounding slot can be expressed as

$$\vec{I}^{(l)} = [g_{12}(1)p^{(l)}(1),\ g_{12}(2)p^{(l)}(2),\ \ldots,\ g_{12}(F)p^{(l)}(F)]^T. \quad (19)$$

From (19) and (13), the interference power variation corresponding to the lth sounding slot can be obtained by

$$\Delta\vec{I}^{(l)} = [\vec{I}^{(l)} - \vec{I}^{(0)}]. \quad (20)$$

After F sounding slots, the response matrix can be constructed as follows,

$$\Delta\mathbf{I} = [\Delta\vec{I}^{(1)},\ \Delta\vec{I}^{(2)},\ \ldots,\ \Delta\vec{I}^{(l)},\ \ldots,\ \Delta I^{(F)}]_{F\times F}. \quad (21)$$

B. Identify Polluted and Polluting Bands

From (13), (19), and (21), the response matrix can be expanded as

$$\Delta\mathbf{I} = \begin{bmatrix} g(1)\Delta p^{(1)}(1) & \ldots & g(1)\Delta p^{(F)}(1) \\ g(2)\Delta p^{(1)}(2) & g(f)\Delta p^{(l)}(f) & g(2)\Delta p^{(F)}(2) \\ \ldots & \ldots & \ldots \\ g(F)\Delta p^{(1)}(F) & \ldots & g(F)\Delta p^{(F)}(F)) \end{bmatrix}, \quad (22)$$

where $\Delta p^{(l)}(f) = p^{(l)}(f) - p^{(0)}(f)$ and $g(f)$ represents $g_{12}(f)$ for simplicity. In (22), the element of the response matrix is determined by both interference channel gain from the exiting Femto BS to the new Femto user, $g(f)$, and power allocation adjustment of the existing Femto BS, $\Delta p^{(l)}(f)$. The former one reflects interference from the existing Femto BS. If the fth band is with a large value of $g(f)$, $1 \leq f \leq F$, the new Femto user is more likely to receive strong interference on the band and vice versa. Then it should be regarded as a polluted band. Consequently, α polluted bands are the ones with the first α largest interference channel gains. It can be observed from (18) and (22) that the power adjustments $\Delta p^{(l)}(f)$ in each column of the response matrix are identical except for the band $f = l$. Then based on a column in (22), α polluted bands can be obtained by comparing $F - 1$ frequency bands, where $f \neq l$. Since the bands with the non-identical power adjustments are different among columns, then α polluted bands can be obtained from all F frequency bands if considering any two columns.

On the other hand, the latter one, i.e., power allocation

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adjustment of the existing Femto BS, $\Delta p^{(l)}(f)$, reflects interference to the existing Femto user. For a given band, say $f = f^*$, if the power allocation adjustment caused by the lth sounding signal, $\Delta p^{(l)}(f^*)$, is large, the new Femto BS introduces severe interference to the existing Femto user on the sounding band. Then it should be regarded as a polluting band. It is observed from (22) that the interference channel gains $g(f)$ in each row of the response matrix are identical¶. If donating β polluting bands, they will be the bands with the first β largest elements in terms of rows in the response matrix. For the similar reason as before, two rows are required to obtain β polluting bands from all F frequency bands.

In general, it is very complicated to obtain the optimal FFD parameters, such as the numbers for polluted and polluting bands, α, β, and the threshold for donor identification, η. For simplicity, we will obtain them through simulation in the next section.

C. Summary of FFD Realization

Femtocells sequentially access available bands in a turn-on order, where only a new femtocell needs to manage the interference with existing ones. Specifically, when a femtocell turns on, it needs to

1) Get available frequency bands throughput a neighboring list or a spectrum database.
2) Measure the average equivalent channel gain to decide whether it is a donor as in Section III.B.
3) If so, first perform proactive spectrum sensing to obtain polluted and polluting bands as in Section IV and then do SFA but without using the polluted and/or polluting bands as in Section III.A. Otherwise, SFA is directly performed by using all available bands as in Section III.A.

V. Simulation Results

In this section, we will first find optimal FFD parameters through simulation and then compare the proposed FFD with other IM methods. In this example, we consider $N = 8$ apartments (5 m^2), $F = 4$ bands (each with 1 MHz bandwidth), and -105 dBm noise power. For the path loss model, $f_c = 2$ GHz, $\varsigma = 2.8$, and $L(n) = 4$.

A. Select Threshold

Figure 4 shows the 5% edge-throughput versus the threshold, η, for different transmit power, P_m. A polluted and a polluting bands are considered, i.e., $\alpha = 1$ and $\beta = 1$.

From the figure, the 5% edge-throughput in general decreases from about 3.5 Mbps to about 2.0 Mbps as the threshold grows from 10^0 to 10^8. It is reasonable since the larger the threshold is, the fewer the number of donors is, and then the lower the edge-throughput becomes. To achieve the largest 5% edge-throughput, optimal thresholds can be obtained for different transmit power, for example, the optimal threshold is $\eta = 10^4$ for $P_m = 5$ dBm. Furthermore, the optimal threshold reduces from about 10^4 to about 10^2 as the transmit power grows from 0 to 20 dBm. This is because high transmit power raises CCI and needs more donors to alleviate it.

¶Since femtocells are for indoor coverage, we assume static channels with a constant channel gain for both initial and data transmission periods.

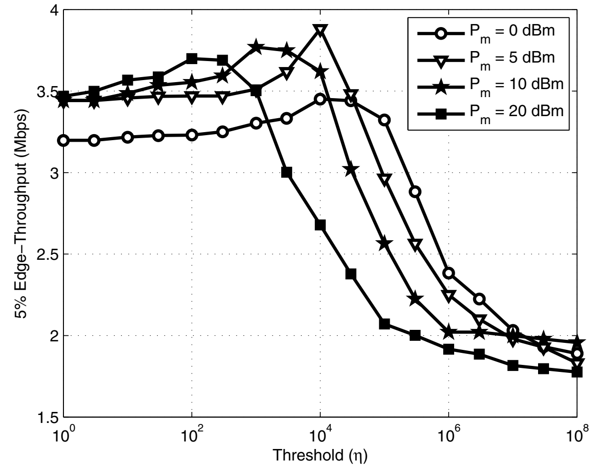

Fig. 4. Threshold selection in different transmit power.

B. Determine the Numbers of Polluted and Polluting Bands

Figure 5 shows the average-throughput versus the 5% edge-throughput, where the ordered pair "(α, β)" represents the numbers of polluted and polluting bands. To guarantee each femtocell accesses at least one band, $\alpha + \beta \leq 3$ needs to be satisfied for $\alpha, \beta \geq 0$. Also, the throughput region between average- and 5% edge-throughput has been provided.

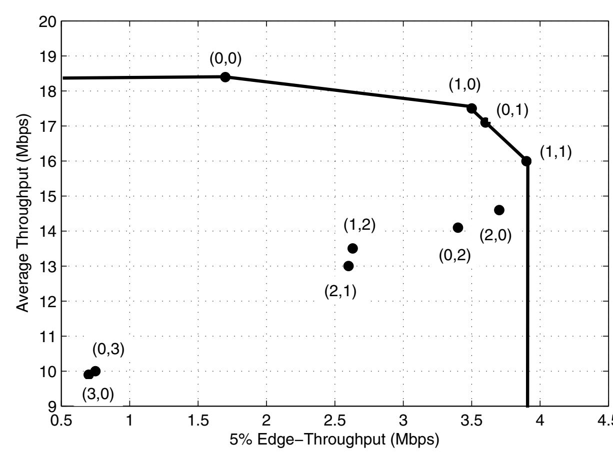

Fig. 5. Average throughput v.s. 5% edge throughput.

From the figure, the highest average-throughput can be achieved when femtocells perform SFA without FFD, i.e., $(0, 0)$, but the edge-throughput is low. When two bands to be donated, i.e., $\alpha + \beta = 2$, donating both polluted and polluting bands, i.e., $(1, 1)$, outperforms donating only polluted or polluting bands, i.e., $(2, 0)$ or $(0, 2)$. Similar results appear when donating three bands, $\alpha + \beta = 3$. Thus, donating both polluted and polluting bands is an effective way to alleviate CCI. Here, the highest 5% edge-throughput can be obtained when $\alpha = 1$ and $\beta = 1$. Furthermore, we plot the throughput region of FFD, which can be used for selecting the proper numbers of polluted and polluting bands in different system requirements.

C. Performance Comparison with Other Methods

Figure 6 compares the performance of the proposed FFD with those of the orthogonal, non-orthogonal, and *fractional frequency reuse* (FFR) methods [14]. Specifically, for the orthogonal method, each femtocells accesses a frequency band with half of the overall time duration. Then four available bands are able to orthogonally serve eight femtocells. In the non-orthogonal method, each femtocell accesses all available bands with equal power allocation, i.e., no IM is considered. In the FFR method, two out of four bands are with the reuse factor of two, where adjacent femtocells are allocated to different bands. The rest two bands are with the reuse factor of one, where all femtocells may access them. If a femtocell's average *signal to interference plus noise ratio* (SINR) is above a threshold, it accesses a band with the reuse factor of one. Otherwise, it accesses the band belonging to its own femtocell. In our simulation, the optimal SINR threshold is searched to obtain the highest 5% edge-throughput.

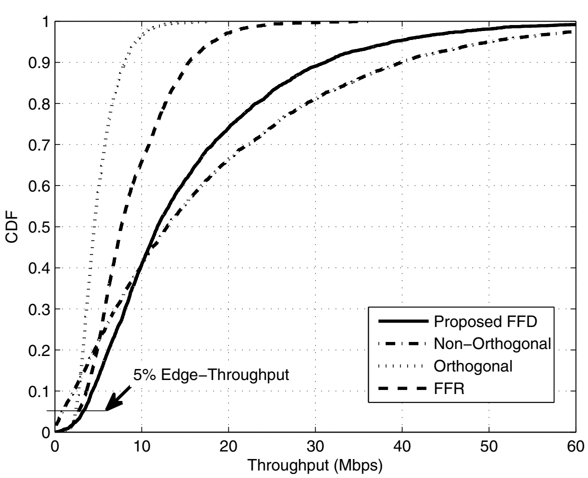

Fig. 6. Performance comparison among different methods.

From the figure, the non-orthogonal method has good performance in high throughput region while the orthogonal one has better performance in low throughput region. The 5% edge-throughputs of the non-orthogonal, orthogonal, FFR, and proposed methods are 0.88 Mbps, 2.4 Mpbs, 2.7 Mbps, and 3.3 Mbps, respectively. While the average-throughput of them are 17.8 Mbps, 5.0 Mbps, 8.9 Mbps, and 15.5 Mbps, respectively. This indicates that the proposed method outperforms the FFR method in all throughput regions. Furthermore, from the perspective of the whole network, FFD can obtain high average-throughput while maintain good edge-throughput. Thus, FFD is more suitable than FFR in femtocell networks, where the number of femtocells may be larger than that of the available bands.

VI. Conclusions

In this paper, we have studied cognitive interference management in selfish femtocells, where everyone in networks intends to obtain the throughput as high as possible and leads to severe co-channel interference. To deal with the issue, we have proposed a fractional frequency donation approach, where each femtocell accesses frequency bands in a turn-on order and manages co-channel interference by asking good femtocells to donate some bands to poor ones. Simulation results have shown that the proposed approach can achieve high average-throughput while maintaining good edge-throughput.

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