Interference Mitigation Techniques for Femtocell Networks

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***Abstract*—In femtocell networks, low-cost and low-power femto base stations are overlaid on macro cellular systems, and thereby interference between the femtocell to the macrocell becomes a major obstacle. In this paper, we propose a distributed beamforming technique to efficiently mitigate the interference for downlink multi-input single-output femtocell networks. First, a beamforming structure for femtocell is presented, and then the beamforming vector is optimized based on Karush-Kuhn-Tucker conditions. Simulation resuslts demonstrate that the proposed method show almost the same performance compared to conventional method with significantly reduced complexity.**

I. Introduction

Next generation wireless systems are expected to provide users with high spectral efficiency and the increased system coverage. To this end, various transmission methods such as multi-input multi-output techniques [1] and coordinated multipoint (CoMP) transmission [2] have been widely studied. Also, from a perspective of a base station (BS) deployment, distributed antenna systems [3], small cells [4] and femtocells [5] have been considered as promising solutions. Among them, femtocells have attained a large amount of attention as a cost-effective deployment method in standard organizations such as 3GPP [6]–[8] as well as academic researches [5], [9]–[12]. The key idea of femtocells is to overlay low-cost and low-power femto BSs on macro cellular systems [5]. As a result, the femtocell network can be modeled as two-tier interference channels.

In comparison to conventional one-tier macro cellular networks, the femtocell network has some important aspects. Due to restricted association between a femto BS and users, the users may be supported by a macro cellular BS instead of the near femto BS, and thereby the macro user may suffer from strong interference caused by the femto BS. Thus, an interference management becomes an important issue in the femtocell network. However, the backhaul signaling for interference coordination is more limited in the femtocell, since femto BSs are generally connected to a macro BS via an internet service provider [11]. Therefore, the interference management is more challenging compared to conventional one-tier macro cellular networks.

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To solve this issue, several efforts have been developed for the femtocell network in the literatures [9]–[12]. In [9] and [10], power control algorithms were proposed based on the distributed utility maximization. The author in [11] introduced subband partitioning and interference cancelation approaches, and an interference alignment technique for cognitive femtocell networks is presented in [12]. In this paper, an interference mitigation method is proposed in order to maximize the system throughput for downlink multi-input single-output (MISO) femtocell networks. Since techniques based on a centralized system require ideal backhaul among a macro BS and femto BSs, which is impractical, we focus on a distributed beamforming method for the femtocell networks which reduces the computational complexity as well as the signaling overhead.

For an efficient design, we first construct the beamforming structure for the femtocell system in which each femto BS has two transmit antennas. Then, based on the desired expression, a closed-form solution is obtained from the Karush-Kuhn-Tucker (KKT) conditions [13]. Simulation results confirm that the proposed scheme provides almost the identical performance compared to conventional algorithms which require computationally intensive exhaustive search or an iterative optimization method.

The following notations are used throughout the paper. We employ uppercase boldface letters for matrices and lowercase boldface for vectors. For any general matrix $\mathbf{A}$, $\mathbf{A}^T$, $\mathbf{A}^*$, $\mathbf{A}^H$ and $\mathrm{Tr}(\mathbf{A})$ denote transpose, conjugate, conjugate transpose and trace, respectively. Also, $\mathbb{C}^{m\times n}$ represents the set of $m \times n$ complex matrices, and $E[\cdot]$ and $\angle(\cdot)$ account for expectation and the angle, respectively. In addition, $\|\cdot\|$ stands for Euclidean 2-norm of a vector, and x^R and x^I indicate the real and imaginary part of a complex value x, respectively.

II. System model

We consider a MISO femtocell network where N femto BSs are deployed within a cell which is supported by a macro BS as depicted in Fig. 1. Let us denote the j-th femto BS as BS_j ($j = 1, \ldots, N$) and the macro BS as BS_0. In our system configuration, BS_j or BS_0 serves its corresponding single mobile station (MS) MS_j or MS_0, respectively, for a given time. We assume that all MSs have a single receive antenna, while BS_0 and BS_j have N_0 and N_j transmit antennas,

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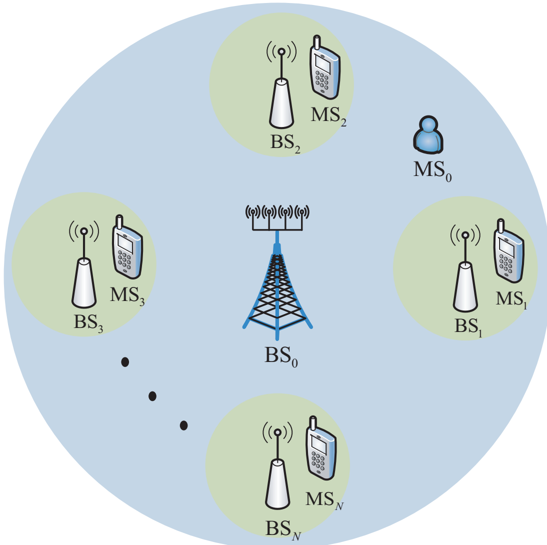

Fig. 1. System model of the femtocell network

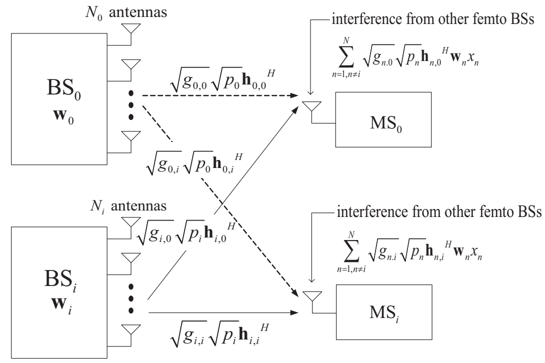

Fig. 2. Channel model at BS$_i$

respectively. In addition, we assume a wall at the boundary of each femtocell whose penetration loss is δ dB, and we define the maximum transmit power as $P_{t,0}$ and $P_{t,j}$ for BS$_0$ and BS$_j$, respectively.

Defining a set S as $S \triangleq \{0, \cdots, N\}$, the received signal at MS$_k$ for $k \in S$, y_k can be expressed as

$$y_k = \sqrt{g_{k,k}}\sqrt{p_k}\mathbf{h}_{k,k}^H\mathbf{w}_k x_k + \sum_{l\in S, l\neq k} \sqrt{g_{l,k}}\sqrt{p_l}\mathbf{h}_{l,k}^H\mathbf{w}_l x_l + n_k \quad (1)$$

where $g_{l,k}$ indicates the long term fading between MS$_k$ and BS$_l$ including pathloss, shadowing, and a penetration loss, p_k is defined as the transmit power at BS$_k$ with power constraint $p_k \leq P_{t,k}$, $\mathbf{h}_{l,k} \in \mathbb{C}^{N_l \times 1}$ is the channel vector for small scale fadings between MS$_k$ and BS$_l$, $\mathbf{w}_l \in \mathbb{C}^{N_l \times 1}$ represents the transmit beamforming vector at BS$_l$ with unit norm ($\|\mathbf{w}_l\|^2 = 1$), x_k denotes the independent data symbol for MS$_k$ with unit variance, i.e, $E[x_k x_k^*] = 1$ and $E[x_k x_l^*] = 0$ for $k \neq l$, and n_k stands for the additive complex Gaussian noise with zero mean and variance σ_k^2.

Let us assume that each BS knows local channel state information between the BS and its supporting MS. The macro user MS$_0$ transmits the reference signal prior to downlink transmission so that all femto BSs can measure short and long term channel statistics between MS$_0$ and BS$_j$, i.e. $\mathbf{h}_{j,j}$, $\mathbf{h}_{j,0}$, $g_{j,j}$, and $g_{j,0}$ are available at BS$_j$. On the other hand, all femto BSs do not have the channel information from other femto MSs due to their low-power usage, the wall penetration loss δ and difficulties in channel estimation, and thus a distributed beamforming strategy for femtocells is inevitable.

Also, it is assumed that BS$_0$ employs maximal ratio transmission (MRT) to support MS$_0$, while BS$_j$ adopts various transmission strategies. Treating interference from other femto BSs as noise, the received signal for MS$_j$ and MS$_0$ seen from BS$_j$ can be modeled as

$$y_j = \sqrt{g_{j,j}}\sqrt{p_j}\mathbf{h}_{j,j}^H\mathbf{w}_j x_j + \sqrt{g_{0,j}}\sqrt{p_0}\mathbf{h}_{0,j}^H\mathbf{w}_0 x_0 + \tilde{n}_j \quad \text{for } j = 1, \cdots, N, \quad (2)$$

$$y_0 = \sqrt{g_{0,0}}\sqrt{p_0}\mathbf{h}_{0,0}^H\mathbf{w}_0 x_0 + \sum_{n=1}^{N} \sqrt{g_{n,0}}\sqrt{p_n}\mathbf{h}_{n,0}^H\mathbf{w}_n x_n + n_0 \quad (3)$$

where $\tilde{n}_j$ is defined by $\sum_{n=1,n\neq j}^{N} \sqrt{g_{n,j}}\sqrt{p_n}\mathbf{h}_{n,j}^H\mathbf{w}_n x_n + n_j$ whose variance equals $\tilde{\sigma}_j^2 = \sigma_j^2 + \sum_{n=1,n\neq j}^{N} g_{n,j}p_n|\mathbf{h}_{n,j}^H\mathbf{w}_n|^2$.

The achievable weighted sum rate (WSR) for the femtocell network R_Σ can be expressed as

$$\begin{aligned} R_\Sigma &= \eta_0 \log_2\left(1 + \frac{g_{0,0}p_0|\mathbf{h}_{0,0}^H\mathbf{w}_0|^2}{\sigma_0^2 + \sum_{n=1}^{N} g_{n,0}p_n|\mathbf{h}_{n,0}^H\mathbf{w}_n|^2}\right) \\ &+ \sum_{j=1}^{N} \eta_j \log_2\left(1 + \frac{g_{j,j}p_j|\mathbf{h}_{j,j}^H\mathbf{w}_j|^2}{\tilde{\sigma}_j^2 + g_{0,j}p_0|\mathbf{h}_{0,j}^H\mathbf{w}_0|^2}\right) \end{aligned} \quad (4)$$

where the weight term η_0 and η_j's are determined depending on the required quality of service for applications [14]. Then the WSR maximization problem becomes

$$\begin{aligned} \max_{\{p_j\},\{\mathbf{w}_j\}} \quad & R_\Sigma \\ \text{subject to} \quad & p_j \leq P_{t,j}, \quad \forall j \\ & \|\mathbf{w}_j\|^2 = 1, \quad \forall j. \end{aligned} \quad (5)$$

III. Proposed Interference Mitigation Method

In this section, we propose a distributed beamforming method to efficiently mitigate the interference for femtocell networks. Since channel information is insufficient in a distributed scenario, it is impossible to identify the optimal solution for maximizing the WSR in (5). Thus, we reformulate the original optimization problem in (5) into a distributed optimization problem for BS$_i$ which denotes the femto BS of interest. Then the effective system model at BS$_i$ is depicted in Fig. 2. In the plot, the channel statistics represented by the solid lines are available at BS$_i$, while the dotted lines are not.

First, we define the distributed WSR at BS_i as

$$\begin{aligned} R_i \;\triangleq\; & \eta_0 \log_2\left(1+\frac{g_{0,0}p_0|\mathbf{h}_{0,0}^H\mathbf{w}_0|^2}{\tilde{\sigma}_{0,i}^2+g_{i,0}p_i|\mathbf{h}_{i,0}^H\mathbf{w}_i|^2}\right) \\ + \; & \eta_i \log_2\left(1+\frac{g_{i,i}p_i|\mathbf{h}_{i,i}^H\mathbf{w}_i|^2}{\tilde{\sigma}_i^2+g_{0,i}p_0|\mathbf{h}_{0,i}^H\mathbf{w}_0|^2}\right). \end{aligned} \quad (6)$$

where $\tilde{\sigma}_{0,i}^2 = \sigma_0^2 + \sum_{n=1,n\neq i}^N g_{n,0}p_n|\mathbf{h}_{n,0}^H\mathbf{w}_n|^2$ and $\tilde{\sigma}_i^2 = \sigma_i^2 + \sum_{n=1,n\neq i}^N g_{n,i}p_n|\mathbf{h}_{n,i}^H\mathbf{w}_n|^2$. Note that as mentioned in Section II, BS_i has only its local channel information and BS_0 employs the MRT beamforming $\mathbf{w}_0 = \frac{\mathbf{h}_{0,0}}{\|\mathbf{h}_{0,0}\|}$ with the full transmit power as $p_0 = P_{t,0}$ to increase the sum rate of MS_0.

To efficiently solve the problem, we take the expectation on R_i in (6) with respect to unknown channel information, i.e., $\mathbf{h}_{0,0},\ \mathbf{h}_{0,i}$, and $\{\mathbf{h}_{n,0},\ \mathbf{h}_{n,i}\}$ for $n \neq i$, and use Jensen's inequality. Then, (6) is lower-bounded as in (7) at the top of the next page.

Here, further approximation can be made for computational conveniences and we employ the following useful equalities

$$E\left[|\mathbf{h}^H\mathbf{h}|^2\right] = E\left[\sum_{i=1}^{N_t}(|h_i^R|^2+|h_i^I|^2)\right] = N_t,\ \ E\left[|\mathbf{h}^H\mathbf{w}|^2\right] = 1$$

where h_i is the i-th element of $\mathbf{h} \in \mathbb{C}^{N_t\times 1} \sim CN(\mathbf{0},\mathbf{I}_{N_t})$ and $\mathbf{w} \in \mathbb{C}^{N_t\times 1}$ denotes a vector uncorrelated to $\mathbf{h}$ with unit norm. Then, by defining the lower bound of (7) as $\tilde{R}_i$, we have

$$\begin{aligned} \tilde{R}_i \;=\; & \eta_0 \log_2\left(1+\frac{g_{0,0}P_{t,0}N_0}{\hat{\sigma}_{0,i}^2+g_{i,0}p_i|\mathbf{h}_{i,0}^H\mathbf{w}_i|^2}\right) \\ + \; & \eta_i \log_2\left(1+\frac{g_{i,i}p_i|\mathbf{h}_{i,i}^H\mathbf{w}_i|^2}{\hat{\sigma}_i^2+g_{0,i}P_{t,0}}\right) \end{aligned} \quad (8)$$

where $\hat{\sigma}_{0,i}^2 = \sigma_0^2 + \sum_{n=1,n\neq i}^N g_{n,0}p_n$ and $\hat{\sigma}_i^2 = \sigma_i^2 + \sum_{n=1,n\neq i}^N g_{n,i}p_n$ equal the variance of the noise plus interference terms. Finally, we reformulate the distributed optimization problem at BS_i as

$$\max_{p_i,\mathbf{w}_i} \ \tilde{R}_i \quad \text{subject to} \ \ p_i \le P_{t,i} \ \text{ and } \ \|\mathbf{w}_i\|^2 = 1, \qquad \forall i. \quad (9)$$

A. Conventional Solutions

Since the problem in (9) is non-convex, it is hard to obtain an analytic solution. Before introducing our proposed scheme, we first present conventional methods for solving the problem in (9).

1) Binary power control (BPC) [15] : This method considers the approximated rate for MS_0 and the allowable interference level $I_{th,0}$ at MS_0, which is normally called the interference temperature [16]. It is obvious that any beamforming strategy increases the interference level at MS_0 except nullforming [17], $\mathbf{w}_{nf}$, where the normalized beamforming vector is computed from the null space of $\mathbf{h}_{i,0}^H$. Thus, in the BPC method for a given $I_{th,0}$, if $g_{i,0}P_{t,i}$ exceeds $I_{th,0}$, we set $\mathbf{w}_i = \mathbf{w}_{nf}$ and $p_i = P_{t,i}$. Otherwise, we have $\mathbf{w}_i = \mathbf{w}_h$ and $p_i = P_{t,i}$ where $\mathbf{w}_h = \frac{\mathbf{h}_{i,i}}{\|\mathbf{h}_{i,i}\|}$ corresponds to the MRT beamforming at BS_i. To obtain acceptable system performance, $I_{th,0}$ is chosen by exhaustive search, and thus the complexity is high. Note that if BS_i has a single antenna, p_i can be either $P_{t,i}$ or 0 depending on $g_{i,0}P_{t,i}$, and thus it is called BPC.

2) Soft interference nulling (SIN) [18] : In this algorithm, the problem (9) is reformulated using the semidefinite programming relaxation [13] as in (10) at the top of the next page where $\mathbf{Q}_i = \mathbf{w}_i\mathbf{w}_i^H$, $\alpha = g_{0,0}P_{t,0}N_0$ and $\beta = \hat{\sigma}_i^2 + g_{0,i}P_{t,0}$. The problem (10) is still non-convex, and thus the problem is further modified using the first-order Taylor series expansion [18], which leads to a convex problem for a given $\bar{\mathbf{Q}}_i$ and can be solved in an iterative manner. Then, the modified convex problem is expressed as in (11) at the top of the next page where $t_i = 1 + \frac{g_{i,0}}{\hat{\sigma}_{0,i}^2}\mathbf{h}_{i,0}^H\bar{\mathbf{Q}}_i\mathbf{h}_{i,0}$ and $\bar{\mathbf{Q}}_i$ is an initial semidefinite matrix for iterations of the SIN algorithm. The problem (11) is efficiently solved by the standard convex tools such as CVX [19]. $\bar{\mathbf{Q}}_i$ is updated in each step of the SIN method until convergence.

B. Proposed Solution

So far, we have investigated conventional methods which require high computational complexity due to employing the exhaustive search or the iterative optimization method. In this subsection, we propose an efficient transmission strategy by introducing the structure of the beamforming vector and using the KKT conditions. The objective of our proposed scheme is to improve the performance of MS_0 while minimizing a performance loss of MS_i.

To this end, we first present the beamforming vector at BS_i as

$$\mathbf{w}_i = r_1 e^{j\theta}\mathbf{w}_{nf} + r_2\mathbf{w}_h \quad (12)$$

where r_1, r_2, and θ are the optimization parameters with $r_1, r_2 > 0$, and $\theta \in [0, 2\pi)$. It is worthwhile to note that this proposed beamforming structure in (12) is optimal for the case of $N_i = 2$, since $\mathbf{w}_i$ can span $\mathbb{C}^{2\times 1}$ by properly adjusting r_1, r_2 and θ. However, if $N_i > 2$, there exist several basis vectors for the null space of $\mathbf{h}_{i,0}^H$, so that $2N_i+1$ optimization parameters are required to span $\mathbb{C}^{N_i\times 1}$, and thereby the optimization procedure becomes more complicated. For this reason, we focus on $N_i = 2$ throughout this paper.

Plugging (12) into (8), the interference term $g_{i,0}p_i|\mathbf{h}_{i,0}^H\mathbf{w}_i|^2$ at MS_0 is controlled by r_2 and p_i since $\mathbf{w}_{nf}$ is in the nullspace of $\mathbf{h}_{i,0}^H$. Meanwhile, r_1, r_2, θ and p_i jointly adjust the desired signal power $g_{i,i}p_i|\mathbf{h}_{i,i}^H\mathbf{w}_i|^2$. Thus, we determine p_i as $p_i = P_{t,i}$ to reduce the number of optimization parameters as well as to maximize the rate of MS_i. Note that although setting $p_i = P_{t,i}$ decreases the rate of MS_0, we can compensate this by controlling r_2. Since the joint optimization for r_1, r_2, θ and finding r_2 is somewhat complicated, we first fix r_2 and identify r_1 and θ, and then r_2 is computed.

$$R_i \geq \eta_0 \log_2\left(1+\frac{g_{0,0}P_{t,0}E[|\mathbf{h}_{0,0}^H\mathbf{h}_{0,0}|^2]}{\sigma_0^2+\sum_{n=1,n\neq i}^N g_{n,0}p_nE[|\mathbf{h}_{n,0}^H\mathbf{w}_n|^2]+g_{i,0}p_i|\mathbf{h}_{i,0}^H\mathbf{w}_i|^2}\right) + \eta_i \log_2\left(1+\frac{g_{i,i}p_i|\mathbf{h}_{i,i}^H\mathbf{w}_i|^2}{\sigma_i^2+g_{0,i}P_{t,0}E[|\mathbf{h}_{0,i}^H\mathbf{w}_0|^2]+\sum_{n=1,n\neq i}^N g_{n,i}p_nE[|\mathbf{h}_{n,i}^H\mathbf{w}_n|^2]}\right) \quad (7)$$

$$\max_{\mathbf{Q}_i} \quad \eta_0 \log_2\left(1+\frac{\alpha}{\hat{\sigma}_{0,i}^2+g_{i,0}\mathbf{h}_{i,0}^H\mathbf{Q}_i\mathbf{h}_{i,0}}\right)+\eta_i\log_2\left(1+\frac{g_{i,i}\mathbf{h}_{i,i}^H\mathbf{Q}_i\mathbf{h}_{i,i}}{\beta}\right)$$
$$\text{subject to} \quad \mathrm{Tr}(\mathbf{Q}_i)\leq P_{t,i} \quad (10)$$

$$\max_{\bar{\mathbf{Q}}_i} \quad \eta_0\log(\hat{\sigma}_{0,i}^2+g_{i,0}\mathbf{h}_{i,0}^H\bar{\mathbf{Q}}_i\mathbf{h}_{i,0}+\alpha)+\eta_i\log(\beta+g_{i,i}\mathbf{h}_{i,i}^H\bar{\mathbf{Q}}_i\mathbf{h}_{i,i})-\eta_0\mathrm{Tr}\Big(\frac{1}{t_i}\frac{g_{i,0}}{\hat{\sigma}_{0,i}^2}\mathbf{h}_{i,0}^H\bar{\mathbf{Q}}_i\mathbf{h}_{i,0}\Big)$$
$$\text{subject to} \quad \mathrm{Tr}(\bar{\mathbf{Q}}_i)\leq P_{t,i} \quad (11)$$

For a given r_2, the optimization problem in (9) is transformed as

$$\max_{\mathbf{w}_i} \quad |\mathbf{h}_{i,i}^H\mathbf{w}_i|^2$$
$$\text{subject to} \quad ||\mathbf{w}_i||^2 = 1. \quad (13)$$

Substituting the proposed beamforming vector (12) to our objective function and constraint, we have

$$\begin{aligned} |\mathbf{h}_{i,i}^H\mathbf{w}_i|^2 &= |\mathbf{h}_{i,i}^H(r_1e^{j\theta}\mathbf{w}_{nf}+r_2\mathbf{w}_h)|^2 \\ &= r_1^2w^2+v^2+2r_1w\cos(\theta+\theta_w)v, \quad (14) \\ ||\mathbf{w}_i||^2 &= r_1^2+2\gamma\cos(\theta_\gamma-\theta)r_1+\beta = 1 \quad (15) \end{aligned}$$

where $w = |\mathbf{h}_{i,i}^H\mathbf{w}_{nf}|$, $\theta_w = \angle\mathbf{h}_{i,i}^H\mathbf{w}_{nf}$, $v = r_2\mathbf{h}_{i,i}^H\mathbf{w}_h$, $\beta = r_2^2$, $\gamma = r_2|\mathbf{w}_{nf}^H\mathbf{w}_h|$ and $\theta_\gamma = \angle\mathbf{w}_{nf}^H\mathbf{w}_h$.

Then, equation (13) can be rewritten in a matrix form as

$$\max_{\mathbf{x}} \quad \mathbf{x}^T\mathbf{A}\mathbf{x}+v^2$$
$$\text{subject to} \quad \mathbf{x}^T\mathbf{B}\mathbf{x} = 1-\beta$$
$$\mathbf{x}^T\mathbf{C}\mathbf{x} = 1 \quad (16)$$

where $\mathbf{x}^T = [\cos\theta \quad \sin\theta \quad r_1]$,

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & wv\cos\theta_w \\ 0 & 0 & -wv\sin\theta_w \\ wv\cos\theta_w & -wv\sin\theta_w & w^2 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & \gamma\cos\theta_\gamma \\ 0 & 0 & \gamma\sin\theta_\gamma \\ \gamma\cos\theta_\gamma & \gamma\sin\theta_\gamma & 1 \end{bmatrix} \text{ and}$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

To efficiently solve the problem (16), we construct the Lagrangian function as

$$\begin{aligned} J(\mathbf{x}) &= \mathbf{x}^T\mathbf{A}\mathbf{x}+v^2+\lambda_1(\mathbf{x}^T\mathbf{B}\mathbf{x}-1+\beta)+\lambda_2(\mathbf{x}^T\mathbf{C}\mathbf{x}-1) \\ &= \mathbf{x}^T\mathbf{D}\mathbf{x}+\text{const} \quad (17) \end{aligned}$$

where λ_1 and λ_2 are the Lagrange multipliers and $\mathbf{D} = \mathbf{A}+\lambda_1\mathbf{B}+\lambda_2\mathbf{C}$. Then, using the KKT conditions [13], it follows

$$\frac{\partial J(\mathbf{x})}{\partial \mathbf{x}} = 2\mathbf{D}\mathbf{x} = 0. \quad (18)$$

From (18), we figure out that $\mathbf{x}$ should be in the null space of $\mathbf{D}$. Applying a Gaussian elimination method [20], we obtain

$$\mathbf{D}\mathbf{x} = \begin{bmatrix} \lambda_2 & 0 & a+\lambda_1 b \\ 0 & \lambda_2 & c+\lambda_1 d \\ 0 & 0 & e+\lambda_1-\frac{(a+\lambda_1 b)^2}{\lambda_2}-\frac{(c+\lambda_1 d)^2}{\lambda_2} \end{bmatrix} \begin{bmatrix} \cos\theta \\ \sin\theta \\ r_1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (19)$$

where $a = vw\cos\theta_w$, $b = \gamma\cos\theta_\gamma$, $c = -vw\sin\theta_w$, $d = \gamma\sin\theta_\gamma$, $e = w^2$.

Then, for a given $r_2 \neq 1$, $e+\lambda_1-\frac{(a+\lambda_1 b)^2}{\lambda_2}-\frac{(c+\lambda_1 d)^2}{\lambda_2}$ should be zero. Thus, we can express λ_2, $\cos\theta$ and $\sin\theta$ as

$$\begin{aligned} \lambda_2 &= \frac{(a+\lambda_1 b)^2+(c+\lambda_1 d)^2}{e+\lambda_1}, \\ \cos\theta &= -\frac{(a+\lambda_1 b)(e+\lambda_1)}{(a+\lambda_1 b)^2+(c+\lambda_1 d)^2}r_1, \\ \sin\theta &= -\frac{(c+\lambda_1 d)(e+\lambda_1)}{(a+\lambda_1 b)^2+(c+\lambda_1 d)^2}r_1. \quad (20) \end{aligned}$$

Employing (20) and the first constraint in (16), finally the solution is given as

$$r_1 = \sqrt{\frac{(a+\lambda_1 b)^2+(c+\lambda_1 d)^2}{(e+\lambda_1)^2}}, \quad (21)$$

$$\theta = \pi \pm\left(\pi-\arccos\left(-\frac{(a+\lambda_1 b)(e+\lambda_1)}{(a+\lambda_1 b)^2+(c+\lambda_1 d)^2}r_1\right)\right) \quad (22)$$

where $\lambda_1 = -w^2-w\sqrt{\frac{(v+\gamma w\cos(\theta_w+\theta_\gamma))^2+\gamma^2w^2(1-cos^2(\theta_w+\theta_\gamma))}{1-\beta+\gamma^2}}$. Note that the above θ is calculated from $\cos\theta$ in (20) and we can identify the unique θ by considering $\sin\theta$ in (20).

TABLE I
SYSTEM PARAMETERS

Number of femto BSs N	25
Maximum transmit power at BS_0	43 dBm
Maximum transmit power at BS_i	23 dBm
Noise power	-101 dBm
Carrier frequency f_c	2.5 GHz
Radius of a macro cell	200 m
Radius of a femto cell	15 m
Penetration loss	5 dB
Network entry policy	CSG

From now on, we present the computation of r_2. Plugging r_1 and θ to (8), $\tilde{R}_i$ is computed as

$$\begin{aligned}\tilde{R}_i &= \eta_0 \log_2\left(1+\frac{g}{\kappa + r_2^2}\right)\\ &+ \eta_i \log_2\left(1+\frac{g_{i,i}P_{t,i}|\mathbf{h}_{i,i}^H(r_1 e^{j\theta}\mathbf{w}_{nf}+r_2\mathbf{w}_h)|^2}{\hat{\sigma}_i^2 + g_{0,i}P_{t,0}}\right)\end{aligned}$$

where $g = \frac{g_{0,0}P_{t,0}N_0}{g_{i,0}P_{t,i}|\mathbf{h}_{i,0}^H\mathbf{w}_h|^2}$ and $\kappa = \frac{\hat{\sigma}_{0,i}^2}{g_{i,0}P_{t,i}|\mathbf{h}_{i,0}^H\mathbf{w}_h|^2}$. To make the above equation tractable, we further simplify this by ignoring the term $r_1 e^{j\theta}\mathbf{w}_{nf}$ as

$$\tilde{R}_i \geq \eta_0 \log_2\left(1+\frac{g}{\kappa + r_2^2}\right) + \eta_i \log_2(1+\tau r_2^2) \tag{23}$$

where $\tau = \frac{g_{i,i}P_{t,i}|\mathbf{h}_{i,i}^H\mathbf{w}_h|^2}{\hat{\sigma}_i^2 + g_{0,i}P_{t,0}}$.

The lower bound of (23) is a function of r_2, and the optimal point exists either at boundary points (0 or 1) or $r_2^\star$ $(0 < r_2^\star < 1)$ satisfying the zero derivative of the above equation (23), which is expressed as in (24) at the top of the next page. Then, we choose final r_2 which maximizes the sum rate among four candidates. It is worthwhile to note that our proposed algorithm provides a closed-form solution while the conventional method such as BPC or SIN requires high computational complexity. Besides, as will be shown in the following section, our proposed scheme provides the almost identical performance compared to the conventional BPC or SIN method.

IV. SIMULATION RESULTS

In this section, we present simulation results to demonstrate the efficacy of our proposed transmission strategy. It is assumed that the channel coefficients are sampled from an independent and identically distributed complex Gaussian random distribution with zero mean and unit variance. Also, we assume that femto BSs are uniformly distributed with equal distance between each other. The system parameters used in our simulations are listed in Table I. Here, we adopt closed subscriber group (CSG) in which MS_0 can be located inside the coverage of a femto BS while connected to a serving macro BS simultaneously. For the pathloss model, we employ the urban macrocell pathloss model [21] as

$$PL(d) = 35.2 + 35\log_{10} d + 26\log_{10}\frac{f_c}{2} \tag{25}$$

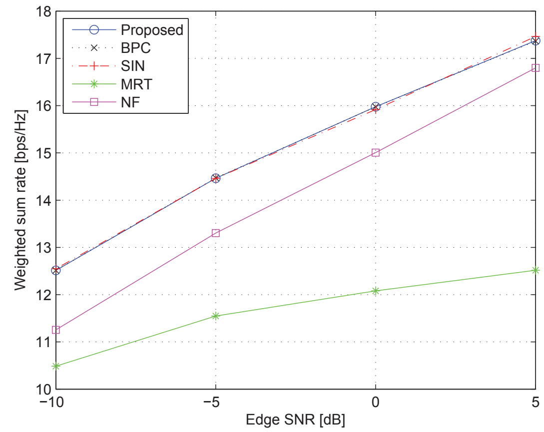

Fig. 3. Average weighted sum rate for femtocell networks with $N_0 = 2$

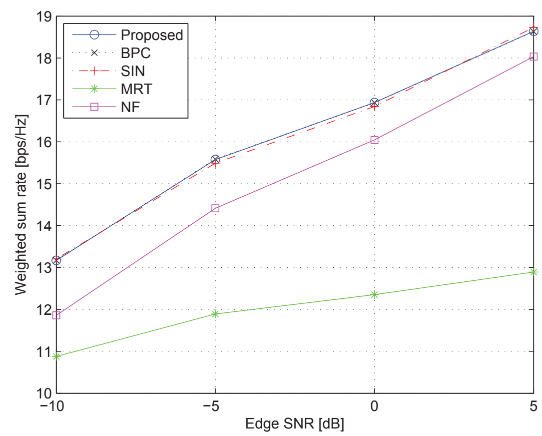

Fig. 4. Average weighted sum rate for femtocell networks with $N_0 = 4$

where d is the distance between a BS and an MS. In addition, we set the weights for MS_0 and MS_i as $\eta_0 = 1$ and $\eta_i = 1/N$ to give more priority to the macro user MS_0.

We compare the sum rate of various schemes in Figures 3 and 4 for femtocell networks with $N_0 = 2$ and 4, respectively, with respect to the cell edge SNR of MS_0 which indicates MS_0's SNR when there are no interference between macrocell and other femtocells. For BPC, we perform exhaustive search among 100 samples for the threshold $I_{th,0}$ in finding the optimal point. Also for the SIN scheme, an identity matrix is applied as an initial point. In both plots, the proposed scheme exhibits almost the same performance compared to conventional BPC and SIN methods, and outperforms simple MRT and nullforming(NF) methods which set $\mathbf{w}_i = \mathbf{w}_h$ and $\mathbf{w}_{nf}$, respectively. Since our proposed scheme provides a closed-form solution, the computational complexity is much reduced compared to the BPC or SIN algorithms. Also we can see that the sum rate of our proposed scheme increases with the cell edge SNR. Comparing Fig. 3 and 4, we can figure out that the weighted sum rate of the femtocell network increases as N_0 grows. This is due to a rate increment of MS_0 by

$$r_2^\star = \sqrt{-\frac{1}{2}\left(2\kappa + \left(1 - \frac{\eta_0}{\eta_i}g\right)\right) \pm \frac{1}{2}\sqrt{\left(2\kappa + \left(1 - \frac{\eta_0}{\eta_i}\right)g\right)^2 - 4\left(\kappa^2 + \left(\kappa - \frac{\eta_0}{\tau\eta_i}\right)g\right)}} \tag{24}$$

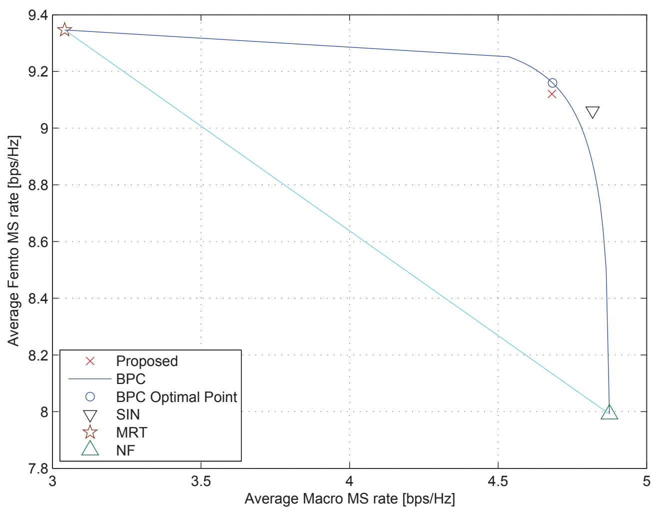

Fig. 5. Achievable rate region for femtocell networks with $N_0 = 4$ and $N = 100$

exploiting a larger diversity gain.

Figure 5 shows the achievable rate region for the femtocell networks with $N_0 = 4$, $N = 100$, and the cell edge SNR = -5 dB. In the plot, the BPC optimal point is obtained by choosing the best performance among 100 thresholds $I_{th,0}$. Note that our proposed scheme achieves almost the same performance with the BPC optimal point with significantly reduced complexity. Also, we can check that MRT and NF can be considered as a special case of the BPC method as depicted in this figure.

V. Conclusion

In this paper, we have proposed a distributed beamforming strategy to efficiently mitigate the interference in downlink MISO femtocell networks. First, we have presented the optimal structure of the beamforming vector. Then, based on the derived expression and the KKT conditions, we have proposed an efficient distributed beamforming design in closed form. From the simulation results, we have confirmed that the performance of our proposed scheme is almost the same as conventional optimization schemes with much reduced complexity and outperforms simple MRT and NF methods.

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