Decentralized Transmit Beamforming Scheme for Interference Coordination in Small Cell Networks

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***Abstract*—To cope with the growing demand of mobile data in hot spot areas of wireless networks, the use of massive small cell deployments with universal frequency reuse is essential. Such an aggressive reuse of spectral resources increases the level of co-channel interference, and calls for advanced multi-cell interference coordination techniques to capitalize cell densification gains. One option to address this problem is to use multiple antennas at the Base Stations (BSs), and implement Transmit Beamforming (TBF) to coordinate the interference generated to neighboring cells. A small cell BS should be low-cost by definition, and should be designed to serve typically a small number of Mobile Stations (MSs). Accordingly, we consider that each BS uses the same TBF vector to communicate with its associated MSs in the whole frequency band, and that the optimal TBF vector is determined utilizing a cooperative decentralized scheme. The proposed scheme seeks the maximization of a global utility function of the whole Small Cell Network (SCN), and relies solely on the exchange of low-rate signaling information among neighboring cells. As expected, the gain of the proposed cooperative TBF scheme increases as the number of MSs per cell decreases. A similar behavior is observed when the number of cooperative BSs per cell cluster grows. Thus, the proposed scheme seems to be applicable to SCNs with notable performance gains.**

I. Introduction

The explosive demand of wireless data services that has been observed lately by mobile operators calls for new solutions which enable a continuous evolution of mobile radio access technologies. One candidate approach to ensure this sustainability is to use dense Small Cell Network (SCN) deployments, in order to allow high data rate transmissions in hotspot areas of a mobile network [1]. In line with this, focused discussions on SCN enhancements have recently been initiated in 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) Release 12 [2].

Spectrum in the lower frequency bands is becoming scarce, and it will likely be reserved to provide wide area coverage with high-power macro Base Stations (BSs). Therefore, higher frequency bands are currently being explored to provide efficient local area coverage with indoor/outdoor small cells [3]. Though a dual-channel scenario avoids cross-layer interference between macrocells and small cells, significant amounts of co-layer interference among small cells will likely remain as their deployments are expected to be unplanned. This problem becomes particularly challenging if small cells are macro-assisted, and only low volumes of signaling information is expected to be exchanged to coordinate the interference in the small cell layer.

In its basic form, a SCN is composed by a dense deployment of self-organizing, low-cost and low-power BSs, and is usually deployed in hotspot areas of a mobile network [1]. Small cells are expected to provide service to static local area users, leaving aside high-mobility wide area users to be served by macrocells [2]. Bringing a Mobile Station (MS) one step closer to the serving BS improves channel conditions, and enables to increase the achievable data rate. However, if good channel conditions to more than one BS exist like in dense unplanned SCN deployments, unpredictable interference patterns may result, and the implementation of interference management mechanisms complicates. In addition, due to the number of MSs per small cell is envisioned to be low, large temporal traffic fluctuations are expected. Thus, an effective interference management technique for dense SCN deployments should be flexible enough, to adapt to the actual traffic conditions in the whole coverage area of the mobile network.

Interference management techniques for SCNs can be grouped into three different categories [4]: time-domain techniques, frequency-domain techniques, and power control techniques. Time- and frequency-domain techniques balance the co-channel interference by controlling the orthogonality of transmissions in time and frequency, respectively. On the other hand, power control techniques seek the reduction of transmit power as much as possible, to keep the level of co-channel interference under control. The spatial-domain can also be used to manage interference in multi-antenna SCN environments, selecting a convenient Transmit Beamforming (TBF) vector to balance the power of both (desired) intra-cell signal and (undesired) inter-cell co-channel interference [5]. Since SCNs are seen as a bridge between fully centralized (cellular) and fully decentralized (peer-to-peer) networks [1], the practical implementation of any interference coordination technique is expected to be done in a decentralized way, possibly in a cooperative fashion with the exchange of low-rate signaling information between cells.

The use of TBF schemes to manage interference in co-channel deployments has been studied for both peer-to-peer [6], [7] and multi-cell wireless networks [8], [9]. Peer-to-peer multi-antenna networks are a collection of Multiple-Input Single-Output (MISO) point-to-point links, often seen as an interference channel since they do not implement any kind of time-frequency resource allocation. For a MISO peer-to-peer network with two users, it was shown in [10] that any point in the Pareto boundary can be achieved by a TBF strategy that combines Maximum Ratio Transmission (MRT) and Zero-Forcing (ZF) beamforming. In a multi-cell wireless network, on the other hand, most part of the work found in the literature considers the case where multiple MSs are served simultaneously on each time-frequency resource block, using a SDMA strategy that selects suitable TBF vectors to keep both intra- and inter-cell interference powers at reasonable levels [11]. As expected, the implementation of a user-specific TBF scheme for multi-cell interference coordination demands the exchange of large amounts of feedback.

To cope with the significant amount of signaling information required to coordinate downlink co-channel interference, we consider that each BS carries out scheduling decisions independently, allocating orthogonal portions of the time-frequency resources to serve each associated MS. On the top of that, we assume that a unique TBF vector is adaptively selected per BS to be applied in the whole transmission bandwidth, to provide a balance between the (desired) intra-cell coherent combining gain and the (unwanted) inter-cell co-channel interference power. To keep the analysis simple, it is assumed that the scheduling weights per cell are known in advance. Then, the focus is put on the selection of the most convenient TBF vector that should be applied per cell, considering that this selection is carried out in a cooperative decentralized way with the aid of low-rate interference prices that inform the effect that local decisions have on the utility function of the neighboring cells [12].

The rest of the paper is organized as follows: Section II introduces the system model and the adopted assumptions. Section III presents the centralized problem to be solved, and derives a decentralized cooperative scheme that enables to achieve a solution of the original problem with a limited exchange of signaling information among coordinating cells. After that, Section IV presents the evaluation assumptions and the simulation results for a dense SCN scenario, followed by a discussion on the performance that is achieved when interference is coordinated using the proposed decentralized approach. Finally, conclusions are drawn in Section V.

II. System model

Our basis setup is a downlink multi-cell scenario with a single carrier, where a certain number of low-power open-access BSs with indexes in set $\mathcal{I} = \{1, \ldots, i, \ldots, I\}$ are randomly deployed to serve a group of MS with indexes in set $\mathcal{K} = \{1, \ldots, k, \ldots, K\}$. Each BS in the network is equipped with an array of M transmit antenna elements, while each MS has a single receive antenna. The multiple transmit antennas of the BSs are used for (single-layer) precoding and interference coordination [5]. As a consequence, data symbols intended to a given MS are only available at the serving BS, and each BS in the network may know the individual channel gains towards each of the MS in the neighborhood. Note that this requires a low-rate feedback mechanism among coordinating cells, which is in line with the idea of macro-assisted SCN deployments currently under analysis in LTE Release 12 [2].

The basic idea behind this decentralized TBF scheme is to adapt the transmitted signal of the different BSs to the instantaneous channel conditions of the coordinating cluster, and enhance the quality of the received signal at each individual MS. When BS i is restricted to apply a unique TBF column vector $\mathbf{v}_i \in \mathbb{C}^{M\times 1}$ to serve its associated MSs with indexes in set $\mathcal{K}_i$, where $\{\mathcal{K}_i : i = 1, \ldots, I\}$ represents a partition of set $\mathcal{K}$ since each MS is served by a unique BS, i.e.,

$$\mathcal{K} = \bigcup_{i\in\mathcal{I}} \mathcal{K}_i, \qquad \mathcal{K}_i \cap \mathcal{K}_j = \emptyset \quad \forall i \neq j, \tag{1}$$

the received signal at the desired destination becomes

$$r_k = (\mathbf{h}_{i,k}\,\mathbf{v}_i)\; s_i + \sum_{j\neq i} (\mathbf{h}_{j,k}\,\mathbf{v}_j)\; s_j + n_k \qquad k \in \mathcal{K}_i, \tag{2}$$

where $\mathbf{h}_{i,k} \in \mathbb{C}^{1\times M}$ is a row vector that contains the channel gains between each transmit antenna of BS i and the receive antenna of MS k, s_i is the information symbol that BS i transmits, and n_k is the Additive White Gaussian Noise (AWGN) that MS k experiences in reception. To keep the notation simple, a frequency-flat channel model is considered.

The intra-cell scheduling decisions are represented by scheduling weights $w_{i,k}$, which inform the fraction of the time-frequency resource blocks that BS i uses to serve each of its associated MS $k \in \mathcal{K}_i$. In practice, scheduling weights are selected with the aid of a resource allocation algorithm, like the one presented in [13], [14]. To simplify the analysis, we assume that the time-frequency resource blocks are infinitely divisible and orthogonally shared among the associated MSs, such that $\sum_{k\in\mathcal{K}_i} w_{i,k} = 1$ holds in all the instances of the resource allocation algorithm for all $i \in \mathcal{I}$. For this reason, no intra-cell interference term appears in the received signal equation (2).

The objective is to maximize the sum-utility function of the whole wireless network in downlink, i.e.,

$$U_{\text{sum}} = \sum_{i\in\mathcal{I}} \sum_{k\in\mathcal{K}_i} w_{i,k}\, f(\gamma_k), \tag{3}$$

where γ_k represents the received SINR at MS k, while $f(x)$ is a utility function that should be properly selected according to the performance metric to be maximized [15]. To simplify the analysis, in this paper we consider that fairness per cell is controlled by selecting fixed values for the scheduling weights $\{w_{i,k} : k \in \mathcal{K}_i\}$ for all $i \in \mathcal{I}$, and that the rate utility function $f(x) = \log_e(1 + x)$ is used in (3). Then, the goal of the interference coordination scheme reduces to selecting the most convenient set of TBF vectors $\{\mathbf{v}_i : i \in \mathcal{I}\}$ to be applied at each BS in downlink, such that the sum-rate of the multi-cell network is maximized.

The SINR that MS k experiences is given by

$$\gamma_k = \frac{g_{i,k}\, p_i}{\sum_{j\neq i} g_{j,k}\, p_j + P_{N,k}} \qquad k \in \mathcal{K}_i, \tag{4}$$

where

$$g_{i,k} = |\mathbf{h}_{i,k}\mathbf{v}_i|^2 = \mathbf{v}_i{}^{\dagger}\, \mathbf{Q}_{i,k}\, \mathbf{v}_i \tag{5}$$

is the equivalent (scalar) channel power gain between BS i and MS k after TBF vector $\mathbf{v}_i$ is applied, $p_i = \mathbb{E}\{|s_i|^2\}$ is the aggregate transmit power that BS i uses to communicate with its associated MSs, and $P_{N,k} = \mathbb{E}\{|n_k|^2\}$ is the background noise power that MS k is experiencing in reception in the whole communication bandwidth. In addition, $\mathbf{Q}_{i,k} = \mathbf{h}_{i,k}{}^{\dagger}\, \mathbf{h}_{i,k}$ is the channel covariance matrix between BS i and MS k, and $(\cdot)^{\dagger}$ denotes the Hermitian transposition operation.

III. Decentralized scheme for downlink interference coordination

When designing an interference coordination scheme for the downlink of a multicellular system, it is important to highlight that the interference power that is generated in a neighboring cell with index $j \neq i$ does not depend on the scheduling weights $\{w_{i,k} : k \in \mathcal{K}_i\}$ that cell i is currently applying to schedule transmission to its associated users. Note that this statement is valid if the network operates under full load, i.e., with all time-frequency resources constantly used in all cells.

Let us assume that the transmit power vector $\mathbf{p} = [p_1 \cdots p_I]$ that contains the powers of the different BSs do not vary during the TBF adaptation part of the downlink interference coordination scheme. Then, the optimization problem that we aim to solve can be written as

$$\begin{array}{ll} \underset{\mathbf{V}}{\text{maximize}} & \sum_{i\in\mathcal{I}} \sum_{k\in\mathcal{K}_i} w_{i,k} f(\gamma_k) \\ \text{subject to} & {\mathbf{v}_i}^{\dagger}\mathbf{v}_i = 1 \qquad \forall i \in \mathcal{I} \end{array}, \tag{6}$$

where the columns of matrix $\mathbf{V} = [\mathbf{v}_1 \cdots \mathbf{v}_I]$ contain the TBF vectors that each BS applies in downlink to serve its MSs. Note that this problem is in general non-concave, even in presence of a concave utility function $f(x)$, since the received SINRs γ_k are coupled. Nevertheless, following [12], any local optimum $\mathbf{V}^*$ of problem (6) must satisfy the Karush-Kuhn-Tucker (KKT) optimality conditions $\forall i$, i.e.,

$$\frac{\partial \mathcal{L}(\mathbf{V}^*, \boldsymbol{\lambda}^*)}{\partial {\mathbf{v}_i}^{\dagger}} = 0, \qquad \frac{\partial \mathcal{L}(\mathbf{V}^*, \boldsymbol{\lambda}^*)}{\partial \lambda_i} = 0, \qquad {\lambda_i}^* \geq 0, \tag{7}$$

where

$$\mathcal{L}(\mathbf{V}, \boldsymbol{\lambda}) = \sum_{i\in\mathcal{I}} \sum_{k\in\mathcal{K}_i} w_{i,k} f(\gamma_k) + \sum_{i\in\mathcal{I}} \lambda_i \left(1 - {\mathbf{v}_i}^{\dagger}\mathbf{v}_i\right) \tag{8}$$

is the Lagrangian function of problem (6) and ${\lambda_i}^*$ is a unique Lagrange multiplier for cell i. Let us define

$$\boldsymbol{\pi}_{j,i} = \sum_{k\in\mathcal{K}_j} w_{j,k} f'(\gamma_k) \frac{g_{j,k}\, p_j\, \mathbf{Q}_{i,k}}{(\sum_{l\neq j} g_{l,k} p_l + P_{N,k})^2} \quad j \neq i \tag{9}$$

as the interference price matrix from cell j to cell i. Then, under the assumption that prices $\boldsymbol{\pi}_{j,i}$ and TBF vectors $\mathbf{v}_j$ remain fixed for all BSs with indexes $j \neq i$, the KKT optimality conditions of problem (6) are equivalent to the KKT conditions of the following set of distributed optimization problems (i.e., one problem per BS $i \in \mathcal{I}$):

$$\begin{array}{ll} \underset{\mathbf{v}_i}{\text{maximize}} & \sum_{k\in\mathcal{K}_i} w_{i,k} f(\gamma_k) - {\mathbf{v}_i}^{\dagger} \left(\sum_{j\neq i} \boldsymbol{\pi}_{j,i}\right) \mathbf{v}_i\, p_i \\ \text{subject to} & {\mathbf{v}_i}^{\dagger}\mathbf{v}_i = 1 \end{array}. \tag{10}$$

Hence, by using the KKT conditions, it is possible to decompose the original optimization problem (6) into I subproblems. In each cell, the BS tries to maximize the surplus function (10), which combines the effect of both intra-cell coherent combining gain and inter-cell co-channel interference.

The solution to problem (10) can be obtained from its Lagrangian function, i.e.,

$$\begin{aligned} \mathcal{L}_i(\mathbf{v}_i, \lambda_i) \;&=\; \sum_{k\in\mathcal{K}_i} w_{i,k} f(\gamma_k) - {\mathbf{v}_i}^{\dagger} \Big(\sum_{j\neq i} \pi_{j,i}\Big) \mathbf{v}_i\, p_i \\ &+\; \lambda_i \left(1 - {\mathbf{v}_i}^{\dagger}\mathbf{v}_i\right), \end{aligned} \tag{11}$$

Algorithm 1 Decentralized Transmit Beamforming scheme

Initialization: Set $n = 1$. Select total downlink transmit power p_i, scheduling weights $\{w_{i,k} : k \in \mathcal{K}_i\}$, and initial TBF vector $\mathbf{v}_i[1]$ for all cells $i \in \mathcal{I}$.
Compute initial pricing matrix $\boldsymbol{\pi}_{j,i}$ $\forall i, j$ with $i \neq j$, using (9). Alternatively, set pricing information matrix equal to the null matrix of size $M \times M$.
repeat
  Set $n \leftarrow n + 1$, $\mathbf{v}_i[n] \leftarrow \mathbf{v}_i[n-1]$ $\forall i$
  for $i = 1$ to I **do**
    Collect pricing matrices $\boldsymbol{\pi}_{j,i}$ $\forall j \neq i$ (i.e., from all cells in neighborhood)
    Solve optimization problem (10), finding the eigenvector ${\mathbf{v}_i}^*$ that corresponds to the maximum eigenvalue of matrix (14)
    Update $\mathbf{v}_i[n]$ using linear combination (15) of new and old TBF vector with step size β_i
    Update pricing matrix $\boldsymbol{\pi}_{i,j}$ $\forall j \neq i$ using (9)
  end for
until Convergence is reached (e.g., infinitesimal variation in local utility functions in two consecutive iterations)

finding the vector ${\mathbf{v}_i}^*$ and the scalar ${\lambda_i}^*$ which satisfy the KKT optimality condition of the problem, i.e.,

$$\frac{\partial \mathcal{L}_i({\mathbf{v}_i}^*, {\lambda_i}^*)}{\partial {\mathbf{v}_i}^{\dagger}} = 0, \quad \frac{\partial \mathcal{L}_i({\mathbf{v}_i}^*, {\lambda_i}^*)}{\partial \lambda_i} = 0, \quad {\lambda_i}^* \geq 0. \tag{12}$$

It is possible to show that the solution to this problem is equivalent to the solution of the well-known eigenvalue problem

$$\mathbf{A}_i\, {\mathbf{v}_i}^* = {\lambda_i}^* {\mathbf{v}_i}^*, \tag{13}$$

where ${\mathbf{v}_i}^*$ is the eigenvector that corresponds to the maximum eigenvalue ${\lambda_i}^*$ of matrix

$$\mathbf{A}_i = \sum_{k\in\mathcal{K}_i} w_{i,k} f'(\gamma_k) \frac{\mathbf{Q}_{i,k}\, p_i}{\sum_{j\neq i} g_{j,k} p_j + P_{N,k}} - \sum_{j\neq i} \boldsymbol{\pi}_{j,i}\, p_i. \tag{14}$$

A summary of this decentralized scheme is presented as Algorithm 1. Note that Algorithm 1 is formulated in downlink, with the assumption that the interference pricing matices are first calculated at the interference victim, and then communicated to the source of interference. This approach represents the only possible alternative in a FDD system. In a TDD system, on the other hand, one could also consider a generalization of the busy burst concept of [16], so that the interference prices would be calculated at the interference source. Finally, it is important to highlight that the proposed decentralized TBF scheme can also be used in uplink with minor modifications.

Convergence is analyzed after all cells update their TBF vectors in an asynchronous fashion. In practice, convergence is assumed when infinitesimally small variations are observed in the utility functions and/or the elements of TBF vectors of all the cells in two consecutive iterations. We have observed that the convergence properties of the proposed decentralized TBF scheme for interference coordination can be kept under control if at each iteration n, the update of the TBF vector per

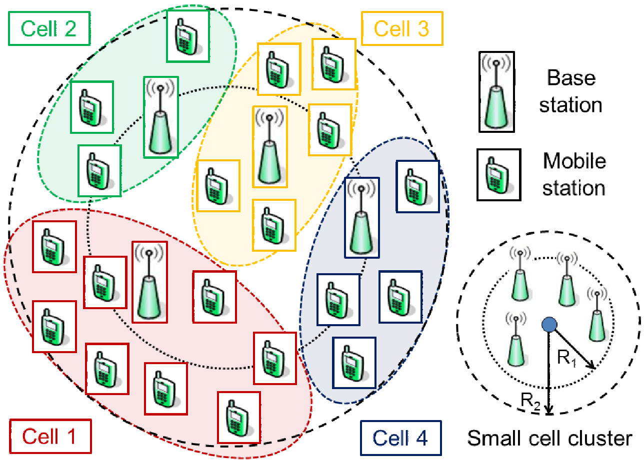


Fig. 1. Layout for the baseline small cell deployment scenario composed by $I = 4$ BSs and $K = 20$ MSs randomly dropped on the surface of two circles with radiuses R_1 and R_2, respectively. Cell association is carried out based on the received SNR in downlink. Signaling links between MSs, which can be macro layer assisted, are used to implement a decentralized cooperative TBF scheme for interference coordination in the small cell cluster.

TABLE I
URBAN MICRO (UMI) PATH LOSS MODEL

Path loss models [dB] (f_c given in GHz, d in meters)	**Shadow fading**	**Applicability range values**
LOS		
$\text{PL} = 22\log_{10}(d) + 28.0 + 20\log_{10}(f_c)$	$\sigma = 3$ dB	$10\,\text{m} \leq d \leq d_{\text{bp}}$
$\text{PL} = 40\log_{10}(d) + 7.8 - 18\log_{10}(h_{\text{bs}} - 1) - 18\log_{10}(h_{\text{ms}} - 1) + 2\log_{10}(f_c)$	$\sigma = 3$ dB	$d_{\text{bp}} \leq d \leq 5000\,\text{m}$
NLOS		
$\text{PL} = 36.7\log_{10}(d) + 22.7 + 26\log_{10}(f_c)$	$\sigma = 4$ dB	$10\,\text{m} \leq d \leq 2000\,\text{m}$
Break point distance: $d_{\text{bp}} = 4\,(h_{\text{bs}} - 1)\,(h_{\text{ms}} - 1)/\lambda_c$		
Carrier wavelength (λ_c) and antenna heights (h_{bs}, h_{ms}) are given in meters		
LOS probability: $P_{\text{LOS}} = \min(18/d, 1)\left(1 - \exp(-d/36)\right) + \exp(-d/36)$		

cell has a controlled step size. In practice, this can be achieved applying at each iteration the linear combination

$$\mathbf{v}_i[n] = \frac{(1-\beta_i)\mathbf{v}_i[n-1] + \beta_i \mathbf{v}_i^*}{\|(1-\beta_i)\mathbf{v}_i[n-1] + \beta_i \mathbf{v}_i^*\|}, \tag{15}$$

where $\mathbf{v}_i^*$ is the solution of the distributed optimization problem (10), $\mathbf{v}_i[n-1]$ is the TBF vector at the beginning of the iteration, and $\beta_i \in [0, 1]$ is a convenient step size selected to guarantee a good tradeoff between convergence probability and convergence speed.

IV. Numerical Results

In this section we analyze the performance of different decentralized schemes, used for interference coordination purposes in a SCN scenario. We first present the simulation scenario, followed by the analysis of results.

A. Simulation scenario

An example of the investigated SCN scenario is illustrated in Fig. 1, which is in line with the evaluation assumptions mentioned in [17] for the so-called Scenario #2a (i.e., dual-channel deployment). The system consists of a cluster of I small cell BSs and K MSs uniformly distributed on the surface of two concentric circles with radiuses $R_1 = 50$ m and $R_2 = 70$ m, respectively. All the BSs in the small cell cluster are open access by definition, and take random locations at each network instantiation, with a minimum distance separation $d_{\text{min,bs-bs}} = 20$ m between each pair of BSs. Similarly, the MSs in the small cell cluster are also randomly deployed, keeping fixed locations at each network snapshot with minimum distance separation to the closest BS $d_{\text{min,bs-ms}} = 5$ m. The association procedure at each cell is based on the values of the mean received power that each MS experience in downlink; so, in case of equal transmit power, each MS is always served by the BS from which it sees the minimum path loss attenuation.

Communication in downlink takes place on a single carrier of bandwidth $B = 10$ MHz, with center frequency $f_c = 3.5$ GHz. The antenna heights at the BSs and MSs are $h_{\text{bs}} = 10$ m and to $h_{\text{ms}} = 1.5$ m, respectively. The distance dependent path loss and the log-normal shadow fading components of the channel gains are modeled according to the Urban Micro (UMi) scenario presented in [18], and the main characteristics are summarized in Table I. Channel gains related to the different antennas of the same BS are modeled as independent and identically distributed (i.i.d.) zero-mean circularly symmetric complex Gaussian Random Variables (RVs). The channel response in the whole frequency band of the unique communication carrier is considered flat.

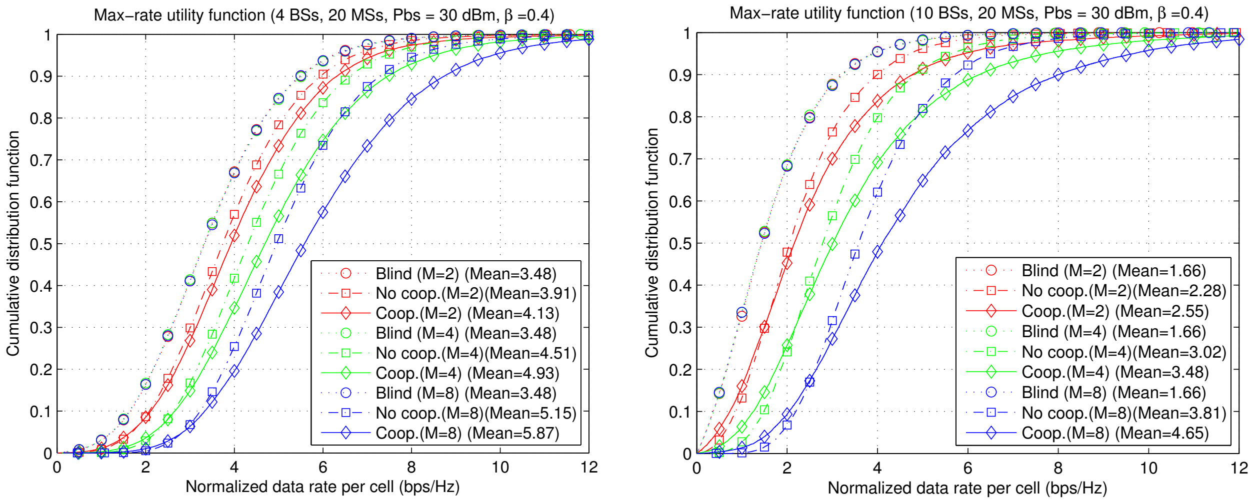
The BS transmission powers and the MS noise figures are set to 30 dBm and 9 dB in all cells, respectively. Total transmit power per BS remains fixed, and a flat power allocation is used across the whole communication bandwidth of the carrier. Intra-cell scheduling decisions are carried out locally at each BS. To simplify the analysis and to be able to focus the attention on the effect of the cooperative selection of TBF vectors within the coordinating cluster, we assume that each BS applies Round Robin (RR) scheduling to allocate an equal share of orthogonal time-frequency resources among all associated MSs, i.e., we set $w_{i,k} = 1/|\mathcal{K}_i|$ for all $i \in \mathcal{I}$. Thus, the max-rate utility function

$$u_i = B \sum_{k \in \mathcal{K}_i} w_{i,l} \log_e(\gamma_k) \qquad i \in \mathcal{I} \tag{16}$$

is used to analyze the performance of the different decentralized schemes at each cell of the cluster.

B. Performance analysis

The results are presented for 2000 random network instantiations, generated according to the aforementioned parameters. To characterize the effect of the number of BSs per cluster in a proper way, only those network instantiations that have at least one MS associated per cell are considered when presenting the performance results. The data rates experienced at each individual cell are first collected after convergence is achieved, and then used to plot the corresponding Cumulative Distribution Functions (CDFs) for the different interference coordination schemes, when the max-rate utility function is used as optimization objective. Convergence is assumed when the sum utility function that corresponds for all the cells in the



(a) 4 small cell BSs (b) 10 small cell BSs

Fig. 2. Cumulative distribution function for downlink achievable spectral efficiency per individual cell. Small cell network scenario composed by 4 BSs (left side) and 10 BSs (right side), 20 MSs randomly deployed in the cluster area, and a single carrier of 10 MHz in the 3.5 GHz band ($P_{\mathrm{tx,bs}} = 30\,\mathrm{dBm}$). Dotted lines with circles: DB-TBF scheme (blind). Dashed-dotted lines with squares: DNC-TBF scheme (non-coop.). Solid lines with diamonds: DC-TBF scheme (coop./pricing). Number of transmit antennas: $M = 2$ (red), $M = 4$ (green), $M = 8$ (blue). Step size: $\beta_i = 0.4$ (all cases).

cluster changes less than $10\,\%$ in two consecutive iterations, or a maximum number of iterations $\mathrm{It}_{\mathrm{max}} = 50$ is reached. Three different interference coordination schemes are considered in these figures:

1) Decentralized Blind (DB)-TBF scheme,
2) Decentralized Non-Cooperative (DNC)-TBF scheme,
3) Decentralized Cooperative (DC)-TBF scheme.

The baseline scheme, referred to as DB-TBF scheme, selects a random TBF vector per cell at each network instantiation, since it lacks any kind of information on channel gains for both intra-cell and inter-cell links. The second alternative, referred to as DNC-TBF scheme, relies solely on information on the intra-cell channel links, and carries out the update of the TBF vector at each cell keeping just in mind the maximization of the *own local utility*; i.e., without considering the effects that local decisions at the target cell have in the local utility function of the neighbors. This is equivalent to forcing the pricing matrix $\boldsymbol{\pi}_{i,j}\ \forall i \neq j$ to be the null matrix of size $M \times M$ in all network instantiations. Finally, the DC-TBF scheme is considered, which represents the pricing alternative and relies on information of both intra-cell and inter-cell channel links. This information must first be estimated in reception at the MSs, and then reported to the BSs via uplink feedback. The DC-TBF scheme carries out the selection of the TBF vectors in a more effective way, with the aid of interference pricing information that is exchanged among the cells that constitute the coordinating cluster.

Figure 2 presents the CDF for the achievable spectral efficiency per cell for different number of transmit antennas (i.e., $M = 2, 4, 8$), when the number of small cell BSs per cluster is set to 4 (left-side) and 10 (right-side), respectively. In both cases, 20 MSs are randomly dropped in the coverage area of the small cell cluster, and MS association is carried out according to the received SNR in downlink. As expected, the DC-TBF scheme is able to select more convenient TBF vectors, when compared to the TBF vectors obtained with the DNC-TBF scheme. This is because the presence of signaling information, in the form of interference prices, enables to provide a balance between the intra-cell coherent combining gain and the inter-cell co-channel interference mitigation capabilities of the decentralized TBF scheme. These gains become more evident as the number of transmit antennas per BS grows, since larger antenna arrays enable to obtain more accurate beams, and use them to steer the signal energy per cell towards more convenient spatial directions from the perspective of the whole multi-cell network. In practice, this can be measured in terms of the achievable sum rate in the whole SCN cluster. At this point, it is noticed that the DB-TBF scheme provides the same achievable spectral efficiency regardless of the number of transmit antennas. As expected, there is no performance gain in absence of intra-cell and inter-cell channel state information at the transmitter side; therefore, the system model reduces to a Single-Input Single-Output (SISO) downlink multi-cell scenario with identical achievable data rates for all M.

The effect that the number of BSs has on the achievable spectral efficiency of the small cell cluster can be appreciated when comparing Fig. 2(a) with Fig. 2(b). As it can be predicted, small cell densification reduces the expected number of MSs to be served per BS, improving the performance gain that cooperation is able to provide when implementing a decentralized TBF scheme to coordinate interference. Furthermore, the more BSs there are in the cluster, the larger the number of interference sources is. As a consequence, it is possible to observe that stronger co-channel interference reduces the achievable spectral efficiencies of the different decentralized TBF schemes as the number of BSs per cluster grows. Based on these results, additional performance improvements are expected to be obtained if downlink power control mechanisms

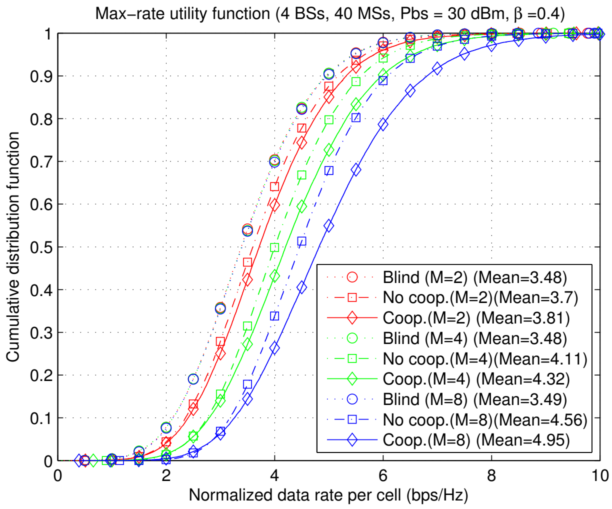


Fig. 3. Cumulative distribution function for the downlink achievable spectral efficiency per individual cell. Small cell network scenario composed by 4 BSs, 40 randomly deployed MSs, and a single 10 MHz carrier at 3.5 GHz ($P_{\rm tx,bs} = 30\,$dBm). Dotted lines with circles: DB-TBF scheme (blind). Dashed-dotted lines with squares: DNC-TBF scheme (non-coop.). Solid lines with diamonds: DC-TBF scheme (coop./pricing). Number of transmit antennas: $M = 2$ (red), $M = 4$ (green), $M = 8$ (blue). Step size: $\beta_i = 0.4$.

are also implemented in a cooperative way [13], to reduce the transmit power in those BSs that dominate the generation of co-channel interference within the cluster of small cells.

Finally, Fig. 3 shows the CDF for the achievable spectral efficiency when the number of BSs is set to 4, but the number of randomly dropped MSs in the cluster is increased to 40. Comparing Fig. 3 with Fig. 2(a), we see that the performance gain of DC-TBF decreases as the number of active MSs in the small cell cluster grows. This is because the larger is the number of MSs in the coordinating area, the more difficult is to find a unique set of TBF vectors that provides notable performance gain for all the MSs that are served by the cluster. Such a behavior makes the proposed DC-TBF scheme more convenient for limited-range small cells with low-power BSs, since the number of MSs to be served per individual cell in this situation is expected to be very low.

V. Conclusion

Co-layer interference represents a serious limitation for dense SCN deployments, and the use of multiple transmit antennas at the BSs provides one option to keep this impairment under control. Trying to tackle this problem, a decentralized TBF scheme was presented in this paper, to coordinate the intra-cluster interference that is generated when all the BSs of a SCN utilize the same downlink carrier. The proposed decentralized scheme was derived from a centralized optimization problem, whose objective was the maximization of a sum utility function in the whole coordinating cluster. The proposed decentralized TBF scheme did not require full knowledge of channel gains between BS-MS pairs of the neighboring cells, and relied solely on the exchange of low-rate signaling information in the form of interference pricing matrices among the coordinating BSs. Transmit power was kept fixed in all BSs, and a flat transmit power allocation was applied across the whole communication bandwidth of the carrier. A simple RR scheduler was used to give an equal orthogonal share of the common time-frequency resources to all MSs in a cell. The obtained results showed that decentralized cooperative TBF schemes have potential to provide notable performance gains as compared with simpler decentralized non-cooperative alternatives. These gains become more evident as the strength of the intra-cluster co-channel interference grows, and as the expected number of MSs to be served per BS decreases.

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