Degrees of Freedom of K-Tier Cognitive Cellular Networks without CSIT

Máximo Morales-Céspedes, Jorge Plata-Chaves, Marc Moonen, Luc Vandendorpe

I. Introduction

Nowadays, interference is the main limitation in cellular networks. On the one hand, several schemes such as Interference Alignment (IA) have been proposed to manage the interference [1]. However, these schemes require accurate knowledge of the Channel State Information at the Transmitter (CSIT) and coordination among the Base Stations (BSs) when applied in a cellular network. Notice that a significant amount of network resources is needed to satisfy these requirements. On the other hand, in [2] the study of the area spectral efficiency lead to reduce the cell size with the aim of reusing the transmission resource, either time or frequency. In consequence, the traditional homogeneous networks are gradually transformed into heterogeneous networks composed of cells with several sizes. In this context, interference management involves to handle a extremely dense and heterogeneous network where providing CSIT or cooperation results unaffordable.

The Degrees of Freedom (DoF) in absence of CSIT have been widely studied for the Broadcast Channel (BC) [3], [4], and homogeneous cellular networks [5], [6] based on the concept of Blind Interference Alignment (BIA). In this work we study the DoF of the K-tier heterogeneous cellular network described in [7] without CSIT or cooperation among BSs.

II. Problem formulation

We consider a K-tier cellular network. The tier k is composed of a set of G BSs, $\mathcal{G} = \{b_{1,k}, b_{2,k}, \ldots, b_{G,k}\}$, equipped with M_k antennas each, where $M_1 \geq M_2 \geq \cdots \geq M_K$. Focused on the tier k, each BS $b_{j,k}$ transmits to a set of $\mathcal{N} = \{n_1, n_2, \ldots, n_{N_k}\}$ users, each equipped with a single reconfigurable antenna that can switch among different preset modes. Each user in tier k receives its desired signal from its corresponding BS, which belongs to the tier k, and it is subject to interference due to transmission in the upper tiers $k' < k$, $k' \in \{1, \ldots, k-1\}$. It is assumed that the interference from lower tiers $k^\star > k$, $k^\star \in \{k+1, \ldots, K\}$, can be treated optimally as noise. If a user receives a strong signal from a lower tier, it proceeds to handover. Moreover, the transmitted signals in the tier k are subject to an average power constraint P_k, where $P_1 \geq P_2 \geq \cdots \geq P_K$. For the considered scenario, we assume that the transmitters do not have any CSIT or cooperation among other BSs.

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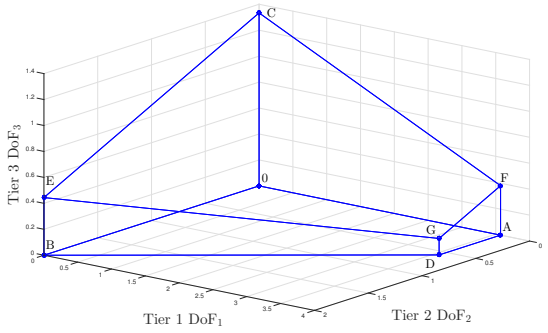


Fig. 1. DoF-region for a 3-tier heterogeneous network. First tier $M_1 = 5$, $N_1 = 10$, second tier $M_2 = 3$, $N_2 = 5$, third tier $M_3 = 2$, $N_3 = 2$.

III. Degrees of Freedom of K-Tier heterogeneous Networks Without CSIT

Theorem 1. *For a K-tier cellular network where the BSs of the k-th tier are equipped with M_k antennas serving N_k users as defined in Section II. In absence of CSIT or cooperation among transmiters, the DoF outer bound of the deepest tier, i.e. the tier K, is given by*

$$d_{\Sigma_K} \leq \frac{M_K N_K}{M_K + N_K - 1}\left(1 - \sum_{k=1}^{K-1} \frac{1}{M_k} d_{\Sigma_k}\right). \tag{1}$$

Corollary 1. *For the consider K-tier network, the outer bound of the DoF for the tier k assuming that each upper tier obtains the optimal DoF is*

$$d_{\Sigma_k} \leq \frac{M_k N_k \prod_{j=1}^{k-1}(M_j - 1)}{\prod_{i=1}^{k}(M_i + N_i - 1)}. \tag{2}$$

Corollary 2. *For the considered K-tier network, transmit zero-DoF in the upper tiers with the aim of improving the performance of the lower tiers involves to achieve less sum-DoF in the whole system than managing the inter-tier interference.*

The DoF-region of a 3-tier network, denoted as macro, micro and femto tiers from now on, is depicted in Fig. 1. First, note that the points A, B, and C correspond to the optimal DoF considering each tier as an independent BC. Focused on the 2-tier case, the planes formed by points A-C-F, A-B-D, and B-C-E correspond to DoF-region for the macro-femto, macro-micro, and micro-femto networks, respectively. For a 3-tier network, the DoF-region is given by the polyhedron shown in Fig. 1. Notice that the sum-DoF at the point G is 4.29 DoF while traditional orthogonal schemes are limited to 1 DoF.

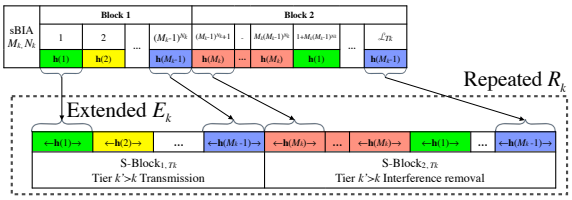


Fig. 2. Construction of the tierBIA supersymbol for the tier k.

IV. Achievability through Blind Interference Alignment

A. Blind Interference Alignment for the Broadcast Channel

The BIA scheme for the MISO BC (sBIA) achieves $\frac{M_k N_k}{M_k+N_k-1}$ DoF where the transmitter is equipped with M_k antennas serving N_k users [4]. By using reconfigurable antennas, the key idea behind sBIA is to create a *supersymbol* where the channel state of any user changes among M_k preset modes while the channel state of all other users remains constant. As is shown in Fig. 2, the supersymbol can be divided in two parts. Block 1 where simultaneous transmission to all users takes place and Block 2 employed to transmit each symbol, which carries M_k DoF, in orthogonal fashion.

B. Blind Interference Alignment for the K-tier network

Checking the supersymbol structure of the sBIA scheme, it can be seen that the interference subspace is transmitted during Block 2. Notice that for the K-tier network model, the user of tiers $k' > k$ can measure the interference subspace of the tier k during Block 2 if the BSs of the tiers $k' > k$ remain in silent during the transmission of Block 2 in tier k, i.e. in a cognitive fashion. We propose a BIA scheme for K-tier networks (tierBIA) based on the *extension* and *repetition* of the sBIA structure of each tier that ensures the alignment among tiers as is shown in Fig. 2. The proposed scheme ensures the subtraction of the intracell and the inter-tier interference.

C. Achievable Rates by tier Blind Interference Alignment

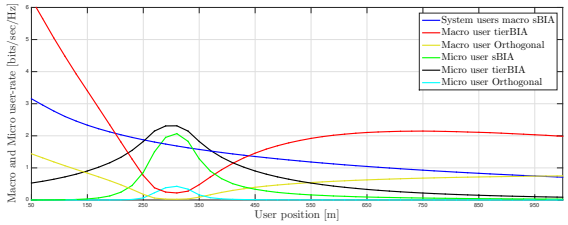
For the user n_i located in the BS j within the tier k, the normalized rate per symbol extension is

$$R^{[n_i,b_{j,k}]} = B_k \mathbb{E}\left[\log\det\left(\mathbf{I} + \bar{P}_k \mathbf{H}^{[b_{j,k},n_i]} \mathbf{H}^{[b_{j,k},n_i]^H} \mathbf{R}_{z_k}^{-1}\right)\right] \quad (3)$$

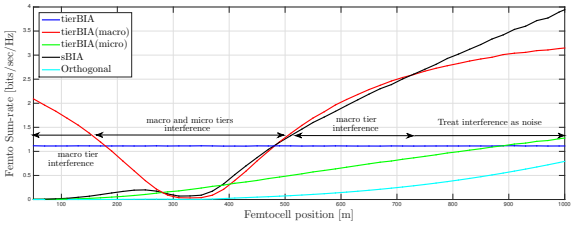
where B_k is the ratio of alignment blocks over the supersymbol length, $\bar{P}_k$ is the power allocated to each stream, and $\mathbf{H}^{[b_{j,k},n_i]}$ is the channel matrix between the BS $b_{j,k}$ and users n_i that contains the value for M_k distinct preset modes, and therefore, it is full rank. Moreover, because of the subtraction of the interference terms, and defining $S_k = \sum_{k'\leq k}^{K} N_{k'}$ and $S'_k = \sum_{k'<k}^{K} N_{k'}$, the covariance matrix of the noise after interference cancellation is $\mathbf{R}_{z_k} = \begin{bmatrix} S_k \mathbf{I}_{M_k-1} & \mathbf{0}_{M_k-1,1} \\ \mathbf{0}_{1,M_k-1} & S'_k \end{bmatrix}$.

V. Simulations Results

In Fig. 3 we show the achievable rates in a one-dimensional 3-tier network where the macro and micro BSs are located in the position 0 and 300 m, respectively, while 5 femtocells are randomly spread. First, notice the poor performance achieved when the macro BS serves all the users as in a 1-tier network. The user rate can be improved by introducing a micro BS as is shown in Fig. 3(a). However, for the micro users the rate achieved by sBIA is subject to interference from the macro tier. By subtracting the interference due to macro tier transmission, the proposed tierBIA outperforms sBIA in the whole distance range. Moreover, since tierBIA does not penalize the performance of the macro tier, this increase corresponds to an improvement in the system rate. For the femto tier, notice in Fig. 3(b) that each femtocell achieves a constant rate for tierBIA considering both macro and micro tiers as sources of interference. However, out of the influence of the micro BS, tierBIA achieves larger rates considering only the macro tier interference. Similarly, beyond the position 730 m the femtocells can treat optimally as noise both sources of interference. Furthermore, the achievable rates are significantly affected by inter-tier interference when it is not managed and the intracell interference is avoided by orthogonal schemes.



(a) Achievable user-rate of the macro and micro tiers.



(b) Achievable sum-rate of a femtocell.

Fig. 3. Comparison of the rates achieved by sBIA, tierBIA considering macro or micro tier, tierBIA considering both macro and micro tier, and orthogonal resource allocations for a 3-tier cellular network. Macro tier $M_1 = 6$, $N_1 = 10$, micro tier $M_2 = 4$, $N_2 = 5$, femto tier $M_3 = 2$, $N_3 = 2$.

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