This document is published in:

Proc. IEEE Globecom. Wireless Communications Symposium (2014) pp. 3725 - 3730

DOI: 10.1109/GLOCOM.2014.7037387

Cognitive Blind Interference Alignment for Macro-Femto Cellular Networks

Máximo Morales Céspedes*, Jorge Plata-Chaves†, Dimitris Toumpakaris‡ and Ana García Armada*
*Department of Signal Theory and Communications. University Carlos III of Madrid, Leganés, Spain
†Stadius Center for Dynamical Systems, Signal Processing and Data Analytics. KU Leuven, Leuven, Belgium
‡Department of Electrical & Computer Engineering. University of Patras, Rio Achaias, Greece
Email: {maximo, agarcia}@tsc.uc3m.es, jplata@esat.kuleuven.be, dtouba@upatras.gr

***Abstract*—A cognitive Blind Interference Alignment scheme is devised for use in macro-femto cellular networks. The proposed scheme does not require any channel state information at the transmitter or data sharing among the Macro Base Station and the Femto Access Points. It achieves transmission to femto cell users without affecting the rates of the Macro users. This is achieved by appropriately combining the supersymbols of the Macro Base Stations and the Femto Access Points. It is shown that in some scenarios the use of this scheme results to considerable rates for Femto users.**

I. Introduction

The increasing demand for high data rates in cellular networks has driven the development of Multiple-Input Multiple-Output (MIMO) systems as a means to achieve high-capacity communications. Moreover, during the last years there has been growing interest in small cells, also known as femtocells. Femto Access Points (FAPs) are Base Stations (BSs) with a reduced radius of coverage operating in the licensed cellular band and usually backhauled onto IP networks through conventional digital subscriber lines (DSL) [1]. They serve a few users, must be low-cost and transmit at low power. Small cells are considered a key element for future cellular networks. Therefore, a heterogeneous network with users connected to several types of cells and often subject to interference from other tiers has to be taken into consideration [2].

Several schemes such as Linear Zero Forcing Beamforming (LZFB) and Interference Alignment (IA) have been proposed to exploit multiple antennas. These transmission techniques try to increase the achievable Degrees of Freedom (DoF), i.e. the multiplexing gain of the system. However, they require coordinated transmission and accurate Channel State Information at the Transmitter (CSIT). To satisfy these requirements high-capacity backhaul links and accurate synchronization between users and BSs are required [3]. As a result, techniques that do not require CSIT are increasingly attractive from an implementation point of view.

Recently, Blind Interference Alignment (BIA) was proposed as a transmission technique that does not require CSIT [4]. Considering the MISO Broadcast Channel (BC) where the transmitter is equipped with N_t antennas and there are K active users, $\frac{N_t K}{N_t+K-1}$ sum DoF can be attained by BIA. Besides, in [4] it is demonstrated that this performance is the maximum achievable in the absence of CSIT. BIA is based on exploiting the channel correlations through a predefined supersymbol. The implementation of [4] requires reconfigurable antennas at the users that can switch their radiation pattern among a set of preset modes [5].

The performance of BIA for homogeneous cellular networks is analyzed in [6]. It is shown that, although the intracell interference can be removed, the remaining intercell interference can have considerable impact on the system performance. The intercell interference can be reduced by coordination of the supersymbols of the BSs. A cooperative BIA solution is proposed for a homogeneous two-cell scenario in [7]. Intercell interference is eliminated by having both BSs transmit the same signals to cell-edge users. Although this solution improves the diversity gain, it is not optimal in terms of DoF. In [8] a transmission scheme based on flexible bandwidth allocation is proposed. It combines the benefits of [6] and [7], and, consequently, performs better in some scenarios.

In this work we propose a BIA scheme for a macro-femto two-tier cellular network that removes the interference caused by the Macro BS to the Femto users without the need for CSIT or data sharing between the Macro BS and the FAPs. The Macro BS transmits using the BIA scheme of [4], whereas the FAPs, whose users are affected by interference from the Macro BS, perform BIA in a cognitive fashion. Therefore, only some synchronization between the Macro BS and the FAPs is required. On the other hand, femtocells far from the Macro BS can treat interference as noise due to path losses [9]. The proposed scheme does not cause any rate loss to macrocell users, which achieve the maximum DoF attainable without CSIT. Moreover, the FAPs are able to transmit non-zero rates to users in their femto cell.

II. System model

We consider a Macro BS equipped with N_m antennas that serves a set $\mathcal{K}_m = \{m_1, \ldots, m_{K_m}\}$ of single-antenna Macro

* This work has been partially funded by research projects COMONSENS (CSD2008-00010) and GRE3N(TEC2011-29006-C03-02).
† This research work was partly carried out at the ESAT Laboratory of KU Leuven in the frame of the Belgian Programme on Interuniversity Attractive Poles Programme initiated by the Belgian Science Policy Office: IUAP P7/23 'Belgian network on stochastic modeling analysis design and optimization of communication systems' (BESTCOM) 2012-2017.
‡ The work of D. Toumpakaris was supported by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program Education and Lifelong Learning of the National Strategic Reference Framework through the Research Funding Program Thales - Investing in knowledge society through the European Social Fund.

users, which are not subject to interference by any other Macro BS or Access Point. Moreover, a set $\mathcal{F} = \{\varphi_1, \ldots, \varphi_F\}$ of FAPs equipped with N_f antennas each, have been deployed randomly over the radio coverage area of the Macro BS. It is assumed that each FAP φ_f transmits to a set $\mathcal{K}_F = \left\{f_{1,\varphi_f}, \ldots, f_{K_f,\varphi_f}\right\}$ of single-antenna Femto users. The set of FAPs, and their users[1], can be categorized as either femtocells limited by interference from the Macro BS or femtocells that can treat it as noise because of path loss. It is assumed that the users are equipped with reconfigurable antennas, which can switch among N_m and N_f preset modes for macro and Femto users, respectively. Since it is assumed that the FAPs do not interfere with each other, only one generic FAP φ_f will be considered from now on. Without loss of generality, the considered scenario for a generic femtocell φ_f is shown in Fig. 1. In the remainder of the paper we will not consider FAPs that treat the interference from the Macro BS as noise. These FAPs can be seen as isolated cells, and therefore, transmission in these cells can be straightforwardly carried out by standard BIA techniques.

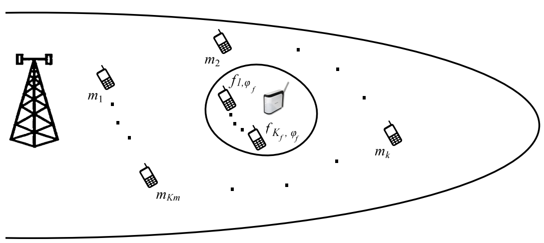

Fig. 1. The considered scenario. The users in femtocell φ_f are subject to interference from the Macro BS that cannot be treated as noise.

The symbols transmitted by the Macro BS can be written in vector form as $\mathbf{x}^{[M]} = \left[x_1^{[M]}, \ldots, x_{N_m}^{[M]}\right]^T$. Due to the low-power transmission of the FAPs, it is assumed that the Macro users are not affected by interference from the FAP. Therefore, if $l^{[m_k]}[i]$ denotes the antenna mode of macro user m_k at time i, the signal received at m_k can be expressed as

$$y^{[m_k]}[i] = \mathbf{h}^{[m_k]}\left(l^{[m_k]}[i]\right)^T \mathbf{x}^{[M]}[i] + z^{[m_k]}[i], \quad (1)$$

where $\mathbf{h}^{[m_k]}(l) \in \mathbb{C}^{N_m \times 1}$, $(l = 1, \ldots, N_m)$ is the channel vector that contains the path loss and shadowing effects between the Macro BS and user m_k for mode l, and $z^{[m_k]}[i]$ is complex circularly symmetric Gaussian noise with unit variance.

Similarly, FAP φ_f transmits a symbol vector $\mathbf{x}^{[\varphi_f]} = \left[x_1^{[\varphi_f]}, \ldots, x_{N_f}^{[\varphi_f]}\right]^T$. However, the Femto users are subject to interference from the Macro BS. Thus, if $l^{[f_{k,\varphi_f}]}[i]$ denotes the antenna mode of Femto user f_{k,φ_f}, the signal received at f_{k,φ_f} at time i can be written as

$$\begin{aligned} y^{[f_{k,\varphi_f}]}[i] = \mathbf{h}^{[f_{k,\varphi_f}]}\left(l^{[f_{k,\varphi_f}]}[i]\right)^T \mathbf{x}^{[\varphi_f]}[i] \\ + \mathbf{h_I}^{[f_{k,\varphi_f}]}\left(l^{[f_{k,\varphi_f}]}[i]\right)^T \mathbf{x}^{[M]}[i] + z^{[f_{k,\varphi_f}]}[i]. \end{aligned} \quad (2)$$

[1]Due to the reduced radius of coverage of the femtocells, it is assumed that all users of a given femtocell are either limited by interference from the Macro BS or can treat it as noise.

In (2), $\mathbf{h}^{[f_{k,\varphi_f}]}\left(l^{[f_{k,\varphi_f}]}[i]\right) \in \mathbb{C}^{N_f \times 1}$, $l^{[f_{k,\varphi_f}]}[i] \in \{1, 2, \ldots, N_f\}$ is the channel vector between the FAP φ_f and user f_{k,φ_f}, whereas $\mathbf{h_I}^{[f_{k,\varphi_f}]}\left(l^{[f_{k,\varphi_f}]}[i]\right) \in \mathbb{C}^{N_m \times 1}$ denotes the channel between the Macro BS and user $f_{k,\varphi_f}[i]$. Moreover, $z^{[f_{k,\varphi_f}]}$ is complex circularly symmetric Gaussian noise with unit variance. We assume that the channel input is subject to an average power constraint $E\left\{\|\mathbf{x}^{[M]}[i]\|^2\right\} \leq P_m$ and $E\left\{\|\mathbf{x}^{[\varphi_f]}[i]\|^2\right\} \leq P_f$. For the sake of simplicity, we focus on the temporal dimension, without loss of generality. Hence, from now on, symbol extension i corresponds to a time slot.

III. Macrocell transmission

The Macro BS employs the BIA scheme of [4], which from now on will be referred to standard BIA (sBIA), without considering the femtocell deployment. The supersymbol is composed of block 1 and block 2, in which simultaneous and orthogonal transmission is employed, respectively. The key idea of the supersymbol design is to create a pattern where *the channel state of the desired user changes while the states of all other users remain constant within the alignment block of the desired user*. Figure 2 shows the supersymbol of the sBIA scheme when the Macro BS is equipped with $N_m = 3$ antennas and there are $K_m = 2$ active users. To simplify the figure, the superscript identifying the macro user has been omitted in the channels between the Macro BS and each Macro user. The first four symbol extensions correspond to block 1 while the following four form block 2. For macro user m_1, the sets of symbol extensions $\{1, 2, 5\}$ and $\{3, 4, 6\}$ form two alignment blocks. In each alignment block 3 DoF are attained by user m_1. Similarly, user m_2 employs two alignment blocks comprising symbol extensions $\{1, 3, 7\}$ and $\{2, 4, 8\}$.

	1	2	3	4	5	6	7	8
m_1	h(1)	h(2)	h(1)	h(2)	h(3)	h(3)	h(1)	h(2)
m_2	h(1)	h(1)	h(2)	h(2)	h(1)	h(2)	h(3)	h(3)

Fig. 2. Supersymbol of the sBIA scheme for $N_m = 3$ and $K_m = 2$.

The transmitted signal corresponding to the supersymbol of Fig. 2 is

$$\mathbf{X}_m = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{u}_1^{[m_1]} \\ \mathbf{u}_2^{[m_1]} \end{bmatrix} + \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \\ \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{u}_1^{[m_2]} \\ \mathbf{u}_2^{[m_2]} \end{bmatrix}, \quad (3)$$

where the vector $\mathbf{u}_i^{[m_k]} \in \mathbb{C}^{3 \times 1}$ contains the symbols transmitted to macro user m_k, $k \in \{1, 2\}$ and $\mathbf{I}$ and $\mathbf{0}$ are the 3×3 identity and zero matrix, respectively.

To decode $\mathbf{u}_\ell^{[m_k]}$ with $\ell \in \{1, 2\}$, user m_k employs the signal received in the ℓ-th alignment block. For instance, the signal received by user m_1 in the first alignment block is given by

$$\begin{bmatrix} y^{[m_1]}[1] \\ y^{[m_1]}[2] \\ y^{[m_1]}[5]\end{bmatrix} = \underbrace{\begin{bmatrix}\mathbf{h}^{[m_1]}(1)^T\\ \mathbf{h}^{[m_1]}(2)^T \\ \mathbf{h}^{[m_1]}(3)^T\end{bmatrix}}_{\mathbf{H}^{[m_1]}} \mathbf{u}_1^{[m_1]} + \underbrace{\begin{bmatrix}\mathbf{h}^{[m_1]}(1)^T\mathbf{u}_1^{[m_2]} \\ \mathbf{h}^{[m_1]}(2)^T\mathbf{u}_2^{[m_2]}\\ \mathbf{0}\end{bmatrix}}_{\text{macro intracell interference}} + \mathbf{z}^{[m_1]}, \tag{4}$$

where $\mathbf{z}^{[m_1]} = \left[z^{[m_1]}[1], z^{[m_1]}[2], z^{[m_1]}[3]\right]^T$. Note that $y^{[m_1]}[1]$ and $y^{[m_1]}[2]$ are received during Block 1, in which simultaneous transmission is employed, and therefore, interference exists. On the other hand, $y^{[m_1]}[5]$ is received during Block 2. Together with $y^{[m_1]}[1]$, $y^{[m_1]}[2]$ and $y^{[m_1]}[5]$ forms a 3×3 system whose unique solution allows user m_1 to decode $\mathbf{u}_1^{[m_1]}$ when the macrocell interference is removed. Moreover, since orthogonal transmission is employed during Block 2, the observation $y^{[m_1]}[5]$ allows the other macro users to measured the interference caused by transmission of $\mathbf{u}_1^{[m_1]}$ during symbol extensions 1 and 2 of Block 1.

Similarly, it can be easily seen that the interference caused by transmission to user m_2 can be measured in symbol extensions $\{7\}$ and $\{8\}$, and, therefore, removed. The signal at m_1 after zero forcing cancellation can be written as

$$\begin{bmatrix} \tilde{y}^{[m_1]}[1] \\ \tilde{y}^{[m_1]}[2] \\ \tilde{y}^{[m_1]}[5]\end{bmatrix} = \begin{bmatrix}\mathbf{h}^{[m_1]}(1)^T\\ \mathbf{h}^{[m_1]}(2)^T \\ \mathbf{h}^{[m_1]}(3)^T\end{bmatrix} \mathbf{u}^{[m_1]} + \begin{bmatrix} z^{[m_1]}[1]-z^{[m_1]}[7] \\ z^{[m_1]}[2]-z^{[m_1]}[8] \\ z^{[m_1]}[3]\end{bmatrix}. \tag{5}$$

Finally, the symbols $\mathbf{u}^{[m_1]}$ are obtained by solving (5).

In the general case, where the Macro BS is equipped with N_m antennas transmitting to K_m users, each user attains N_m DoF in each of $(N_m-1)^{K_m-1}$ alignment blocks. Block 1 occupies $(N_m-1)^{K_m}$ symbol extensions. Because an additional symbol extension per alignment block is required for each user during orthogonal transmission, Block 2 occupies $K_m(N_m-1)^{K_m-1}$ symbol extensions. Therefore, since $K_m N_m (N_m-1)^{K_m-1}$ DoF are achievable during $(N_m-1)^{K_m} + K_m(N_m-1)^{N_m-1}$ symbol extensions, the normalized sum DoF for the Macro users is

$$DoF_{macro} = \frac{K_m N_m (N_m-1)^{K_m-1}}{(N_m-1)^{K_m} + K_m(N_m-1)^{K_m-1}} = \frac{N_m K_m}{N_m + K_m - 1}. \tag{6}$$

In [4] it is shown that sBIA achieves the maximum sum DoF in the absence of CSIT. Therefore, since it has been assumed that the Macro users do not receive signals from any FAP, it is clear that the Macro users achieve the maximum possible sum DoF by using BIA.

IV. Femtocell transmission Using Cognitive Blind Interference Alignment

Although transmission of the FAPs does not cause interference to the Macro users, transmission in Femto users close to the Macro BS are affected by interference. By inspecting the sBIA supersymbol, it can be seen that the Femto users can measure the interference caused by the Macro BS during Block 2, which will be denoted as m-Block 2 from now on. Moreover, because the FAPs do not cause interference to the Macro users, they can transmit during block 1 of the Macro BS, called m-Block 1 from now on, without affecting the rates of the Macro users. In other words, the FAPs carry out a cognitive strategy by transmitting during m-Block 1 while remaining silent during m-Block 2 in order to measure the interference caused by the Macro BS. Consider, now, the simplest case where a Macro BS with $N_m = 2$ antennas serves $K_m = 2$ users and a FAP with only $N_f = 1$ antenna transmits to only $K_f = 1$ user. As can be seen in Fig. 3, the Macro BS employs sBIA and transmits

$$\mathbf{X}_m = \begin{bmatrix}\mathbf{I}\\ \mathbf{I}\\ \mathbf{0}\end{bmatrix}\mathbf{u}_1^{[m_1]} + \begin{bmatrix}\mathbf{I}\\ \mathbf{0}\\ \mathbf{I}\end{bmatrix}\mathbf{u}_1^{[m_2]}. \tag{7}$$

Note that symbols $\mathbf{u}_1^{[m_1]}$ and $\mathbf{u}_1^{[m_2]}$ are sent simultaneously in the first symbol extension (m-Block 1), and in an orthogonal fashion during the following two time slots. Thus, the interference due to transmission of $\mathbf{u}_1^{[m_1]}$ and $\mathbf{u}_1^{[m_2]}$ by the Macro BS can be measured entirely during the last two symbol extensions. This allows the Femto user to remove the interference in slot 1. Therefore, it can receive the signal sent by the FAP in slot 1 without interference.

	1	2	3
m_1	$\mathbf{h}(1)$	$\mathbf{h}(2)$	$\mathbf{h}(1)$
m_2	$\mathbf{h}(1)$	$\mathbf{h}(1)$	$\mathbf{h}(2)$
$f_{1,\varphi f}$	$\mathbf{h}(1)$	$\mathbf{h}(1)$	$\mathbf{h}(1)$

Fig. 3. Supersymbol of the proposed cognitive BIA scheme for $N_m = 2$, $K_m = 2$, $N_f = 1$, and $K_f = 1$.

Assuming that the FAP transmits symbol $\mathbf{u}_1^{[f_{1,\varphi_f}]} \in \mathbb{C}^{1\times 1}$, which corresponds to 1 DoF, the signal received by Femto user f_{1,φ_f} during the first symbol extension is

$$\begin{aligned} y^{[f_{1,\varphi_f}]}[1] &= \mathbf{h}^{[f_{1,\varphi_f}]}(1)^T \mathbf{u}_1^{[f_{1,\varphi_f}]} \\ &\quad + \mathbf{h}_{\mathbf{I}}^{[f_{1,\varphi_f}]}(1)^T \left(\mathbf{u}_1^{[m_1]} + \mathbf{u}_1^{[m_2]}\right) + z^{[f_{1,\varphi_f}]}[1]. \end{aligned} \tag{8}$$

The interference from the Macro BS can be measured in symbol extensions 2 and 3 and removed afterwards. Hence, the signal after zero forcing cancellation is

$$\tilde{y}^{[f_{1,\varphi_f}]}[1] = \mathbf{h}^{[f_{1,\varphi_f}]}(1)^T \mathbf{u}_1^{[f_{1,\varphi_f}]} + \tilde{z}^{[f_{1,\varphi_f}]}[1], \tag{9}$$

where $\tilde{z}^{[f_{1,\varphi_f}]}[1] = z^{[f_{1,\varphi_f}]}[1] - \left(z^{[f_{1,\varphi_f}]}[2] + z^{[f_{1,\varphi_f}]}[3]\right)$. Therefore, each macro user achieves 2 DoF over 3 symbol extensions, which corresponds to the maximum achievable DoF without CSIT, the Femto user attains 1 DoF over the entire supersymbol length, even though it is subject to interference from the Macro BS.

For general N_f and K_f, it may not be possible for the FAPs to implement BIA in only one m-Block 1. This can be easily handled by using multiple macro sBIA supersymbols. In Fig. 4, we show the structure of the supersymbol for this general case, which consists of Super-Block 1 (S-Block 1) and Super-Block 2 (S-Block 2). For the Macro users, S-Block 1 and

S-Block 2 consist of $L_{f-SS} = (Nf-1)^{K_f} + K_f(N_f-1)^{K_f-1}$ repetitions of m-Block 1 and m-Block 2 of a BIA code for K_m users and N_m transmit antennas. On the other hand, for the Femto users S-Block 1 contains $n = (N_m-1)^{K_m}$ re-ordered sBIA Femto supersymbols (f-SS) for K_f Femto users and N_f transmit antennas. The aforementioned re-ordering ensures that the channel mode of each Femto user is constant along any alignment block of any Macro user. This way, the interference caused by the transmission from the Macro BS to any Macro user during one of its alignment blocks is always aligned into one dimension in the signal subspace of any Femto user. Since orthogonal transmission to the Macro users is carried out during S-Block 2, the Femto users can measure the interference from the Macro BS in a cognitive fashion. Clearly, the length of S-Block 1 equals the least common multiple of the lengths of m-Block 1 and f-SS.

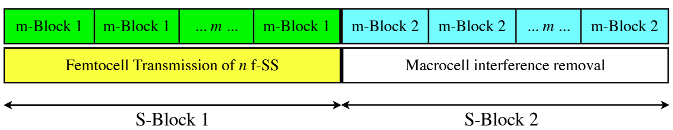

Fig. 4. Structure of the super symbol of cognitive BIA.

In the following we provide a more general example compared to Fig. 3 to demonstrate the construction of the supersymbol of the cognitive BIA scheme. Assuming $N_f = 2$ and $K_f = 2$, the supersymbol of Fig. 5 is used by the FAP.

	1	2	3
f_{1,φ_f}	$\mathbf{h}(1)$	$\mathbf{h}(2)$	$\mathbf{h}(1)$
f_{2,φ_f}	$\mathbf{h}(1)$	$\mathbf{h}(1)$	$\mathbf{h}(2)$

Fig. 5. f-SS for $N_f = 2$ and $K_f = 2$.

Consider, now, the scenario of Fig. 2. Recall that $N_m = 3$ and $K_m = 2$. Following the proposed supersymbol structure, it is possible to build the supersymbol of Fig. 6. The supersymbol of the FAP (f-SS) occupies $(2-1)^2 + 2(2-1) = 3$ symbol extensions while m-Block 1 is made up of $(3-1)^2 = 4$ slots. The least common multiple of 3 and 4 is 12. It can be seen that m-Block 1 is repeated $m = 3$ times during the first 12 symbol extensions and that $n = 4$ f-SSs are used in S-Block 1. Finally, the last 12 symbol extensions, which correspond to S-Block 2, are employed for orthogonal transmission by the Macro users and for cognitive interference removal by the Femto users. By inspecting the supersymbol of Fig. 6, the symbol extensions $\{1,5\}$ constitute an alignment block for Femto user f_{1,φ_f}. The signal received at f_{1,φ_f} is

$$\begin{bmatrix} y^{[f_{1,\varphi_f}]}[1] \\ y^{[f_{1,\varphi_f}]}[5] \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_f}]}(1)^T \\ \mathbf{h}^{[f_{1,\varphi_f}]}(2)^T \end{bmatrix}}_{\mathbf{H}^{[f_{1,\varphi_f}]}} \mathbf{u}_1^{[f_{1,\varphi_f}]} + \underbrace{\begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_f}]}(1)^T \mathbf{u}_1^{[f_{2,\varphi_f}]} \\ \mathbf{0} \end{bmatrix}}_{\text{intracell interference from the FAP}}$$
$$+ \underbrace{\begin{bmatrix} \mathbf{h_I}^{[f_{1,\varphi_f}]}(1)^T \left(\mathbf{u}_1^{[m_1]} + \mathbf{u}_1^{[m_2]}\right) \\ \mathbf{h_I}^{[f_{1,\varphi_f}]}(2)^T \left(\mathbf{u}_3^{[m_1]} + \mathbf{u}_3^{[m_2]}\right) \end{bmatrix}}_{\text{intercell interference from the Macro BS}} + \begin{bmatrix} z^{[f_{1,\varphi_f}]}[1] \\ z^{[f_{1,\varphi_f}]}[5] \end{bmatrix}. \tag{10}$$

Note that there are two terms of interference originating from the FAP and the Macro BS, respectively. The first step is to remove the cross-tier interference from the Macro BS. This interference can be measured in symbol extensions $\{13,19\}$ and $\{15,21\}$ for time slots 1 and 5, respectively. Then the intracell interference from the FAP can be canceled by measuring it in symbol extension 9 in f-Block 2. However, the signal received by f_{1,φ_f} in this time slot is given by

$$y^{[f_{1,\varphi_f}]}[9] = \mathbf{h}^{[f_{1,\varphi_f}]}(1)\left(\mathbf{u}_1^{[f_{1,\varphi_f}]} + \mathbf{u}_5^{[m_1]} + \mathbf{u}_5^{[m_2]}\right) + z^{[f_{1,\varphi_f}]}[9], \tag{11}$$

i.e., it also contains interference from transmission of the symbols $\mathbf{u}_5^{[m_1]}$ and $\mathbf{u}_5^{[m_2]}$ by the Macro BS. Hence, it is necessary to first cancel the interference from the Macro BS by measuring it in symbol extensions $\{17,23\}$, and remove the femtocell interference afterwards. The signal received during the first alignment block of user f_{1,φ_f} after zero forcing interference cancelation can be written as

$$\begin{bmatrix} \tilde{y}^{[f_{1,\varphi_f}]}[1] \\ \tilde{y}^{[f_{1,\varphi_f}]}[5] \end{bmatrix} = \begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_f}]}(1)^T \\ \mathbf{h}^{[f_{1,\varphi_f}]}(2)^T \end{bmatrix} \mathbf{u}_1^{[f_{1,\varphi_f}]}$$
$$+ \begin{bmatrix} z^{[f_{1,\varphi_f}]}[1] - \left(\tilde{z}^{[f_{1,\varphi_f}]}[9] + z^{[f_{1,\varphi_f}]}[13] + z^{[f_{1,\varphi_f}]}[19]\right) \\ z^{[f_{1,\varphi_f}]}[5] - \left(z^{[f_{1,\varphi_f}]}[15] + z^{[f_{1,\varphi_f}]}[21]\right) \end{bmatrix}, \tag{12}$$

where $\tilde{z}^{[f_{1,\varphi_f}]}[9] = z^{[f_{1,\varphi_f}]}[9] - \left(z^{[f_{1,\varphi_f}]}[17] + z^{[f_{1,\varphi_f}]}[23]\right)$. Note that the Femto users suffer a greater noise increment because of interference cancelation. Nevertheless, since in a femtocell the SNR is typically high, the effect of this noise increment may not be significant.

In the general case the Macro BS employs a m-Block 1 comprising of $L_{m-Block1} = (N_m-1)^{K_m}$ symbol extensions, while f-SS occupies $L_{f-SS} = (N_f-1)^{K_f} + K_f(N_f-1)^{K_f-1}$ symbol extensions. In the worst case, where $L_{m-Block1}$ and L_{f-SS} do not have any common factors, m-Block 1 and f-SS are repeated L_{f-SS} and $L_{m-Block1}$ times, respectively. Therefore, each Femto user employs $(N_f-1)^{K_f-1}(N_m-1)^{K_m}$ alignment blocks and attains N_f DoF in each. Since $L_{S-Block1} = L_{f-SS}(N_m-1)^{K_m}$ symbol extensions are used for femto transmission and $L_{S-Block2} = L_{f-SS}K_m(N_m-1)^{K_m-1}$ are required for cognitive macro interference removal, the normalized sum

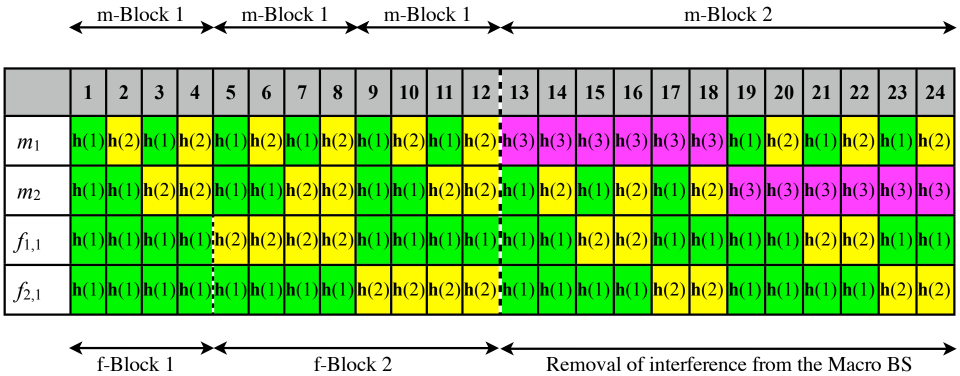

Fig. 6. Cognitive BIA supersymbols for $N_m = 3$, $K_m = 2$, $N_f = 2$ and $K_f = 2$.

DoF per symbol extension for the Femto users is

$$DoF_{femto} = \frac{N_f K_f (N_f-1)^{K_f-1}(N_m-1)^{K_m}}{L_{S-Block1}+L_{S-Block2}} = \frac{N_f K_f (N_m-1)}{(N_m+K_m-1)(N_f+K_f-1)}. \quad (13)$$

Note that the rate of the Macro users is not affected by transmission of the FAP in the proposed scheme. Therefore, the achievable sum DoF_{macro} are given by (6).

V. Achievable rates

In this section we derive closed-form expressions for the achievable rates of the proposed scheme. Similar to [4], equal power allocation to each symbol is assumed.

Since the rates of the Macro users are not affected by interference from the FAPs, the achievable rates are the same as sBIA. Thus, the normalized rate of the m_k-th user is

$$R^{[m_k]} = B_m \mathbb{E}\left[\log\det\left(\mathbf{I} + \bar{P}_m \mathbf{H}^{[m_k]} \mathbf{H}^{[m_k]^H} \mathbf{R}_z^{[m_k]^{-1}}\right)\right], \quad (14)$$

where $\mathbf{H}^{[m_k]} = \left[\mathbf{h}^{[m_k]}(1)^T \quad \dots \quad \mathbf{h}^{[m_k]}(N_m)^T\right]^T \in \mathbb{C}^{N_m \times N_m}$ contains the channel coefficients between macro user m_k and the Macro BS, $B_m = \frac{1}{N_m+K_m-1}$ is the ratio of alignment blocks per macro user over the total number of symbol extensions, $\bar{P}_m = \frac{N_m+K_m-1}{N_m^2 K_m} P_m$ is the power allocated to each symbol and

$$\mathbf{R}_z^{[m_k]} = \begin{bmatrix} K_m \mathbf{I}_{N_m-1} & \mathbf{0}_{N_m-1,1} \\ \mathbf{0}_{1,N_m-1} & 1 \end{bmatrix} \quad (15)$$

is the covariance matrix of the noise after zero forcing cancelation at the receiver.

For Femto user f_{k,φ_f} subject to interference from the Macro BS, the received signal $\mathbf{y}_i^{[f_{k,\varphi_f}]} = \left[y_i^{[f_{k,\varphi_f}]}(1), \dots, y_i^{[f_{k,\varphi_f}]}(N_f)\right]^T$ during a generic alignment block after zero forcing cancelation can be written as

$$\begin{bmatrix} \tilde{y}^{[f_{k,\varphi_f}]}[1] \\ \vdots \\ \tilde{y}^{[f_{k,\varphi_f}]}[N_f] \end{bmatrix} = \begin{bmatrix} \mathbf{h}^{[f_{k,\varphi_f}]}(1)^T \\ \vdots \\ \mathbf{h}^{[f_{k,\varphi_f}]}(N_f)^T \end{bmatrix} \mathbf{u}^{[f_{k,\varphi_f}]} + \tilde{\mathbf{z}}^{[f_{k,\varphi_f}]}, \quad (16)$$

where

$$\tilde{\mathbf{z}}^{[f_{k,\varphi_f}]} = \begin{bmatrix} z^{[f_{k,\varphi_f}]}[1] - \sum_{k=1}^{K_m+K_f-1} z^{[f_{k,\varphi_f}]}[k] \\ \vdots \\ z^{[f_{k,\varphi_f}]}[N_f-1] - \sum_{k=1}^{K_m+K_f-1} z^{[f_{k,\varphi_f}]}[k] \\ z^{[f_{k,\varphi_f}]}[N_f] - \sum_{k=1}^{K_m} z^{[f_{k,\varphi_f}]}[k] \end{bmatrix} \quad (17)$$

is the noise after zero forcing. For simplicity, in (17) we use the index k to refer the symbol extension of Block 2 over which the interference caused by the transmission to a Macro user or a Femto user different from f_{k,ϕ_f} can be measured.

Since equal power allocation is assumed and the FAPs only transmit during m-Block 1 while remain silent during m-Block 2, the power allocated to each symbol is $\bar{P}_f = \frac{(N_f+K_f-1)(N_m+K_m-1)}{N_f^2 K_f (N_m-1)} P_f$. Moreover, $(N_f-1)^{K_f-1}$ alignment blocks repeated $(N_m-1)^{K_m}$ times are used to transmit to each Femto user over the total supersymbol length. Hence, the ratio of alignment blocks per Femto user over the total supersymbol length is

$$B_f = \frac{(N_f-1)^{K_f-1}(N_m-1)^{K_m}}{L_{S-Block1}+L_{S-Block2}} = \frac{N_f-1}{(N_m+K_m-1)(N_f+K_f-1)}. \quad (18)$$

Therefore, the normalized rate of each Femto user f_{k,φ_f} is

$$R^{[f_{k,\varphi_f}]} = B_f \mathbb{E}\left[\log\det\left(\mathbf{I} + \bar{P}_f \mathbf{H}^{[f_{k,\varphi_f}]} \mathbf{H}^{[f_{k,\varphi_f}]^H} \mathbf{R}_z^{[f_{k,\varphi_f}]^{-1}}\right)\right], \quad (19)$$

where $\mathbf{H}^{[f_{k,\varphi_f}]} = \left[\mathbf{h}^{[f_{k,\varphi_f}]}(1)^T \quad \dots \quad \mathbf{h}^{[f_{k,\varphi_f}]}(N_f)^T\right]^T \in \mathbb{C}^{N_f \times N_f}$ are the channel coefficients between f_{k,φ_f} and FAP φ_f, and

$$\mathbf{R}_z^{[f_{k,\varphi_f}]} = \begin{bmatrix} (K_m+K_f)\mathbf{I}_{N_f-1} & \mathbf{0}_{N_f-1,1} \\ \mathbf{0}_{1,N_f-1} & K_m \end{bmatrix}. \quad (20)$$

VI. Simulation results

Figure 7 shows the achievable DoF when cognitive BIA is employed in a macro-femto network. Note that in contrast to other intercell interference mitigation solutions such as Frequency Reuse (FR), cognitive BIA does not involve any rate penalty for the Macro users. Therefore, Femto users achieve nonzero rates, which may be considerable in some scenarios, without any negative consequences for the Macro users. As can be seen, by increasing the number of Macro users the achievable DoF of the Femto users decrease. This is not surprising since the dimensions occupied by the interference from the Macro BS, which has to be removed by measuring it during S-Block 2, increase with the number of Macro users.

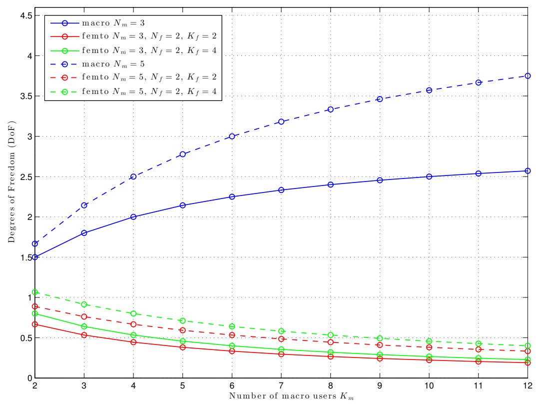

Fig. 7. Achievable sum DoF for macro and Femto users when using the proposed cognitive scheme.

In Fig. 8 the achievable sum rates of the proposed scheme are compared with sBIA and with the FR scheme of [8]. We consider a one-dimensional configuration where a FAP equipped with N_f antennas is located at distance d from a Macro BS with N_m antennas. The path loss model of [3] is used

$$g(d) = \frac{G_0 \delta^{\kappa}}{\delta^{\kappa} + d^{\kappa}}, \tag{21}$$

where κ is the propagation exponent, δ is the 3 dB breakpoint distance, and G_0 fixes the transmitted power at the BS. For the Macro BS, $\kappa = 3.8$, $\delta = 0.05$ km and $G_0 = 80$ dB, whereas for the FAP, $\kappa = 5$, $\delta = 5$ m and $G_0 = 20$ dB.

As can be seen in the figure, the cognitive scheme performs better than the previously proposed schemes in a wide range of d. Note that there is a distance beyond which full frequency reuse (sBIA) achieves better performance than the proposed scheme. Beyond that point it is better to treat interference from the Macro BS as noise. Note also that the sum rate of the Femto users in the absence of interference (the value at 3 km can be considered a reference point where the Femto users are free of interference from the Macro BS) is almost double compared to the sum rate attained by the cognitive scheme. Another way to avoid the interference from the Macro BS would be to split the bandwidth between the transmission of the Macro BS and the FAPs. This approach divides the achievable rates of sBIA for macro and FAP transmission by 2. Therefore, Femto users achieve roughly the same rate by splitting the available bandwidth. However, this FR solution also halves the sum rate of the Macro users. Thus, the proposed cognitive scheme improves the sum rate significantly without affecting the rates of the Macro users.

VII. Conclusions

A cognitive Blind Interference Alignment scheme for femtocell networks limited by cross-tier Macro BS interference is developed in this work. It is shown that the proposed scheme allows the Femto users to remove the interference from an interfering Macro BS without affecting the rates of the users served by the Macro BS. The proposed strategy does not require any CSIT or backhaul data exchange between the Macro BS and the femtocells. Only synchronization is needed to implement cognitive BIA. It is shown that the cognitive scheme attains better performance compared to previously proposed schemes when femtocell transmission is heavily limited by interference from the Macro BS.

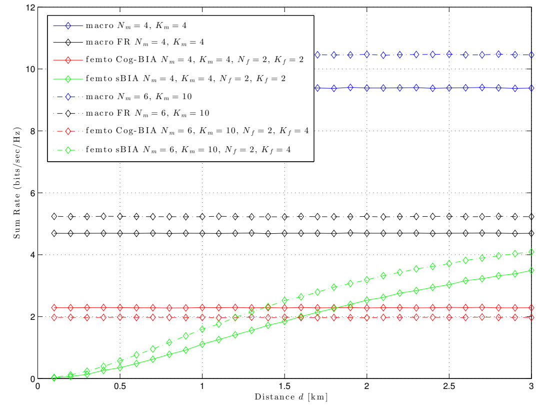

Fig. 8. Comparison of the sum achievable rates. sBIA: standard BIA used by the FAP over the entire supersymbol of the Macro BS (full frequency reuse). FR: Frequency Reuse scheme of [8].

References

[1] V. Chandrasekhar, J. G. Andrews and A. Gatherer, "Femtocell networks: a survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59-67, September 2008.

[2] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Q. S. Quek and J. Zhang, "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 22-30, June 2011.

[3] S. A. Ramprashad, G. Caire and H. C. Papadopoulos, "Cellular and Network MIMO architectures: MU-MIMO spectral efficiency and costs of channel state information," *in Proc. of the Forty-Third Asilomar Conference on Signals, Systems and Computers*, pp. 1811–1818, Nov. 2009.

[4] T. Gou, C. Wang and S. A. Jafar, "Aiming Perfectly in the Dark-Blind Interference Alignment Through Staggered Antenna Switching," *IEEE Trans. Signal Process.*, vol. 59, no. 6, pp. 2734–2744, Jun. 2011.

[5] Q. Rongrong, M. Sellathurai and D. Wilcox, "On the design of Blind Interference Alignment using ESPAR antenna," *International ICST Conference on Communications and Networking in China (CHINACOM), 2012 7*, pp. 866-870, 8-10 Aug. 2012

[6] C. Wang, H. C. Papadopoulos, S. A. Ramprashad and G. Caire, "Design and operation of Blind Interference Alignment in cellular and cluster-based systems," *in Proc. Inf. Theory and Applications (ITA)*, Feb. 2011.

[7] S. Akoum, C. S. Chen, M. Debbah and R. W. Heath Jr, "Data Sharing Coordination and Blind Interference Alignment for Cellular Networks," in *Proc. of IEEE Global Telecommunications Conf.*, Dec, 2012.

[8] M. Morales Céspedes, J. Plata-Chaves, d. Toumpakaris and A. García Armada, "On the Choice of Blind Interference Alignment Strategy for Cellular Systems with Data Sharing," *IEEE International Conf. on Comm. (ICC)*, Jun. 2014.

[9] C. Geng, N. Naderializadeh, A. S. Avestimehr and S. A. Jafar, "On the optimality of treating interference as noise," *51st Annual Allerton Conference on Communication, Control, and Computing*, pp. 1166-1173, 2-4 Oct. 2013.