Cognitive Blind Interference Alignment for Macro-Femto Networks

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***Abstract*—We propose a cognitive blind interference alignment (BIA) scheme for macro-femto two-tier networks where the users are equipped with a single reconfigurable antenna. The proposed scheme fully cancels the intracell interference in both the upper and lower tiers. Moreover, it provides the optimal Degrees of Freedom (DoF) in the macro-tier while the lower tier subject to inter-tier interference achieves non-zero DoF. To do so, the proposed scheme relies on a topology management scheme where the users belong to the macro-tier if and only if they can optimally treat the interference caused by the transmission at the femto-tier as noise. The proposed scheme does not require any channel state information at the transmitter or data sharing between the macro- and femto-tiers. An outer bound of the DoF is derived for the considered macro-femto network. It is demonstrated that the proposed scheme can attain the outer bound subject to optimal sum DoF for the macro-tier. Furthermore, compared to previous approaches, cognitive BIA can achieve better sum rates for macro-femto networks for femtocells subject to different levels of inter-tier interference.**

***Index Terms*—Blind interference alignment, channel state information, degrees of freedom, heterogeneous networks, reconfigurable antennas.**

I. Introduction

THE continuous increasing demand on high data rates for wireless communications results in the development of Multiple-Input Multiple-Output (MIMO) systems or the deployment of heterogeneous networks. The study of the area spectral efficiency for cellular networks carried out in [1] lead to reduce the cell size with the aim of reusing the transmission resource, either time or frequency. As a consequence, the traditional homogeneous cellular networks become heterogeneous and composed by cells of several sizes [2]. In this context, several wireless communication systems have proposed the use of small cells that have low power transmission and that are randomly and sparsely deployed within the coverage area of a macro BS [3], [4]. In this sense, one of the most interesting results shown in [5] is that in principle, with open access and strongest cell selection, adding a lower tier in the traditional deployment does not involve worse interference conditions. However, interference caused by the transmission in the downlink of the upper tier can degrade the performance achieved by the small cells within their coverage area.

Several schemes such as Linear Zero Forcing Beamforming (LZFB) [6] or Interference Alignment (IA) [7] have been proposed to manage interference. These transmission schemes are based on maximizing the Degrees of Freedom (DoF), also known as multiplexing gain, by exploiting the interference instead of treating it as noise. However, besides requiring some feasibility conditions [8], they assume accurate knowledge of the Channel State Information at the Transmitter (CSIT) and coordination among the BSs when applied in a cellular network. To satisfy these requirements, high-capacity backhaul links and synchronization among the users and the BSs are required. Often, a significant amount of network resources is needed to satisfy these requirements [9]. Therefore, techniques based on full CSIT are challenging to implement in a heterogeneous network, where a large amount of small cells coexist with the traditional deployments. Thus, efficient interference management in heterogeneous networks is still an open issue.

Blind Interference Alignment (BIA) was proposed as a transmission scheme that does not require CSIT by considering heterogeneous block fading models [10]. BIA is based on exploiting a sequence of symbol extensions over which the channel state of each user varies according to a predefined pattern, which is referred to as supersymbol. For instance, considering time-selective and frequency-selective users. However, these channel state variations do not occur naturally in most of the scenarios. To generate this predefined pattern of channel states, i.e., the supersymbol, the authors in [11] propose a BIA scheme where each user is equipped with a single reconfigurable antenna. For transmission over a coherence block in which the physical channel is assumed to remain constant, the reconfigurable antenna of each user is able to switch its radiation pattern among a set of preset modes [12]. From now

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on, we consider the use of reconfigurable antennas as the usual concept of BIA. For the Multiple-Input Single-Output Broadcast Channel (MISO BC) where the transmitter is equipped with N_t antennas and there are K active users, a sum-DoF equal to $\frac{N_t K}{N_t+K-1}$ is attained using BIA. In [13] it is demonstrated that this is the maximum achievable DoF in the absence of CSIT.

BIA was initially devised for the BC, and its implementation in a cellular network is not straightforward. The performance of BIA in a homogeneous cellular network was analyzed in [14], [15]. In [16] a novel BIA scheme was proposed for interference networks where the channel have a limited coherence time. By introducing a penalty in the achievable DoF, this scheme is able to reduce the supersymbol length while removing both intra and inter cell interference. However, since this scheme assumes that each transmitter is connected to every receiver, it does not leverage the partial connectivity of the network and, therefore, cancels all the interference signals, which can be unnecessary in practical cellular networks [17]. At this point, the use of the network topology is proposed to manage the interference based on the principle of treating the interference optimally as noise [18]. Basically, the treat interference as noise area of a channel corresponds to the levels of interference where greater performance in terms of capacity or DoF is achievable by considering the interference as a source of noise instead of managing it [19], [20]. Motivated by this approach, to cancel all the intracell interference and the intercell interference that cannot be treated as noise, several BIA schemes [21], [22] were derived. These schemes are based on categorizing the receivers into either *private* users, which receive a weak signal from their neighboring BSs and can treat that interference as noise or *shared* users receiving a strong signal from all BSs managing them as useful signals. Unfortunately, none of them are DoF-optimal. More recently, based on the previous categorization, in [23] the authors propose a BIA scheme that achieves the optimal sum-DoF in symmetric partially connected networks. Nonetheless, when this scheme is implemented in a two-tier network, neither the upper nor lower tiers achieve the optimal sum-DoF. Moreover, several BSs of different tiers need to cooperate in order to jointly transmit data to their corresponding shared users.

In a heterogeneous deployment where several Femtocells Access Points (FAPs) are randomly spread over the coverage area of a macrocell, femto users may receive a strong signal from the macro BS. Note that cooperative schemes between tiers are generally avoided, since they waste a large amount of network resources for signaling [24]. Some techniques that avoid the cooperation between the macro and femto tiers are based on fractional frequency reuse, distributed power control and static resource partitioning [25], [27]. However, the performance of these techniques is generally suboptimal in terms of sum-rate or sum-DoF. There also exist a few recent schemes [28], [29] that apply BIA. In [28], the authors propose several heuristic schemes that exploit the location information of the users and the BSs to reduce the supersymbol length. Moreover, in [29] a Kronecker product representation is used to design a BIA scheme for specific two-tier networks. Although these schemes cancel the intracell and the inter-tier interference through coordinated transmission between both tiers without CSIT, they are generally suboptimal in the DoF sense.

This work considers a macro-femto cellular network where each user is equipped with one reconfigurable antenna. Building on our preliminary work [30], it addresses the design of a transmission scheme that employs BIA to fully cancel both the intracell interference of both tiers as well as the inter-tier interference. The proposed scheme does not require CSIT or data sharing between the two tiers. Only some synchronization in the transmission structure of the femto tier is required. Since the proposed scheme is based on measuring the interference subspace because of the macro BS transmission at the femto users while the FAPs are in silent and subtract this inter-tier interference afterwards from the symbol extension where the FAPs are active, we can considered the proposed scheme as *cognitive*. Moreover, due to this cognitive approach, under the proposed scheme the deployment of cells at the femto tier is transparent for the macro tier. Given these desirable features, the main contributions of this work can be summarized as highlighted below.

Maximum DoF for macro users: Since the macro BS does not employ any of its resources for transmission or cooperation to the femto tier, the macro users obtain the maximum sum-DoF without CSIT given by [10], [13].

Non-zero DoF for femto users: In contrast to the use of other approaches applied to macro-femto networks, e.g. [16], [22], [23], achieving the optimal DoF in the macro tier, i.e., occupying all the signal dimensions without CSIT, does not involve to obtain zero-DoF at the femto users subject to inter-tier interference by leveraging on the partial connectivity of the macro-femto network.

DoF for two-tier networks: For a two-tier network, we derive an upper bound for the sum-DoF of the lower (femto) tier as a function of the sum-DoF of the upper (macro) tier in which the lower tier is contained. We show that under the constraint that the sum-DoF of the macro tier be maximized, the proposed cognitive scheme attains the optimal sum-DoF in the femto tier.

Grow of the DoF in the femto tier: Since adding a new femtocell does not involve a penalty for the macro users without the need for cooperation or resource division, within the range of femtocell density where the intercell interference between femtocells can be treated optimally as noise, which is discussed in detail during Section VII, the achievable sum-DoF of the system can grow linearly with the number of femtocells.

Achievable rate: Through extensive computer simulations, it is shown that the sum-DoF achieved by the proposed scheme results in achievable rates that outperform other BIA schemes applied to the macro-femto networks.

The remainder of the paper is organized as follows. In Section II the system model is presented. Section III provides a brief overview of the implementation of BIA in a single-tier network. Moreover, to provide a baseline scheme where the macro and femto tiers can cooperate, Section III extends the nBIA scheme proposed in [23] to the considered macro-femto network. Next, Section IV presents the proposed cognitive BIA (cogBIA) scheme. In Section V, we show the sum-DoF optimality of cogBIA by providing an outer bound for the sum-DoF in a two-tier network. In Section VI, closed-form expressions are provided for the rates achieved by the cogBIA scheme. Section VII presents some simulation results where the performance of cogBIA is compared to other BIA-based schemes. Finally, Section VIII provides concluding remarks.

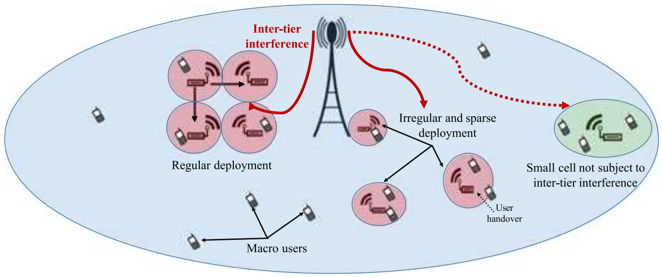

Fig. 1. Two-tier cellular network.

II. System model

We consider a macro-femto cellular network[1] as is shown in Fig. 1. In this network, there is a macro BS equipped with N_m antennas. Additionally, a set of F FAPs, i.e., $\mathcal{F} = \{\varphi_1, \ldots, \varphi_F\}$, each equipped with N_f antennas, has been randomly deployed over the radio coverage area of the macro BS. For the considered scenario, a set of $\mathcal{K}_{tot} = \{1, \ldots, K_{tot}\}$ users are randomly distributed over the cellular network. Each of these users is equipped with one single reconfigurable antenna that can switch among different preset modes. Since the macrocell is generally overwhelmed as the density of users increases, we aimed at maximizing the use of the lower tier. Thus, we assume that the users within the coverage footprint of a femtocell are always served by the corresponding FAP even if they are subject to macro tier interference. Therefore, we can distinguish between macro users, which are out of the footprint area of any FAP by definition, and femto users served by the femtocell deployment.

After categorizing the set of users, the macro BS serves a set of K_m macro users $\mathcal{K}_m = \{m_1, \ldots, m_{K_m}\}$. The symbols transmitted by the macro BS can be written in vector form as $\mathbf{x}^{[M]} = \left[x_1^{[M]}, \ldots, x_{N_m}^{[M]}\right]^T$. Thus, the signal received by macro user m_k at time i can be written as

$$y^{[m_k]}[i] = \mathbf{h}^{[m_k,M]}\left(l^{[m_k]}[i]\right)^T \mathbf{x}^{[M]}[i] + \underbrace{\sum_{f=1}^{F} \mathbf{h}^{[m_k,\varphi_f]}\left(l^{[m_k]}[i]\right)^T \mathbf{x}^{[\varphi_f]}}_{\text{inter-tier interference}} + z^{[m_k]}[i] \quad (1)$$

$$\approx \mathbf{h}^{[m_k,M]}\left(l^{[m_k]}[i]\right)^T \mathbf{x}^{[M]}[i] + z^{[m_k]}[i], \quad (2)$$

where $\mathbf{h}^{[m_k,M]}\left(l^{[m_k]}[i]\right) \in \mathbb{C}^{N_m \times 1}$ is the channel vector that contains the path loss and shadowing effects between the N_m antennas of the macro BS at the l-th preset antenna mode $(l = 1, \ldots, N_m)$ of the reconfigurable antenna of macro user m_k at time instant i and $z^{[m_k]}[i]$ is complex circularly symmetric Gaussian noise with zero mean and unit variance. Besides, in (1) the macro user can receive the signal because of transmission in the femto tier where $\mathbf{x}^{[\varphi_f]} \in \mathbb{C}^{N_f \times 1}$ is the signal transmitted by the FAP φ_f and where $\mathbf{h}^{[m_k,\varphi_f]}\left(l^{[m_k]}[i]\right) \in \mathbb{C}^{N_f \times 1}$ denotes the channel vector between the FAP φ_f and the macro user m_k at preset mode l and time i. According to the strategy described above, a macro user is only connected to the macro tier if and only if it can optimally treat the interference from the femto tier as noise. That is, if the macro user is out of the footprint of any FAP, and therefore, greater performance in terms of capacity or DoF, is achievable by computing the signal received from the set of FAPs as noise than managing them as useful signals or dividing the transmission resource, either time or frequency, to avoid its influence. Under this condition the signal received by the macro user m_k at time i can be approximated as in (2). If a macro user moves to the footprint of a FAP it proceeds to hand over to the femto tier, which contributes to unload the macrocell.

[1]Although we focus on a macro-femto network, notice that the considered system model as well as the derived results are applicable to any other kind of two-tier network.

Similarly, the signal transmitted by the FAP φ_f can be written as $\mathbf{x}^{[\varphi_f]} = \left[x_1^{[\varphi_f]}, \ldots, x_{N_f}^{[\varphi_f]}\right]^T$. For the considered macro-femto network, each femto user is connected to the strongest FAP from which receives signal. In this context, there exist femtocells that do not receive a strong interference from the macro BS and that can optimally treat the inter-tier interference as noise. That is, greater performance can be achievable by treating the inter-tier interference because of macro BS transmission as noise than avoiding it through orthogonal resource division or managing it as a useful signal. As a result, these femtocells can transmit and manage the intracell interference as isolated BSs. Being the focus of the paper from now on, there also exist femtocells whose users are subject to strong interference caused by the transmission of the macro tier. The signal received by the user f_{k',φ_f} in this kind of femtocells is given by

$$y^{[f_{k',\varphi_f}]}[i] = \mathbf{h}^{[f_{k',\varphi_f},\varphi_f]}\left(l^{[f_{k',\varphi_f}]}[i]\right)^T \mathbf{x}^{[\varphi_f]}[i] + z^{[f_{k',\varphi_f}]}[i] + \mathbf{h}^{[f_{k',\varphi_f},M]}\left(l^{[f_{k',\varphi_f}]}[i]\right)^T \mathbf{x}^{[M]}[i] + \underbrace{\sum_{f^\star=1}^{F} \mathbf{h}^{[f_{k',\varphi_f},\varphi_{f^\star}]}\left(l^{[f_{k',\varphi_f}]}[i]\right)^T \mathbf{x}^{[\varphi_{f^\star}]}}_{\mathcal{I}_{f^\star}} \quad (3)$$

where, for the l-th antenna mode and time i, $\mathbf{h}^{[f_{k',\varphi_f},\varphi_f]}(l^{[f_{k',\varphi_f}]}[i]) \in \mathbb{C}^{N_f \times 1}$ is the channel vector between the FAP φ_f and user f_{k',φ_f}, $\mathbf{h}^{[f_{k',\varphi_f},M]}(l^{[f_{k',\varphi_f}]}[i]) \in \mathbb{C}^{N_m \times 1}$ denotes the channel between the macro BS and femto user f_{k',φ_f} and $z^{[f_{k',\varphi_f}]}[i]$ denotes complex circularly symmetric Gaussian noise with zero mean and unit variance. Moreover, in (3) the term $\mathcal{I}_{f^\star}$ corresponds to the intercell interference in the lower tier. Assuming that the density of the femtocell deployment is not very high, the term $\mathcal{I}_{f^\star}$ will be optimally treated as noise, i.e. $\mathcal{I}_{f^\star} \approx 0$. Here, we use index k' instead of k to distinguish from macro users in further derivations. Additionally, if a femto user moves out of the operating range of the femtocell, we consider that it proceeds to hand over to the macro tier.

We assume that the transmitted signals are subject to an average power constraint $\mathbb{E}[\|\mathbf{x}^{[M]}[i]\|^2] \leq P_m$ and $\mathbb{E}[\|\mathbf{x}^{[\varphi_f]}[i]\|^2] \leq P_f$. We also assume that the switching pattern functions $l^{[m_k]}[i]$ and $l^{[f_{k',\varphi_f}]}[i]$ are predetermined and known beforehand. On the contrary, the transmitters do not have any CSIT. The channel coefficients between each user and the transmitter, macro or femto, are drawn from a continuous distribution and, therefore, are linearly independent almost surely. Additionally, we assume that the channels stay constant for a sufficiently large number of time or frequency slots. For simplicity, we focus on the temporal dimension without loss of generality. Therefore, each symbol extension corresponds to a time slot i. Nevertheless, all results can be easily applied to the frequency domain.

In the considered model, the macro BS sends data to macro user m_k at rate $R^{[m_k]}$. From the definitions in [11], note that the rate tuple $R^{[m]} = (R^{[m_1]}, \ldots, R^{[m_k]}, \ldots, R^{[m_{K_m}]})$ is achievable if every macro user can decode its desired symbols with arbitrarily small probability of error by coding over sufficient channel uses. From the closure of all the achievable rate tuples of the macro users, which is denoted as the capacity region of the macro users $\mathcal{C}^{[m]}$, the sum-DoF of the macro users is defined as

$$d_{\Sigma_{\text{macro}}} = \lim_{P_m \to \infty} \max_{R^{[m]} \in \mathcal{C}^{[m]}} \frac{\sum_{k=1}^{K_m} R^{[m_k]}}{\log(P_m)}. \quad (4)$$

Similarly, the sum-DoF for the femto users of an arbitrary FAP φ_f is defined as

$$d_{\Sigma_{\text{femto}}} = \lim_{P_f \to \infty} \max_{R^{[f]} \in \mathcal{C}^{[f]}} \frac{\sum_{k'=1}^{K_f} R^{[f_{k',\varphi_f}]}}{\log(P_f)} \quad (5)$$

where $\mathcal{C}^{[f]}$ denotes the capacity region of the femto users at the FAP φ_f, $R^{[f]} = (R^{[f_{1,\varphi_f}]}, \ldots, R^{[f_{k',\varphi_f}]}, \ldots, R^{[f_{K_f,\varphi_f}]})$ with $R^{[f_{k',\varphi_f}]}$ denoting the rate of femto user f_{k',φ_f}.

It is interesting to remark that the DoF metric corresponds to the measure of the accessible dimensions, the multiplexing gain or the pre-log factor of the capacity. As such the fundamental significance of the DoF metric is evident. Considering a macro-femto network the DoF can be interpreted as the pre-log factor of the sum-rate when the interference is avoided. Therefore, assuming a femtocell heavily limited by inter-tier interference, since the FAP can provide high SNR within the short range of the femtocell footprint [3], the DoF corresponds to the pre-log factor of the femto users once the interference has been canceled, for instance through a transmission scheme such as the proposed cogBIA scheme.

III. Blind Interference Alignment for Two-Tier Networks

A. Standard BIA

We begin with a brief overview of the scheme derived in [11], which we refer to as standard BIA (sBIA). In particular, to introduce some useful notation and provide a starting point in the derivation of the proposed cognitive scheme, we focus on the use of sBIA by the macro BS without considering the femtocell deployment.

Following the scheme in [11], the mode l of the antenna at the different macro users should follow a pattern along a sequence of symbol extensions over which transmission to the macro users takes place. This sequence is called supersymbol, and consists of a total of

$$L_{\text{M-SS}} = (N_m - 1)^{K_m} + K_m(N_m - 1)^{K_m - 1} \quad (6)$$

symbol extensions divided in two blocks. On the one hand, Block 1 is composed of the first $(N_m - 1)^{K_m}$ symbol extensions over which simultaneous transmission to all macro users takes place. On the other hand, Block 2 is formed by the last $K_m(N_m - 1)^{K_m - 1}$ symbol extensions over which orthogonal transmission is employed.

For each macro user, the supersymbol consists of $(N_m - 1)^{K_m - 1}$ alignment blocks, each formed by N_m symbol extensions over which N_m DoF are obtained. During each alignment block, the user m_k switches through all N_m preset modes to ensure decodability of the desired symbols. On the contrary, the channels $\mathbf{h}^{[m_j]}$ of all other users, $j \neq k$, remain in a specific preset mode to align the signal intended to user m_k into one dimension at their signal space. From now on, we refer to as *BIA criterion* the condition from which the channel state of a user changes during each of its alignment blocks while the channel state of all other users remains constant over groups within the alignment block of the considered user.

According to the definition of alignment block, if we ignore the noise, we can express the received signal vector $\mathbf{y}^{[m_k]}$ by macro user m_k in any of its alignment blocks as

$$\mathbf{y}^{[m_k]} = \mathbf{H}^{[m_k]}\mathbf{u}_\ell^{[m_k]} + \underbrace{\begin{bmatrix} \mathbf{h}^{[m_k]}(1)^T \sum_{j \neq k} \mathbf{u}^{[m_j]} \\ \vdots \\ \mathbf{h}^{[m_k]}(N_m - 1)^T \sum_{j \neq k} \mathbf{u}^{[m_j]} \\ 0 \end{bmatrix}}_{\text{interference}} \quad (7)$$

where $\mathbf{H}^{[m_k]} = \text{col}\{\mathbf{h}^{[m_k]}(l)^T\}_{l=1}^{N_m} \in \mathbb{C}^{N_m \times N_m}$ is a full-rank matrix almost surely and $\mathbf{u}_\ell^{[m_k]} \in \mathbb{C}^{N_m \times 1}$ contains the N_m symbols transmitted by the macro BS to user m_k in its ℓ-th alignment block. As explained in [11], the first $N_m - 1$ symbol extensions of one alignment block belong to Block 1, while the last symbol extension belongs to Block 2. Since simultaneous transmission takes place during Block 1, transmission in the first $N_m - 1$ symbol extensions of the alignment block causes interference to other macro users. However, since orthogonal transmission is employed in Block 2 and the channel mode of all other macro users m_j is kept constant along the alignment block of macro user m_k, i.e., the alignment blocks satisfy the BIA criterion this interference can be removed by applying zero forcing based on the signal received by macro user m_j during the last symbol extension of the alignment block of m_k. Similarly, the interference terms in the alignment block of user m_k (see (7)) can be removed by measuring it in appropriate slots of Block 2. Then, as long as the $\{\mathbf{h}^{[k]}(m)\}_{m=1}^{M}$ are linearly independent, the N_m data streams in $\mathbf{u}_\ell^{[m_k]}$ can be decoded by solving the resulting linear system $\tilde{\mathbf{y}}^{[m_k]} = \mathbf{H}^{[m_k]}\mathbf{u}_\ell^{[m_k]}$, where $\tilde{\mathbf{y}}^{[m_k]}$ is the received signal after subtracting the interference measured in Block 2.

Since each of the K_m users achieves N_m DoF in each of its $(N_m - 1)^{K_m - 1}$ alignment blocks, which are distributed over a supersymbol of $(N_m - 1)^{K_m} + K_m(N_m - 1)^{K_m - 1}$ symbol extensions, the sum-DoF per symbol extension achieved by the K_m macro users equals

$$\text{DoF}_{\text{m,sBIA}} = \frac{N_m K_m}{N_m + K_m - 1}. \quad (8)$$

Note that sBIA achieves the optimal sum-DoF for the macro BS in absence of CSIT [13]. For a macro-femto cellular network, note also that the macro users can only achieve (8) if the macro BS does not transmit data to the femto users.

B. Network BIA for the Macro-Femto Network

The network BIA scheme (nBIA) devised in [23] can be applied to a macro-femto network. In summary, the key idea of nBIA lies in the construction of a supersymbol formed by alignment blocks for networks with partial connectivity. If a user k is served by N_k transmit antennas, its alignment block consists of N_k symbol extensions over which its antenna switches through N_k different preset modes in order to receive N_k distinguishable data streams. At the same time, to align the aforementioned N_k beams into one dimension at other users subject to interference caused by the transmission to user k, their channel state is maintained constant over the symbol extensions that form the alignment block of user k.

Focused on a macro-femto cellular network, according to [23] users are *private* if they only receive the signals of the N_m antennas of the macro BS. As a result, *private* users can treat the inter-tier interference as noise. On the other hand, users are considered to be *shared* users if they receive signals with similar power from both the N_f antennas of a neighboring FAP and the N_m antennas of the macro BS. Taking all these features into account, from [23] we can adapt the nBIA scheme for a macro-femto network that has one macro BS with N_m antennas and K_m marco (*private*) users as well as F FAPs, each with N_f antennas and K_f femto (*shared*) users. Since for the nBIA scheme the macro BS transmits data to both the macro and the femto users, the transmission of data to either a macro or a femto user causes interference to the rest of users in the network. As a result, the beams transmitted to any of the users in the network need to be aligned into one dimension at all other users. For the nBIA scheme the supersymbol comprises a Block 1 consisting of

$$L_{\mathrm{SB1,nBIA}} = (N_m - 1)^{K_m} \, (N-1)^{K_f} \tag{9}$$

symbol extensions over which simultaneous transmission takes place, with $N = N_m + N_f$. Since $(N_m - 1)$ symbol extensions of the alignment block of a macro user belong to Block 1, a total of $(N_m - 1)^{K_m - 1}(N-1)^{K_f}$ alignment blocks are allocated for each macro user. Similarly, since $(N-1)$ symbol extensions of the alignment block of a femto user belong to Block 1, the supersymbol has $(N_m - 1)^{K_m} \, (N-1)^{K_f - 1}$ alignment blocks for each femto user.

To complete the alignment block of any user and allow the other users to measure the interference created within the alignment block, each user employs one symbol extension of Block 2 over which the beams associated with the considered alignment block are transmitted free of interference. Therefore,

$$t_{\mathrm{p,nBIA}} = K_m \left[(N_m - 1)^{K_m - 1} \, (N-1)^{K_f} \right] \tag{10}$$

and

$$t_{\mathrm{s,nBIA}} = F \, K_f \left[(N-1)^{K_f - 1} \, (N_m - 1)^{K_m} \right] \tag{11}$$

symbol extensions are required in Block 2 to complete the alignment blocks of all the macro and femto users, respectively. Noting that each macro and femto user achieves N_m and N DoF per alignment block, respectively, the sum-DoF per symbol extension for the K_m macro users achieved by adopting the nBIA scheme of [23] equals

$$\mathrm{DoF}_{\mathrm{p,nBIA}} = \frac{N_m K_m (N-1)}{(N-1)(N_m + K_m - 1) + F \, K_f (N_m - 1)}, \tag{12}$$

whereas the sum-DoF per symbol extension achieved by the K_f femto users jointly served by both tiers is

$$\mathrm{DoF}_{\mathrm{s,nBIA}} = \frac{N K_f (N_m - 1)}{(N-1)(N_m + K_m - 1) + F \, K_f (N_m - 1)}. \tag{13}$$

IV. Cognitive Blind Interference Alignment

Although the nBIA approach of the previous section cancels both the intracell and the inter-tier interference, it requires to waste a large amount of network resources for cooperation of both tiers. Furthermore, since some of the macro users could optimally treat the inter-tier interference as noise, under nBIA notice that the DoF achieved by these users decrease with the number of FAPs F, as can be seen from (12).

In the following we formulate the DoF achievable by the femto users as a function of the DoF, i.e., the signal space, of the macro tier in which the femto users are contained.

Theorem 1: For a macro-femto network where the macro BS has N_m antennas that serve K_m macro users and each FAP is equipped with N_f antennas serving K_f users as defined in Section II. In the absence of CSIT, the DoF outer bound for a generic FAP subject to macro-femto interference is given by

$$d_{\Sigma_{\mathrm{femto}}} \leq \frac{K_f N_f}{K_f + N_f - 1} \left[1 - \frac{K_m}{\max{(N_m, N_f)}} d_{\Sigma_{\mathrm{macro}}} \right] \tag{14}$$

where $d_{\Sigma_{\mathrm{femto}}}$ and $d_{\Sigma_{\mathrm{macro}}}$ denote the sum-DoF for the femto and macro tier, respectively.

Proof: See Section V. ■

In this section, we derive a BIA scheme that achieves the outer bound (14). We propose a novel cognitive BIA (cogBIA) scheme where the macro BS exclusively transmits to users that can optimally treat the inter-tier interference as noise. On the contrary, unlike the nBIA scheme, under the cogBIA scheme the femto tier exclusively transmits to users within the coverage footprint of a femtocell even if they are heavily limited by inter-tier interference. The inter-tier interference subspace because of macro BS transmission can be measured at the femto users during some periods of the supersymbol where the FAPs remain in silent as in a *cognitive* fashion. By following the aforementioned categorization of macro and femto users, the proposed scheme let the macro BS transmit independently of the femtocell deployment and let the macro users attain the optimal sum-DoF without CSIT. That is, the macro BS occupies all the signal dimensions in absence of CSIT. Despite this fact, unlike other existing interference management techniques, e.g., [16], [22], [23], the proposed cogBIA interestingly provides non-zero DoF to the femto users by leveraging the partial connectivity of the network. In other words, the inter-tier interference is avoided without dividing the transmission resources of the macro BS or the need for cooperation between tiers.

A. Femtocell Transmission Using Cognitive BIA

To illustrate the proposed cognitive scheme, we first consider a toy macro-femto network formed by $F = 1$ FAP with $N_f = 2$

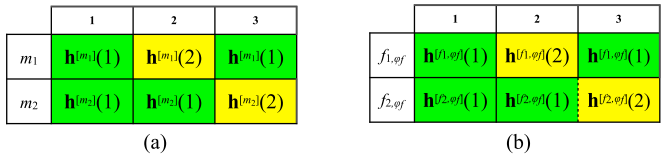

Fig. 2. Supersymbol of the sBIA scheme for a) $N_m = 2$ transmit antennas serving $K_m = 2$ macro users and for b) $N_f = 2$ and $K_f = 2$ femto users.

antennas and $K_f = 2$ femto users as well as one macro BS that has $N_m = 2$ antennas transmitting data to $K_m = 2$ macro users. To let the macro users achieve the optimal sum-DoF in the absence of CSIT, the macro BS implements the sBIA scheme with the supersymbol shown in Fig. 2(a). The signal transmitted by the macro BS is given by

$$\mathbf{X}_m = \begin{bmatrix} \mathbf{x}^{[M]}[1] \\ \mathbf{x}^{[M]}[2] \\ \mathbf{x}^{[M]}[3] \end{bmatrix} = \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_2 \\ \mathbf{0}_2 \end{bmatrix} \mathbf{u}_1^{[m_1]} + \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{0}_2 \\ \mathbf{I}_2 \end{bmatrix} \mathbf{u}_1^{[m_2]}, \tag{15}$$

where $\mathbf{u}_1^{[m_k]} \in \mathbb{C}^{2\times 1}$ contains the symbols to macro user m_k. For the toy example, the supersymbol of the macro users consists of 3 symbols. The first symbol extension belongs to Block 1, referred to as m-Block 1, while the last 2 symbol extensions form Block 2, referred to as m-Block 2.

With the aim of achieving as many DoF as possible without CSIT, we also assume that each FAP employs the sBIA scheme to transmit data to its users and manage the intracell interference. Hence, the supersymbol of the FAP (f-SS) is as shown in Fig. 2(b). Analogously to the supersymbol of the macro users, the supersymbol f-SS consists of two blocks, referred to as f-Block 1 and f-Block 2. Recall that the users are only served by the macro BS if and only if they can optimally treat the inter-tier interference caused by the transmission of the femto tier as noise. As a result, each FAP can implement the sBIA scheme and transmit data to its femto users without causing interference in the macrocell users. However, according to the proposed topological approach notice that the macro-femto interference hampers the femto users when they decode the signals transmitted from the FAP.

Since the macro BS transmits to the macro users in an orthogonal fashion during m-Block 2, the symbol extensions of this block can be leveraged by the femto users to measure the macro-femto interference. To achieve this, the FAPs do not transmit during m-Block 2, and therefore only transmit data to their corresponding femto users during m-Block 1. Moreover, the alignment blocks of the resulting supersymbol comprising macro and femto transmission must satisfy the BIA criterion. That is, at each femto user both the signal received as a result of the orthogonal transmission of $\mathbf{u}_\ell^{[m_k]}$ during m-Block 2 and the macro-femto interference caused by the repeated transmission of $\mathbf{u}_\ell^{[m_k]}$ over different symbol extensions of m-Block 1 need to be aligned into the same dimension.

For the toy example and for the general case, the length of m-Block 1, referred to as q, is not equal to the length of supersymbol f-SS. When the macro BS implements a sBIA scheme for K_m users served by N_m antennas, from [11]

$$q = (N_m - 1)^{K_m}. \tag{16}$$

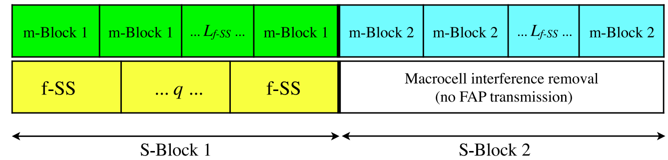

Fig. 3. Macro and femto supersymbol for cogBIA.

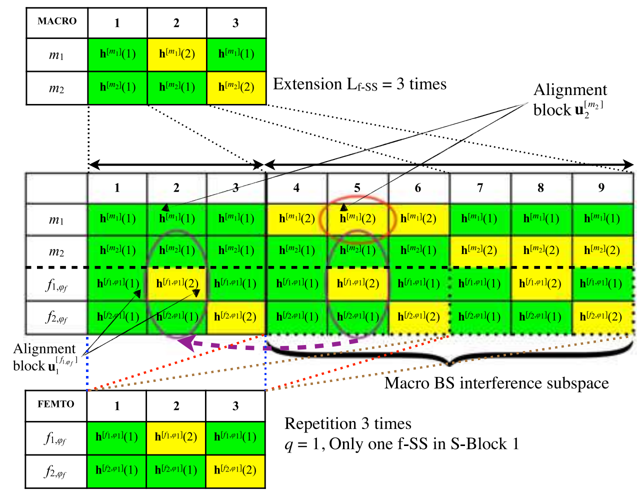

Fig. 4. Construction of the cogBIA supersymbol for $N_m = N_f = 2$ and $K_m = K_f = 2$.

On the contrary, if each FAP transmits to K_f femto users by employing N_f antennas the length of supersymbol f-SS is

$$L_{\text{f-SS}} = (N_f - 1)^{K_f} + K_f (N_f - 1)^{K_f - 1}, \tag{17}$$

which is not necessarily equal to q. As a result, a FAP might not be able to implement a supersymbol f-SS within one m-Block 1 so that the antenna switching pattern of each femto user aligns into one dimension the intracell interference and the macro-femto interference caused by the transmission of $\mathbf{u}_\ell^{[m_k]}$ from the macro BS. This issue can be handled by extending and repeating properly the supersymbol of the macro and femto users. As shown in Fig. 3, this approach results in a supersymbol whose Block 1, referred to as S-Block 1, consists of q identical supersymbols f-SS and $L_{\text{f}-\text{SS}}$ m-Blocks 1 for the femto and macro users, respectively.

The resulting supersymbol consists on extending the sBIA supersymbol for the macro users $L_{\text{f}-\text{SS}} = 3$ times as is shown in Fig. 4. Thus, the macro users obtain $L_{\text{f}-\text{SS}}$ identical m-Blocks 1. Mathematically, it corresponds to extend each symbol extension of the sBIA supersymbol for the macro users $L_{\text{f}-\text{SS}}$ times, which results in a S-Block 1 comprising 3 symbol extensions corresponding to the channel state $\mathbf{h}^{[m_k]}(1)$, $k = \{1, 2\}$, for the considered toy example. Thus, the temporal correlation function of the macro user m_k is

$$g_{m_k}(i) = \mathbf{h}^{[m_k]}(1) \text{ if } i \in \{1, 2, 3\}. \tag{18}$$

Notice that after extending the sBIA supersymbol of the macro users the S-Block 1 comprises 3 symbol extensions where the preset mode of the macro users equals $\mathbf{h}^{[m_k]}(1)$ allowing to align a complete f-SS supersymbol, i.e., satisfying the BIA criterion. That is, the femto users can modify their channel state while the macro users maintain a constant channel state. Therefore, the FAP φ_f can transmit a entire f-SS supersymbol, comprising f-Block 1 and f-Block 2, during the three symbol extensions that compose the S-Block 1 as is shown in Fig. 4. The temporal correlation function for the femto user f_{k',φ_f} during the symbol extensions $\{1,2,3\}$ is

$$g_{f_{k',\varphi_f}}(i) = \begin{cases} \mathbf{h}^{[f_{k',\varphi_f}]}(2) & \text{if } i = k'+1 \\ \mathbf{h}^{[f_{k',\varphi_f}]}(1) & \text{otherwise} \end{cases}, \quad (19)$$

which, for this particular toy example, corresponds to $q = 1$ f-SS supersymbol.

As a result of extending the sBIA supersymbol of the macro users $L_{\text{f-SS}} = 3$ times, each macro user $m_k, k = \{1,2\}$, obtains 3 alignment blocks corresponding to the symbols $\mathbf{u}_\ell^{[m_k]} \in \mathbb{C}^{2\times 1}$, $\ell = \{1,2,3\}$, each. Since each macro user requires a symbol extension with the preset mode $\mathbf{h}^{[m_k]}(2)$ to complete each alignment block, the S-Block 2 comprises 6 symbol extension. For instance, the symbol extensions $\{1,4\}$, $\{2,5\}$ and $\{3,6\}$ constitute the 3 alignment blocks for the macro user m_1 as can be seen in Fig. 4. Moreover, the macro BS transmits each symbol $\mathbf{u}_\ell^{[m_k]}$ to the macro user m_k in orthogonal fashion during S-Block 2. Thus, each macro user $m_j \neq m_k$ can measure the interference because of transmission of $\mathbf{u}_\ell^{[m_k]}$ by simply selecting the channel state where this symbol interferes. For the considered toy example this condition is satisfied by maintaining the channel state $\mathbf{h}^{[m_j]}(1)$ during the symbol extension where the symbol $\mathbf{u}_\ell^{[m_k]}$ is transmitted during S-Block 2. Mathematically, for the symbol extensions comprising S-Block 2, i.e., $i \in \{L_{\text{f-SS}} + (k-1)L_{\text{f-SS}} + \ell\}_{\ell=1}^3$ where $\ell = \{1,2,3\}$ and $k = \{1,2\}$, the correlation function of the macro user m_j, $j = \{1,2\}$, is given by

$$g_{m_j}(i) = \begin{cases} \mathbf{h}^{[m_j]}(1) & \text{if } j \neq k \\ \mathbf{h}^{[m_j]}(2) & \text{if } j = k \end{cases} \quad (20)$$

Note that besides letting each macro user complete its alignment blocks, the symbol extensions of the macro users in S-Block 2 provide the interference subspace because of macro BS transmission for the femto users to cancel the macro-femto inter-tier interference caused during S-Block 1. To do so, each femto user only needs to apply zero forcing based on its received signals during S-Block 2. As a consequence, the FAP must remain in silent while measuring the interference subspace because of macro BS transmission. Furthermore, its antenna switching pattern needs to align into one dimension the macro-femto interference caused by the repeated transmission of each data stream $\mathbf{u}_\ell^{[m_k]}$. This alignment of the macro-femto interference can be achieved if each femto user keeps the same channel mode along all symbol extensions over which $\mathbf{u}_\ell^{[m_k]}$ is repeatedly transmitted. Therefore, the femto users must select the channel state where transmission of $\mathbf{u}_\ell^{[m_k]}$ interferes in its received signal. Since the construction of the cogBIA supersymbol satisfies the BIA criterion, any femto user maintains a constant channel state during the alignment block corresponding to the transmission of $\mathbf{u}_\ell^{[m_k]}$. For instance, it can be seen in Fig. 4 that transmission of $\mathbf{u}_2^{[m_1]}$ comprises the symbol extension 2 and 5 in S-Block 1 and S-Block 2, respectively. Since transmission of $\mathbf{u}_2^{[m_1]}$ in symbol extension 2 interferes in femto transmission, the femto users must select the channel state of this symbol extension during the symbol extension 5 of S-Block 2 with the aim of measuring the inter-tier interference because of transmission of $\mathbf{u}_2^{[m_1]}$. Mathematically, the channel state of the femto user f_{k',φ_f} corresponds to the channel state selected by f_{k',φ_f} during the transmission of the ℓ-th alignment block of the macro user m_k, i.e., $g_{f_{k',\varphi_f}}(\ell)$, $\ell = .\{1,2,3\}$, for this particular toy example.

These conditions determines how the $L_{\text{f-SS}}$ m-Blocks 1 and the q supersymbols f-SS should be combined to form S-Block 1. According to the extension of the sBIA supersymbol for the macro users explained above, the signal transmitted by the macro BS during the entire cogBIA supersymbol can be written as

$$\mathbf{X}_m = \left[\begin{bmatrix}\mathbf{I}_2\\ \mathbf{I}_2\\ \mathbf{0}_2\end{bmatrix} \otimes \mathbf{I}_3\right] \begin{bmatrix}\mathbf{u}_1^{[m_1]}\\ \mathbf{u}_2^{[m_1]}\\ \mathbf{u}_3^{[m_1]}\end{bmatrix} + \left[\begin{bmatrix}\mathbf{I}_2\\ \mathbf{0}_2\\ \mathbf{I}_2\end{bmatrix} \otimes \mathbf{I}_3\right] \begin{bmatrix}\mathbf{u}_1^{[m_2]}\\ \mathbf{u}_2^{[m_2]}\\ \mathbf{u}_3^{[m_2]}\end{bmatrix}$$
$$= \begin{bmatrix}\mathbf{I}_6\\ \mathbf{I}_6\\ \mathbf{0}_6\end{bmatrix} \begin{bmatrix}\mathbf{u}_1^{[m_1]}\\ \mathbf{u}_2^{[m_1]}\\ \mathbf{u}_3^{[m_1]}\end{bmatrix} + \begin{bmatrix}\mathbf{I}_6\\ \mathbf{0}_6\\ \mathbf{I}_6\end{bmatrix} \begin{bmatrix}\mathbf{u}_1^{[m_2]}\\ \mathbf{u}_2^{[m_2]}\\ \mathbf{u}_3^{[m_2]}\end{bmatrix}, \quad (21)$$

where $\mathbf{X}_m = \text{col}\{\mathbf{x}^{[M]}[i]\}_{i=1}^9$ and $\otimes$ denotes the Kronecker product. On the other hand, FAP transmission comprises a single f-SS supersymbol during S-Block 1 while remains in silent in a cognitive fashion during S-Block 2. Thus, the signal transmitted during the first three symbol extensions follows the beamforming of (15) applied for the femto users while FAP does not transmit in the following symbol extensions of the cogBIA supersymbol.

Denoting $\mathbf{X} = \text{col}\{\mathbf{x}[i]\}_{i=1}^9$ with $\mathbf{x}[i] = \text{col}\{\mathbf{x}^{[M]}[i], \mathbf{x}^{[\varphi_1]}[i]\}$ formed by the signals $\mathbf{x}^{[M]}[i] \in \mathbb{C}^{2\times 1}$ and $\mathbf{x}^{[\varphi_1]}[i] \in \mathbb{C}^{2\times 1}$ transmitted by the antennas of the macro BS and the FAP, respectively, the signal transmitted by the considered macro-femto network can be written as

$$\mathbf{X} = \underbrace{\begin{bmatrix}\mathbf{I}_{12}\\ \mathbf{I}_{12}\\ \mathbf{0}_{12}\end{bmatrix}\mathbf{u}^{[m_1]} + \begin{bmatrix}\mathbf{I}_{12}\\ \mathbf{0}_{12}\\ \mathbf{I}_{12}\end{bmatrix}\mathbf{u}^{[m_2]}}_{\text{macro users}} + \underbrace{\begin{bmatrix}\begin{bmatrix}\mathbf{I}_4 & \mathbf{I}_4\\ \mathbf{I}_4 & \mathbf{0}_4\\ \mathbf{0}_4 & \mathbf{I}_4\end{bmatrix}\\ \mathbf{0}_{24\times 8}\end{bmatrix}\mathbf{u}^{[\varphi_1]}}_{\text{femto users}}, \quad (22)$$

where $\mathbf{u}^{[m_k]} = \text{col}\{\mathbf{u}_\ell^{[m_k]}\}_{\ell=1}^3$, $\mathbf{u}^{[\varphi_1]} = \text{col}\{\mathbf{u}_1^{[f_{k',\varphi_1}]}\}_{k'=1}^2$ where $\mathbf{u}_1^{[f_{k',\varphi_1}]} = \text{col}\{\mathbf{0}_{2,1}, \mathbf{u}_1^{[f_{k',\varphi_1},\varphi_1]}\} \in \mathbb{C}^{4\times 1}$, $\mathbf{u}_\ell^{[m_k]} = \text{col}\{\mathbf{u}_\ell^{[m_k,M]}, \mathbf{0}_{2,1}\} \in \mathbb{C}^{4\times 1}$ with $k, k' \in \{1,2\}$. In the following we show the decodability of the symbols transmitted to the macro and femto users.

Unlike the nBIA scheme, each femto user f_{k',φ_1} only receives desired signals from the $N_f = 2$ antennas of its FAP φ_1, which only transmits during S-Block 1. To send $N_f = 2$ distinguishable data streams, i.e., $\mathbf{u}_{\ell'}^{[f_{k',\varphi_1},\varphi_1]} \in \mathbb{C}^{2\times 1}$, without CSIT, the FAP repeatedly transmits $\mathbf{u}_{\ell'}^{[f_{k',\varphi_1},\varphi_1]}$ during an alignment block composed of two symbol extensions over which the antenna of femto user f_{k',φ_1} switches between 2 different modes. For instance, from the antenna switching pattern of femto user f_{1,φ_1} in Fig. 4 and its corresponding beamforming matrices in (22), the signal received by femto user f_{1,φ_1} during its first alignment block is given by

$$\mathbf{y}^{[f_{1,\varphi_1}]} = \mathbf{H}^{[f_{1,\varphi_1}]}\mathbf{u}_1^{[f_{1,\varphi_1},\varphi_1]} + \underbrace{\mathbf{G}^{[f_{1,\varphi_1}]}(\mathbf{u}_1^{[m_1,M]} + \mathbf{u}_1^{[m_2,M]})}_{\text{macro-femto interference}} + \underbrace{\begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_1},\varphi_1]}(1)^T\mathbf{u}_1^{[f_{2,\varphi_1},\varphi_1]} \\ 0 \end{bmatrix}}_{\text{intracell femto interference}}, \quad (23)$$

where $\mathbf{H}^{[f_{1,\varphi_1}]} = \text{col}\{\mathbf{h}^{[f_{1,\varphi_1},\varphi_1]}(l)^T\}_{l=1}^{N_f}$ and $\mathbf{G}^{[f_{1,\varphi_1}]} = \text{col}\{\mathbf{h}^{[f_{1,\varphi_1},M]}(l)^T\}_{l=1}^{N_f}$, with $\mathbf{y}^{[f_{1,\varphi_1}]} = \text{col}\{y^{[f_{1,\varphi_1}]}[1], y^{[f_{1,\varphi_1}]}[2]\}$, $\mathbf{h}^{[f_{1,\varphi_f},M]}(l) \in \mathbb{C}^{2\times 1}$ and $\mathbf{h}^{[f_{1,\varphi_1},\varphi_1]}(l) \in \mathbb{C}^{2\times 1}$ containing the channel coefficients between the transmit antennas of the macro BS and FAP φ_1 to femto user f_{1,φ_1} at the preset mode l, respectively. Since the channels $\mathbf{h}^{[f_{1,\varphi_1},\varphi_1]}(l) \in \mathbb{C}^{2\times 1}$, $l \in \{1,2\}$, are linearly independent almost surely, femto user f_{1,φ_1} can decode $\mathbf{u}_1^{[f_{1,\varphi_1},\varphi_1]} \in \mathbb{C}^{2\times 1}$ once all interference is removed.

Next, notice that the FAP does not transmit data to the femto users during S-Block 2. Hence, since each femto user keeps the same radiation pattern along the symbol extensions over which $\mathbf{u}_\ell^{[m_k]}$ is transmitted, it can apply zero forcing based on the signals received in S-Block 2 to remove the macro-femto interference caused by the transmission of $\mathbf{u}_\ell^{[m_k]}$. For example, if we ignore the noise, during the alignment block of macro user m_1 the signal received by femto user f_{1,φ_1} is

$$\begin{bmatrix} y^{[f_{1,\varphi_1}]}[1] \\ y^{[f_{1,\varphi_1}]}[4] \end{bmatrix} = \begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_1},\varphi_1]}(1)^T\mathbf{u}_1^{[f_{1,\varphi_1},\varphi_1]} \\ 0 \end{bmatrix} + \underbrace{\begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_f},M]}(1)^T\left(\mathbf{u}_1^{[m_1,M]} + \mathbf{u}_1^{[m_2,M]}\right) \\ \mathbf{h}^{[f_{1,\varphi_f},M]}(1)^T\mathbf{u}_1^{[m_1,M]} \end{bmatrix}}_{\text{macro-femto interference}} + \underbrace{\begin{bmatrix} \mathbf{h}^{[f_{1,\varphi_1},\varphi_1]}(1)^T\mathbf{u}_1^{[f_{2,\varphi_1},\varphi_1]} \\ 0 \end{bmatrix}}_{\text{femto intracell interference}}. \quad (24)$$

From (24) it can be seen that femto user f_{1,φ_1} can remove the macro-femto interference caused by the transmission of $\mathbf{u}_1^{[m_1,M]}$ by applying zero forcing based on the signal received during symbol extension 4. Similarly, using the signals received during symbol extensions $\{5,7,8\}$, femto user f_{1,φ_1} can remove the remaining macro-femto interference in its first alignment block. Afterwards, the only remaining interference is caused by the transmission from the FAP to other femto users. However, the intracell interference at the FAP can be removed by applying the same procedure as in the sBIA once the macro tier interference has been removed.

In summary, the supersymbol of the proposed cognitive scheme consists of two blocks of symbol extensions, S-Block 1 and S-Block 2. DuringS-Block 1, the macro BS and the FAPs transmit to the macro and the femto users using $L_{\text{f-SS}}$ m-Blocks 1 and q f-SS supersymbols. On the contrary, during S-Block 2, only the macro BS transmits to the macro users. This transmission is undertaken in an orthogonal fashion using $L_{\text{f-SS}}$ m-Blocks 2, which allows the femto users to measure the entire macro-femto interference subspace. In the following, we provide a systematic procedure to combine the supersymbols and build the alignment blocks.

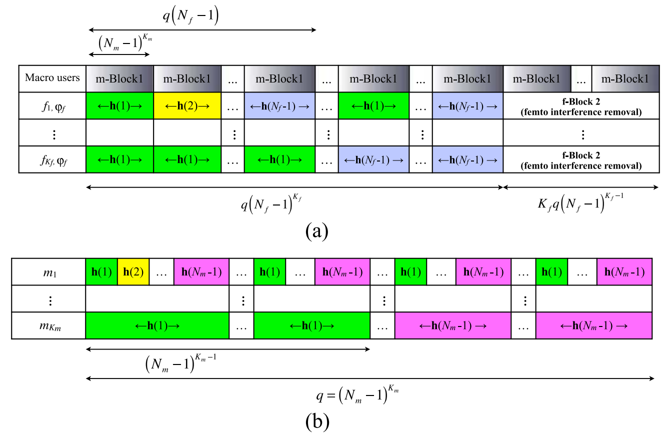

Fig. 5. a) S-Block 1 of the cogBIA scheme and b) m-Block 1 for transmission to K_m macro users

B. Design of the Supersymbol and the Beamforming Matrices

1) Design of S-Block 1 for macro users: For macro users the goal is to maximize the sum-DoF. Moreover, the resulting S-Block 1 should allow each femto user to implement different f-SS supersymbols so that the macro-femto interference can be aligned into its signal space. To achieve all these goals, the antenna switching pattern and the beamforming matrices of the macro users along S-Block 1 result from the extension to $L_{\text{f-SS}}$ m-Blocks 1, with $L_{\text{f-SS}}$ defined in (17) (see Figs. 3 and 5(a)). Thus, recalling that the length of m-Block 1 is $q = (N_m - 1)^{K_m}$ symbol extensions, the length of S-Block 1 is

$$L_{\text{S-Block1}} = qL_{\text{f-SS}}. \quad (25)$$

Since m-Block 1 is extended $L_{\text{f-SS}}$ times in S-Block 1, from the sBIA scheme proposed in [11] the temporal correlation function of the macro user m_k is

$$g_{m_k}(i) = \mathbf{h}^{[m_k]}(l) \text{ if } \mod\left(i, (N_m - 1)^k\right) \in \mathcal{I}_{m_k}(l), \quad (26)$$

where $i \in \{1, 2, \ldots, L_{\text{S-Block1}}\}$, $l \in \{1, 2, \ldots, N_m - 1\}$ and

$$\mathcal{I}_{m_k}(l) = \left\{(l-1)(N_m - 1)^{k-1} + 1, \ldots, l\,(N_m - 1)^{k-1} - 1\,, \mod\left(l\,(N_m - 1)^{k-1}, (N_m - 1)^k\right)\right\}.$$

Moreover, since each m-Block 1 consists of the first $N_m - 1$ symbol extensions of each alignment block of macro user m_k, the first $N_m - 1$ symbol extensions of the ℓ-th alignment block of macro user m_k are in S-Block 1 and correspond to

$$\left\{p_m(\ell,k)(N_m - 1)^k + \kappa(N_m - 1)^{k-1} + \varsigma_m(\ell,k)\right\}_{\kappa=0}^{N_m-2}, \quad (27)$$

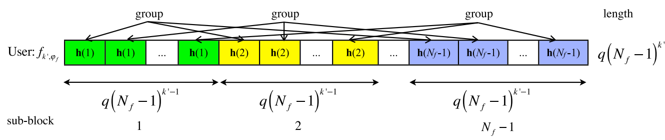

Fig. 6. Building block of femto user f_{k',φ_f}.

where

$$\varsigma_m(\ell, k) = \text{mod}(\ell - 1, (N_m - 1)^{k-1}) + 1 \tag{28}$$

$$p_m(\ell, k) = \left\lfloor \frac{\ell - 1}{(N_m - 1)^{k-1}} \right\rfloor, \tag{29}$$

with $\ell \in \{1, 2, \ldots, L_{\text{f-SS}}(N_m - 1)^{K_m - 1}\}$ and $k \in \{1, 2, \ldots, K_m\}$. Note that the elements in (27) fully characterize the beamforming matrix of macro user m_k.

2) Design of S-Block 1 for femto users: As can be seen in Fig. 5(a), S-Block 1 of the femto users is closely based on the supersymbol of a sBIA scheme aimed at transmitting from N_f antennas to K_f femto users. In particular, S-Block 1 of the femto users can be divided into two blocks, namely f-Block 1 and f-Block 2, which are subject to interference because of transmission from the macro BS. The first $L_{\text{f}-\text{Block1}} = q(N_f - 1)^{K_f}$ symbol extensions belong to f-Block 1, while the last $L_{\text{f}-\text{Block2}} = qK_f(N_f - 1)^{K_f - 1}$ symbol extensions correspond to f-Block 2, with q defined in (16).

During f-Block 1, the mode of a femto user f_{k',φ_f} is periodic with the building block shown in Fig. 6, which is repeated $(N_f - 1)^{K_f - k'}$ times to form S-Block 1, where $k' \in \{1, \ldots, K_f\}$. Similarly to the supersymbol of a sBIA scheme, the building block is composed of $N_f - 1$ sub-blocks. However, for the considered f-Block 1, the length of each sub-block equals $q(N_f - 1)^{k'-1}$. Considering this last fact and that femto user f_{k',φ_f} sets the l-th mode in its l-th sub-block, $l \in \{1, 2, \ldots, N_f - 1\}$, the temporal correlation function for user f_{k',φ_f} at femtocell $f \in \{1, 2, \ldots, F\}$ during f-Block 1 is

$$g_{f_{k',\varphi_f}}(i) = \mathbf{h}^{[f_{k',\varphi_f}]}(l) \text{ if mod}\left(i, q\left(N_f - 1\right)^{k'}\right) \in \mathcal{I}_{f_{k'}}(l), \tag{30}$$

where $i \in \{1, 2, \ldots, L_{\text{f}-\text{Block1}}\}$ and

$$\begin{aligned}\mathcal{I}_{f_{k'}}(l) = \Big\{&(l-1)q(N_f-1)^{k'-1} + 1 \\ &, \ldots, l\, q(N_f - 1)^{k'-1} - 1 \\ &, \text{mod}\left(l\, q(N_f - 1)^{k'-1}, q(N_m - 1)^{k'}\right)\Big\}.\end{aligned}$$

Similarly to Block 1 of the sBIA scheme, simultaneous transmission to all femto users takes place during the symbol extensions that constitute f-Block 1. The signals transmitted to femto user f_{k',φ_f} are the result of multiplying its associated beamforming matrix and the following data vector

$$\mathbf{u}^{[f_{k',\varphi_f}]} = \text{col}\left\{\mathbf{u}_{\ell'}^{[f_{k',\varphi_f}]}\right\}_{\ell'=1}^{L_{\text{f-Block2}}/K_f}, \tag{31}$$

where $\mathbf{u}_{\ell'}^{[f_{k',\varphi_f}]} = \text{col}\{\mathbf{0}_{N_m \times 1}, \mathbf{u}_{\ell'}^{[f_{k',\varphi_f},\varphi_f]}\} \in \mathbb{C}^{N \times 1}$, with $\mathbf{u}_{\ell'}^{[f_{k',\varphi_f},\varphi_f]} \in \mathbb{C}^{N_f \times 1}$ denoting the N_f symbols transmitted from the f-th FAP to femto user f_{k',φ_f} during its ℓ'-th alignment block. Hence, each block of $N = N_m + N_f$ consecutive columns of the beamforming matrix of a femto user corresponds to a different alignment block.

To determine the symbol extensions that form the alignment blocks of each femto user two requirements have to be taken into consideration. On the one hand, the data beams of one alignment block should be kept distinguishable at the femto user for which they are intended. Hence, the antenna of the femto user should employ a different mode at each symbol extension of the alignment block. On the other hand, to align the aforementioned data beams into one dimension of the signal space of all users subject to interference, the antenna of the affected users need to use the same radiation pattern.

The decodability and interference alignment requirements can be satisfied during f-Block 1 by forming *groups* of symbol extensions. For each femto user, each *group* consists of the first $N_f - 1$ symbol extensions of each one of its alignment blocks. Given the antenna switching pattern of the femto users during f-Block 1, the ℓ'-th *group* in a specific building block is the result of selecting the ℓ'-th symbol extensions of the $(N_f - 1)$ sub-blocks within that particular building block (see Fig. 6). Recalling that S-Block 1 of femto user $f_{k'\varphi_f}$ consists of $(N_f - 1)^{K_f - k'}$ building blocks of $q\,(N_f - 1)^{k'}$ symbol extensions, the ℓ'-th *group* in the p'-th building block of femto user f_{k',φ_f} comprises symbol extensions

$$\left\{p'q(N_f - 1)^{k'} + \kappa q(N_f - 1)^{k'-1} + \ell'\right\}_{\kappa=0}^{N_f-2}, \tag{32}$$

where $\ell' \in \{1, 2, \ldots, q(N_f - 1)^{k'-1}\}$, $p' \in \{1, 2, \ldots, (N_f - 1)^{K_f - k'}\}$ and q is defined in (16). Since a total of $q(N_f - 1)^{k'-1}$ *groups* can be formed within one building block, from (32) the symbol extensions of the ℓ'-th *group* of f_{k',φ_f} are

$$\{p_f(\ell', k')q(N_f - 1)^{k'} + \kappa(N_f - 1)^{k'-1} + \varsigma_f(\ell', k')\}_{\kappa=0}^{N_f-2}, \tag{33}$$

where

$$\varsigma_f(\ell', k') = \text{mod}(\ell' - 1, q(N_f - 1)^{k'-1}) + 1 \tag{34}$$

$$p_f(\ell', k') = \left\lfloor \frac{\ell' - 1}{q(N_f - 1)^{k'-1}} \right\rfloor, \tag{35}$$

with $k' \in \{1, 2, \ldots, K_f\}$. By evaluating

$$f_{b-f}(i) = \{iN + i'\}_{i'=1}^{N} \tag{36}$$

at each symbol extension in (33), we can determine the rows of f-Block 1 that correspond to a $N \times N$ identity matrix in the ℓ'-th column of the beamforming matrix of femto user f_{k',φ_f}.

At this point, we only need to design the antenna switching pattern and the beamforming matrices during f-Block 2. Since $q(N_f - 1)^{K_f - 1}$ *groups* are distributed over f-Block 1 for each femto user, a total of $q(N_f - 1)^{K_f - 1}$ symbol extensions are needed to complete the alignment blocks of each femto user. For femto user f_{k',φ_f}, these symbol extensions are

$$\{L_{\text{f}-\text{Block1}} + (k' - 1)q(N_f - 1)^{K_f - 1} + \ell'\}_{\ell'=1}^{L_{\text{f-Block2}}/K_f}. \tag{37}$$

Since the ℓ'-th element of the previous set corresponds to the last symbol extension of the ℓ'-th alignment block of femto user f_{k',φ_f}, the evaluation of (36) at this element in (37) indicates the only set of rows of f-Block 2 that should have a $N \times N$ identity matrix in the ℓ'-th block column of the beamforming matrix of femto user f_{k',φ_f}.

During each symbol extension in (37), the FAP φ_f only transmits to femto user f_{k',φ_f}. To ensure the decodability of these signals, which correspond to the data stream $\mathbf{u}_{\ell'}^{[f_{k',\varphi_f}]}$ repeatedly transmitted over the ℓ'-th group of f_{k',φ_f} (see (33)), the femto user uses the N_f-th channel mode. On the contrary, to satisfy the interference alignment requirement, other femto users f_{j',φ_f}, $j' \neq k'$ needs to employ the same channel mode as the one used by their antenna during the ℓ'-th *group* of femto user f_{k',φ_f}. Since femto user f_{j',φ_f} has the same channel mode along the ℓ'-th *group* of femto user f_{k',φ_f}, the channel state of f_{j',φ_f} during the ℓ'-th symbol extension in (37) is

$$g_{f_{j',\varphi_f}}(p_f(\ell', k')q(N_f - 1)^{k'-1} + \varsigma_f(\ell', k')), \tag{38}$$

with $g_{f_{k',\varphi_f}}(\cdot)$, $\varsigma_f(\ell', k')$ and $p_f(\ell', k')$ defined in (30), (34) and (35), respectively. This way, the antenna switching pattern of all femto users during f-Block 2 is fully determined.

3) Design of S-Block 2 and cognitive-based cancellation of the inter-tier interference: Within S-Block 2, each supersymbol of cogBIA provides an additional symbol extension to complete each alignment block of a specific macro user. Since there are $L_{\text{f-SS}}(N_m - 1)^{Km-1}$ alignment blocks for each of the K_m macro users, the length of S-Block 2 is

$$L_{\text{S-Block2}} = K_m\, L_{\text{f-SS}}\, (N_m - 1)^{Km-1}, \tag{39}$$

which is divided in K_m blocks, each associated with one specific macro user. For macro user m_k, the corresponding sub-block is formed by the following set of symbol extensions

$$\left\{q\, L_{\text{f-SS}} + (k-1)L_{\text{f-SS}}(N_m - 1)^{K_m-1} + \ell\right\}_{\ell=1}^{L_{\text{S-Block2}}/K_m}. \tag{40}$$

The ℓ-th element of the previous set corresponds to the last symbol extension of the ℓ-th alignment block of macro user m_k. As a result, the evaluation of (36) at the ℓ-th element in (40) yields the only set of rows of S-Block 2 that should have an $N \times N$ identity matrix in the ℓ-th block column of the beamforming matrix of macro user m_k.

In consequence, the macro BS only transmits signals to macro user m_k during the symbol extensions specified in (40). To ensure the decodability of the data stream $\mathbf{u}_\ell^{[m_k]}$ repeatedly transmitted along the ℓ-th *group* of macro user m_k, the receiver of macro user m_k uses the N_m-th mode. On the contrary, during the ℓ-th symbol extension in (27) any other macro user $m_j \neq m_k$ needs to employ the same channel mode as the one used by its antenna during the ℓ-th *group* of macro user m_k. Therefore, using (27), the channel state of macro user m_j during the ℓ-th symbol extension in (40) equals

$$g_{m_j}(p_m(\ell, k)(N_m - 1)^k + \varsigma_m(\ell, k)), \tag{41}$$

with $g_{m_j}(\cdot)$, $\varsigma_m(\ell, k)$ and $p_m(\ell, k)$ defined in (26), (28) and (29), respectively. This way, the macro user m_j can measure and cancel the macro intracell interference created by the transmission of $\mathbf{u}_\ell^{[m_k]}$.

Since the femto users satisfy the decodability and alignment conditions during S-Block 1, we can easily check that each femto user can remove the femto intracell interference and decode all its desired data, i.e., $\{\mathbf{u}_{\ell'}^{[f_{k',\varphi_f}]}\}_{\ell'=1}^{L_{\text{f-Block2}}/K_f}$. However, due to the transmission of the macro BS to the macro users during S-Block 1, this is only possible if the macro-femto interference is fully cancelled. Towards this goal, the femto users employ the symbol extensions of S-Block 2.

To measure the signal $\mathbf{u}_\ell^{[m_k]}$ transmitted from the macro BS during (40), the FAP φ_f does not transmit any signal during S-Block 2. Thus, the beamforming matrix of any femto user is an all-zero matrix. Moreover, to ensure that the measured signal is aligned with the $N_m - 1$ transmissions of $\mathbf{u}_\ell^{[m_k]}$ during S-Block 1, each femto user f_{k',φ_f} uses the same channel mode as the one employed along the ℓ-th *group* of macro user m_k. In particular, during the ℓ-th symbol extension in (40), from (27) the channel mode of femto user f_{k',φ_f} is

$$g_{f_{k',\varphi_f}}\left(p_m(\ell, k)(N_m - 1)^k + \varsigma_m(\ell, k)\right) \tag{42}$$

for $k' \in \{1, 2, \ldots, K_f\}$ and all $f \in \{1, 2, \ldots, F\}$ and with $\varsigma_m(\ell, k)$, $p_m(\ell, k)$ and $g_{f_{k',\varphi_f}}(\cdot)$ defined in (28), (29) and (30), respectively. Note that, at this point each femto user f_{k',φ_f} can simply apply zero forcing based on the signal received during the ℓ-th symbol extension in (40) in order to remove the macro-femto interference caused by the repeated transmission of $\mathbf{u}_\ell^{[m_k]}$ along the ℓ-th *group* of macro user m_k.

C. Achievable Degrees of Freedom

In the proposed scheme the macro BS employs BIA transmission independently of the femto tier. Since each user attains N_m DoF in each of the $L_{\text{f-SS}}(N_m - 1)^{K_m-1}$ alignment blocks, the normalized sum-DoF for the macro users is

$$\text{DoF}_\text{m} = \frac{K_m L_{\text{f-SS}} N_m (N_m - 1)^{K_m-1}}{L_{S-Block1} + L_{S-Block2}} = \frac{N_m K_m}{N_m + K_m - 1}. \tag{43}$$

As expected, the achievable DoF are not affected by the femto tier deployment and do not depend on any of its parameters.

In the proposed scheme, each femto user employs $q\,(N_f - 1)^{K_f-1}$ alignment blocks, with q defined in (16). Each of these alignment blocks is formed by N_f symbol extensions over which the femto user receives N_f desired data beams transmitted from the FAP. Since the femto intracell and macro-femto inter-tier interference can be fully removed, each femto user can attain N_f DoF in each alignment block. Because $L_{S-Block1}$ symbol extensions are employed for femto transmission and $L_{S-Block2}$ symbol extensions are required to measure the macro-femto interference in a cognitive fashion, the sum-DoF per symbol extension for the femto users is

$$\text{DoF}_\text{f} = \frac{N_f K_f (N_m - 1)}{(N_m + K_m - 1)(N_f + K_f - 1)}. \tag{44}$$

Remark 1: The proposed cogBIA scheme can be extended to the case where any tier employs other BIA-based transmission scheme (e.g., based on hierarchical BIA [16] or nBIA [23]) by following the same procedure as described above.

V. Optimality of Cognitive Blind Interference Alignment

In this section, we analyze the optimality of the proposed scheme in terms of DoF. Toward this goal, we derive an outer bound for the sum-DoF of the lower tier as a function of the sum-DoF of the upper tier for the considered two-tier network.

Consider a macro BS equipped with N_m antennas transmitting to K_m macro users. The messages and the rates of the macro users are denoted as $W^{[m_1]}, \dots, W^{[m_{K_m}]}$ and $R^{[m_1]}, \dots, R^{[m_{K_m}]}$, respectively. Moreover, we define the whole set of messages of macro users as

$$\mathcal{W}^{[M]} = \left\{ W^{[m_1]}, \dots, W^{[m_{K_m}]} \right\}. \tag{45}$$

When obtaining an outer bound of the DoF, i.e. $P \to \infty$, notice that the interfering signal strength from the macro BS to each femto user f_{k',φ_f} does not depend on the femtocell φ_f where the user is located. As a result, for the sake of simplicity, the index φ_f has been omitted in this proof. Similarly to the macro users, the set of messages and rates of the femto users in a generic FAP φ_f are denoted as $W^{[f_1]}, \dots, W^{[f_{K_f}]}$ and $R^{[f_1]}, \dots, R^{[f_{K_f}]}$, respectively. Thus, we can define the whole set of messages of the femto users as

$$\mathcal{W}^{[\varphi_f]} = \left\{ W^{[f_1]}, \dots, W^{[f_{K_f}]} \right\}. \tag{46}$$

Without loss of generality, let us focus on femto user f_1, which desires the message $W^{[f_1]}$ at a rate $R^{[f_1]}$. Suppose that the femto user selects the mode $l \in \{1, 2, \dots, N_f\}$ during symbol extensions i and that its received signal is $y_l^{[f_1]}$ as described in Section II. Note that the received signal changes with the selected mode l.

Applying Fano's inequality to codebooks spanning n channel uses, we have

$$\begin{aligned} nR^{[f_1]} &\le I\left(W^{[f_1]}; \left(y_l^{[f_1]}\right)^n\right) + o(n) \\ &\le h\left(\left(y_l^{[f_1]}\right)^n\right) - h\left(\left(y_l^{[f_1]}\right)^n |W^{[f_1]}\right) + o(n). \end{aligned} \tag{47}$$

Since this is true for every $l \in \{1, 2, \dots, N_f\}$, we can add up the inequality (47) corresponding to all N_f realizations in order to get (48)–(55) shown at the bottom of this page. For step (48)–(49), we use $h(A, B) \le h(A) + h(B)$. Step (49)–(50) follows from $I(X, Y|Z) = h(X|Z) - h(X|Y, Z)$ and the step (50)–(51) uses $I(X, Y|Z) = h(Y|Z) - h(Y|X, Z)$ and the independence between any pair of messages. Moreover, we denote the regular entropy as $H(\cdot)$ while the differential entropy

$$nN_f R^{[f_1]} \le \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n |W^{[f_1]}\right) + o(n) \tag{48}$$

$$\le \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - h\left(\left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |W^{[f_1]}\right) + o(n) \tag{49}$$

$$\begin{aligned} &= \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - I\left(W^{[f_2]}, \dots, W^{[f_{K_f}]}; \left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |W^{[f_1]}\right) \\ &\quad - h\left(\left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n | \underbrace{W^{[f_1]}, W^{[f_2]}, \dots, W^{[f_{K_f}]}}_{\mathcal{W}^{[\varphi_f]}}\right) + o(n) \end{aligned} \tag{50}$$

$$\begin{aligned} &= \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - H\left(W^{[f_2]}, \dots, W^{[f_{K_f}]} |W^{[f_1]}\right) + H\left(W^{[f_2]}, \dots, W^{[f_{K_f}]} | \left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n, W^{[f_1]}\right) \\ &\quad - h\left(\left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |\mathcal{W}^{[\varphi_f]}\right) + o(n) \end{aligned} \tag{51}$$

$$\le \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - H\left(W^{[f_2]}, \dots, W^{[f_{K_f}]} |W^{[f_1]}\right) - h\left(\left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |\mathcal{W}^{[\varphi_f]}\right) + o(n) \tag{52}$$

$$= \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - \sum_{j'=2}^{K_f} R^{[f_{j'}]} - h\left(\left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |\mathcal{W}^{[\varphi_f]}\right) + o(n) \tag{53}$$

$$\begin{aligned} nN_f R^{[f_1]} &\le \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - \sum_{k'=2}^{K_f} R^{[f_{k'}]} - I\left(\mathcal{W}^{[M]}; \left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |\mathcal{W}^{[\varphi_f]}\right) \\ &\quad - h\left(\left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n |\mathcal{W}^{[M]}, \mathcal{W}^{[\varphi_f]}\right) + o(n) \end{aligned} \tag{54}$$

$$= \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) - \sum_{j'=2}^{K_f} R^{[f_{j'}]} - H\left(\mathcal{W}^{[M]} |\mathcal{W}^{[\varphi_f]}\right) + H\left(\mathcal{W}^{[M]} | \left(y_1^{[f_1]}, y_2^{[f_1]}, \dots, y_{N_f}^{[f_1]}\right)^n, \mathcal{W}^{[\varphi_f]}\right) + o(n) \tag{55}$$

is denoted as $h(\cdot)$. Notice that from the set of N_f outputs $\big(y_1^{[f_1]}, y_2^{[f_1]}, \ldots, y_{N_f}^{[f_1]}\big)^n$ it is possible to decode the whole set of messages for the femto users $\mathcal{W}^{[\varphi_f]}$. In consequence, the entropy $H(W^{[f_2]}, \ldots, W^{[f_{K_f}]} | (y_1^{[f_1]}, y_2^{[f_1]}, \ldots, y_{N_f}^{[f_1]})^n, W^{[f_1]}) \leq o(n)$. In other words, it carries 0 DoF. By using this fact and the chain rule of the entropy, i.e. $h(A,B) = h(A) + h(B|A)$, we can obtain (52) from (51). Finally, due to the independence between any pair of messages, we can use $h\big(W^{[f_2]}, \ldots, W^{[f_{K_f}]} | W^{[f_1]}\big) = \sum_{j'=2}^{K_f} R^{[f_{j'}]}$ to obtain (53) from (52). At this point, we distinguish between two particular cases regarding the amount of transmit antennas in each tier.

A. Case $N_f \geq N_m$

First, let us consider the case where $N_f \geq N_m$. From (53) and $I(X;Y|Z) = h(X|Z) + h(X|Y,Z)$, we can introduce the set of messages $\mathcal{W}^{[M]}$ in (54). Moreover, given both $\mathcal{W}^{[M]}$ and $\mathcal{W}^{[\varphi_f]}$, notice that the uncertainty of the received signals is only due to noise. As a result, $h((y_1^{[f_1]}, y_2^{[f_1]}, \ldots, y_{N_f}^{[f_1]})^n | \mathcal{W}^{[M]}, \mathcal{W}^{[\varphi_f]})$ also carries 0 DoF. Applying $I(X;Y|Z) = h(Y|Z) + h(Y|X,Z)$ in (54), given the set of messages of the femto users $\mathcal{W}^{[\varphi_f]}$, notice that we can subtract the symbols sent by the FAP from the received signals at any femto user. Furthermore, since $N_f \geq N_m$, from N_f observations of the remaining macro BS signals, note that we can invert the channel from the macro BS to resolve all the messages of macro users $\mathcal{W}^{[M]}$ subject to noise distortion. Therefore, in (54),

$$H\left(\mathcal{W}^{[M]} | \left(y_1^{[f_1]}, y_2^{[f_1]}, \ldots, y_{N_f}^{[f_1]}\right)^n, \mathcal{W}^{[\varphi_f]}\right) \leq o(n).$$

Thus, due to the independence between any pair of messages we can re-write (55) as

$$\begin{aligned} nN_f R^{[f_1]} &\leq nN_f \left(\log(P_f) + o\left(\log(P_f)\right)\right) \\ &\quad - \sum_{j'=2}^{K_f} nR^{[f_{j'}]} - \sum_{j=1}^{K_m} nR^{[m_j]} + o(n) \end{aligned} \tag{56}$$

where P_f is the total transmit power constraint at the FAP.

After dividing (56) by $n\log(P_f)$, taking first the limit $n \to \infty$ and then the limit $P_f \to \infty$, a rearrangement of the terms yields the following DoF outer bound

$$d^{[f_1]} \leq 1 - \frac{1}{N_f} \sum_{j'=2}^{K_f} d^{[f_{j'}]} - \frac{d_{\Sigma_{\text{macro}}}}{N_f} \tag{57}$$

where $d_{\Sigma_{\text{macro}}} = \sum_{j=1}^{K_m} d^{[m_j]}$ denotes the sum-DoF for the macro tier. Following a procedure similar to (47)–(57), note that

$$d^{[f_{k'}]} \leq 1 - \frac{1}{N_f} \sum_{j'=1; j' \neq k'}^{K_f} d^{[f_{j'}]} - \frac{d_{\Sigma_{\text{macro}}}}{N_f} \tag{58}$$

for any $k' \in \{1, 2, \ldots, K_f\}$. If we now sum the previous K_f inequalities over all femto users, we can check that

$$d_{\Sigma_{\text{femto}}} \leq \frac{K_f N_f}{K_f + N_f - 1} \left[1 - \frac{d_{\Sigma_{\text{macro}}}}{N_f}\right] \tag{59}$$

where $d_{\Sigma_{\text{femto}}} = \sum_{j'=1}^{K_f} d^{[f_{j'}]}$.

B. Case $N_m > N_f$

For each femto user, let us generate $N_m - 1$ auxiliary femto users who want the same message and have the same channel statistics. Without loss of generality, consider again femto user f_1, which desires the message $W^{[f_1]}$ at rate $R^{[f_1]}$ and receives the signal $y_l^{[f_1]}$ that switches among $l \in \{1, 2, \ldots, N_f\}$ channel modes. The $N_m - 1$ auxiliary users of user f_1, denoted as $\{f_1^1, \ldots, f_1^{N_m - 1}\}$, also want the message $W^{[f_1]}$ at rate $R^{[f_1]}$ and receive the signals $y_l^{[f_1^1]}, \ldots, y_l^{[f_1^{N_m-1}]}$, respectively, which also change among N_f modes. Note that $y_l^{[f_1]}, y_l^{[f_1^1]}, \ldots, y_l^{[f_1^{N_m-1}]}$ are statistically equivalent but correspond to independent channel realizations. Therefore, proceeding as in (48)–(53) for the N_f realizations in each of the $N_m - 1$ auxiliary users of femto user f_1, we can obtain $N_m - 1$ inequalities with the same form as in (53). By summing all these $N_m - 1$ inequalities and (53), we can obtain (60)–(62) shown at the bottom of this page. In the right hand side of the resulting inequality, notice that the entropy of N_f received signals appears N_m times. However, due to the statistical equivalence between the signals received by auxiliary

$$\begin{aligned} nN_m N_f R^{[f_1]} \leq & \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1]}\right)^n\right) + \sum_{a=1}^{N_m-1} \sum_{l=1}^{N_f} h\left(\left(y_l^{[f_1^a]}\right)^n\right) - N_m \sum_{k'=2}^{K_f} R^{[f_{k'}]} + o(n) \\ & - h\left(\left(y_1^{[f_1]}, \ldots, y_{N_f}^{[f_1]}\right)^n | \mathcal{W}^{[\varphi_f]}\right) - \sum_{a=1}^{N_m-1} h\left(\left(y_1^{[f_1^a]}, \ldots, y_{N_f}^{[f_1^a]}\right)^n | \mathcal{W}^{[\varphi_f]}\right) \end{aligned} \tag{60}$$

$$\leq nN_m N_f \left(\log(P_f) + o\left(\log(P_f)\right)\right) - N_m \sum_{k'=2}^{K_f} R^{[f_{k'}]} - N_f h\left(\left(y_1^{[f_1]}, \ldots, y_{N_m}^{[f_1]}\right)^n | \mathcal{W}^{[\varphi_f]}\right) + o(n) \tag{61}$$

$$\leq nN_m N_f \log(P_f) - N_m \sum_{k'=2}^{K_f} R^{[f_{k'}]} - N_f \sum_{k=1}^{K_m} R^{[m_k]} + o\left(\log(P_f)\right) + o(n) \tag{62}$$

the users, notice that

$$h\left(\left(y_1^{[f_1]},\ldots,y_{N_f}^{[f_1]}\right)^n|\mathcal{W}^{[\varphi_f]}\right) + \sum_{a=1}^{N_m-1} h\left(\left(y_1^{[f_1^a]},\ldots,y_{N_f}^{[f_1^a]}\right)^n|\mathcal{W}^{[\varphi_f]}\right) \geq N_f h\left(\left(y_1^{[f_1]},\ldots,y_{N_m}^{[f_1]}\right)^n|\mathcal{W}^{[\varphi_f]}\right)$$

is verified. As a result, (60) can be rewritten as (61). Afterwards, we introduce the set of messages of all macro users as in step (53)–(54). Since all the messages intended to the macro users $\mathcal{W}^{[M]}$ can be decoded from N_m received signals at femto user f_1 once $\mathcal{W}^{[\varphi_f]}$ is known, the entropy $h\left(\mathcal{W}^{[M]}|\left(y_1^{[f_1]},\ldots,y_{N_m}^{[f_1]}\right)^n,\mathcal{W}^{[\varphi_f]}\right)\leq o(n)$. Thus, we can proceed as in (54)–(55) to obtain (62) from (61).

By dividing (62) by $n\log(P_f)$ and taking the limits $n\to\infty$ and $P_f\to\infty$, some algebraic manipulations yield

$$d^{[f_1]} \leq 1-\frac{1}{N_f}\sum_{j'=2}^{K_f} d^{[f_{j'}]} - \frac{d_{\Sigma_{\text{macro}}}}{N_m}. \tag{63}$$

The procedure undertaken from (60) to (62) can be repeated to obtain a similar outer bound for any femto user $f_{k'}$. If all the resulting K_f outer bonds are summed, we can verify that

$$d_{\Sigma_{\text{femto}}} \leq \frac{K_f N_f}{K_f+N_f-1}\left[1-\frac{d_{\Sigma_{\text{macro}}}}{N_m}\right]. \tag{64}$$

In this way, the proof is concluded.

From the previous theorem, we can check that the information theoretic outer bound for the sum-DoF of the femto users in a generic femtocell φ_f is

$$d_{\Sigma_{\text{femto}}} \leq \frac{N_f K_f\,(N_m-1)}{(N_f+K_f-1)\,(N_m+K_m-1)} \tag{65}$$

when $N_f\geq N_m$ and subject to optimal-DoF for the macro tier in the absence of CSIT, i.e., $d_{\Sigma_{\text{macro}}}=\frac{K_m N_m}{N_m+K_m-1}$. Notice that this is exactly the same sum-DoF achieved by the femto users when the proposed cogBIA scheme is implemented.

VI. Achievable Rates by Cognitive Blind Interference Alignment

To complete the characterization of the proposed scheme, this section analyzes its performance in the finite SNR regime. Assuming equal power allocation to each stream, we derive the closed-form expressions for the achievable rates of cogBIA.

Since the macro users are not affected by the interference caused by the transmission of the FAPs, their achievable rates are given by the sBIA expressions in the absence of intercell interference (see [11]). Thus, the normalized rate per symbol extension of macro user m_k is

$$R^{[m_k]} = B_m\mathbb{E}\left[\log\det\left(\mathbf{I}+\bar{P}_m\mathbf{H}^{[m_k]}{\mathbf{H}^{[m_k]}}^H{\mathbf{R}_z^{[m_k]}}^{-1}\right)\right], \tag{66}$$

where $\mathbf{H}^{[m_k]}=\text{col}\{\mathbf{h}^{[m_k]}(l)^T\}_{l=1}^{N_m}\in\mathbb{C}^{N_m\times N_m}$, $B_m=\frac{1}{N_m+K_m-1}$ 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

$$\mathbf{R}_z^{[m_k]} = \begin{bmatrix} K_m\mathbf{I}_{N_m-1} & \mathbf{0}_{N_m-1,1} \\ \mathbf{0}_{1,N_m-1} & 1\end{bmatrix} \tag{67}$$

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

For the femto user f_{k',φ_f}, which is subject to interference from the macro BS, the signal $\mathbf{y}^{[f_{k',\varphi_f}]}=\text{col}\{y^{[f_{k',\varphi_f}]}[1],\ldots,y^{[f_{k',\varphi_f}]}(N_f)\}$ received during a generic alignment block after zero-forcing interference cancelation is

$$\tilde{\mathbf{y}}^{[f_{k',\varphi_f}]} = \mathbf{H}^{[f_{k',\varphi_f}]}\mathbf{u}^{[f_{k',\varphi_f}]} + \tilde{\mathbf{z}}^{[f_{k',\varphi_f}]}, \tag{68}$$

where $\mathbf{H}^{[f_{k',\varphi_f}]}=\text{col}\{\mathbf{h}^{[f_{k',\varphi_f},\varphi_f]}(l)^T\}_{l=1}^{N_f}\in\mathbb{C}^{N_f\times N_f}$, $\tilde{\mathbf{y}}^{[f_{k',\varphi_f}]}=\text{col}\{\tilde{y}^{[f_{k',\varphi_f}]}(1),\ldots,\tilde{y}^{[f_{k',\varphi_f}]}(N_f)\}$ and

$$\tilde{\mathbf{z}}^{[f_{k',\varphi_f}]} = \begin{bmatrix} z^{[f_{k',\varphi_f}]}[1]-\sum_{\tau=1}^{K_m+K_f-1} z[\tau] \\ \vdots \\ z^{[f_{k',\varphi_f}]}[N_f-1]-\sum_{\tau=1}^{K_m+K_f-1} z[\tau] \\ z^{[f_{k',\varphi_f}]}[N_f]-\sum_{\tau=1}^{K_m} z[\tau]\end{bmatrix}. \tag{69}$$

Since equal power allocation is assumed and the FAPs do not transmit during m-Block 2, the power allocated to each symbol transmitted by the FAP is $\bar{P}_f=\frac{N_f+K_f-1}{N_f^2 K_f}P_f$. 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 overall supersymbol length. Hence, the ratio of alignment blocks of each femto user over the total supersymbol length is

$$B_f = \frac{N_m-1}{(N_m+K_m-1)(N_f+K_f-1)}. \tag{70}$$

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

$$R^{[f_{k',\varphi_f}]} = B_f\mathbb{E}\left[\log\det\left(\mathbf{I}+\frac{\bar{P}_f}{1+P_{\mathcal{I}_{f^\star}}}\mathbf{A}^{[f_{k',\varphi_f}]}{\mathbf{R}_z^{[f_{k'}]}}^{-1}\right)\right], \tag{71}$$

where $\mathbf{A}^{[f_{k',\varphi_f}]}=\mathbf{H}^{[f_{k',\varphi_f}]}{\mathbf{H}^{[f_{k',\varphi_f}]}}^H$, $P_{\mathcal{I}_{f^\star}}$ is the equivalent power due to the intercell interference in the lower tier, which is treated optimally as noise and

$$\mathbf{R}_z^{[f_{k'}]} = \begin{bmatrix} (K_m+K_f)\,\mathbf{I}_{N_f-1} & \mathbf{0}_{N_f-1,1} \\ \mathbf{0}_{1,N_f-1} & K_m\end{bmatrix} \tag{72}$$

is the covariance matrix of the noise for each femtocell user after zero-forcing cancelation.

VII. Simulation Results

The DoF region for a two-tier network in absence of CSIT is depicted in Fig. 7. For illustrative purposes, we first consider the use of orthogonal resource allocation, e.g., frequency division, between both tiers implementing sBIA independently in each of them. Although this approach improves considerably the system sum-DoF as compared to traditional orthogonal approaches such as TDMA, which obtain 1 DoF per cell, it can be seen that more sophisticated schemes such as nBIA or cogBIA obtain a considerable increase in DoF. Since nBIA was originally devised

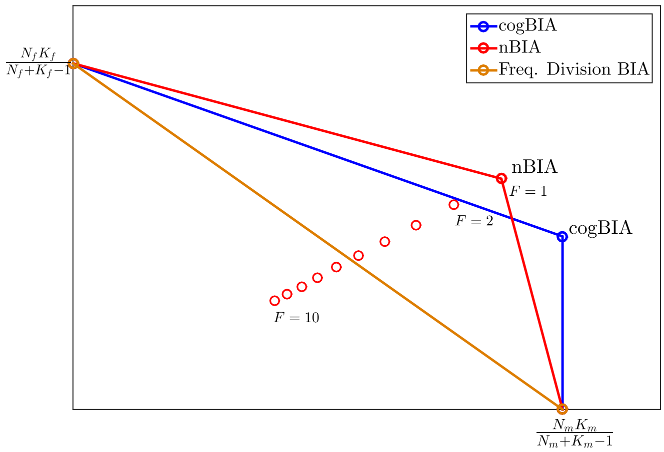

Fig. 7. DoF region of macro users and each femtocell for several BIA-based schemes. The achievable sum-DoF is depicted for $F = (1, 10)$.

TABLE I
SIMULATION PARAMETERS

Macrocell radius	1.6 Km
Femtocell footprint	30 m
Transmit power in macro BS	40 dBm
Transmit power in FAP [31]	$\{10, 17, 21\}$ dBm
Noise power	-104 dBm
Path loss macro transmission	COST231
Path loss femto transmission	$15.3 + 37.6 \log_{10}(d_f)$

to maximize the sum-DoF in homogeneous networks, it achieves greater sum-DoF for only one BS in the lower tier. In this sense, notice that nBIA does not achieve the optimal DoF in any tier. Besides, as the number of BSs in the lower tier increases the sum-DoF decreases since, as can be checked in (12)–(13), the sum-DoF depends inversely proportional on this parameter. For the proposed cogBIA scheme the upper tier achieves the optimal sum-DoF while the lower tier achieves non-zero DoF without involving a penalty in DoF to the upper tier. Moreover, as long as the intercell interference can be optimally treated as noise in the lower tier, the sum-DoF increases linearly with the amount of cells in that tier.

Beyond the theoretical achievable sum-DoF, we focus on the accuracy of the proposed two-tier model and the achievable rates of the proposed schemes. For simplicity, and without loss of generality, we consider a two-tier network composed of macro and femto tiers. Specifically, we consider a macro BS and FAPs equipped with $N_m = 6$ and $N_f = 2$ antennas, respectively, where the macro BS serves $K_m = 12$ macro users while each FAP sends data to $K_f = 2$ users. The system parameters are summarized in Table I. Moreover, the FAPs are uniformly distributed over the coverage radius of the macrocell while the macro and femto users are uniformly distributed over the coverage radius of its corresponding BS.

The growth of the achievable rates in the lower tier for the proposed cogBIA scheme regarding the number of FAPs is shown in Fig. 8. For a transmit power in the FAP of 21, 17, and 10 dBm the 37.5%, 40% and 50%, respectively, of the femtocells in the considered scenario achieve greater sum rate using cogBIA regarding sBIA. Moreover, it can be checked

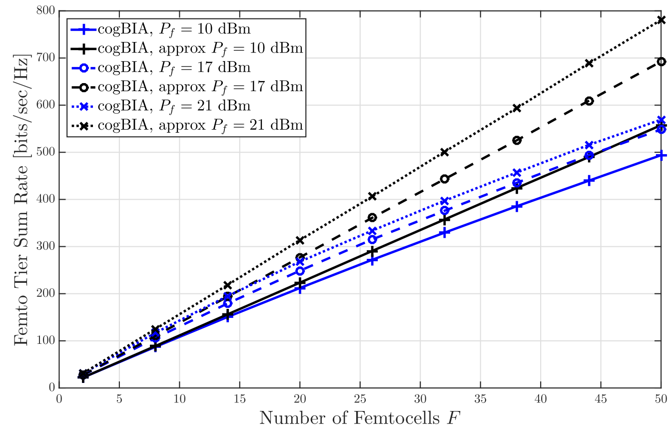

Fig. 8. Achievable sum rate in the femto tier regarding the number of FAPs deployed. Approximation considers $\mathcal{I}_f \approx 0$.

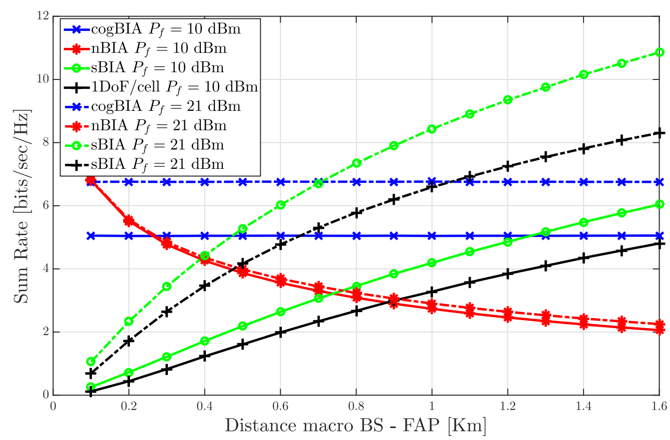

Fig. 9. Comparison of the achievable sum-rate in each femtocell for cogBIA, nBIA, sBIA and the open-loop data transmission scheme where 1DoF is allocated per cell without any management of the interference.

that the approximation $\mathcal{I}_{f^\star} \approx 0$ (see (3)) results accurate when the small cells density is below the 50 femtocells. Beyond this point, a strategy to manage this source of interference, e.g. FR within the lower tier, would be required. Specifically, for $P_f = 21$ dBm this approximation involves an error below 10% and 25% when the number of FAPs is 14 and 50, respectively. For 26 FAPs an error below 12% occurs when $P_f = 17$ dBm, which corresponds to the maximum transmit power for multiple antenna FAPs [31], while a deployment of 50 FAPs can be considered below that error for $P_f = 10$ dBm.

Fig. 9 shows a comparison of the achievable sum-rate in each femtocell of the considered scenario for $P_f = \{10, 21\}$ dBm. As expected, FAPs equipped with higher transmit power $P_f = 21$ dBm provides higher sum rates. In this case, it can be seen that the proposed cogBIA scheme outperforms sBIA when the distance between FAP and the macro BS is lower than 0.7 Km. This distance increase until 1.3 Km when $P_f = 10$ dBm. Note that the use of nBIA penalizes the femtocells performance considerably since FK_f terms of interference must be subtracted instead of the K_f terms for sBIA or cogBIA. Curiously, notice that reducing the transmitted power from 21 dBm to 10 dBm involves a significant reduction of the sum rate achieved by sBIA, around 4 bits/sec/Hz when the distance between macro BS and

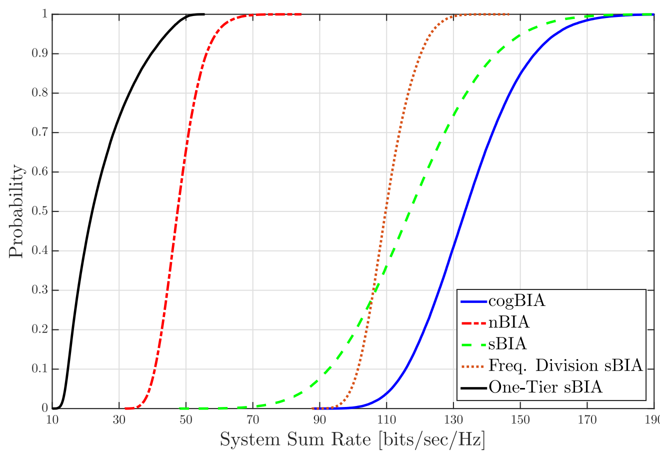

Fig. 10. Cumulative distribution of the overall achievable sum-rate. The label 1-Tier sBIA refers to the case where the macro BS serves to the whole set of users in the network.

FAP is 1 Km, while this penalty is only 1.7 bits/sec/Hw for cogBIA in the whole range. Therefore, the use of cogBIA could lead to a reduction of the power consumption in the femto tier.

The cumulative distribution functions (CDF) of the achievable sum rate over the entire network are depicted in Fig. 10. For illustrative purposes we consider the cases where the macro BS serves the $K_m + FK_f$ users as a one-tier network using sBIA and the use of frequency division between both tiers each implementing sBIA independently. First, it can be seen that the introduction of two-tier networks increases considerably the overall sum-rate regarding the one-tier case. Moreover, cooperation between both tiers based on nBIA yields in a great noise increase penalizing considerably the overall sum rate. For the considered setting, the proposed cogBIA for the femtocells subject to inter-tier interference outperforms sBIA and sBIA based on frequency division. Specifically, for the percentile 50^{th} the use of cogBIA lead to an increase of the overall sum rate of 15% and 20% regarding sBIA and sBIA based on frequency division, respectively.

VIII. Conclusions and Future Directions

A cognitive Blind Interference Alignment scheme for macro-femto two-tier networks is developed in this work. Without requiring CSIT or data exchange between the macro BS and the FAPs, the proposed scheme allows femto users to measure and fully cancel both the intracell and the inter-tier interference in a cognitive fashion. In this context, femto users attain a significant amount of Degrees of Freedom without affecting the rates of the macro users, which achieve the optimal sum-DoF in absence of CSIT. It is proved that the proposed scheme yields optimal sum-DoF at the femto users subject to optimal sum-DoF for the macro users. Furthermore, it is shown that the proposed cogBIA scheme can attain more sum DoF than cooperative schemes where both the macro BS and the FAPs jointly transmit to the femto users.

An interesting future direction is to determine the DoF of the K-tier cellular network. Moreover, assuming ultra-dense deployments, the derivation of the DoF in K-tier networks and its achievability lead to a mixture of several BIA schemes, which are optimal in the MISO BC, homogeneous or heterogeneous networks depending on the network topology. Another interesting direction is the formulation of optimization problems jointly derived from the knowledge of the network topology to maximize the achievable sum-rate in heterogeneous networks or the use of BIA with the aim of overcoming the CSI bottleneck in Massive MIMO operating in Frequency Division Duplex (FDD) [32].

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