LOCATION AIDED SEMI-BLIND INTERFERENCE ALIGNMENT FOR CLUSTERED SMALL CELL NETWORKS

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ABSTRACT

We consider the applications of blind and semi-blind interference alignment in multicell scenarios, specifically in clustered small cells. As a first step, two simple straight forward extensions of blind interference alignment are examined and it is observed that neither of them is uniformly superior. Then, we propose exploiting the location information of the users and base stations in the cluster to enhance the performance of fully blind schemes for any given user distribution scenario. Our aim is to group suitable users that can be served at the same time to minimize the supersymbol length for each cluster. Since the defined problem is NP-hard, we propose a heuristic algorithm that can provide an effective solution without too much complexity. By numerical simulations, we show that the proposed semi blind algorithm, Top.BIA, uniformly performs better than pure blind interference alignment schemes for any possible user distribution scenario.

***Index Terms*—** Small cell, semi-blind interference alignment, super symbol design, location awareness

1. INTRODUCTION

In recent years, wireless communications has seen unprecedented growth and an explosive demand for mobile data. Denser networks with small cells is proposed as an effective solution to increase the capacity of the network and the quality of user experience (QoE) without any significant increase in the network management costs [1]. However, massive deployment of small cells also creates new issues to be dealt with, such as interference.

Relation to Prior Work: Interference alignment (IA) is a revolutionary wireless transmission strategy that can reduce the impact of interference in the system by aligning multiple transmitters' interference at the receivers. In recent years, there has been an ongoing research on interference alignment mainly focused on interference alignment's ability to achieve the maximum number of degrees of freedom (DoF) [2–4], algorithms for determining alignment solutions [5–7] and application to cellular networks [8–10]. In [11], it has been shown that even if the transmitters have no knowledge of channel coefficient values, they can still align interference based on the knowledge of only the channel autocorrelation structures of different users. Then, in [12], a blind interference alignment (BIA) scheme was proposed where receivers can switch between reconfigurable antenna modes to create short term channel fluctuation patterns that can be exploited by the transmitter. Later, in [13, 14], BIA idea was examined in cellular and cluster based systems to control intra-cell and inter-cell interference in the context of power allocation, frequency reuse and alignment code reuse. In [15], data sharing for cell edge users for blind interference alignment technique was introduced and performance increase with the additional cost of data sharing was shown. In [16], the information theoretic capacity (wired) and DoF (wireless) of partially connected SISO linear communication networks with no CSIT, where the network topology is known to all sources and destinations, are studied.

Contributions: Blind interference alignment was introduced as a transmission scheme without considering multicells. It can remove intracell interference completely, but for the multicell scenarios, it does not address the intercell interference. As in [14], BIA can be used for each cell in a synchronized fashion. Then, each user experiences only a limited intercell interference from the signal that is transmitted to other users in other cells that are using the same timeslot in the supersymbol. We propose another simple fully blind scheme, Ext.BIA, in which we extend the supersymbol to remove the intercell interference completely at the expense of a bigger supersymbol structure. However, if the intercell interference is not high enough, this approach can lower the total network throughput. Ext.BIA or Sync.BIA can provide superior performance based on the user distribution in the system. Therefore there is a need for new scheme that can uniformly enhance the performance of Sync. and Ext.BIA for all user distribution scenarios with limited additional information. Knowing location information of the users and BSs (long term CSI such as path loss information) in the cluster can lead us to design location aided semi blind interference alignment scheme where transmitters are more aware of the environment without knowing the perfect CSIT. By using location information, our aim is to group the suitable users that can be served at the same time to minimize the supersymbol length for each cluster. Since the defined problem is NP-hard, we propose a heuristic algorithm that can provide an effective solution without too much complexity. Our algorithm, top level semi-blind supersymbol design (Top.BIA), is a centralized approach which employs a grouping indicator matrix to determine the user groups. We show that the proposed semi blind algorithm, Top.BIA, uniformly performs better than pure blind interference alignment schemes for any possible user distribution scenario.

2. SYSTEM MODEL

Consider a small cell network in which neighboring cells are clustered. There are $N = SC$ cells in the network comprised of S clusters, each consists of C small cells. Each small cell BS is equipped with M transmit antennas and serves K users with single reconfigurable antenna that is capable of switching to M different modes as

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in [12]. At each mode, user sees a channel which is independent of the other channels that are seen in the different antenna modes. User association and clustering of the small cells are assumed to be given. Finally, the channel coherence time is assumed to be long enough as in [12], so that it remains constant during one supersymbol.

Let $h_{jd}^{[k,ic]}(m) \in C^{1\times M}$ denotes the channel between jth BS in the dth cluster and kth user with mth antenna mode that is associated to ith BS in the cth cluster ; where $k \in \{1, 2, ..., K\}$; $i, j \in \{1, 2, ..., C\}$; $c, d \in \{1, 2, ..., S\}$ and $m \in \{1, 2, ..., M\}$. Then, the received signal for the kth user with mth antenna mode in ith cell of cth cluster at time t is,

$$y^{[k,ic]}(t) = \sqrt{g(d_{ic}^{[k,ic]})} h_{ic}^{[k,ic]}(m) x_{ic}(t) + \sum_{\substack{j=1 \\ j\neq i}}^{C} \sqrt{g(d_{jc}^{[k,ic]})} h_{jc}^{[k,ic]}(m) x_{jc}(t) + \sum_{\substack{s=1 \\ s\neq c}}^{S} \sum_{j=1}^{C} \sqrt{g(d_{js}^{[k,ic]})} h_{js}^{[k,ic]}(m) x_{js}(t) + z^{[k,ic]}(t) \quad (1)$$

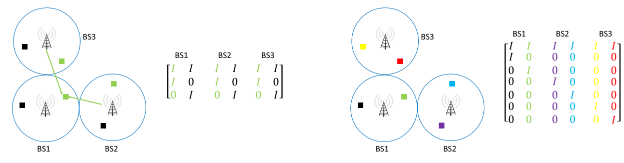
where $x_{ic}(t)$ is the transmitted symbol at time t from ith BS in cth cluster and $g(d_{ic}^{[k,ic]})$ is distance depended path loss model. $d_{jd}^{[k,ic]}$ is the distance between jth BS in dth cluster and kth user that is associated to ith BS in cth cluster. $h_{jd}^{[k,ic]}(m)$ is small scale fading at mth antenna mode. $z^{[k,ic]}(t)$ is the complex white Gaussian noise, $z^{[k,ic]}(t) \sim CN(0, \sigma_w^2)$. It is assumed that antenna switching patterns are known to the base stations and users before the transmission starts as in [12].

3. SIMPLE APPLICATIONS OF BLIND INTERFERENCE ALIGNMENT IN SMALL CELL NETWORKS

The reasoning behind the blind interference alignment (BIA) idea is as follows: even if the transmitters have no knowledge of channel coefficient values, they can still align interference based on the knowledge of only the channel autocorrelation structures of different users [11]. Antenna switching based BIA is proposed in [12] and it is used as a basis in this paper. It can create the desired predetermined channel fluctuation patterns for different users in each cluster which can be exploited by transmitters to implement the alignment schemes. To understand the BIA idea, one can examine the simple example where we have two user 2 x 1 MIMO BC channel in a one cell system, which is discussed in [12] in Section III.B..

3.1. Synchronized BIA

BIA techniques can cancel all the intracell interference however, if you consider multicell scenarios, it is not enough to deal with the intercell interference. Sycnhronized BIA (Sync. BIA) is a simple approach where each base station uses the same beamformer for transmission and same receiver antenna switching patterns. The word sychronized came from the fact that transmission of base stations should be synchronized so that even if all intercell interference is not canceled, some portion of it is coped with. The idea is illustrated in an environment where we have three cells each has two users, color coded in green and black, and two transmit antennas. The beamformer for base stations can be seen in Fig. 1(a) (vertical axis represents time domain). For each cell, we know that the green user does not see the data transmitted to the black user after applying necessary steps that is discussed in [12]. Consider the green user



(a) (b)

Fig. 1. For 3 cell 2 user setting with 2 transmit antennas at BSs (a) Sync. BIA (b) Ext. BIA

in BS1. Since, each base station use the same transmission scheme, intercell interference coming from BS2 and BS3 related to the black user data can be canceled out while green user data results in interference. Throughput at kth user in ith cell of cth cluster is ;

$$R_{[k,ic]}^{Sync} = \frac{1}{T_s} E\left[log \left| \left(I + \frac{T_s P}{M^2 K} \right) H_{ic}^{[k,ic]} H_{ic}^{[k,ic]^+} R_z^{-1} \right| \right] \quad (2)$$

where $T_s = M-1+K$ and $R_z = N_0 I + \sum_{\substack{j=1 \\ j\neq i}}^{C} P \check{H}_{jc}^{[k,ic]} \check{H}_{jc}^{[k,ic]^+} + \sum_{\substack{s=1 \\ s\neq c}}^{S} \sum_{j=1}^{C} P \check{H}_{js}^{[k,ic]} \check{H}_{js}^{[k,ic]^+}$. Also,

$$H_{ic}^{[k,ic]} = \sqrt{g(d_{ic}^{[k,ic]})} \times \left[\frac{1}{\sqrt{K}} h_{ic}^{[k,ic]}(1), ..., \frac{1}{\sqrt{K}} h_{ic}^{[k,ic]}(M-1), h_{ic}^{[k,ic]}(M) \right]^T \quad (3)$$

$$\check{H}_{js}^{[k,ic]} = \sqrt{g(d_{js}^{[k,ic]})} \left[h_{js}^{[k,ic]}(1), ..., h_{js}^{[k,ic]}(M-1), h_{js}^{[k,ic]}(M) \right]^T \quad (4)$$

Throughput equation is a modified version of the one that is presented in [12]. The main difference is the R_z term. It represents the intercell and inter cluster interferences which is a consequence of using Sync. BIA in a clustered small cell environment.

3.2. Extended BIA

Ext. BIA is a straight forward extension of the traditional single cell BIA for the multicell scenarios. Our aim is to design a simple supersymbol structure that is very similar to the BIA for single cell scenario. We consider the cluster as one big cell and apply the BIA directly. Consider a scenario where we have three cells, each with two users and two transmit antennas. For this environment, supersymbol for the Ext. BIA is the same as the traditional BIA where we have one BS with two transmit antennas and six users. The beamformer for this environment can be seen in Fig. 1(b) from which we can conclude that there will be no intra and intercell interference in the system. In this scheme, we do not assume any data sharing between the BSs. Each user data is transmitted by its own BS according to the predetermined supersymbol structure. Throughput of the kth user in the ith cell of the cth cluster is;

$$R_{[k,ic]}^{Ext} = \frac{1}{T_e} E\left[log \left| \left(I + \frac{T_e P}{M^2 K} \right) H_{ic}^{[k,ic]} H_{ic}^{[k,ic]^+} R_z^{-1} \right| \right] \quad (5)$$

where $R_z = N_0 I + \sum_{\substack{s=1\\ s\neq c}}^{S} \sum_{j=1}^{C} P \check{H}_{js}^{[k,ic]} \check{H}_{js}^{[k,ic]^+}$, $T_e = M-1+CK$ and $H_{ic}^{[k,ic]}$ is similar to (3) with $\sqrt{CK}$ as normalization term. $\check{H}_{js}^{[k,ic]}$ is same as (4).

4. LOCATION AIDED SEMI-BLIND INTERFERENCE ALIGNMENT

Instead of fully blind schemes, one can use a small amount of guidance to boost the performance of the system with minimal overhead. Knowing location information of the users and the BSs in the cluster gives us the opportunity to design more situational aware algorithm. For each cluster, we define a grouping indicator matrix to label the interference limited users with the help of location information. An example can be seen in Fig. 2. We see that BS3 creates strong interference to the user 2 in BS1. Therefore, user 2 is not suitable for grouping with user 5 and user 6 from BS3 and it is indicated with 0s. BS3 also creates strong interference to the user 3 in BS2. Because of the same reasoning, user 3 is not suitable for grouping with user 5 and user 6 from BS3. This matrix also points out the users in the same cell which can not be grouped because of the intracell interference issues. Therefore; user 1 and 2, user 3 and 4, user 5 and 6 are not suitable for grouping and it is indicated with zeros in the matrix. Grouping indicator matrix is a symmetric matrix and its diagonal is all ones since each user is suitable for grouping with itself.

Given the grouping indicator matrix, our aim is to design a transmission scheme that minimizes the supersymbol length for each cluster. In other words, proposed algorithm should determine the users that can be grouped and then they should serve these users at the same time via Sync. BIA approach. At the end, we want to serve each user during one supersymbol and maximize the size of the user groupings to minimize the supersymbol length. This problem, which is studied comprehensively in [17], is NP-Hard and one need to design a heuristic algorithm that can provide an effective solution without too much complexity. Top level semi-blind supersymbol design (Top. BIA) aims to group the suitable users as much as possible without examining all possibilities. This approach may lead us to a sub-optimal solution but it is much simpler.

Top. BIA Supersymbol Design: We examine the proper submatrices of grouping matrix G and compare it with all $1s$ matrix to group the users. For a cluster that has C cells with K users, size of G is $CK \times CK$. Note that the maximum size of the group can be C because of the reason that users in the same cell can not be grouped. In the most desirable scenario, we want C users to be grouped together. Therefore, we at first examine the size $C \times C$ submatrices of G (with symmetric row and column indicies) and compare it all $1s$ matrix with the same size. If the condition is satisfied, we group the corresponding users and throw away the related columns and rows from G and repeat the process with the remaining matrix with size $(CK-C)\times(CK-C)$. If the condition is not satisfied, then we reduce the size to the $(C-1)\times(C-1)$ and apply the same process. For example in Fig. 2(a), the submatrix formed by the indices {1,4,6} is all ones and we group them together. Then we remove the 1^{st}, 4^{th} and 6^{th} rows and columns from the matrix and examine the remaining one. The remaining 3×3 matrix is not all ones and so we start to examine the random 2×2 matrix. Finally we group users {2,3} and the final user groupings are {{1,4,6},{2,3},{5}} as can be seen in Fig. 2(a) (same color corresponds to same time slot usage). After determining the user groups, transmit beamformers can be constructed as in Fig. 2(b).

Throughput Calculation: We define T as supersymbol length and $L^{[k,ic]}$ as the set of base stations who transmits some data during

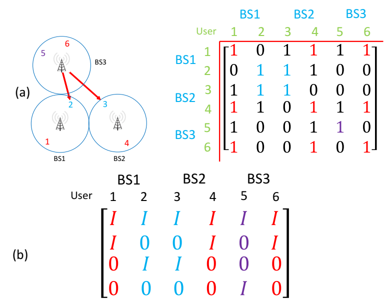


Fig. 2. (a) Grouping indicator matrix and user groups, which is formed by Top. BIA. (b) Transmit beamformer

the time slot of user k. Both of these parameters can be found from the constructed transmit beamformers. Throughput of user k in cell i of cluster c is;

$$R_{[k,ic]}^{Semi} = \frac{1}{T} E\left[log \left| \left(I + \frac{TP}{M^2 K}\right) H_{ic}^{[k,ic]} H_{ic}^{[k,ic]^+} R_z^{-1} \right| \right] \quad (6)$$

where, $R_z = N_0 I + \sum_{j=1, j\neq i, j\in L^{[k,ic]}}^{C} P \check{H}_{jc}^{[k,ic]} \check{H}_{jc}^{[k,ic]^+}$ $+ \sum_{\substack{s=1\\ s\neq c}}^{S} \sum_{j=1}^{C} P \check{H}_{js}^{[k,ic]} \check{H}_{js}^{[k,ic]^+}$. $H_{ic}^{[k,ic]}$ is similar to (3) with $\sqrt{T-1}$ as normalization term. $\check{H}_{js}^{[k,ic]}$ is same as (4).

Threshold Iteration: We indicate the interference with 1s and 0s in the grouping indicator matrix. However this is not true in practice and we need to introduce a threshold value to convert the interference to a binary variable by exploiting the location information of the users and BSs in the cluster. For each BS-user pair, one can calculate the corresponding long term SINR value and compare it with the threshold to get 1 or 0. Also for the given user distribution, we need to choose the threshold value properly so that semi-blind schemes can give higher throughput results than the purely blind schemes (Sync. BIA and Ext.BIA).

First, we calculate the long term pairwise SINR values for each user-interfering BS pair in the cluster by using the location information. Initial threshold value is chosen as the minimum across those pairwise SINR values. Then we calculate and compare the expected network throughput of semi blind scheme and blind schemes. For the non-greedy approach, we continue to iterate the process (threshold value is updated with the second smallest SINR and so on) until semi blind scheme can provide better performance than the blind schemes. For the greedy approach, we continue to update until we see a decrease in the throughput of semi blind scheme.

Complexity: Assume that we have n users, c BSs in the cluster and each BS has k users ($n = c*k$). The worst case complexity will be [1]:

$$\begin{aligned} (c)^2 \binom{n}{c} + (c-1)^2 \binom{n}{c-1} + \ldots + 2^2 \binom{n}{2} &\leq c^2 \sum_{i=1}^{c} \binom{n}{i} \\ &\leq \frac{c^2}{c!} n^{c+1} \\ &\leq O(n^{c+1}) \quad (7) \end{aligned}$$

[1]Note that comparing a submatrix of size $m \times m$ to all ones matrix is $O(m^2)$. Last step assumes that $c > 3$

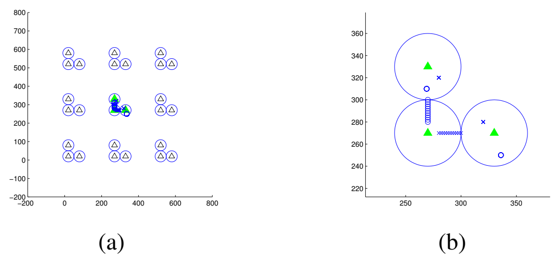


Fig. 3. (a) Small cell network that is used in the simulations (b) Moving the users in BS1(in the center cluster) towards to the cell edges for the first simulation scenario

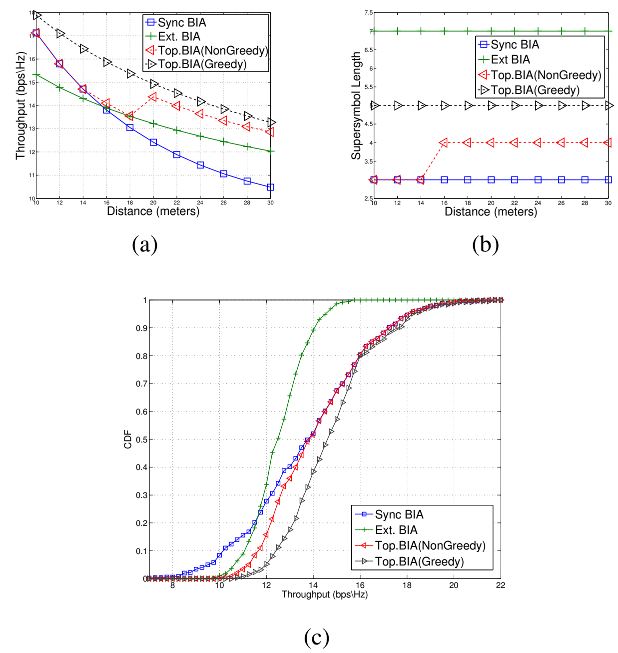


Fig. 4. (a) Total throughput in the center cluster vs users distance to the BS1 as shown in Fig. 3(b) (b) Supersymbol length vs users distance to the BS1 (c) CDF of the throughput in the center cluster

5. SIMULATION RESULTS

In this section, we examine the performance of the proposed algorithms in a clustered small cell network which is shown in Fig. 3(a). Distance between clusters is 250m and footprint of each cell is 30m. Each BS has two antennas and serves 2 user with a transmit power of 20dBm. Path loss model is chosen as $15.3 + 37.6\log_{10}(d)$. Small scale fading is Rayleigh with $CN(0, 1)$. We analyze the total throughput in the center cluster for 2 different scenarios via monte carlo simulations.

In the first simulation scenario, our aim is to examine the effect of intercell interference in the system. For this, we move the users from cell center to cell edge in one cell while we fix the location of the users in other cells as in Fig. 3(b). At each position, we run 1000 realizations of the channel and calculate the total network throughput in the center cluster for each algorithm which is shown in Fig. 4(a). As expected Sync. BIA can give better performance than Ext. BIA when the users in BS1 are close to the cell center, d=10 to d=16m. In that region, majority of the users are not interference limited and therefore, extending the supersymbol to deal with all intercell interference degrades the performance. However after some point, d=16m, Ext. BIA starts to perform better than the Sync. BIA because intercell interference becomes high and it has to be coped with. The aim of non-greedy threshold version of the Top. BIA is to get a reasonably good performance that is better than fully blind schemes. As can be seen from the Fig. 4(a), the proposed non greedy algorithm give the same performance as Sync. BIA for d=10m to d=14m. Since we desire the best performance with minimum supersymbol length, our algorithm start with a supersymbol that is used in Sync. BIA (Fig. 4(b)). If it can give the best performance among fully blind schemes, then non-greedy version of the proposed algorithm stops its threshold iteration and choose Sync. BIA as its transmission approach. After d=16m, we see that the performance of the Ext. BIA starts to dominate the Sync. BIA. In this region, our proposed algorithm tries to find a scheme that can give better performance than the Ext. BIA but use a smaller supersymbol for the transmission as in Fig. 4(a)(b). Finally, greedy threshold version of the Top. BIA is not only better than the maximum performance of fully blind schemes, but also it is trying to maximize the network throughput which can be seen in Fig. 4(a). One can also conclude that for the user distribution that is shown in Fig. 3, the supersymbol length that maximizes the throughput is 5 as in Fig. 4(b).

In the second simulation scenario, we generate 250 realizations of user locations in the center cluster and for each user distribution, 1000 channel realizations are simulated to generate the CDF curves of the throughput of the proposed algorithms and Sync. BIA. As can be seen in Fig. 4(c), semi-blind scheme has better performance results than the fully blind schemes for any user distribution scenario. The improvement is significant for the user distributions where the corresponding total network throughput is between 10-16 bps/Hz. On the other hand, the performance of the Top. BIA converges to the Sync. BIA or Ext. BIA in extreme user distribution scenarios. When the total network throughput is higher than 16 bps/Hz (users are close to the cell center), Sync. BIA performance is much higher than Ext. BIA and Top. BIA converge to the Sync. BIA. On the contrary, when the total network throughput is lower than 10 bps/Hz (users are close to the cell edge), Top. BIA converge to Ext.BIA which is better than Sync. BIA in this region. Another thing to point out is that, greedy versions of the proposed algorithm boost performance over the non greedy version at the expense of increased complexity.

6. CONCLUSIONS

Some simple extensions of the blind interference alignment can be applied to multicell scenarios, however their performance is directly related to the user distribution among the cluster. To enhance the performance uniformly, we proposed a semi-blind scheme, Top. BIA, which uses the location information of the users and BSs in the cluster. By numerical simulations, we showed that the Top. BIA can give better performance results than the fully blind schemes for any user distribution scenario.

7. ACKNOWLEDGMENT

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