Adaptive Interference Alignment for Femtocell Networks

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Abstract—**In this paper, we propose a spectral efficient transmission scheme for femtocell networks, which includes an adaptive subband partition method and an adaptive interference alignment transceiver. By introducing random frequency hopping to achieve the subband partition, we do not need a central coordinator to control the interference among the femtocells, and we can adjust the number of the interference in each subband. By employing adaptive interference alignment transceiver, the interference led by the subband collision can be suppressed. Simulation results show that the transmission scheme improves the system throughput significantly.**

I. Introduction

Interference management is crucial for achieving various benefits of femtocell networks, where the home base stations (HeNB) are not expected to share the information of their users for coherent cooperative transmission [1]. Orthogonal resource partition provides interference free transmission among the femtocells [2]. However, this will reduce the spectral efficiency considerably, especially due to the fact that the HeNBs are located in an ad hoc manner and the topology is dynamic.

Interference alignment is an appealing concept for interference management in distributed networks [3-6]. By minimizing the subspace dimension occupied by the interference signals while keeping more subspace for the desired signal, high multiplexing gain is attained.

However, exact interference alignment is achieved only for an exact number of users [6]. Moreover, channel information among all transmitters and all receivers is required for the precoding, which is hard to acquire especially for the distributed networks such as the femtocells.

In this paper, we design a transmission scheme for femtocell networks where each HeNB and each user have multiple antennas. We introduce random frequency hopping to judiciously control the number of users operated in the same time-frequency resource. Then we employ interference alignment to cope with the interference led by the inevitable frequency subband collision. To reduce the demands for obtaining the extensive channel information, we resort to a distributed interference alignment algorithm which only needs local channel information and the sum of the interference channel information [4], considering that the indoor channels are quasi-static. In contrast to dividing the entire bandwidth into multiple non-overlapped subbands for all users in a static manner, the proposed scheme with random frequency hopping and interference alignment provides high spectral efficiency even without any coordination among the home base stations and without a central coordinator.

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II. System Model

Consider a femtocell network with K HeNBs and each HeNB serves one user. We assume that the kth HeNB and its user are equipped with M_k and N_k antennas respectively. A femtocell network example with three HeNBs and three users is shown in Fig. 1. We divide the whole frequency band into R subbands, then each HeNB uses one subband to convey its message. Let $\mathcal{K}_r, \square r = 1, \cdots, R$ denotes the HeNB index set including HeNBs using the rth subband.

A time division duplexing (TDD) system is considered, and the channels of the uplink and downlink are reciprocal.

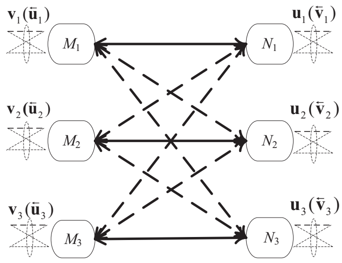

Fig 1. A femtocell network example with three HeNBs and three users

A. Communication in the Downlink

The transmit signal vector of the ith HeNB on the rth subband is expressed as

$$\mathbf{x}_i^r = \begin{cases} \mathbf{v}_i d_i, \square i \in \mathcal{K}_r \\ \mathbf{0}, \quad \square i \notin \mathcal{K}_r \end{cases}, r = 1, \cdots, R \tag{1}$$

where $\mathbf{v}_i \in \mathbb{C}^{M_i \times 1}$ is the pre-processing vector satisfying $\mathbf{v}_i^\dagger \mathbf{v}_i \le 1$, $\mathbf{v}_i^\dagger$ represents the conjugate transpose of vector $\mathbf{v}_i$, and d_i is the transmitted symbol for the ith user, which satisfies $E\{|d_i|^2\} = P_i$.

Then the received signal vector of the kth user is

$$\mathbf{y}_k^r = \sum_{i \in \mathcal{K}_r} \mathbf{H}_{ki} \mathbf{x}_i^r \square \mathbf{w}_k^r, \square k \in \mathcal{K}_r, r = 1, \cdots, R \tag{2}$$

where $\mathbf{H}_{ki} \in \mathbb{C}^{N_k \times M_i}$ is the channel matrix between the ith HeNB and the kth user, and $\mathbf{w}_k^r \in \mathbb{C}^{N_k \times 1}$ is the zero mean unit variance additive white Gaussian noise (AWGN) vector at the rth subband of the kth user.

The desired symbol of the kth user can be estimated as

$$\hat{d}_k = \mathbf{u}_k^\dagger \mathbf{y}_k^r, \square k \in \mathcal{K}_r, r = 1, \cdots, R \tag{3}$$

where $\mathbf{u}_k \in \mathbb{C}^{N_k \times 1}$ is the post-processing vector of the kth user.

B. Communication in the Uplink

In the uplink, the role of the transmitters and the receivers are switched. The signal vector transmitted by the ith user can be expressed as

$$\bar{\mathbf{x}}_i^r = \begin{cases} \bar{\mathbf{v}}_i \bar{d}_i, \forall i \in \mathcal{K}_r \\ \mathbf{0}, \quad \forall i \notin \mathcal{K}_r \end{cases}, r = 1, \cdots, R \tag{4}$$

where $\bar{\mathbf{v}}_i \in \mathbb{C}^{N_i \times 1}$ is the pre-processing vector of the ith user satisfying $\bar{\mathbf{v}}_i^\dagger \bar{\mathbf{v}}_i \le 1$. The transmitted symbol $\bar{d}_i$ is also assumed to satisfy $E\{|\bar{d}_i|^2\} = P_i$.

Then the received signal vector of the kth HeNB is

$$\bar{\mathbf{y}}_k^r = \sum_{i \in \mathcal{K}_r} \bar{\mathbf{H}}_{ki} \bar{\mathbf{x}}_i^r + \bar{\mathbf{w}}_k, \forall k \in \mathcal{K}_r, \; r = 1, \cdots, R \tag{5}$$

where $\bar{\mathbf{w}}_k^r \in \mathbb{C}^{M_k \times 1}$ is the zero mean unit variance AWGN vector of the kth HeNB at the rth subband, and $\bar{\mathbf{H}}_{ki} \in \mathbb{C}^{M_k \times N_i}$ is the channel matrix between the ith user and the kth HeNB. Considering the reciprocity of the uplink and downlink channel, we have $\bar{\mathbf{H}}_{ki} = \mathbf{H}_{ik}^\dagger, \forall i, k \in \mathcal{K}_r, \; r = 1, \cdots, R$.

Similar to the downlink signal model, the desired symbol of the kth HeNB can be estimated as $\hat{\bar{d}}_k = \bar{\mathbf{u}}_k^\dagger \bar{\mathbf{y}}_k$, where $\bar{\mathbf{u}}_k \in \mathbb{C}^{M_k \times 1}$ is the post-processing vector.

III. Distributed Adaptive Interference Alignment

In this section, we propose a transmission scheme aiming at managing the downlink interference among the femtocells, which consists of an adaptive interference alignment (AIA) transceiver and an adaptive subband partition method. We first introduce the AIA transceiver in [4], and provide comprehensive explanation on both why it works well and the condition it required. Then we provide the adaptive subband partition method, which is designed to exploit the benefit of the AIA transceiver.

A. Adaptive Interference Alignment Transceiver

From (2) and (3), we can obtain the signal-to-interference-plus-noise ratio (SINR) of the kth user as

$$SINR_k = \frac{P_k \mathbf{u}_k^\dagger \mathbf{H}_{kk} \mathbf{v}_k \mathbf{v}_k^\dagger \mathbf{H}_{kk}^\dagger \mathbf{u}_k}{\mathbf{u}_k^\dagger \mathbf{B}_k \mathbf{u}_k} \tag{6}$$

where

$$\mathbf{B}_k = \sum_{i \in \mathcal{K}_r} P_i \mathbf{H}_{ki} \mathbf{v}_i \mathbf{v}_i^\dagger \mathbf{H}_{ki}^\dagger - P_k \mathbf{H}_{kk} \mathbf{v}_k \mathbf{v}_k^\dagger \mathbf{H}_{kk}^\dagger + \mathbf{I}_{N^k} \tag{7}$$

is the interference-plus-noise covariance matrix.

The optimization problem to jointly design the pre- and post-processing vectors that maximizes the SINR can be formulated as

$$\begin{aligned} \max_{\{\mathbf{v}_k, \mathbf{u}_k\}} \quad & SINR_k, \\ s.t. \quad & \mathbf{v}_k^\dagger \mathbf{v}_k \le 1. \end{aligned} \tag{8}$$

Unfortunately, it is impossible to find an analytical solution for this problem. However, consider that the indoor channels are quasi-static, we are able to use the iterative algorithm presented in [4] to obtain $\mathbf{u}_k$ and $\mathbf{v}_k$. The steps of the iteration are given as follows,

1. Start with any $M_k \times 1$ vector as the pre-processing vector $\mathbf{v}_k$ of the HeNB $k, \forall k \in \mathcal{K}_r$, $r = 1, \cdots, R$.
2. Compute $\mathbf{B}_k$ shown in (7) of the kth user.
3. Compute the post-processing vector of the kth user as
$$\mathbf{u}_k = \frac{\mathbf{B}_k^{-1} \mathbf{H}_{kk} \mathbf{v}_k}{\left\| \mathbf{B}_k^{-1} \mathbf{H}_{kk} \mathbf{v}_k \right\|}, \forall k \in \mathcal{K}_r. \tag{9}$$
4. Reverse the communication direction and use the post-processing vector as the pre-processing vector,
$$\bar{\mathbf{v}}_k = \mathbf{u}_k, \forall k \in \mathcal{K}_r. \tag{10}$$
5. In the reciprocal link, compute $\bar{\mathbf{B}}_k$ of the kth HeNB.
6. Compute the post-processing vector $\bar{\mathbf{u}}_k$ of the kth HeNB.
7. Reverse the communication direction and use the post-processing vector as the pre-processing vector,
$$\mathbf{v}_k = \bar{\mathbf{u}}_k, \forall k \in \mathcal{K}_r. \tag{11}$$
8. Repeat until convergence.

In the forthcoming analysis, we will see that the transceiver achieves interference alignment at high signal-to-noise ratio (SNR) level and suppresses the interference adaptively in a sense that no user number needs to be specified in advance. Therefore we call this transceiver as the AIA transceiver.

As shown in (9), to obtain the post-processing vector $\mathbf{u}_k$ of the kth user, both the local channel matrix $\mathbf{H}_{kk}$ and the interference-plus-noise covariance matrix $\mathbf{B}_k$ are required. We assume the ideal knowledge of $\mathbf{H}_{kk}$. From (2) and (7), $\mathbf{B}_k$ can be estimated as

$$\hat{\mathbf{B}}_k = \mathbf{R}_{\mathbf{y}_k^r} - P_k \mathbf{H}_{kk} \mathbf{v}_k \mathbf{v}_k^\dagger \mathbf{H}_{kk}^\dagger. \tag{12}$$

where $\mathbf{R}_{\mathbf{y}_k^r} = E\{\mathbf{y}_k^r \mathbf{y}_k^{r\dagger}\}$ is the covariance matrix of the kth user's received signal.

When the transmitter uses a T-length training sequences $s_i(n), n = 1, \cdots, T$ for local channel estimation, the nth received signal of the receiver k on the rth subband is obtained as

$$\mathbf{y}_k^r(n) = \sum_{i \in \mathcal{K}_r} \mathbf{H}_{ki} \mathbf{v}_i s_i(n) + \mathbf{w}_k(n), \forall k \in \mathcal{K}_r. \tag{13}$$

Then the maximal likelihood estimate of $\mathbf{R}_{\mathbf{y}_k^r}$ can be obtained as [7]

$$\hat{\mathbf{R}}_{\mathbf{y}_k^r} = \frac{1}{T} \sum_{n=1}^{T} \mathbf{y}_k^r(n) \mathbf{y}_k^{r\dagger}(n). \tag{14}$$

To understand the performance of the AIA transceiver, in Fig. 2, we show the throughput per user of a K-user network when AIA is applied, where $M_k = N_k = 2$. From the simulation result, we have the following observations.

***Observation 1* (Max-SINR and Interference Alignment)**: It is worth to note that the SINR in the downlink is

$$SINR_k = \frac{P_k \left| \mathbf{u}_k^\dagger \mathbf{H}_{kk} \mathbf{v}_k \right|^2}{\sum_{i \in \mathcal{K}_r} P_i \left| \mathbf{u}_k^\dagger \mathbf{H}_{ki} \mathbf{v}_i \right|^2 - P_k \left| \mathbf{u}_k^\dagger \mathbf{H}_{kk} \mathbf{v}_k \right|^2 + 1}, \tag{15}$$

and the signal-to-leakage-and-noise ratio (SLNR) in the uplink can be obtained as

$$\overline{SLNR}_k = \frac{P_k \left| \bar{\mathbf{u}}_k^\dagger \bar{\mathbf{H}}_{kk} \bar{\mathbf{v}}_k \right|^2}{\sum_{i \in \mathcal{K}_r} P_i \left| \bar{\mathbf{u}}_i^\dagger \bar{\mathbf{H}}_{ik} \bar{\mathbf{v}}_k \right|^2 - P_k \left| \bar{\mathbf{u}}_k^\dagger \bar{\mathbf{H}}_{kk} \bar{\mathbf{v}}_k \right|^2 + 1}. \tag{16}$$

Since the role of the transmitters and receivers in the uplink and downlink are switched, i.e. $\bar{\mathbf{v}}_k = \mathbf{u}_k$ and $\bar{\mathbf{u}}_k = \mathbf{v}_k$, and the channel is reciprocal, i.e. $\bar{\mathbf{H}}_{ik} = \mathbf{H}_{ki}^{\dagger}$, we have $\left|\bar{\mathbf{u}}_i^{\dagger}\bar{\mathbf{H}}_{ik}\bar{\mathbf{v}}_k\right|^2 = \left|\mathbf{v}_i^{\dagger}\mathbf{H}_{ki}^{\dagger}\mathbf{u}_k\right|^2 = \left|\mathbf{u}_k^{\dagger}\mathbf{H}_{ki}\mathbf{v}_i\right|^2$. Substituting the transceivers in both links into (15) and (16), we can see that $\overleftarrow{SLNR}_k = SINR_k$. It implies that the post-processing vector $\mathbf{u}_k$ as shown in (9) is a multiuser detector which is designed to maximize the SINR. In the uplink, when we let $\bar{\mathbf{v}}_k = \mathbf{u}_k$, $\bar{\mathbf{v}}_k$ becomes a multiuser precoder which maximizes the SLNR [8]. Therefore, in order to maximize the SINR for each user, the designed transceiver aims to suppress the multiuser interference from others meanwhile to mitigate the leakage interference from itself to others. After limited iterations, the interference can be compressed into a less-dimensional space. In the case of $K = 3$ shown in Fig. 2, the simulation result is the same as that in [3], and which represents that interference alignment is achieved at high SNR [3]. It means that each receiver can employ one antenna to remove the two interference sources completely since the interference from other two users are aligned into one-dimensional signal subspace. In other words, the iteration between a Max-SINR multiuser detector and a Max-SLNR multiuser precoder finally achieves perfect interference alignment in the high SNR region.

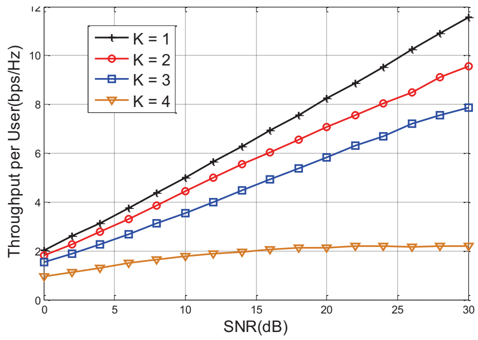

Fig 2. Throughput per user of the K-user interference channel using the AIA transceiver with 20 iterations, $M_k = N_k = 2$.

***Observation 2* (Adaptive Interference Suppression)**: From the steps of the iteration we can see that neither the interference channel information nor the number of the interference users is required by the AIA. The iteratively achieved transceiver can suppress the interference according to the adaptively estimated interference-plus-noise covariance matrix $\mathbf{B}_k$.

***Observation 3* (Interference Number Threshold)**: It is shown from Fig. 2 that the AIA performs well if $K \le 3$, but the performance degrades dramatically when $K = 4$. It is well understood that the capability of linear beamformers to suppress the interference depends on the number of antennas at the transmitter and receiver [7]. The interference alignment can be viewed as a special class of linear beamforming, thus it is nature that the AIA has similar behavior. This implies that we should control the number of the interference to be less than three in order to exploit the potential of the AIA. Given M_k and N_k, there exists a number A which represents the number of interference users in one subband. If $K \le A$, each user can be provided with a reliable communication link. Otherwise, all users will suffer from severe performance loss. We denote A as an *interference number threshold* (INT).

B. Adaptive Subband Partition

In order to ensure that the number of users in one subband will not exceed the INT, we divide the whole bandwidth into R orthogonal subbands. Each HeNB randomly selects one of these subbands to communicate with its user. We optimize R to reduce the probability of no more than A HeNBs colliding in one subband.

The probability that each subband is chosen by one user is $1/R$. Since every user selects the subband independently, the probability that c users select the same subband can be obtained as

$$p_{Collide}(c, R) = C_K^c \left(\frac{1}{R}\right)^c \left(\frac{R-1}{R}\right)^{K-c}. \tag{17}$$

Then the probability of more than A users colliding in one subband is achieved as

$$p_{Collide}(c > A, R) = \sum_{i=A+1}^{K} p_{Collide}(i, R) = \sum_{i=A+1}^{K} C_K^i \left(\frac{1}{R}\right)^i \left(\frac{R-1}{R}\right)^{K-i}. \tag{18}$$

Even though the collision probability decreases as the number of subband R increases, we cannot increase R without limitation because if R is too large, the available bandwidth for one user is too small. Given an acceptable upper-bound of the collision probability η, we can find the minimal number of subbands R which ensures the collision probability is lower than η. The optimization problem can be formulated as

$$\begin{aligned} \min \quad & R, \\ s.t. \quad & p_{Collide}(c > A, R) \le \eta. \end{aligned} \tag{19}$$

With limited times of searching and comparison, we can obtain the optimal R.

In practice, the proposed transmission scheme consisting of the adaptive subband partition and the AIA transceiver can be implemented as follows,

1. Based on the antenna configuration, determine the INT, A.
2. According to the collision probability upper-bound η, design the optimal number of subbands, R.
3. Employ the AIA transceiver in each subband.

IV. Simulation Results

In this section, we will evaluate the performance of the proposed scheme through simulations.

We first compare the spectral efficiency of the proposed scheme (shown as AIA in the legend for short though the scheme includes both the transceiver and the adaptive subband partition) with the scheme only using adaptive subband partition but without AIA (shown as w/o AIA in the legend), as well as with the scheme only using AIA but with fixed subband partition (the number of the subband is shown in the legend). The results are shown in Fig. 3 and Fig. 4

respectively. In these simulations, both HeNBs and the users are equipped with two antennas, and all channel coefficients are independent and identically distributed (i.i.d.) zero mean unit variance complex Gaussian variables. The large scale fading of the local channel and the interference channel are set to be the same.

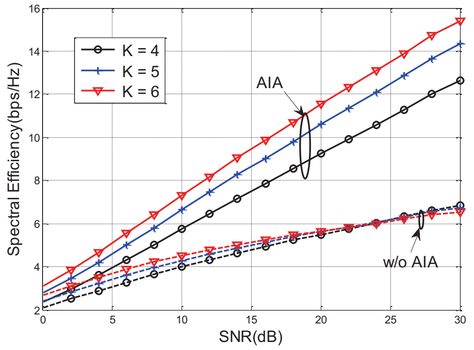

Fig 3. Spectral efficiency of random frequency hopping systems with or without the AIA, R = 3.

In Fig.3, without the AIA transceiver, the system suffers from a severe performance loss once the selected subband colliding with others, hence its INT is only $A=1$.When using the AIA transceiver, each user is capable of suppressing interference, and the INT becomes $A=3$. Table I shows the collision probability $p_{Collide}\left(c > A, R\right)$ obtained from (18). The collision probability reduces effectively when the AIA transceiver is used because the increase of the interference number threshold A, which results in a significant spectral efficiency improvement.

TABLE I. THE PROBABILITY OF MORE THAN A USERS COLLIDING IN ONE SUBBAND, $R=3$.

	$K=4$	$K=5$	$K=6$
AIA: A=3	0.01	0.04	0.10
w/o AIA: A=1	0.80	0.86	0.91

Then we evaluate the performance of the adaptive subband partition method. Set the collision probability upper-bound as $\eta = 0.25$, from (19) we can obtain the optimal number of subband R for arbitrary K, which is listed in Table II.

TABLE II. ADAPTIVE SUBBAND PARTITION, $\eta = 0.25$.

K	1	2	3	4	5	6	7	8	9	10	11	12	13	14
R	1	1	1	2	2	3	3	3	4	4	5	5	5	6

In Fig. 4, when the adaptive subband partition is used, the number of subbands R is adaptively chosen from Table II. We can observe that the adaptive subband partition always outperforms the fixed subband partition for arbitrary number of users.

In the above simulations, the average interference power of each link is set to be the same as the signal power to highlight the impact of interference. We evaluate the proposed scheme under more practical assumption in Fig. 5, where the penetration loss in [9] is considered. Furthermore, due to that the topology of femtocells is in an ad hoc manner and the interference environment of any femtocell is unpredictable, we simulate the performance of a femtocell which is surrounded by different number of femtocells (shown as NF in the legend). It shows that the proposed transmission scheme provides significant performance gain over the scheme without any coordination (shown as NC in the legend).

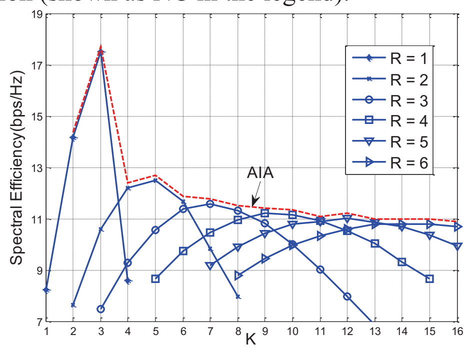

Fig 4. Performance of adaptive and fixed subband partition versus *K*.

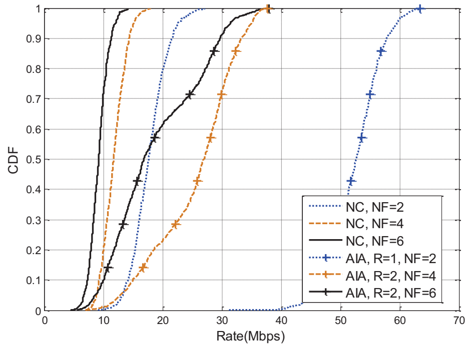

Fig 5. CDF of user data rate with 6MHz bandwidth, SNR=30dB.

V. CONCLUSION

In this paper, we propose a transmission scheme for managing the interference among the femtocells, which consists of an adaptive subband partition method and an adaptive interference alignment transceiver. The proposed scheme is able to provide spectral efficient transmission for any number of HeNBs without the help of a central coordinator and without the exchanging of any information among HeNBs.

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