An Opportunity Downlink Interference Alignment Algorithm Based on Punch Scheduling in Cognitive Heterogeneous Networks

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Abstract. For the hierarchical structure and frequency reuse of cognitive heterogeneous networks, it is inevitable to effectively deal with interference while gaining capacity. In this article, we consider the downlink cognitive heterogeneous network, in which a macro base station can serve a certain number of macro users, and each macro cell is composed of a certain number of micro cells. An opportunistic downlink interference alignment (ODIA) algorithm for cognitive heterogeneous networks based on puncture scheduling is proposed. First, we designed a pair of precoding and decoding matrices to eliminate co-layer interference. Second, in order to reduce the overhead required to transmit system state information (CSI), we proposed a user scheduling algorithm that not only can obtain a larger interference-free size, but also improvements in fairness, system capacity and overflow probability. The simulation results show that the proposed ODIA scheme is superior to the existing interference management algorithms in terms of interference, system capacity and fairness of system resource allocation.

1. Introduction
Heterogeneous networks (HetNets) have been taken into account as a promising method to adapt to explosive wireless data growth and ensure users experience for 5G evolution[1][2]. Besides the explosive growth of data services, the existing spectrum resources have been almost exhausted, but these spectrum resources have not been fully utilized[3]. Cognitive heterogeneous network is based on cognitive radio, giving heterogeneous networks the ability to perform cognitive learning on complex and diverse heterogeneous environments, channels, and users[4]. The architecture and structure of heterogeneous networks and the frequency reuse of cognitive radio technology will cause a series of interference problems to the network.

In recent years, as an effective interference suppression technology, the method of combining interference alignment (IA) and opportunistic communication to form opportunistic interference alignment (OIA) has received extensive research and attention. The introduction of multi-antenna MIMO technology into cognitive radio can open up new spectrum resources, namely airspace resources, and cognition of airspace channels will further improve the spectrum utilization, network capacity and performance of primary users [4]. Interference alignment is to optimize the problem of user interference in the interference channel from the angle of freedom [5]. However, the achievement of IA requires methodical global channel state information (CSI) at the transmitter, so its comparatively efficient throughput hinge on a large extent of the feedback overhead and accuracy of CSI[6][7]. In addition, for
MIMO interference channels or interference broadcast channels, the application of highly complex iterative algorithms was used to calculating the decoding and precoding matrix\cite{8}. Opportunistic Interference Alignment (OIA) has become a substitution to traditional IA, which has decreased CSI feedback overhead and is effortless to implement.

A puncture scheduling algorithm based on fairness was proposed in\cite{9}, which has the advantages of better fairness between users and throughput of edge cells. However, since real-time services are extremely sensitive to the packet loss rate, the scheduling algorithm should consider various factors related to the packet loss rate and delay when implementing the scheduling strategy, such as instantaneous or average channel conditions, and transmission queue length. An opportunistic downlink interference alignment algorithm was proposed in a multi-cell MIMO network\cite{10}. However, the algorithm for selecting users only considers the index of minimizing interference leakage. Interference alignment algorithm based on round-robin mechanism is proposed\cite{11}, while the round-robin scheduling algorithm allows all users to obtain transmission opportunities, it ignores the user channel quality factor, which in turn reduces the performance of spectrum utilization and system throughput. In mobile communication, each user’s communication request is burst and random, the data packet sent to the user will be invalid if it cannot be successfully sent within the required time delay, affecting communication performance and user experience.

As a means of effective interference management in the downlink, we utilize opportunistic interference alignment for aligning interference signal to mitigate the interference that exists in cognitive heterogeneous networks based on\cite{10}. Then an improved Punch Scheduling (PS) was proposed to obtain multiuser diversity gain and decrease overflow probability, which takes into account the buffer queue length parameter. The cache information of each queue is closely related to the user’s quality of service (QoS). Experimental results show that the performance of system capacity is improved while obtaining more interference-free sizes.

2. System Model
The cellular network is the downlink of a cognitive heterogeneous network with a macro cell at the center and multiple FBS distributed over the macro cell coverage area. The existing cognitive IA solutions mainly focus on cross-layer interference caused to the macro users. The macro user’s (MU) interference to the cognitive user is not suppressed, which may cause severe performance degradation. Therefore, this paper studies the intra-layer and inter-layer interference existing in the micro cell. Assuming that both the FBS and the cognitive user in the femtocells (FU) are equipped with multiple antennas. Since the deployment of femtocell has the characteristics of self-organization and self-optimization, the network model proposed in this paper does not consider the cooperation between femtocell base stations and micro base station (MBS). Hence, there is no need to consider the cross-layer interference of macro base stations to FU. Model the downlink as a \((K+1)\)-cell MIMO interference broadcast channel (IBC) model, where each femtocell cell consists of one BS with M antennas and N users having L antennas each, as shown in Figure 1. A total of \(M\) transmitter antennas are configured at the micro station transmitter terminal, which serves N multi-antenna cognitive users through cognitive access to specific authorized frequency bands, each with \(M\) antennas and random distribution over a small area. S users are now selected from N waiting for communication service users. Assume that each selected user receives a separate stream of data. To take into account the special case, let’s assume that \(L<(K-1)S+1\), because otherwise all small interval interference can be completely eliminated at the receiver (i.e. the user). In addition, the number of user antennas is usually limited due to the size of the shape factor, so it is safer to assume that L is relatively small compared to \(L<(K-1)S+1\).
Figure 1. Downlink heterogeneous network transmission model.

The signal received at the PU can be expressed as:

\[ y^{i,j} = H^{i,j}_k V_k x_k + \sum_{k=1}^{K} H^{i,j}_k V_k x_k + z^{i,j} \]

\[ = \underbrace{H^{i,j}_1 V^{i,j}_1 x_1 + \sum_{k=1, k \neq i}^{K} H^{i,j}_k V^{i,j}_i x_s + z^{i,j}}_{\text{desired signal}} + \underbrace{\sum_{k=1, k \neq i}^{K} H^{i,j}_k V^{i,j}_k x_k}_{\text{co-interference}} + \underbrace{z^{i,j}}_{\text{cross-interference}} \]  

Where \( H^{i,j}_k \in \mathbb{C}^{L \times M} \) is the channel matrix of the \( k \)-th micro-base station to the \( j \)-th cognitive user, \( i, k \in \{1, \ldots, K\} \) and \( j \in \{1, \ldots, N\} \). \( V_i \) is a user-specific pre-coded matrix that eliminates the same layer of interference, \( x_s = [x^{i,1}, \ldots, x^{i,S}]^T \) is the expected signal which the micro-base station sends to the \( s \)-th cognitive user. \( z^{i,j} \) represents additive noise accepted by the PU, each of which is subject to an independent, identically distributed complex Gaussian with an mean of zero and a variance of \( N_0 \).

3. Proposed algorithm

3.1 Broadcast signal subspace

The \( k \)-th FBS defines the interference subspace \( P_k = \{P_{i,x}, \ldots, P_{i,s}\} \) in the sub-region, then broadcasts it to neighbouring FBS and users in the \( k \)-th FBS.

3.2 Feedback scheduling metrics

Scheduling metric can be defined as sum of interference received from other FBS

\[ \eta_{i,j}^{k} = \sum_{k=1}^{K} \|u^{[i,j],[k]} H_{k}^{[i,j]} P_k \| \]  

In addition to feedback to the corresponding base station, each user also feedbacks the following vector

\[ f_{i,j}^{k} = \left( \left\| u^{[i,j],[k]} H_{k}^{[i,j]} P_k \right\| \right)^{H} \]
3.3 receive beamforming

We should minimize the sum interference by receiving beamforming at the user in order to maximize the achievable degree of freedom, sum-interference is denoted as $\sum_{i=1}^{k} \sum_{j=1}^{s} I_{ij}^{(l,j)}$. For

$$I_{ij}^{(l,j)} = \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=1}^{N} \|H_{k}^{(l,j)}P_{m}\|^2 \cdot \text{SNR} = \sum_{i=1}^{s} \eta_{ij}^{(l,j)} \cdot \text{SNR}$$

(4)

Therefore, the smaller $\eta_{ij}^{(l,j)}$ is, the received less sum-interference is. Thus the minimized receive beamforming vector can be

$$u_{ij}^{(l,j)} = \arg \min_{u} \eta_{ij}^{(l,j)} = \arg \min_{u} \sum_{k=1}^{K} \sum_{m=1}^{M} \|u^{(l,j)}H_{k}^{(l,j)}P_{m}\|^2$$

(5)

We denote the augmented interference matrix by

$$G^{[k,l]} = \begin{bmatrix} H_{1}^{[k,l]}P_{1} & \cdots & H_{T}^{[k,l]}P_{1} & \cdots & H_{1}^{[k,l]}P_{T} & \cdots & H_{T}^{[k,l]}P_{T} \end{bmatrix} \in \mathbb{C}^{(K-1)\times T}$$

(6)

After calculation, $u_{ij}^{(l,j)}$ is the right singular value vector of $G^{[k,l]}$.

3.4 User scheduling

Add the following conditions after the conditions selected by the user in the ODIA algorithm[10] maximum value of $M_{i,p}$. When there are no users in urgent need of communication in the system, in order to make the allocation of communication resources relatively fair, an improved puncture scheduling algorithm is used to select communication users. The metrics of the improved puncture scheduling algorithm are as follows:

$$M_{i,p} = \frac{r_{i,p}(t)}{R_{i}(t)} \times \frac{1}{w_{p}(t)} \times Q_{i}(t) \times \frac{1}{1 + C_{i}(t)}$$

(7)

where,

$$R_{i}(t) = (1 - 1/t_{c}) \times R_{i}(t-1) + 1/t_{c} \times r_{i,p}(t-1)$$

(8)

and $r_{i,p}(t-1)$ is the instantaneous support rate of user $i$-th on the $p$-th PRB, $R_{i}(t)$ is the average transmission throughput, $w_{p}(t)$ is the current transmission block size of user $i$ on the $p$-th PRB.

t_{c} is the length of the sliding window. $C_{i}(t)$ is the total number of holes punched by user $i$. $Q_{i}$ represents the length of the transmission queue of the $i$-th user.

a) If $s < S$, we could select users from the next user set which is

$$N_{s+1} = \{j : j \in N_{s}, j \neq \pi(s), \frac{I_{ij}^{(l,j)}b_{j}}{\|H_{i}^{(l,j)}P_{i}\|^2} < \alpha\}, s = s + 1$$

(9)

where $\alpha > 0$ is a positive constant.

3.5 Eliminates co-interference

In order to eliminate co-interference, we design a user-specific beamforming matrix $V_{t} \in \mathbb{C}^{s \times s}$ as

$$V_{t} = \left[ \begin{array}{ccc} V_{t}^{(l,1)} & \cdots & V_{t}^{(l,s)} \end{array} \right]$$

$$= \begin{bmatrix} u_{i}^{(l,1)^{H}}H_{i}^{(l,1)}P_{i} & 0 & \cdots & 0 \\ u_{i}^{(l,2)^{H}}H_{i}^{(l,2)}P_{i} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ u_{i}^{(l,s)^{H}}H_{i}^{(l,s)}P_{i} & 0 & \cdots & 0 \end{bmatrix}$$

(10)
where $\gamma_{ij}^{[i,j]}$ is the normalization factor that satisfies the unit transmit power constraint of each spatial stream, and $\gamma_{ij}^{[i,j]} = 1/\|P_i V_{ij}^{[i,j]}\|$

4. Simulation Results

In this section, we build a cognitive heterogeneous network model through MATLAB and evaluate the performance of the proposed interference alignment scheme. In the simulation, it is compared with the 'min-INR' [12] technology which select users with the minimum inter-cell and intra-cell interference, and the ODIA algorithm [10]. The compared performance includes sum-interference, sum rate and overflow probability.

When $K=3$, $M=4$, $L=2$, and $SNR=20dB$, the comparison of sum-interference received by all users under different numbers of users in each cell is shown in Figure 2. Since our proposed interference alignment scheme eliminates the same-layer interference, it can be seen from the figure that the PS-ODIA we proposed achieves a higher interference attenuation rate than min-INR and ODIA algorithm.

![Figure 2: sum-interference versus $N$](image)

![Figure 3: sum-rate versus transmit power](image)

Figure 2 is a comparison of the total system capacity when $K=3$, $M=4$, $L=2$, $S=2$, and $SNR=20dB$. It can be seen that as the number of users increases, the total system capacity of the three algorithms continues to increase. The reason for this achievement is that the proposed algorithm completely eliminates intra-cell interference and minimizes inter-cell interference.

Figure 4 is the average queue overflow probability is plotted against the transmit power for the PS-ODIA algorithm, min-INR and ODIA. The picture shows that the overflow probability of all algorithms decreases as the transmit power increases. However, the PS-ODIA algorithm can obtain a lower overflow probability than the other two non-queue-based parameter based algorithms.

![Figure 4: Average queue overflow probability](image)
Figure 4. Overflow Probability versus Transmit Power

5. Conclusion
In this paper, we propose an opportunistic interference alignment scheme for cognitive heterogeneous networks, which combines user scheduling, transmit beamforming, and receive beamforming. The opportunistic interference alignment scheme based on the improved puncture scheduling algorithm can obtain more interference-free sizes, and at the same time make the allocation of system resources more fair, and better meet the needs of users for real-time and QoS performance. The simulation results show that the algorithm proposed in this paper has significant improvement in interference, system capacity and fairness.

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