THE DESIGN OF OPTIMAL RECEIVER FOR OPPORTUNISTIC INTERFERENCE ALIGNMENT

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ABSTRACT

Opportunistic interference alignment (OIA) has been known to asymptotically achieve the optimal degrees-of-freedom (DoF) in multi-input multi-output (MIMO) interfering multiple-access channels (IMACs) as the number of users scales with signal-to-noise ratio, even though no collaboration between base stations (BSs) is assumed. In some previous studies on OIA, the zero-forcing (ZF) receiver has been used at the BSs since it is sufficient to achieve the optimal DoF. In this paper, we propose a simple minimum distance (MD) receiver in a MIMO IMAC model, enabling us to implement the OIA scheme with no information of other-cell interfering links. Surprisingly, we show that as the number of users increases, the MD receiver not only guarantees the optimal DoF but also asymptotically achieves the optimal capacity obtained along with full information of other-cell interfering links. Simulation results indicates that the MD receiver indeed outperforms the conventional ZF receiver even in practical cellular setups.

Index Terms— Degrees-of-freedom (DoF), opportunistic interference alignment (OIA), minimum distance (MD) receiver, multi-input multi-output (MIMO) interfering multiple-access channels (IMACs).

1. INTRODUCTION

Interference alignment (IA) [1, 2] is the key ingredient to achieve the optimal degrees-of-freedom (DoF) of a variety of interference channel models [3]. However, the conventional IA framework has several well-known practical challenges: global channel state information (CSI) and arbitrarily large frequency/time-domain dimension extension.

Recently, the concept of opportunistic interference alignment (OIA) was introduced in [4, 5] for the K-cell N-user single-input multiple-output (SIMO) interfering multiple-access channel (IMAC), where each base station (BS) equips M antennas. In the OIA scheme for the SIMO IMAC, S ($S \leq M$) users amongst the N users are opportunistically selected in each cell in the sense that inter-cell interference is aligned at a predefined interference space. Although several studies have independently addressed one or a few of practical problems [6, 7], the OIA scheme simultaneously resolves the aforementioned problems; that is, the OIA scheme operates with i) local CSI acquired via pilot signaling, ii) no dimension extension in the time/frequency domain, iii) no channel randomness for every snap shot, iv) no iterative optimization of precoders, and v) no collaboration between the users or the BSs. For the SIMO IMAC, the OIA scheme was shown to asymptotically achieve KS DoF for $0 < S \leq M$, if N scales faster than $\text{SNR}^{(K-1)S}$ [8], where SNR denotes the received signal-to-noise ratio (SNR). The above OIA research was recently extended to a K-cell multi-input multi-output (MIMO) IMAC model having L antennas at each user [8, 9]. It was shown that the user scaling condition to achieve KS DoF can be greatly reduced to $\text{SNR}^{(K-1)S-L+1}$ with the use of singular value decomposition (SVD)-based beamforming at each user, by further reducing the generating interference level. Note that the optimal DoF achieved in the MIMO IMAC, given by KM, remains the same as that in the SIMO IMAC.

In the existing OIA framework, the zero-forcing (ZF) receiver at the BSs has been used since it is sufficient to guarantee the optimal DoF. However, the achievable rate based on the ZF receiver is in general far below the channel capacity, and the gap increases as the dimension of channel matrices grows. In this paper, we propose an enhanced receiver design at the BSs in pursuit of improving the achievable rate based on the ZF receiver. Our design is challenging since we assume local CSI and no collaboration between the BSs, thus resulting in no available information of inter-cell interfering links at each BS. Assuming no such information, the covariance matrix of the effective noise cannot be estimated, and thus the maximum likelihood (ML) or even minimum mean square

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error (MMSE) decoding is not possible at each BS. We instead propose a simple *minimum distance (MD)* receiver, where the ML cost-function is used assuming the identity noise covariance matrix, which does not require any information of interfering links. We show that this MD receiver asymptotically achieves the channel capacity as the number of users increases. Simulation results are also provided to evaluate the performance of the MD receiver.

We refer to our full paper [10] for more detailed description and all the rigorous proofs.

2. SYSTEM AND CHANNEL MODELS

We consider the time division duplexing MIMO IMAC with K cells, each of which consists of a BS with M antennas and N users, each having L antennas, as depicted in Fig. **??**. It is assumed that each selected user transmits a single spatial stream. In each cell, S ($S \leq M$) users are selected for uplink communication. The channel matrix from user j in the i-th cell to BS k (in the k-th cell) is denoted by $\mathbf{H}_k^{[i,j]} \in \mathbb{C}^{M\times L}$. A frequency-flat fading and the reciprocity between uplink and downlink channels are assumed. Each element of $\mathbf{H}_k^{[i,j]}$ is assumed to be an identical and independent complex Gaussian random variable with zero mean and variance of $1/L$. User j in the i-th cell estimates the uplink channel of its own link, $\mathbf{H}_k^{[i,j]}$ ($k = 1, \ldots, K$), via downlink pilots transmitted from the BSs; that is, local CSI is utilized as in [7]. Without loss of generality, the indices of the selected users in each cell are assumed to be $(1, \ldots, S)$ for notational simplicity. Then, the received signal at BS i is expressed as:

$$\mathbf{y}_i = \sum_{j=1}^{S} \mathbf{H}_i^{[i,j]}\mathbf{w}^{[i,j]}x^{[i,j]} + \underbrace{\sum_{k=1,k\neq i}^{K}\sum_{m=1}^{S}\mathbf{H}_i^{[k,m]}\mathbf{w}^{[k,m]}x^{[k,m]}}_{\text{inter-cell interference}} + \mathbf{z}_i, \qquad (1)$$

where $\mathbf{w}^{[i,j]} \in \mathbb{C}^{L\times 1}$ and $x^{[i,j]}$ are the weight vector and transmit symbol with unit average power at user j in the i-th cell, respectively, and $\mathbf{z}_i \in \mathbb{C}^{M\times 1}$ denotes additive white Gaussian noise (AWGN) at BS i, with zero mean and the covariance of $N_0\mathbf{I}_M$.

3. OPPORTUNISTIC INTERFERENCE ALIGNMENT

For the completeness of our achievability result, we briefly describe the overall procedure for all the steps of the OIA scheme [8, 9].

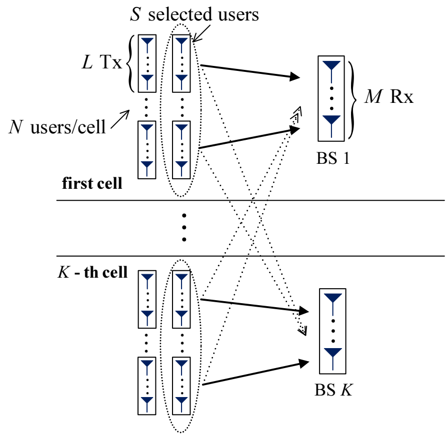

Fig. 1. The MIMO IMAC model.

3.1. Offline Procedure - Reference Basis Broadcasting

The orthogonal reference basis matrix at BS k, to which the received interference vectors are aligned, is denoted by $\mathbf{Q}_k = [\mathbf{q}_{k,1}, \ldots, \mathbf{q}_{k,M-S}] \in \mathbb{C}^{M\times(M-S)}$. Here, BS k in the k-th cell, $k \in \mathcal{K} \triangleq \{1, \ldots, K\}$, independently and randomly generates $\mathbf{q}_{k,m} \in \mathbb{C}^{M\times 1}$ ($m = 1, \ldots, M-S$) from the M-dimensional sphere. BS k also finds the null space of $\mathbf{Q}_k$, defined by $\mathbf{U}_k = [\mathbf{u}_{k,1}, \ldots, \mathbf{u}_{k,S}] \triangleq \text{null}(\mathbf{Q}_k)$, where $\mathbf{u}_{k,i} \in \mathbb{C}^{M\times 1}$ is orthonormal, and then broadcasts it to all users. Note that this process is required only once prior to data transmission and does not need to change with respect to channel instances.

3.1.1. Stage 1 (Weight Vector Design)

Let us define the unit-norm weight vector at user j in the i-th cell by $\mathbf{w}^{[i,j]}$, i.e., $\left\|\mathbf{w}^{[i,j]}\right\|^2 = 1$. From the notion of $\mathbf{U}_k$ and $\mathbf{H}_k^{[i,j]}$, user j in the i-th cell calculates the *leakage of interference (LIF)* [8, 9], which is received at BS k and not aligned at the interference space $\mathbf{Q}_k$, from

$$\tilde{\eta}_k^{[i,j]} = \left\|\text{Proj}_{\perp\mathbf{Q}_k}\left(\mathbf{H}_k^{[i,j]}\mathbf{w}^{[i,j]}\right)\right\|^2 = \left\|\mathbf{U}_k^H\mathbf{H}_k^{[i,j]}\mathbf{w}^{[i,j]}\right\|^2,$$

where $i \in \mathcal{K}$, $j \in \mathcal{N}$, and $k \in \mathcal{K} \setminus i = \{1, \ldots, i-1, i+1, \ldots, K\}$. The scheduling metric of user j in the i-th cell, denoted by $\eta^{[i,j]}$, is defined by the sum of LIFs, which are not aligned to the interference spaces at neighboring cells. That is,

$$\eta^{[i,j]} = \sum_{k=1,k\neq i}^{K} \tilde{\eta}_k^{[i,j]}.$$

All the users report their LIF metrics to corresponding BSs.

3.1.2. Stage 2 (User Selection)

Upon receiving N users' scheduling metrics in the serving cell, each BS selects S users having smallest LIF metrics. Without loss of generality, Note again that we assume that user j, $j = 1, \ldots, S$, in each cell have the smallest LIF metrics and thus are selected. Subsequently, user j in the i-th cell forwards the information on $\mathbf{w}^{[i,j]}$ to BS i for coherent decoding.

3.1.3. Stage 3 (Uplink Communication)

The transmit signal vector at user j in the i-th cell is given by $\mathbf{w}^{[i,j]}x^{[i,j]}$, where $x^{[i,j]}$ is the transmit symbol with unit average power, and the received signal at BS i can be written as:

$$\mathbf{y}_i = \underbrace{\sum_{j=1}^{S} \mathbf{H}_i^{[i,j]} \mathbf{w}^{[i,j]} x^{[i,j]}}_{\text{desired signal}} + \underbrace{\sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} x^{[k,m]}}_{\text{inter-cell interference}} + \mathbf{z}_i,$$

where $\mathbf{z}_i \in \mathbb{C}^{M\times 1}$ denotes the additive noise, each element of which is independent and identically distributed complex Gaussian with zero mean and the variance of SNR^{-1}. As in SIMO IMAC [4, 5], the linear ZF detection is applied at the BSs to null out inter-user interference for the home cell users' signals. From the notion of $\mathbf{H}_i^{[i,j]}$ and $\mathbf{w}^{[i,j]}$, BS i obtains the sufficient statistics for parallel decoding

$$\mathbf{r}_i = [r_{i,1}, \ldots, r_{i,S}]^{\mathrm{T}} \triangleq \mathbf{F}_i{}^H \mathbf{U}_i^H \mathbf{y}_i,$$

where $\mathbf{U}_i$ is multiplied to remove the inter-cell interference components that are aligned at the interference space of BS i, $\mathbf{Q}_i$, and $\mathbf{F}_i \in \mathbb{C}^{S\times S}$ is the ZF equalizer defined by

$$\mathbf{F}_i = [\mathbf{f}_{i,1}, \ldots, \mathbf{f}_{i,S}] \triangleq \left(\left[\mathbf{U}_i{}^H \mathbf{H}_i^{[i,1]} \mathbf{w}^{[i,1]}, \ldots, \mathbf{U}_i{}^H \mathbf{H}_i^{[i,S]} \mathbf{w}^{[i,S]} \right]^{-1} \right)^H.$$

4. ASYMPTOTICALLY OPTIMAL RECEIVER DESIGN

While using the ZF receiver is sufficient to achieve the maximum DoF, we study the design of an enhanced receiver at the BSs in pursuit of improving the achievable rate. Recall that it is not available for each BS to have CSI of the cross-links from the users in the other cells, because no coordination between the BSs is assumed. The main challenge is thus to decode the desired symbols with no CSI of other-cell interfering links at the receivers. For convenience, let us rewrite the received signal at BS i in (1) as

$$\mathbf{y}_i = \tilde{\mathbf{H}}_i^{(c)} \mathbf{x}_i + \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} x^{[k,m]} + \mathbf{z}_i,$$

where $\tilde{\mathbf{H}}_i^{(c)} \triangleq \left[\mathbf{H}_i^{[i,1]} \mathbf{w}^{[i,1]}, \ldots \mathbf{H}_i^{[i,S]} \mathbf{w}^{[i,S]} \right] \in \mathbb{C}^{M\times S}$ and $\mathbf{x}_i \triangleq \left[x^{[i,1]}, \ldots, x^{[i,S]} \right]^{\mathrm{T}} \in \mathbb{C}^{S\times 1}$. The channel capacity I_{C} is now given by [11]

$$I_{\mathrm{C}} = \log_2 \det \left(\mathbf{R}_c^{-1/2} \tilde{\mathbf{H}}_i^{(c)} \left(\tilde{\mathbf{H}}_i^{(c)} \right)^{\mathrm{H}} \mathbf{R}_c^{-1/2} + \mathbf{I}_M \right),$$

where

$$\mathbf{R}_c = \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \left(\mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \right)^{\mathrm{H}} + N_0 \mathbf{I}_M,$$

which is not available at BS i due to the assumption of unknown inter-cell interfering links. The channel capacity I_{C} is achievable with the optimal ML decoder

$$\hat{\mathbf{x}}_i^{\mathrm{ML}} = \arg\min_{\mathbf{x}} \left(\mathbf{y}_i - \tilde{\mathbf{H}}_i^{(c)} \mathbf{x} \right)^{\mathrm{H}} \mathbf{R}_c^{-1} \left(\mathbf{y}_i - \tilde{\mathbf{H}}_i^{(c)} \mathbf{x} \right), \quad (2)$$

which is infeasible to implement due to unknown $\mathbf{R}_c$. After nulling out interference by multiplying $\mathbf{U}_i$, the received signal is given by

$$\tilde{\mathbf{y}}_i = \mathbf{U}_i^{\mathrm{H}} \mathbf{y}_i = \tilde{\mathbf{H}}_i \mathbf{x}_i + \underbrace{\sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \mathbf{U}_i^{\mathrm{H}} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} x^{[k,m]} + \mathbf{U}_i^{\mathrm{H}} \mathbf{z}_i}_{\tilde{\mathbf{z}}_i}, \quad (3)$$

where $\tilde{\mathbf{H}}_i \triangleq \left[\mathbf{U}_i^{\mathrm{H}} \mathbf{H}_i^{[i,1]} \mathbf{w}^{[i,1]}, \ldots \mathbf{U}_i^{\mathrm{H}} \mathbf{H}_i^{[i,S]} \mathbf{w}^{[i,S]} \right] \in \mathbb{C}^{S\times S}$ and $\tilde{\mathbf{z}}_i \in \mathbb{C}^{S\times 1}$ represents the effective noise. Let us denote the effective noise covariance matrix after interference nulling by

$$\mathbf{R} \triangleq E\left\{ \tilde{\mathbf{z}}_i \tilde{\mathbf{z}}_i{}^{\mathrm{H}} \right\} = \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \mathbf{U}_i^{\mathrm{H}} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \left(\mathbf{U}_i^{\mathrm{H}} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \right)^{\mathrm{H}} + N_0 \mathbf{I}_S.$$

Then, the ML decoder for the modified channel (3) becomes $\arg\min_{\mathbf{x}} \left(\tilde{\mathbf{y}}_i - \tilde{\mathbf{H}}_i \mathbf{x} \right)^{\mathrm{H}} \mathbf{R}^{-1} \left(\tilde{\mathbf{y}}_i - \tilde{\mathbf{H}}_i \mathbf{x} \right)$, which is also infeasible to implement since the term $\mathbf{U}_i^{\mathrm{H}}\mathbf{H}_i^{[k,m]}\mathbf{w}^{[k,m]}$ ($k \in \{1, \ldots, i-1, i+1, \ldots, K\}$, $m \in \{1, \ldots, S\}$) is not available at BS i.

As an alternative approach, we now introduce the following MD receiver after interference nulling at BS i:

$$\hat{\mathbf{x}}_i = \arg\min_{\mathbf{x}} \left\| \tilde{\mathbf{y}}_i - \tilde{\mathbf{H}}_i \mathbf{x} \right\|. \tag{4}$$

It is worth noting that the receiver in (4) is not universally optimal since $\mathbf{R}$ is not an identity matrix for given channel instance. Now, we show the achievable rate based on the use of the receiver in (4). The maximum achievable rate of any suboptimal receiver, referred to as *mismatch capacity* [12, 13], is lower-bounded by the generalized mutual information, defined as [12, 13]

$$I_{\mathrm{GMI}} = \sup_{\theta \geq 0} I(\theta),$$

where

$$I(\theta) \triangleq E\left[\log_2 \frac{Q(\tilde{\mathbf{y}}_i|\mathbf{x}_i)^{\theta}}{E\left[Q(\tilde{\mathbf{y}}_i|\mathbf{x}_i)^{\theta} \middle| \tilde{\mathbf{y}}_i, \tilde{\mathbf{H}}_i\right]} \middle| \tilde{\mathbf{H}}_i \right]$$

and $Q(\tilde{\mathbf{y}}_i|\mathbf{x}_i)$ is the decoding metric expressed in probability. The following theorem characterizes the achievable rate of the proposed MD decoder.

Theorem 1 (Asymptotic Capacity) *The GMI I_{GMI} of the OIA with the MD decoder in (4) is given by*

$$I_{GMI} = \sup_{\theta \geq 0} -\frac{\theta}{\log 2} tr(N_0^{-1}\mathbf{R}) + \frac{\theta}{\log 2}\left[tr\left(N_0^{-1} \mathbf{\Omega}'^{-1} \left(\tilde{\mathbf{H}}_i \tilde{\mathbf{H}}_i^H + \mathbf{R} \right) \right) \right] + \log_2 \det(\mathbf{\Omega}'), \tag{5}$$

which asymptotically achieves the channel capacity I_C if $N = \omega\left(SNR^{(K-1)S-L+1}\right)$, where $\mathbf{\Omega}' = \theta N_0^{-1} \tilde{\mathbf{H}}_i \tilde{\mathbf{H}}_i^H + \mathbf{I}_S$.

As shown in Theorem 1, the MD receiver asymptotically achieves the channel capacity even without any coordination between the BSs or users. However, it is worth noting that if the interference alignment level is too low due to small N to satisfy the user scaling condition $N = \omega(\mathrm{SNR}^{(K-1)S-L+1})$, then the achievable rate in (5) may be lower than that of the ZF receiver. Thus, in realistic environments (i.e., small N regimes), there may exist crossovers, where the achievable rate of the two schemes is switched, which will be shown in Section 5 via numerical evaluation. We conclude our discussion on the receiver design with the following remark.

Remark 1 (DoF Achievability of the Optimal Receiver) *Even with the use of the ML receiver in (2) based on full knowledge of $\mathbf{R}_c$, the user scaling condition to achieve KS DoF is the same as that that based on the ZF receiver case, which makes the amount of interference bounded even for increasing SNR.*

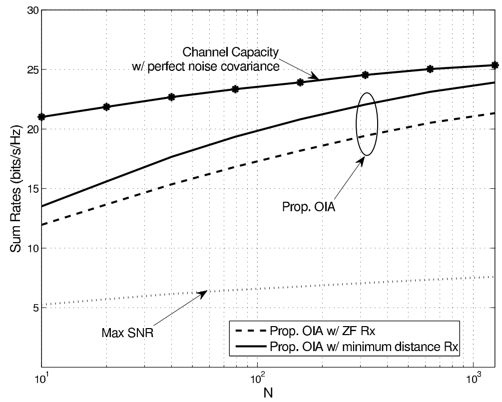

Fig. 2. The achievable rate versus N when $K = 2$, $M = 3$, $L = 2$, $S = 2$, and SNR=20dB.

5. NUMERICAL EVALUATION

In this section, we run computer simulations to verify the performance of the OIA using the proposed MD receiver. For comparison, the max-SNR scheme is used, in which each user employs eigen-beamforming in terms of maximizing its received SNR and the belonging BS selects the S users who have the SNR values up to the S-th largest one. The channel capacity is also shown to see the fundamental limit under the assumed model.

Figure 1 shows a log-linear plot of the achievable rate versus N when $K = 2$, $M = 3$, $L = 2$, $S = 2$, and SNR=20dB. As shown in Theorem 1, it is seen that the GMI of the OIA using the MD receiver asymptotically achieves the channel capacity as N increases. On the other hand, the achievable rate of the OIA using the ZF receiver exhibits a constant gap even in large N regime, compared to that of the MD receiver. This observation is consistent with previous results on the single-user MIMO channel, showing that there exists a constant SNR gap between the channel capacity and the achievable rate based on the ZF receiver in the high SNR regime.

6. CONCLUSION

For the MIMO IMAC, we have proposed the simple MD receiver for the OIA scheme that does not require any information of inter-cell interfering links. Surprisingly, we have shown that the MD receiver not only achieves the optimal DoF but also asymptotically approaches the channel capacity as N increases. Numerical examples have shown that the MD receiver significantly enhances the achievable rate based on the ZF receiver especially in the low to mid SNR regimes.

Future research in this area includes an optimal transceiver design that asymptotically achieves the channel capacity for the MIMO interfering broadcast channel on top of the opportunistic downlink IA framework in [14].

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