Opportunistic Interference Alignment for Interference-Limited Cellular TDD Uplink

Bang Chul Jung, *Member, IEEE*, and Won-Yong Shin, *Member, IEEE*

***Abstract*—We introduce an opportunistic interference alignment (OIA) for cellular networks, where a user scheduling strategy is utilized in time-division duplexing uplink communication environments with time-invariant channel coefficients and multi-antenna base stations (BSs). In the OIA scheme, each BS opportunistically selects users who generate the minimum interference to the other BSs. More specifically, each BS broadcasts its pre-designed interference directions, e.g., orthonormal random vectors, to all the users in other cells. Then, each user computes the amount of its generating interference, affecting the other BSs, and feedbacks it to its home cell BS. Note that the proposed OIA does not require global channel state information, time/frequency expansion, and a number of iterations, thereby resulting in easier implementation. Simulation results show that the proposed scheme provides significant improvement in terms of sum rates.**

***Index Terms*—Cellular network, interference, opportunistic interference alignment (OIA), user scheduling.**

I. INTRODUCTION

INTERFERENCE between wireless links has been taken into account as a critical problem in communication systems. Recently, interference alignment (IA) was proposed for fundamentally solving the interference problem when there are multiple communication pairs [1]. It was shown that the IA scheme can achieve the optimal degrees-of-freedom (DoFs), which is equal to $K/2$, in the K-user interference channel with time-varying coefficients. The basic idea of IA is to confine all the undesired interference from other communication links into a pre-defined subspace, whose dimension is the same as that of the desired signal space, thus enabling all users to achieve one half of the DoFs that can be obtained in the absence of interference. Since then, interference management schemes based on IA have been further developed and analyzed in various wireless network environments: multiple-input multiple-output (MIMO) interference network [2], [3], X network [4], [5], and cellular network [6]. However, the conventional IA schemes [1], [3] require global channel state information (CSI) which includes the CSI of other communication pairs. Furthermore, a huge number of dimensions based on time/frequency expansion are needed to achieve the optimal DoFs. In [2], a distributed IA scheme was used for the MIMO channel with time-invariant coefficients, where it requires only local CSI at each node whose receiving channel links are assumed to be acquired, thus resulting in more feasible implementation. However, a great number of iterations should be conducted until generating transmit/receive beamforming vectors converge prior to data transmission.

In this paper, we introduce an *opportunistic* IA (OIA) technique for cellular networks. IA was first applied to cellular networks [6], where the scheme also has practical challenges including the dimension extension to achieve the optimal DoFs. The proposed OIA scheme adopts the notion of multi-user diversity (MUD) gain, as in [7]–[9], for constructing IA. An opportunistic user scheduling strategy is utilized in time-division duplexing (TDD) uplink multi-cell environments with time-invariant channel coefficients and multi-antenna base stations (BSs). To be specific, each BS broadcasts a set of its orthonormal random vectors, which is also used for signal detection at the receivers, to all the users in other cells.[1] Each user computes the amount of its generating interference affecting to the other BSs, and feedbacks it to its home cell BS. According to this procedure, each BS selects users generating the minimum interference to the other BSs, while in the conventional opportunistic algorithms [7]–[9], users with the maximum signal strength at the desired BS are selected for data transmission. To validate the OIA scheme, computer simulations are performed—the amount of interference leakage is evaluated as in [2], [11], and the achievable sum rates are also shown.

In addition, we remark that the same terminology OIA has also been used in [10], where the two-user interference channel was considered for cognitive radio environments—the primary user maximizes its data rate by using water-filling based power allocation without any concerns of the secondary user, which opportunistically utilizes signal directions unused by the primary user.

The rest of this paper is organized as follows. Section II describes the system and channel models. In Section III, the proposed OIA strategy is characterized in cellular networks. Section IV shows simulation results under the OIA scheme. Finally, we summarize the paper with some concluding remark in Section V. Throughout this paper, the superscript T, H, and $\dagger$ denote the transpose, conjugate transpose, and pseudo-inverse of a matrix (or a vector), respectively. $\|\cdot\|$ and $\mathbf{I}_n$ indicate L_2-norm of a vector and the identity matrix of size $n \times n$, respectively.

II. SYSTEM AND CHANNEL MODELS

Consider the interfering multiple-access channel (IMAC) model [6], referred to as an uplink scenario, to describe practical cellular networks with multiple cells, each of which has multiple mobile users. Under the model, each BS is assumed to be interested only in traffic demands of users in the corresponding cell. Suppose that there are K cells and

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[1] Alternatively, a set of vectors can be generated with prior knowledge in a pseudo-random manner, and thus can be acquired by all users before data transmission without signaling.

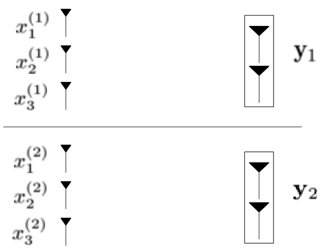

Fig. 1. The IMAC model with K=2, $N = 3$, and $M = 2$.

there are N users in a cell. We assume that each user is equipped with a single-antenna and each cell is covered by one BS having M antennas. The channel in a single-cell can then be regarded as the single-input multiple-output MAC. The example for $K = 2$, $N = 3$, and $M = 2$ is illustrated in Fig. 1. If N is much greater than M, then it is possible to exploit the channel randomness and thus to obtain the MUD gain in the IMAC environment.

The term $\mathbf{h}_{i,j}^{(k)} \in \mathbb{C}^{M\times 1}$ denotes the channel vector between user j in the k-th cell and BS i, where $j \in \{1, \cdots, N\}$ and $i, k \in \{1, \cdots, K\}$. The channel is assumed to be Rayleigh, whose elements have zero-mean and unit variance, and to be independent across different i, j, and k. We assume a block-fading model, i.e., the channel vectors are constant during one block (e.g., frame) and changes independently between blocks. The received signal vector $\mathbf{y}_i \in \mathbb{C}^{M\times 1}$ at BS i is given by

$$\mathbf{y}_i = \sum_{j=1}^{S} \mathbf{h}_{i,j}^{(i)} x_j^{(i)} + \sum_{k=1, k\neq i}^{K-1} \sum_{n=1}^{S} \mathbf{h}_{i,n}^{(k)} x_n^{(k)} + \mathbf{z}_i,$$

where $x_j^{(i)}$ is the transmit symbol of user j in the i-th cell, S represents the number of selected users in a cell for data transmission, and $S \in \{1, \cdots, M-1\}$. The received signal $\mathbf{y}_i$ at BS i is corrupted by the independently identically distributed and circularly symmetric complex additive white Gaussian noise vector $\mathbf{z}_i \in \mathbb{C}^{M\times 1}$ whose elements have zero-mean and variance N_0. We assume that each user has an average transmit power constraint P (constant). Then, the received signal-to-noise ratio (SNR) at each BS is expressed as a function of P and N_0, which depends on the decoding process at the receiver side. In this work, we consider a simple zero-forcing (ZF) receiver, which will be discussed in Section III.

III. OIA IN CELLULAR NETWORKS

The proposed OIA scheme is now described, where the overall procedure is possible by using the channel reciprocity of TDD systems. First, BS i in the i-th cell generates a set of orthonormal random vectors $\mathbf{v}_m^{(i)} \in \mathbb{C}^{M\times 1}$ for all $m = 1, \cdots, M-S$ and $i = 1, \cdots, K$, where $\mathbf{v}_m^{(i)}$ corresponds to its pre-defined interference direction, and then broadcasts the vectors to all the users in other cells. That is, the interference subspace is broadcasted. With this scheme, it is important to see how closely the channels of selected users are aligned with the *span* of broadcasted interference vectors. Specifically, let $\{\mathbf{u}_1^{(i)}, \cdots, \mathbf{u}_S^{(i)}\}$ denote an orthonormal basis for the null space $U^{(i)}$ (i.e., kernel) of the interference subspace. User $j \in \{1, \cdots, N\}$ in the i-th cell then computes the orthogonal projection onto $U^{(k)}$ of its channel vector $\mathbf{h}_{k,j}^{(i)}$, which is given by

$$\mathrm{Proj}_{U^{(k)}}\left(\mathbf{h}_{k,j}^{(i)}\right) = \sum_{m=1}^{S} \left(\mathbf{u}_m^{(k)H} \mathbf{h}_{k,j}^{(i)}\right) \mathbf{u}_m^{(k)},$$

and the value $L_{k,j}^{i}$

$$L_{k,j}^{i} = \left\| \mathrm{Proj}_{U^{(k)}}\left(\mathbf{h}_{k,j}^{(i)}\right) \right\|^2, \tag{1}$$

which is called *leakage of interference (LIF)*, for $k \in \{1, \cdots, i-1, i+1, \cdots, K\}$. For example, if the LIF of a user is given by 0 for a certain another BS $k \in \{1, \cdots, i-1, i+1, \cdots, K\}$, then it indicates that the user's channel vector is perfectly aligned to interference direction of BS k and thus the user's signal does not interfere with detection at the BS. For user j in the i-th cell, two types of user scheduling metrics L_j^i, Min-Total-LIF and Min-Max-LIF, are finally expressed as

$$L_j^i = \sum_k L_{k,j}^i \tag{2}$$

and

$$L_j^i = \max_k L_{k,j}^i, \tag{3}$$

respectively, for $k \in \{1, \cdots, i-1, i+1, \cdots, K\}$. After computing the metric representing either the total sum or the maximum of $K-1$ LIF values in (1), each user feedbacks the value to its home cell BS i.[2] Thereafter, BS i selects S users who feedback the values up to the S-th smallest one by computing one of the metrics. The selected S users in each cell then start to transmit their data packets.

At the receiver side, each BS performs a ZF filtering based on random vectors $\{\mathbf{v}_1^{(i)}, \cdots, \mathbf{v}_{M-S}^{(i)}\}$ and the intra-cell channel vectors $\{\mathbf{h}_{i,1}^{(i)}, \cdots, \mathbf{h}_{i,S}^{(i)}\}$, to detect the signal from its home cell users, which enables to capture enough DoFs in interference networks [1]. Then, the resulting signal (symbol), postprocessed by ZF matrix $\mathbf{G}_i \in \mathbb{C}^{S\times M}$ at BS i, is given by

$$\begin{bmatrix} \hat{x}_1^{(i)} & \cdots & \hat{x}_S^{(i)} \end{bmatrix}^T = \mathbf{G}_i \mathbf{y}_i,$$

where

$$\mathbf{G}_i = \mathbf{A} \cdot \begin{bmatrix} \mathbf{h}_{i,1}^{(i)} & \cdots & \mathbf{h}_{i,S}^{(i)} & \mathbf{v}_1^{(i)} & \cdots & \mathbf{v}_{M-S}^{(i)} \end{bmatrix}^{\dagger}$$

and $\mathbf{A}$ is the $S \times M$ matrix made by the first S rows of M-dimensional identity matrix $\mathbf{I}_M$. Note that the ZF filtering is performed at the receiver without any CSI between the BS and other-cell users.

Since the interference from the users of other cells is not perfectly aligned to the interference subspace for finite N, there exists ϵ-loss on the DoFs of each user compared to those of the case without inter-cell interferences, where $\epsilon > 0$ is an arbitrarily small constant. Hence, the achievable DoFs in each cell would approach $(1-\epsilon)S$. We remark that parameter ϵ tends to decrease with the help of MUD gain as the number N of users in a cell increases, which will be numerically shown in Section IV.

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[2] An opportunistic feedback strategy can be adopted in order to reduce the amount of feedback overhead without any performance loss, as done in MIMO broadcast channels [12].

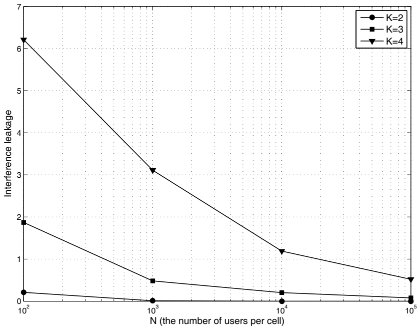

Fig. 2. The leakage interference with respect to N for some K. The system with $M = 2$, $S = 1$ is considered.

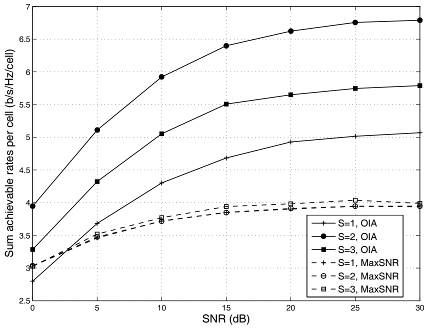

Fig. 3. The achievable sum rates per cell with respect to SNR. The system with $M = 4$, $K = 2$, and $N = 100$ is considered.

IV. NUMERICAL EVALUATION

In this section, we perform computer simulations to validate the performance of the OIA scheme in cellular networks. Min-Total-LIF in (2) is simply applied to all the numerical examples.[3] In Fig. 2, the average amount of interference leakage is evaluated as the number N of users in a cell increases.[4] The interference leakage is interpreted as the total interference power remaining in each desired signal space (from the users in other cells) after the ZF filter is applied, assuming that the received signal power from a desired transmitter is normalized to 1 in the signal space. This performance measure enables to measure the quality of IA or equivalently to numerically evaluate the DoFs, as shown in [2], [11]. In Fig. 2, the simulation environments are given by $M = 2$ and $S = 1$. It is shown that when K varies from 2 to 4, the interference leakage increases due to more interferers, which is rather obvious.

In addition, as illustrated in Fig. 3, the achievable sum rates of the OIA scheme are evaluated according to received SNRs (in dB scale) and are compared with those of the conventional opportunistic user scheduling method in which the users having the maximum SNR value are selected for data transmission (we represent it with *MaxSNR* in the figure). It is shown that the OIA scheme outperforms the conventional one for almost all the SNR regimes. It is also examined how efficiently we decide the number S of active users per cell for $S \in \{1, \cdots, M-1\}$ in terms of maximizing the sum rates. When the case with $N = 100$, $M = 4$, and $K = 2$ is assumed, the optimal S is given by 2 (see Fig. 3). Assuming less S corresponds to smaller DoFs per cell, but reduces the inter-cell interference in each desired signal space. On the other hand, the more S we have in a cell, the more DoFs it may enable to capture at the cost of increased interference. It is thus not clear whether having more S is beneficial or not in terms of sum rates. Hence, for given parameters M, K, and N, the vaule S needs to be carefully chosen for better sum-rate performance. Note that the optimal S can be numerically decided prior to data transmission and the OIA scheme operates with the optimal parameter. The optimal value of S is summarized for various system parameters in Table I.

TABLE I
OPTIMAL VALUE OF S FOR VARIOUS SYSTEM PARAMETERS ($N = 300$)

	$M = 3$	$M = 4$	$M = 5$	$M = 6$	$M = 7$	$M = 8$
$K = 2$	2	2	3	3	4	4
$K = 3$	2	2	2	3	3	4
$K = 4$	1	2	2	3	3	4

V. CONCLUSION

The OIA method was proposed in cellular networks, where it does not require the global CSI, infinite dimension expansion, and parameter adjustment through iterations. Simulation results showed that the interference leakage is significantly reduced with the help of the MUD gain as the number N of users in a cell increases. It was also shown that the proposed OIA scheme outperforms the conventional one in terms of sum rates. Finally, the optimal number S of active users per cell was examined for various system parameters.

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[3] Note that two scheduling metrics (2) and (3) have almost the same performance, even if the comparison is not shown in this paper.

[4] Although it seems unrealistic to have a great number of users in a cell, the range for parameter N is taken into account to precisely see some trends of curves varying with N.