

# Energy-Efficient Opportunistic Interference Alignment With MMSE Receiver

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**Abstract:** This paper introduces a refined opportunistic interference alignment (OIA) technique that uses minimum mean square error (MMSE) detection at the receivers in multiple-input multiple-output multi-cell uplink networks. In the OIA scheme under consideration, each user performs the optimal transmit beamforming and power control to minimize the level of interference generated to the other-cell base stations, as in the conventional energy-efficient OIA. The result showed that owing to the enhanced receiver structure, the OIA scheme shows much higher sum-rates than those of the conventional OIA with zero-forcing detection for all signal-to-noise ratio regions.

**Keywords:** Energy efficiency, Minimum mean square error (MMSE) detection, Multi-cell uplink network, Opportunistic interference alignment (OIA)

## 1. Introduction

Interference management is considered a crucial problem in wireless communication systems, where multiple users share the same resources. Considerable research has been carried out to characterize the asymptotic capacity of interference channels using the simple notion of degrees-of-freedom (DoF). Recently, interference alignment (IA) was proposed as a novel approach to fundamentally solve the interference problem when there are two communication pairs [1]. Cadambe and Jafar [2] reported that the IA scheme can achieve the optimal DoF, equal to  $K/2$ , in the  $K$ -user interference channel with the time-varying channel coefficients. The underlying idea in references [1, 2] has led to interference management schemes based on IA in a range of wireless network environments, such as multiple-input multiple-output (MIMO) interference networks [3, 4], X networks [5], and cellular networks [6].

This paper considers the interfering multiple-access channel (IMAC), which is referred to as a practical multi-cell uplink network. In addition to the IA scheme reported by Suh and Tse [6], the concept of an opportunistic IA (OIA) [7, 8] was introduced recently in the single-input multiple-output IMAC with time-invariant channel coefficients. The OIA scheme intelligently combines user

scheduling into the classical IA framework in signal vector space by selecting opportunistically certain users in each cell to align the inter-cell interference at a pre-defined interference space. One study [8] reported that a full DoF can be achieved asymptotically provided that the number of users scales at least to a certain value. Their work [8] was extended to the MIMO IMAC model using various types of pre-processing methods [9, 10]. Moreover, to take energy efficiency into account [11, 12], which is a growing issue in the telecommunication community, a new energy-efficient OIA protocol [13] for MIMO multi-cell uplink networks, i.e., MIMO IMACs, was proposed based on the existing OIA framework. In an energy-efficient OIA, the optimal transmit beamforming vector design and power control strategy were performed jointly at each user to minimize the amount of interference generated to other-cell base stations (BSs) in a distributed manner, which leads to significant performance enhancement on the sum-rates even with reduced transmit power consumption, resulting in higher energy efficiency compared to the conventional OIA scheme [9].

In previous work [6-10, 13], the OIA framework was designed using a simple zero-forcing (ZF) decoder based on the received intra-cell channel links because ZF detection at the receivers is sufficient to guarantee the optimal DoF in the IMAC model. On the other hand, the

system performance may be improved further compared to the ZF detection case using a more enhanced receiver structure in terms of the sum-rates. This paper introduces a refined energy-efficient OIA technique using minimum mean square error (MMSE) detection at the receivers in the MIMO IMAC model with time invariant channel coefficients. In the OIA scheme under consideration, each user jointly performs the optimal transmit beamforming and power control, as in the conventional energy-efficient OIA case [13]. The results suggest that owing to the enhanced receiver structure, the proposed OIA scheme shows much higher sum-rates than those of the conventional OIA with ZF detection for all signal-to-noise ratios (SNRs) regions.

The remainder of this paper is organized as follows. Section 2 describes the system and channel models. In Section 3, the new energy-efficient OIA protocol is specified. Section 4 presents the numerical results of the OIA scheme. Finally, Section 5 summarizes the paper with some concluding remarks.

## 2. System and Channel Models

This study considered the MIMO IMAC model [9] to describe one of the realistic cellular uplink networks. Suppose that there are  $K$  cells, each of which has  $N$  users. Also assume that each user is equipped with  $L$  transmit antennas and each cell is covered by one BS with  $M$  receive antennas. Under the model, each BS in a cell is interested only in the traffic demands of the users in its cell.

The term,  $\mathbf{H}_{c,a}^g \in \mathbb{C}^{M \times L}$ , indicates the channel matrix between BS  $g$  and the  $a^{\text{th}}$  user in cell  $c$ . A block fading channel model is assumed, where the channel is constant during a transmission block and changes independently for every transmission block. The channel matrices are assumed to be Rayleigh, whose elements follow an independent complex Gaussian distribution  $\mathcal{CN}(0,1)$ . Each selected user is assumed to transmit a single data stream at one time. Let  $\phi_g(1), \dots, \phi_g(S)$  denote the  $S$  users who obtain transmission opportunities among  $N$  users in cell,  $g \in \{1, \dots, K\}$ , where  $S \in \{1, \dots, M\}$ . When  $S$  symbols per cell are transmitted using the transmit beamforming vectors,  $\mathbf{v}_{g,\phi_g(1)}, \dots, \mathbf{v}_{g,\phi_g(S)} \in \mathbb{C}^{L \times 1}$ , the signal,  $\mathbf{r}_g \in \mathbb{C}^{M \times 1}$ , received at BS  $g$  is given by

$$\mathbf{r}_g = \sum_{s=1}^S \mathbf{H}_{g,\phi_g(s)}^g \mathbf{v}_{g,\phi_g(s)} m_{g,\phi_g(s)} + \sum_{k=1, k \neq g}^K \sum_{s=1}^S \mathbf{H}_{k,\phi_k(s)}^g \mathbf{v}_{k,\phi_k(s)} m_{k,\phi_k(s)} + \mathbf{n}_g,$$

where  $m_{g,\phi_g(s)} \in \mathbb{C}$  is the transmit message at user  $\phi_g(s)$  in cell  $g$  and  $\mathbf{n}_g \in \mathbb{C}^{M \times 1}$  denotes the independent and identically distributed (i.i.d.) and circularly symmetric complex additive Gaussian noise (AWGN), whose elements have a zero-mean and unit variance. Each transmit beamforming vector is assumed to be normalized

to  $\|\mathbf{v}_{g,a}\|^2 = 1$  and each user has an average transmit power constraint,  $p_{g,a} = \mathbb{E}[|m_{g,a}|^2] \leq \eta$ .

## 3. OIA With MMSE Detection

This section describes the overall energy-efficient OIA protocol and then specifies the MMSE detection structure.

### 3.1 Protocol Description

The overall procedure of the proposed energy-efficient OIA is essentially the same as that reported elsewhere [13]. Therefore, the material of this subsection is retaken in part from reference [13].

The procedure is based on the channel reciprocity of time-division multiplexing systems. Each BS broadcasts its receive subspace,  $\mathbf{W}_g = [\mathbf{w}_g(1), \dots, \mathbf{w}_g(S)]$ , where  $\mathbf{w}_g(s) \in \mathbb{C}^{M \times 1}$  is an orthonormal basis vector of  $\mathbf{W}_g$ . Each user can then align its signal to the space orthogonal to the receive subspace of the other cells (i.e., interference subspace). Thereafter, the  $a^{\text{th}}$  user in cell  $g$  calculates the total amount of generating interference affecting the receive subspaces of the other cells, termed *leakage of interference (LIF)*, which is given by the following:

$$\text{LIF}_{g,a}(p_{g,a}, \mathbf{v}_{g,a}) = p_{g,a} \mathbf{v}_{g,a}^H \mathbf{C}_{g,a} \mathbf{v}_{g,a},$$

where  $\mathbf{C}_{g,a} = \sum_{k=1, k \neq g}^K \mathbf{H}_{g,a}^k \mathbf{H}_{g,a}^{kH} \mathbf{W}_k \mathbf{W}_k^H \mathbf{H}_{g,a}^k$ .

The MIMO IMAC model considers a power control strategy that can reduce the LIF further compared to the OIA with no power control, while maintaining the pre-defined signal quality. The OIA protocol including both transmit beamforming vector design and power control performed at each user, which basically consists of the following four steps, is described as follows:

**Step 1:** Each BS randomly chooses and broadcasts an  $S$ -dimensional receive space.

**Step 2:** Suppose that the required received power level of the desired signal,  $\rho$ , is known a priori at each user. Each user finds the transmit power and vector terms  $\{p_{g,a}, \mathbf{v}_{g,a}\}$ , such that its LIF is minimized while maintaining the desired signal quality in a distributed manner. The optimization problem at MS  $a$  belonging to cell  $g$  is given by the following:

$$\{\hat{p}_{g,a}, \hat{\mathbf{v}}_{g,a}\} = \arg_{p_{g,a}, \mathbf{v}_{g,a}} \min \text{LIF}_{g,a}(p_{g,a}, \mathbf{v}_{g,a}) \quad (1a)$$

subject to

$$p_{g,a} \mathbf{v}_{g,a}^H \mathbf{C}_{g,a} \mathbf{v}_{g,a} = \rho, \quad (1b)$$

$$\|\mathbf{v}_{g,a}\|^2 = 1, p_{g,a} \leq \eta, \quad (1c)$$

where  $\mathbf{G}_{g,a} = \mathbf{H}_{g,a}^g \mathbf{H}_{g,a}^g \mathbf{W}_g \mathbf{W}_g^H \mathbf{H}_{g,a}^g$ . Note that at a given constraint (1b), the received SNR at BS  $g$  is expressed as  $\rho$ .

**Step 3:** The users who have a feasible solution set  $\{\hat{p}_{g,a}, \hat{v}_{g,a}\}$  send the computed LIF to their home cell BSs. The users who do not satisfy the two constraints, (1b) and (1c), do not feed the LIFs back to their home cell BSs.

**Step 4:** Each BS selects its  $S$  home cell users yielding LIF values up to the  $S^{\text{th}}$  smallest one.

Finally, the selected users in each cell begin to send their data packets using the optimized pre-processor (i.e., the transmit beamforming and power terms). Each BS decodes the users' signal by treating all interference as noise.

### 3.2 MMSE Receiver Design

This subsection describes the receiver structure using MMSE filtering under an energy-efficient OIA framework. The BS employing ZF detection does not need to acquire channel links between the BS itself and other-cell users. The scheme using ZF detection however has practical challenges because the number of per-cell users,  $N$ , is not sufficiently large. Because interference is not aligned perfectly for a finite  $N$ , the remaining amount of interference in each received subspace may reduce the signal-to-interference-and-noise ratio, resulting in the performance degradation on the sum-rates.

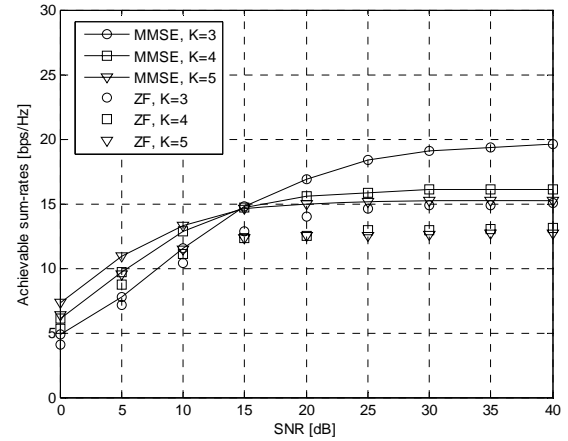
If it is assumed that the inter-cell interference (i.e., the channel links between the BS and other-cell users) is known to the receivers (BSs), each BS can effectively suppress the remaining interference level in each receive subspace while decoding the home-cell users' signal. The MMSE and receive subspace filtering were designed based on this additional information indicating the channel links between the BS and other-cell users. Let  $\mathbf{u}_{g,\phi_g(s)} \in \mathbb{C}^{M \times 1}$  denote the post-processing vector at BS  $g$  used to decode the signal sent from user  $\phi_g(s)$  in cell  $g$ . Assuming that the signal sent from user  $\phi_g(s)$  in cell  $g$  is decoded ( $s \in \{1, \dots, S\}$ ), the MMSE-based receive vector can then be expressed as

$$\mathbf{u}_{g,\phi_g(s)} = \mathbf{e}_M \left( \left( \mathbf{T}_{g,\phi_g(s)} \right)^{-1} \mathbf{Q}_{g,\phi_g(s)} \right), \quad (2)$$

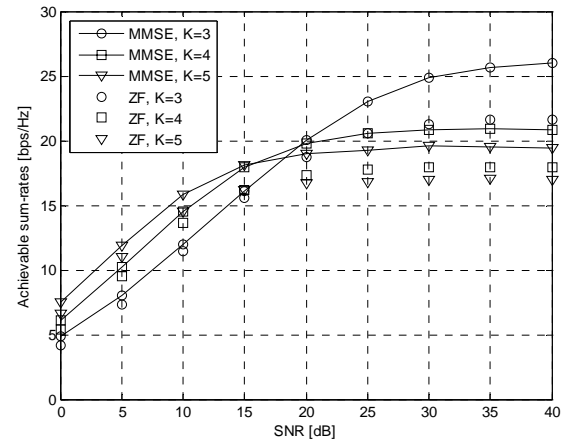
where

$$\begin{aligned} \mathbf{T}_{g,\phi_g(s)} &= \mathbf{I}_M \\ &+ \sum_{a=1, a \neq s}^S p_{g,\phi_g(a)} \mathbf{H}_{g,\phi_g(a)}^g \mathbf{v}_{g,\phi_g(a)} \left( \mathbf{H}_{g,\phi_g(a)}^g \mathbf{v}_{g,\phi_g(a)} \right)^H \\ &+ \sum_{k=1, k \neq g}^K \sum_{a=1}^S p_{k,\phi_k(a)} \mathbf{H}_{k,\phi_k(a)}^g \mathbf{v}_{k,\phi_k(a)} \left( \mathbf{H}_{k,\phi_k(a)}^g \mathbf{v}_{k,\phi_k(a)} \right)^H, \\ \mathbf{Q}_{g,\phi_g(s)} &= \mathbf{H}_{g,\phi_g(s)}^g \mathbf{v}_{g,\phi_g(s)} \left( \mathbf{H}_{g,\phi_g(s)}^g \mathbf{v}_{g,\phi_g(s)} \right)^H, \end{aligned}$$

and  $\mathbf{e}_M(\cdot)$  denotes the normalized eigenvector



**Fig. 1.** Sum-rates with respect to the SNR. The system with  $M = 2$ ,  $L = 2$ ,  $S = 1$ , and  $N = 10$  is considered.



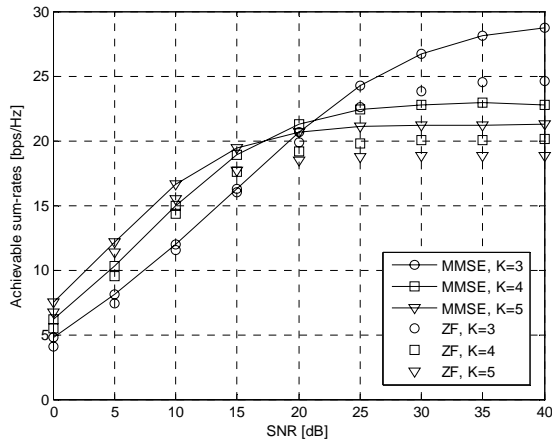
**Fig. 2.** Sum-rates with respect to the SNR. The system with  $M = 2$ ,  $L = 2$ ,  $S = 1$ , and  $N = 50$  is considered.

corresponding to the maximum eigenvalue of a matrix.

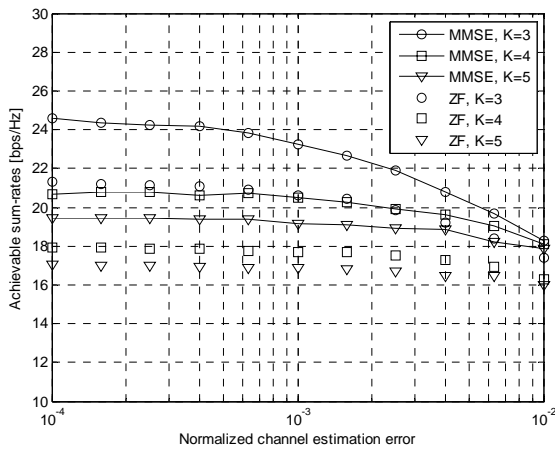
Some trade-off between ZF and MMSE detections exist in multi-cell uplink networks. Because the ZF-based receiver operates based only on the intra-cell channel links received, each BS does not need to acquire inter-cell interference, resulting in a slight overhead reduction compared to the MMSE-based receiver requiring knowledge of the inter-cell interfering links. On the other hand, the OIA scheme using MMSE detection ensures much higher sum-rates than those of the ZF detection case for all SNR regions, which will be verified by computer simulations.

## 4. Numerical Evaluation

This section examines the performance of the proposed OIA scheme with MMSE detection through computer simulations of the sum-rates. For comparison, the performance of the OIA algorithm based on ZF detection was also evaluated [13]. The simulation environments are given by  $M = 2$ ,  $L = 2$ ,  $S = 1$ . The transmit power



**Fig. 3.** Sum-rates with respect to the SNR. The system with  $M = 2$ ,  $L = 2$ ,  $S = 1$ , and  $N = 100$  is considered.



**Fig. 4.** Sum-rates with respect to the normalized channel estimation error. The system with  $M = 2$ ,  $L = 2$ ,  $S = 1$ ,  $N = 50$  and  $\text{SNR} = 30\text{dB}$  is considered.

constraint,  $\eta$ , the required received power level of the desired signal,  $\rho$ , were set to  $\eta = \rho = \text{SNR}$  under the unit noise variance assumption.

The sum-rates of both OIA schemes with 1) ZF and 2) MMSE detections were evaluated for  $K = 3, 4, 5$  according to the received SNRs (in dB scale). As shown in Fig. 1, the sum-rates were obtained when  $N = 10$ . This confirms that the proposed OIA scheme with MMSE detection outperforms the conventional one with ZF detection for almost all SNR regions. A performance gain of up to 25% compared to the conventional scheme was obtained. Figs. 2 and 3 show the sumrates when  $N = 50$  and 100, respectively. The sum-rate curves in Figs. 2 and 3 show similar trends to those in Fig. 1. To determine the robustness of the proposed scheme according to the estimation error of inter-cell channels (i.e., channel links between the BS and other-cell users), which are difficult to acquire precisely in practice, the sum-rates were also evaluated in the presence of inter-cell channel estimation errors. Fig. 4 shows the sum-rates according to the

estimation error normalized to the true channel gain when  $N = 50$  and  $\text{SNR} = 30\text{dB}$ . Note that the users with a higher LIF value were selected due to the inaccurate other-cell channel estimates at the transmitters, resulting in performance degradation for the OIA schemes using ZF detection and MMSE detection. Moreover, MMSE filtering can cause additional performance degradation because of the inaccurate inter-cell channel estimates at the receivers. On the other hand, the proposed OIA scheme with MMSE detection still outperformed that with ZF detection, even when the estimation error was increased to  $10^{-2}$ .

## 5. Conclusion

This paper introduced the refined energy-efficient OIA scheme with MMSE detection in the MIMO IMAC, while it operates in a distributed manner at the cost of a slightly increased amount of feedback/feedforward overhead and receiver complexity, compared to the conventional energy-efficient OIA with ZF detection [13]. The MMSE receiver structure was specified based on the OIA framework. The proposed OIA scheme showed much higher sum-rates than those of the conventional OIA for the given practical system parameters.

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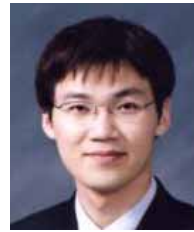
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