Regularized Zero-Forcing Interference Alignment for the Two-Cell MIMO Interfering Broadcast Channel

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Abstract

In this paper, we propose transceiver design strategies for the two-cell multiple-input multiple-output (MIMO) interfering broadcast channel where inter-cell interference (ICI) exists in addition to inter-user interference (IUI). We first formulate the generalized zero-forcing interference alignment (ZF-IA) method based on the alignment of IUI and ICI in multi-dimensional subspace. We then devise a minimum weighted-mean-square-error (WMSE) method based on "regularizing" the precoders and decoders of the generalized ZF-IA scheme. In contrast to the existing weighted-sum-rate-maximizing transceiver, our method does not require an iterative calculation of the optimal weights. Because of this, the proposed scheme, while not designed specifically to maximize the sum rate, is computationally efficient and achieves a faster convergence compared to the known weighted-sum-rate maximizing scheme. Through analysis and simulation, we show the effectiveness of the proposed regularized ZF-IA scheme.

I. Introduction

Multi-cell and multi-user downlink transmission schemes such as network MIMO and coordinated multi-point (CoMP) transmission and reception methods have received a great deal of attention for being able to boost the system performance with base station (BS) cooperation. As a practical scenario of the multi-cell and multi-user downlink transmission, one may consider the heterogeneous networks, e.g., macro-pico or macro-femto cellular networks where the dominant interference can be much stronger than the residual interferences from adjacent cells. This scenario can be modelled as a two-cell interfering broadcast channel (IBC).

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To improve communication over the two-cell IBC, various MIMO transmission strategies that combine the spectral efficiency of MIMO spatial division multiple access and the interference mitigation capability of BS cooperation have been investigated [1]–[5]. An iterative weighted-sum-rate-maximizing transceiver design method for the multi-cell MIMO IBCs has been proposed [1], [2]. An analytical expression for the degree of freedom (DoF) for the two-cell MIMO IBC has been provided in [3]. However, the corresponding achievable DoF is distinctly lower than the trivial outer-bound on DoF of [6]. To improve the DoF, the authors of [4], [5] have introduced modified interference alignment (IA) methods which reduce the interference dimension by aligning ICI or IUI. The IA condition of [4], however, has been developed for the limited user configuration of two users per cell. In [5], a zero-forcing IA (ZF-IA) method for the K-user per cell case has been proposed. It is well known that the original MIMO IA method of [7], which has been developed for the MIMO interference channel, is sub-optimal at any finite SNR regime despite of its ability to achieve the DoF. Given the sub-optimality of IA in the interference channel, it is reasonable to expect the suboptimality of ZF-IA at finite SNRs for the IBC.

We accordingly propose a new IA scheme based on ZF-IA for the two-cell MIMO IBC. To proceed, we first generalize the ZF-IA method of [5] from *single* stream transmission to *multiple* stream transmission for each communication link. Then, to improve the sum-rate at finite SNRs, we propose a method of "regularizing" the ZF-IA scheme based on the WMSE criterion. Through analysis and numerical simulation, we verify that the proposed regularized ZF-IA scheme indeed improves on the generalized ZF-IA method and outperforms the existing weighted sum-rate-maximizing method if the number of iterations for transceiver filter computation is limited.

The following notations are used. We employ upper case boldface letters for matrices and lower case boldface letters for vectors. For any general matrix $\mathbf{X}$, $\mathbf{X}^*$, $\mathbf{X}^H$, Tr$(\mathbf{X})$, det$(\mathbf{X})$, and SVD$(\mathbf{X})$ denote the conjugate, the Hermitian transpose, the trace, the determinant, and the singular value decomposition, respectively. The symbol $\mathbf{I}_n$ denotes an identity matrix of size n.

II. System Model

We consider the two-cell MIMO interfering broadcast channel. The m-th base station B_m equipped with M antennas supports K users $\{\mathsf{D}_{mk}\}$ in the corresponding cell, and each user has N antennas $\big(m \in (1,2), k \in (1,\cdots,K)\big)$. Denoting $\mathbf{y}^{[m,k]}$ as the signal vector received by the k-th user in the m-th cell D_{mk}, the two-cell MIMO interfering broadcast channel is mathematically described as

$$\begin{aligned}\mathbf{y}^{[m,k]} =& \mathbf{H}_m^{[m,k]}\mathbf{T}^{[m,k]}\mathbf{s}^{[m,k]} + \mathbf{H}_m^{[m,k]}\sum_{i\neq k}^{K}\mathbf{T}^{[m,i]}\mathbf{s}^{[m,i]} \\ &+ \mathbf{H}_{\overline{m}}^{[m,k]}\sum_{i=1}^{K}\mathbf{T}^{[\overline{m},i]}\mathbf{s}^{[\overline{m},i]} + \mathbf{n}^{[m,k]}\end{aligned} \tag{1}$$

where $\mathbf{T}^{[m,k]} \in \mathcal{C}^{M\times L_s}$ is the precoding matrix for D_{mk}, $\mathbf{s}^{[m,k]} \in \mathcal{C}^{L_s\times 1}$ stands for the signal vector of length L_s transmitted for D_{mk}, $\mathbf{n}^{[m,k]}$ is the additive Gaussian noise at D_{mk} with $\mathcal{CN}(0,\sigma_n^2)$ and $\mathbf{H}_{\overline{m}}^{[m,k]} \in \mathcal{C}^{N\times M}$ is the channel matrix from $\mathsf{B}_{\overline{m}}$ to D_{mk}; here we define $\overline{1} = 2$ and $\overline{2} = 1$. It is assumed that the channel elements are independent identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance and $\mathbb{E}[\mathbf{s}^{[m,k]}\mathbf{s}^{[m,k]H}] = \mathbf{I}_{L_s}$. The transmit precoder at B_m satisfies the power constraint $\sum_k \mathrm{Tr}(\mathbf{T}^{[m,k]}\mathbf{T}^{[m,k]^H}) \leq P_m$, where P_m is the maximum transmit power of B_m. The estimated output vector at D_{mk} is obtained with the receive filter $\mathbf{U}^{[m,k]} \in \mathcal{C}^{M\times L_s}$ as $\hat{\mathbf{s}}^{[m,k]} = \mathbf{U}^{[m,k]^H}\mathbf{y}^{[m,k]}$.

III. Two-cell zero-forcing interference alignment

In this section, we present a generalized zero-forcing IA (ZF-IA) method in the two-cell MIMO interfering broadcast channel. First, we briefly review the existing ZF-IA scheme. Then, we describe generalized ZF-IA for multiple stream transmission for each link. This generalized ZF-IA will serve as a basis of the regularized ZF-IA scheme which will be described in Section IV.

A. Review of the ZF-IA method

To achieve $\frac{K}{K+1}$ DoF-per-cell[1] without BS cooperation, the transmit precoders are written as $\mathbf{T}^{[m,k]} = \mathbf{P}\mathbf{v}^{[m,k]}$ where $\mathbf{P} \in \mathcal{C}^{M\times N_p}$ is introduced for each BS to spread N_p streams over M-dimensional transmit antenna resource $(M > N_p)$ and $\mathbf{v}^{[m,k]}$ [5]. The ZF-IA method is available in the symmetric antenna configuration [5]; from this point on we focus on symmetric cases, i.e. $M = N$.

The ZF-IA scheme of [5] assumes a single stream reception with each receiver filter $\{\mathbf{u}^{[m,k]}\}$. The receive filter output of D_{mk} is written as (2) in the below, where $\overline{\mathbf{H}}_{\overline{m}}^{[m,k]} \triangleq \mathbf{H}_{\overline{m}}^{[m,k]}\mathbf{P}$. To null out the ICI, the third term on the right hand side of (2), $\mathbf{u}^{[m,k]} \in \mathcal{C}^{M\times 1}$, lies in the null space of $\overline{\mathbf{H}}_{\overline{m}}^{[m,k]}$. To guarantee the existence of these receive filters $\{\mathbf{u}^{[m,k]}\}$, the dimension of the spreading matrix $\mathbf{P}$ should be $(K+1)\times K$, i.e. $M = K+1$ and $N_p = K$. The remaining IUI is cancelled with a transmit channel inversion method [8]. From the ICI nulling process $\mathbf{u}^{[m,k]^H}\overline{\mathbf{H}}_{\overline{m}}^{[m,k]} = \mathbf{0}^T$ and IUI cancellations

[1] Compared to the DoF definition in [7], the notion of DoF-per-cell is based on normalization of the DoF by the dimensionality.

$$\hat{s}^{[m,k]} = \mathbf{u}^{[m,k]H}\overline{\mathbf{H}}_m^{[m,k]}\mathbf{v}^{[m,k]}s^{[m,k]} + \mathbf{u}^{[m,k]H}\overline{\mathbf{H}}_m^{[m,k]}\sum_{i\neq k}^{K}\mathbf{v}^{[m,i]}s^{[m,i]} + \mathbf{u}^{[m,k]H}\overline{\mathbf{H}}_{\overline{m}}^{[m,k]}\sum_{i=1}^{K}\mathbf{v}^{[\overline{m},i]}s^{[\overline{m},i]} + \mathbf{u}^{[m,k]H}\mathbf{n}^{[m,k]} \tag{2}$$

$\mathbf{u}^{[m,k]H}\overline{\mathbf{H}}_m^{[m,k]}\mathbf{v}^{[m,i]} = 0$ $(i \neq k)$, it is easily verified that both ICI and IUI are aligned in the null space of $\mathbf{u}^{[m,k]}$.

B. Generalized ZF-IA

Although the ZF-IA scheme achieves $\frac{K}{K+1}$ DoF-per-cell, only a *single* stream transmission is allowed at each user node. To transmit L_s $(L_s > 1)$ streams at each user node, we propose a generalized ZF-IA transceiver design method. At first, for the spreading matrix $\mathbf{P}$, to guarantee the existence of null space of $\overline{\mathbf{H}}_{\overline{m}}^{[m,k]}$ with rank $= L_s$, we pick an arbitrary $K(L_s+1) \times KL_s$ full rank matrix whose columns are orthonormal to each other, i.e., $\mathbf{P}^H\mathbf{P} = \mathbf{I}_{N_p}$. Then, the received signal (1) is rewritten as

$$\begin{aligned}\mathbf{y}^{[m,k]} =& \overline{\mathbf{H}}_m^{[m,k]}\mathbf{V}^{[m,k]}\mathbf{s}^{[m,k]} + \overline{\mathbf{H}}_m^{[m,k]}\sum_{i\neq k}^{K}\mathbf{V}^{[m,i]}\mathbf{s}^{[m,i]} \\ &+ \overline{\mathbf{H}}_{\overline{m}}^{[m,k]}\sum_{i=1}^{K}\mathbf{V}^{[\overline{m},i]}\mathbf{s}^{[\overline{m},i]} + \mathbf{n}^{[m,k]}\end{aligned} \tag{3}$$

where $\mathbf{V}^{[m,k]} \in \mathcal{C}^{N_p \times L_s}$. To cancel out the ICI, the front end of the receiver filter $\bar{\mathbf{U}}^{[m,k]} \in \mathcal{C}^{M \times L_s}$ is chosen from the null space of $\overline{\mathbf{H}}_{\overline{m}}^{[m,k]}$, which can be obtained as

$$\text{SVD}(\overline{\mathbf{H}}_{\overline{m}}^{[m,k]}) = [\tilde{\bar{\mathbf{U}}}^{[m,k]}, \bar{\mathbf{U}}^{[m,k]}]\bar{\mathbf{\Sigma}}^{[m,k]}\bar{\mathbf{V}}^{[m,k]H}$$

Now B_m performs block diagonalization (BD) to eliminate IUI, the BD precoder $\bar{\mathbf{V}}^{[m,k]}$ is identified as

$$\text{SVD}(\mathbf{H}_{\text{C}}^{[m,k]}) = \bar{\mathbf{U}}_{\text{C}}^{[m]}\bar{\mathbf{\Sigma}}_{\text{C}}^{[m]}[\tilde{\bar{\mathbf{V}}}^{[m,k]}, \bar{\mathbf{V}}^{[m,k]}]^H, \tag{4}$$

where $\mathbf{H}_{\text{C}}^{[m,k]} = \left[\mathbf{\Omega}_m^{[m,1]H}, \cdots, \mathbf{\Omega}_m^{[m,k-1]H}, \mathbf{\Omega}_m^{[m,k+1]H}, \cdots\right]^H$ and $\mathbf{\Omega}_{\overline{m}}^{[m,k]} \triangleq \bar{\mathbf{U}}^{[m,k]H}\overline{\mathbf{H}}_{\overline{m}}^{[m,k]}$.

Assume the final ZF-IA transceivers are $\mathbf{T}_{\text{GZF-IA}}^{[m,k]} = \mathbf{P}\bar{\mathbf{V}}^{[m,k]}\hat{\mathbf{V}}^{[m,k]}\mathbf{\Phi}^{[m,k]\frac{1}{2}}$ and $\mathbf{U}_{\text{GZF-IA}}^{[m,k]} = \bar{\mathbf{U}}^{[m,k]}\hat{\mathbf{U}}^{[m,k]}$; then the estimated signal is written as

$$\hat{\mathbf{s}}^{[m,k]} = \hat{\mathbf{U}}^{[m,k]H}\mathbf{H}_{\text{eff}}^{[m,k]}\hat{\mathbf{V}}^{[m,k]}\mathbf{\Phi}^{[m,k]\frac{1}{2}}\mathbf{s}^{[m,k]} + \hat{\mathbf{n}}^{[m,k]}, \tag{5}$$

where the effective channel $\mathbf{H}_{\text{eff}}^{[m,k]} \in \mathcal{C}^{L_s \times L_s}$ and the effective noise $\hat{\mathbf{n}}^{[m,k]} \in \mathcal{C}^{L_s \times 1}$ are defined by $\mathbf{H}_{\text{eff}}^{[m,k]} = \bar{\mathbf{U}}^{[m,k]H}\overline{\mathbf{H}}_m^{[m,k]}\bar{\mathbf{V}}^{[m,k]}$ and $\hat{\mathbf{n}}^{[m,k]} = \hat{\mathbf{U}}^{[m,k]H}\bar{\mathbf{U}}^{[m,k]H}\mathbf{n}^{[m,k]}$, respectively. The other transmit-receive matrices $\hat{\mathbf{V}}^{[m,k]}$ and $\hat{\mathbf{U}}^{[m,k]}$ are identified by channel diagonalization with $\text{SVD}\big(\mathbf{H}_{\text{eff}}^{[m,k]}\big) =$

$\hat{\mathbf{U}}^{[m,k]}\hat{\mathbf{\Sigma}}^{[m,k]}\hat{\mathbf{V}}^{[m,k]H}$. Note that because $\hat{\mathbf{U}}^{[m,k]}$ and $\bar{\mathbf{U}}^{[m,k]}$ are composed of orthonormal columns, $\mathbb{E}(\hat{\mathbf{n}}^{[m,k]}\hat{\mathbf{n}}^{[m,k]H}) = \sigma_n^2\mathbf{I}_{L_s}$. Then the information rate of D_{mk} can be computed as

$$\mathrm{R}_{\text{ZF-IA}}^{[m,k]} = \log\{\det(\mathbf{I}_{L_s} + \sigma_n^{-2}\hat{\mathbf{\Sigma}}^{[m,k]2}\mathbf{\Phi}^{[m,k]})\}. \tag{6}$$

Because this scheme causes no ICI, the sum rate over the m-th cell $\sum_{k=1}^{K}\mathrm{R}_{\text{ZF-IA}}^{[m,k]}$ is independent of the power allocation at $\mathsf{B}_{\overline{m}}$. Thus, the sum-rate-maximizing power allocation problem

$$\max_{\{\mathbf{\Phi}^{[m,k]}\}}\sum_{m=1}^{2}\sum_{k=1}^{K}\mathrm{R}_{\text{ZF-IA}}^{[m,k]} \quad \text{subject to} \sum_{k=1}^{K}\mathrm{Tr}(\mathbf{\Phi}^{[m,k]}) \leq P_m, \forall m$$

is divided into the following *individual-cell* sum-rate-maximizing problem (in which the optimal power allocation matrix $\{\mathbf{\Phi}^{[m,k]}\}$ is calculated with the water-filling solution)

$$\max_{\{\mathbf{\Phi}^{[m,k]}\}}\sum_{k=1}^{K}\mathrm{R}_{\text{ZF-IA}}^{[m,k]} \quad \text{subject to} \sum_{k=1}^{K}\mathrm{Tr}(\mathbf{\Phi}^{[m,k]}) \leq P_m \tag{7}$$

where the power constraint $\mathrm{Tr}(\mathbf{T}_{\text{GZF-IA}}^{[m,k]}\mathbf{T}_{\text{GZF-IA}}^{[m,k]H}) = \mathrm{Tr}(\mathbf{\Phi}^{[m,k]})$ is obtained using $\mathbf{P}^H\mathbf{P} = \mathbf{I}_{N_p}$. Let us call this scheme *generalized* ZF-IA (GZF-IA). Note that the proposed GZF-IA scheme still preserves $\frac{K}{K+1}$ DoF-per-cell[2] and is implemented without BS cooperation.

IV. Proposed regularized ZF-IA method

Due to the inherent limitations of ZF schemes, the original IA method of [7] is distinctly sub-optimal in the low-to-mid SNR regime. We surmise that GZF-IA is also suboptimal. We propose a regularized GZF-IA algorithm which regularizes the precoders and decoders of the GZF-IA scheme in an effort to improve upon the sum rate performance of GZF-IA.

A. Transceiver design

To achieve regularization, the proposed scheme minimizes the weighted MSE defined as

$$\min\sum_{m=1}^{2}\sum_{k=1}^{K}\mathbb{E}\{|\mathbf{\Lambda}^{[m,k]}\mathbf{s}^{[m,k]} - \hat{\mathbf{s}}^{[m,k]}|^2\}$$
$$\text{subject to}\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{T}^{[m,k]}\mathbf{T}^{[m,k]H}) \leq P_m, \forall m \tag{8}$$

where $\mathbf{\Lambda}^{[m,k]}$ is introduced to improve the sum-rate performance by preventing weaker subchannels from being assigned more power. Accordingly, $\mathbf{\Lambda}^{[m,k]}$ is chosen as the effective channel gain matrix to D_{mk}, $\mathbf{\Lambda}^{[m,k]} = \mathbf{U}_{\text{GZF-IA}}^{[m,k]H}\mathbf{H}_m^{[m,k]}\mathbf{T}_{\text{GZF-IA}}^{[m,k]}$. Then the Lagrangian function of (8) is formed as (9) in the below,

$$\mathcal{L} = \sum_{m=1}^{2}\sum_{k=1}^{K} \mathrm{Tr}\Big\{\mathbf{\Lambda}^{[m,k]2} - \mathbf{U}^{[m,k]H}\overline{\mathbf{H}}_m^{[m,k]}\mathbf{V}^{[m,k]}\mathbf{\Lambda}^{[m,k]H} - \mathbf{\Lambda}^{[m,k]}\mathbf{V}^{[m,k]H}\overline{\mathbf{H}}_m^{[m,k]H}\mathbf{U}^{[m,k]} + \sigma_n^2\mathbf{U}^{[m,k]H}\mathbf{U}^{[m,k]}$$
$$+ \sum_{n=1}^{2}\sum_{i=1}^{K}\mathbf{U}^{[m,k]H}\overline{\mathbf{H}}_n^{[m,k]}\mathbf{V}^{[n,i]}\mathbf{V}^{[n,i]H}\overline{\mathbf{H}}_n^{[m,k]H}\mathbf{U}^{[m,k]}\Big\} + \sum_{m=1}^{2}\mu_m\Big(\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{V}^{[m,k]}\mathbf{V}^{[m,k]H}) - P_m\Big) \tag{9}$$

where $\{\mu_m\}$ is the Lagrangian multiplier and the transmit power at B_m is given by $\mathrm{Tr}(\mathbf{T}^{[m,k]}\mathbf{T}^{[m,k]H}) = \mathrm{Tr}(\mathbf{V}^{[m,k]}\mathbf{V}^{[m,k]H})$ using $\mathbf{P}^H\mathbf{P} = \mathbf{I}_{N_p}$. Because the transceiver matrix $\{\mathbf{V}^{[m,k]}\}$ and $\{\mathbf{U}^{[m,k]}\}$ are inter-related, it is difficult to optimize simultaneously. Thus, we rely on an alternating optimization method which iteratively finds local optimal solutions. First, we design the optimal precoder assuming the receive filters are given. From $\nabla_{\mathbf{V}^{[m,k]*}}\mathcal{L} = \mathbf{0}$, the precoder for D_{mk} is derived as:

$$\mathbf{V}^{[m,k]} = \Big(\sum_{n=1}^{2}\sum_{i=1}^{K}\mathbf{\Xi}_m^{[n,i]} + \mu_m\mathbf{I}_{N_p}\Big)^{-1}\overline{\mathbf{H}}_m^{[m,k]H}\mathbf{U}^{[m,k]}\mathbf{\Lambda}^{[m,k]} \tag{10}$$

where $\mathbf{\Xi}_m^{[n,i]} \triangleq \overline{\mathbf{H}}_m^{[n,i]H}\mathbf{U}^{[n,i]}\mathbf{U}^{[n,i]H}\overline{\mathbf{H}}_m^{[n,i]}$. Since the m-th BS transmit power, $\sum_{k=1}^{K}\mathrm{Tr}(\mathbf{V}^{[m,k]}\mathbf{V}^{[m,k]H})$, is a monotonically decreasing function with respect to μ_m (the proof is omitted due to the space limitation), μ_m can be efficiently solved to satisfy the power constraint by a bisection method.

Next, we derive the receive filter $\{\mathbf{U}^{[m,k]}\}$ with the given precoders $\{\mathbf{V}^{[m,k]}\}$. The optimal receive filter for D_{mk} is simply derived with $\nabla_{\mathbf{U}^{[m,k]*}}\mathcal{L} = \mathbf{0}$ and is given by:

$$\mathbf{U}^{[m,k]} = \Big\{\sum_{n=1}^{2}\sum_{i=1}^{K}\mathbf{\Psi}_{[n,i]}^{[m,k]} + \sigma_n^2\mathbf{I}_M\Big\}^{-1}\overline{\mathbf{H}}_m^{[m,k]}\mathbf{V}^{[m,k]}\mathbf{\Lambda}^{[m,k]H} \tag{11}$$

where $\mathbf{\Psi}_{[n,i]}^{[m,k]} \triangleq \overline{\mathbf{H}}_n^{[m,k]}\mathbf{V}^{[n,i]}\mathbf{V}^{[n,i]H}\overline{\mathbf{H}}_n^{[m,k]H}$. Since the transceivers in (10) and (11) are inter-dependent, the algorithm shown in the table below is used to find the optimal transceivers. This algorithm is provable

Algorithm 1 Obtaining optimal regularized ZF-IA transceivers

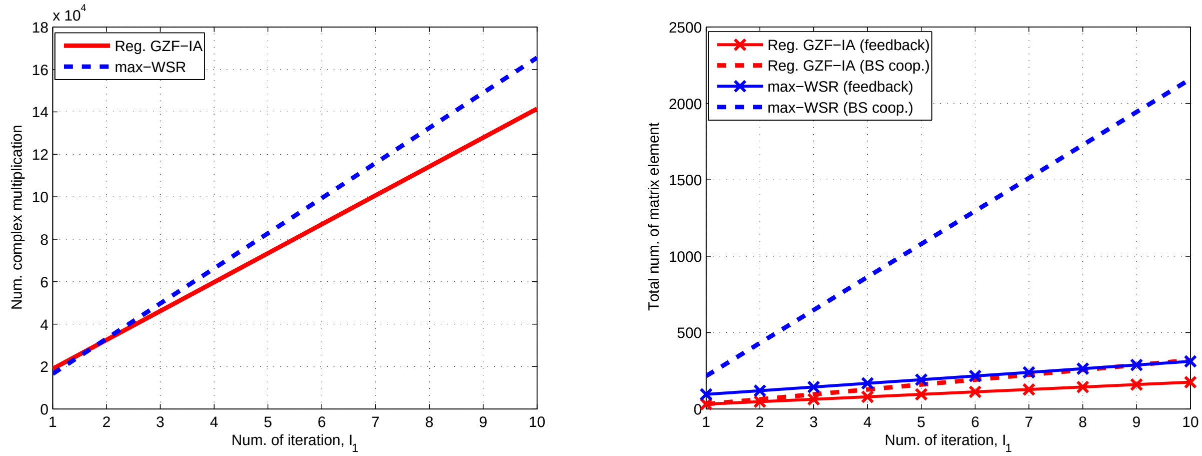
Initialize $\mathbf{U}^{[m,k]} = \mathbf{U}_{\text{GZF-IA}}^{[m,k]}$ and compute the MSE weight $\mathbf{\Lambda}^{[m,k]}$, $\forall m, k$.

Step 1: Compute $\{\mathbf{V}^{[m,k]}\}$ using (10).

Step 2: Compute $\{\mathbf{U}^{[m,k]}\}$ using (11).

Step 3: Go back to Step 2 until convergence.

[2] DoF-per-cell is $\frac{2KL_s}{2(K+1)L_s} = \frac{K}{K+1}$.



(a) Computational complexity (b) Prerequisite information to B_m

Fig. 1. Computation complexity and feedback/BS cooperation resources required versus number of iterations, I_1

convergent at least to a local minimum.

We note that even though the MSE weights $\{\mathbf{\Lambda}^{[m,k]}\}$ of the proposed regularized ZF-IA algorithm is not optimum in sense of the sum rate, they are obtained non-iteratively with the GZF-IA method, which is near-optimum in the high SNR region. In the following, we discuss the advantages of *one-shot* calculation of the MSE weights.

V. Discussion: Computational complexity and prerequisite information exchange

Here we analyze computational complexity and the amount of prerequisite information of the proposed regularized ZF-IA (RZF-IA) method. For comparison, we also analyze those of the weighted-sum-rate-maximizing method (called 'max-WSR method') of [1].

A. Computational complexity

We consider the number of complex multiplications as a complexity measure. Fig.1 (a) illustrates the computational complexity for $K = 2$, $M = 6$, $L_s = 2$, $N_p (= M - KL_s) = 2$ and I_2 (the number of iterations for bisection) $= 10$. In each iteration, both RZF-IA and max-WSR schemes calculate the transmit and receiver filters. The max-WSR scheme additionally includes MSE-weight updating in the iteration loop, whereas the MSE weights of RZF-IA are calculated in a non-iterative manner. Therefore, as the number of iterations I_1 increases, the computational efficiency of the RZF-IA method becomes relatively higher.

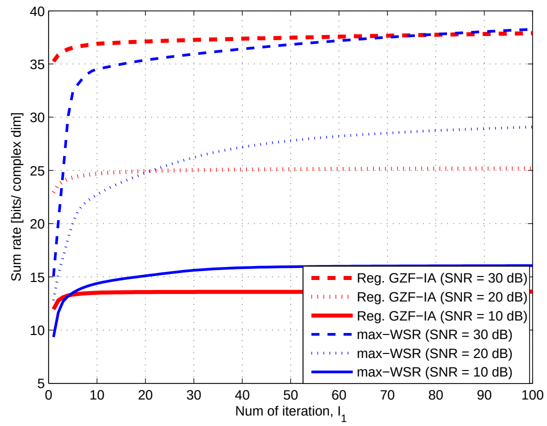


Fig. 2. Convergence of RZF-IA and max-WSR methods

B. Prerequisite information exchange

To find the weighted-MSE-minimizing transmit precoders, each BS requires prerequisite information through feedback and BS cooperations. Due to the one-shot calculation of the MSE weights in RZF-IA, only the effective channels $\mathbf{U}^{[m,k]H}\mathbf{H}_m^{[m,k]}\mathbf{P} \in \mathcal{C}^{L_s \times N_p}, \forall k$ are fedback iteratively for updating $\{\mathbf{V}^{[m,k]}\}$. However, the max-WSR method requires the channel information and receiver filter coefficients separately to update the transmit filters as well as MSE weights. For the same reason, RZF-IA requires a smaller amount of resources for BS cooperations. Fig.1(b) clearly shows that the RZF-IA scheme is advantageous in terms of the amount of prerequisite information. Note that unlike GZF-IA which can be implemented without BS cooperation, both RZF-IA and max-WSR require BS cooperation. Nevertheless, considering that BS cooperation will be part of future wireless communication standards [9], the overhead associated with BS cooperation of both methods seems reasonable.

VI. NUMERICAL RESULTS

This section evaluates the sum rate performance of various transmission strategies over two-cell MIMO interfering broadcast channels. For the simulation results, we set $M = 6$, $K = 2$, $L_s = 2$, $P_m = P, \forall m$. The SNR is defined as $\frac{P}{\sigma_n^2}$. Also, we assume that the elements of the channel matrix are i.i.d. complex Gaussian with zero mean and unit variance. Fig. 2 illustrates the convergence behavior of the RZF-IA method and max-WSR method. This plot shows that while RZF-IA is not as good as max-WSR as a large number of iterations is allowed, especially at low SNRs, the former algorithm converges faster than

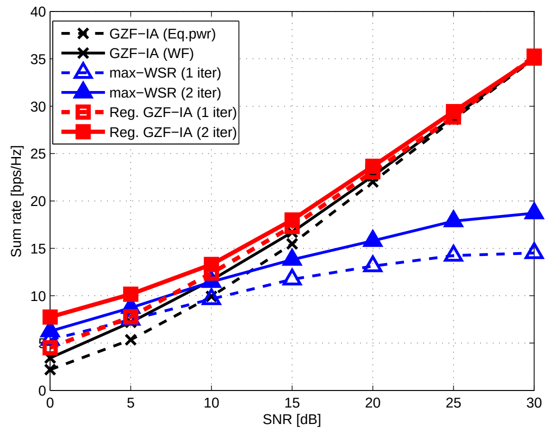


Fig. 3. Sum rate performance at small number of iterations

the latter method. In fact, at a small number of iteration, RZF-IA performs better than max-WSR.

Fig. 3 shows the sum rate performance at a small number of iterations $I_1 = 1, 2$. Specifically, at $I_1 = 2$, due to the fast convergence, RZF-IA indeed shows better performance than max-WSR. We also confirm that RZF-IA enhances the performance of GZF-IA. At a sufficient number of iterations, e.g., at $I_1 = 100$, the RZF-IA scheme shows a significant degradation, especially when SNR is not very large, compared to max-WSR due to the sub-optimality of the MSE weights, a price paid for reduced computational complexity and prerequisite information.

VII. Conclusion

In this paper, we have investigated generalized ZF-IA in the two-cell MIMO interfering broadcast channel and subsequently proposed regularized ZF-IA methods to improve its sum rate performance. To execute the regularization process efficiently, we have utilized the WMSE metric whose weight terms are computed from the effective channel gain of the generalized ZF-IA scheme. With these weights, the regularized ZF-IA method iteratively calculates the transceivers. Unlike the existing max-WSR method where weights are found with iterations, the weights of the regularized ZF-IA scheme are obtained *non-iteratively* from the generalized ZF-IA method. Overall, the proposed regularized ZF-IA scheme consumes less resources and converges faster. Through analysis and numerical simulation, the effectiveness of the regularized ZF-IA scheme has been confirmed.

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