New Interference Suppression Precoding Scheme for Downlink Multi-User Multi-Stream MIMO Systems

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Abstract—**In this paper, an interference-aware linear precoding scheme, called generalized singular value decomposition based interference suppression precoding (GSVD-ISP), is proposed. GSVD-ISP scheme employs a whitening filter for interference suppression at the receiver and a novel precoder considering other cells' interference for each user at the transmitter. Through slightly loosening the constraint on the signal-to-leakage-plus-noise (SLNR) maximization for multi-user multiple-input multiple-output (MU-MIMO) systems with multiple data streams per user and the use of GSVD algorithms, the proposed scheme decreases redundant computational complexity and reduces the gap between any couple of the stream effective channel gains compared with the original interference-aware enhancement to SLNR precoding scheme—multiuser generalized eigenmode transmission (MGET). Simulation results demonstrate that the proposed GSVD-ISP technique achieves considerable gains in terms of bit error rate (BER) over MGET technique with multi-stream and the traditional interference-aware block diagonalization (BD) scheme while maintaining roughly the same achievable sum-rate.**

I. INTRODUCTION

Recently, multi-user multiple-input multiple-output (MU-MIMO) technique has attracted much attention due to its potential to achieve high capacity with the benefit of space-division-multiple-access (SDMA). With perfect channel state information (CSI) and complete knowledge of the transmitted signals, the dirty paper coding (DPC) can achieve the sum capacity of the MIMO Broadcast channel (BC) in theory [1], [2]. However, it is impractical to deploy DPC in real-time systems because of its high computational complexity.

Alternatively, linear precoding techniques with lower complexity have been proposed. To design the optimal linear MU-MIMO precoding scheme, it is often desirable to maximize the output signal-to-interference-plus-noise ratio (SINR) for each user, but this approach is challenging due to its coupled characteristic and lack of closed-form solution. A more tractable but suboptimal design is to enforce a zero co-channel interference (CCI), such as block diagonalization (BD) and zero forcing (ZF) [3]. Another design is to suppress the CCI rather than perfectly canceling the CCI for each user, for example, to maximize the signal-to-leakage-plus-noise ratio (SLNR), where the signal leakage means the interference caused by signal intended for a desired user on the other users [4].

However, the BD, ZF and SLNR-based precoding algorithms neglect the inter-cell interference (ICI). In cellular systems, ICI has been proved to significantly degrade the quality of service (QoS) especially for the users at the cell edge [5]-[7]. In [8], an ICI-aware method based on BD is presented which can improve the cell edge users' performance considerably, but this scheme imposes restriction on the system configuration that the number of antennas at the transmitter side should be larger than the sum of receive antennas of all selected users. A linear precoding technique called MGET uses a whitening filter for interference suppression at the receiver and a novel precoder using the interference-plus-noise covariance matrix for each user at the transmitter is proposed in [9], which is an interference-aware enhancement to SLNR precoding scheme. This method is not constrained by the system configuration and achievable sum-rate outperforms the ICI-aware BD scheme, but the system performance degrades seriously when each user transmits multi-stream data simultaneously.

In this paper, we present a new generalized singular value decomposition based interference suppression precoding (GSVD-ISP) scheme for downlink multi-stream MU-MIMO channel. GSVD-ISP uses a whitening filter for interference suppression at the receiver and a novel precoder considering ICI for each user at the transmitter that uses the GSVD algorithm [10] instead of the conventional generalized eigenvalue decomposition (GEVD) algorithm used in the MGET. Compared with GEVD algorithm, GSVD algorithm avoids any matrix 'squaring' operations, removing redundant computational loads. And the GSVD technique also can reduce the margin between the effective SINRs of multiple data streams. It is shown in [11] that the performance of each user in MU-MIMO systems is decided by the worst SINR of multiple data streams, so the performance of each user who uses the GSVD-ISP is significantly improved when each user transmits multiple data streams. To do this, slight relaxation for pursuing SLNR maximization and a little sum-rate loss are introduced when multi-stream data are transmitted.

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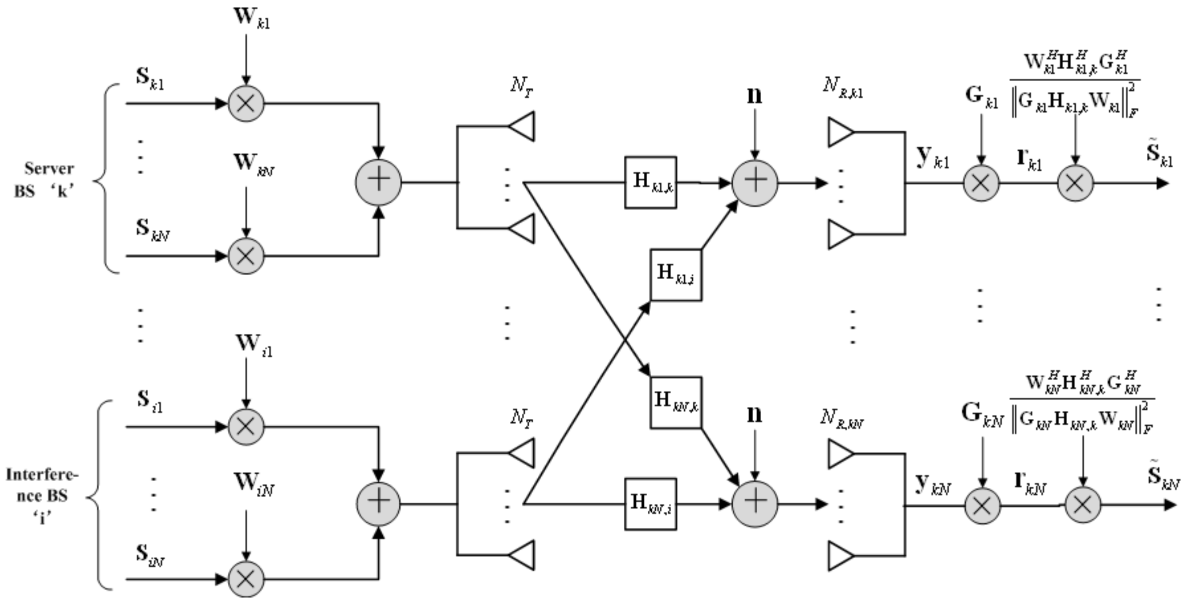

Fig.1 Interference-aware downlink multi-stream MU-MIMO model

The remainder of this paper is organized as follows. In Section II, the system model is described. GSVD-ISP technique and receiver structure are proposed in Section III. Section IV presents simulation results to verify our analysis. The paper ends up with some discussions and conclusions in Section V.

Throughout the paper, we use the following notations: $\mathbb{E}(\bullet)$, $\mathrm{Tr}(\bullet)$, $(\bullet)^{-1}$, $(\bullet)^{T}$ and $(\bullet)^{H}$ denote expectation, trace, pseudo-inverse, transpose and conjugate transpose, respectively. $\|\bullet\|_F$ represents the Frobenius norm. $\mathbf{I}_N$ is the $N\times N$ identity matrix. $\mathrm{diag}(a_1,\cdots,a_N)$ is diagonal matrix with element a_n on the n-th diagonal. Besides, $\mathbb{C}^{M\times N}$ represents the set of $M\times N$ matrices in complex field. $[\mathbf{A}]_{i:j}$ denotes the submatrix from the i-th column to the j-th column of $\mathbf{A}$.

II. Downlink MIMO And Multi-Cell Interference Model

Consider an interference-aware downlink multi-stream MU-MIMO scenario as figure 1 shows. Each base station (BS) communicates with N users simultaneously, i.e., for k-th BS, $k1,\ldots,kn,\ldots kN$ denote its N users and the corresponding channel matrices are $\mathbf{H}_{k1,k},\ldots,\mathbf{H}_{kn,k},\ldots,\mathbf{H}_{kN,k}$, respectively. There are K base stations (BSs), for the source BS the other $K-1$ BSs are interferers. Each BS employs N_T transmit antennas and each user could be equipped with multiple antennas as well. Let $N_{R,kn}$ denote the number of receive antennas at the kn-th user and $M=\sum_{i=1}^{N} N_{R,ki}$. Assuming a frequency flat fading channel, the received signal $\mathbf{y}_{kn}\in\mathbb{C}^{N_{R,kn}\times 1}$ for the kn-th user can be represented as

$$\begin{aligned}\mathbf{y}_{kn} &= \mathbf{H}_{kn,k}\mathbf{W}_{kn}\mathbf{S}_{kn} + \underbrace{\mathbf{H}_{kn,k}\sum_{j=1,j\neq n}^{N}\mathbf{W}_{kj}\mathbf{S}_{kj}}_{\text{co-channel interference}} \\ &\quad + \underbrace{\sum_{i=1,i\neq k}^{K}\mathbf{H}_{kn,i}\left(\sum_{j=1}^{N}\mathbf{W}_{ij}\mathbf{S}_{ij}\right)+\mathbf{n}}_{\text{inter-cell interference plus noise}}\end{aligned} \tag{1}$$

where $\mathbf{S}_{kn}\in\mathbb{C}^{m\times 1}$ is the transmitted signal of the kn-th user, m ($<N_{R,kn}$) is the number of data streams supported for the kn-th user and is assumed to be equal for all the users for simplicity. The signal vector satisfies the power constraint $\mathbb{E}\left(\mathbf{S}_{kn}\mathbf{S}_{kn}^{H}\right)=\mathbf{I}$. Let $\mathbf{W}_{kn}\in\mathbb{C}^{N_T\times m}$ denotes the precoding matrix, $\mathbf{W}_{kn}$ are assumed to be normalized as $\mathrm{Tr}\left(\mathbf{W}_{kn}^{H}\mathbf{W}_{kn}\right)=1$. $\mathbf{n}$ is the additive complex Gaussian noise vector with zero mean and covariance matrix $\sigma^2\mathbf{I}_{N_{R,kn}}$. In (1), the second term means CCI and last two terms mean inter-cell interference plus noise. We denote $\mathbf{Z}_{kn}=\sum_{k=1,k\neq k}^{K}\mathbf{H}_{kn,i}\left(\sum_{j=1}^{N}\mathbf{W}_{ij}\mathbf{S}_{ij}\right)+\mathbf{n}$, (1) can be changed into:

$$\mathbf{y}_{kn}=\mathbf{H}_{kn,k}\mathbf{W}_{kn}\mathbf{S}_{kn}+\mathbf{H}_{kn,k}\sum_{j=1,j\neq n}^{N}\mathbf{W}_{kj}\mathbf{S}_{kj}+\mathbf{Z}_{kn} \tag{2}$$

And the inter-cell interference plus noise covariance matrix of the kn-th user is given by

$$\mathbf{Q}_{kn}=\mathbb{E}\left(\mathbf{Z}_{kn}\mathbf{Z}_{kn}^{H}\right) \tag{3}$$

The estimation of inter-cell interference plus noise covariance matrix can be implemented by various methods including the usage of silent period of the desired signal [12], the usage of pilot signal [13] and blind estimation [14] according to multiple access strategies. After estimating the covariance matrix at each receiver, the receiver should inform this to the transmitter by using uplink feedback channel. In this paper, we assume the inter-cell interference plus noise covariance matrix is known at the transmitter without dealing with detailed feedback protocols.

III. PROSPOSED GSVD-ISP SCHEME

This section proposes a new GSVD-ISP scheme which is also an interference-aware enhancement to SLNR precoding for downlink multi-stream MU-MIMO systems.

Define $\mathbf{G}_{kn} = \mathbf{Q}_{kn}^{-1/2}$ and multiply it by the two sides of (2), we get the following expression

$$\mathbf{r}_{kn} = \mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{kn}\mathbf{S}_{kn} + \mathbf{G}_{kn}\mathbf{H}_{kn,k}\sum_{j=1,j\neq n}^{N}\mathbf{W}_{kj}\mathbf{S}_{kj} + \mathbf{G}_{kn}\mathbf{Z}_{kn} \tag{4}$$

The SINR at the kn - th user is then given by

$$\begin{aligned}\mathrm{SINR}_{kn} &= \frac{\|\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{kn}\|_F^2}{\sum_{i=1,i\neq n}^{N}\|\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{ki}\|_F^2 + \|\mathbf{G}_{kn}\mathbf{Z}_{kn}\|_F^2} \\ &= \frac{\|\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{kn}\|_F^2}{\sum_{i=1,i\neq n}^{N}\|\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{ki}\|_F^2 + N_{R,kn}}\end{aligned} \tag{5}$$

Consequently the ICI is successfully suppressed with $\mathbf{G}_{kn}$. From the equation (5), we could see all the precoding matrices $\mathbf{W}_{kn}$ are coupled together, requiring an iterative algorithm and there is not a closed-form solution [15]. An alternative approach is to define SLNR [4] as

$$\begin{aligned}\mathrm{SLNR}_{kn} &= \frac{\|\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{kn}\|_F^2}{\sum_{i=1,i\neq n}^{N}\|\mathbf{G}_{ki}\mathbf{H}_{ki,k}\mathbf{W}_{kn}\|_F^2 + N_{R,kn}} \\ &= \frac{tr(\mathbf{W}_{kn}^H\mathbf{H}_{kn,k}^H\mathbf{G}_{kn}^H\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{kn})}{tr(\mathbf{W}_{kn}^H(\tilde{\mathbf{H}}_{kn,k}^H\tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T})\mathbf{W}_{kn})}\end{aligned} \tag{6}$$

where we define $\tilde{\mathbf{H}}_{kn,k}$ as follows:

$$\begin{aligned}\tilde{\mathbf{H}}_{kn,k} = [&\mathbf{G}_{k1}\mathbf{H}_{k1,k};\ldots;\mathbf{G}_{k(n-1)}\mathbf{H}_{k(n-1),k};\ldots \\ &\mathbf{G}_{k(n+1)}\mathbf{H}_{k(n+1),k};\ldots;\mathbf{G}_{kN}\mathbf{H}_{kN,k}] \in \mathbb{C}^{(M-N_{kn,k})\times N_T}\end{aligned} \tag{7}$$

And the semicolon ';' denotes the vertical concatenation of matrices. In the conventional MGET scheme, the precoding matrices $\mathbf{W}_{kn}$ is obtained based on the purpose of maximizing the SLNR_{kn}

$$\mathbf{W}_{kn} = \arg\max_{\mathbf{W}_{kn}\in\mathbb{C}^{N_T\times m}} \mathrm{SLNR}_{kn} \tag{8}$$

Since $\mathbf{H}_{kn,k}^H\mathbf{G}_{kn}^H\mathbf{G}_{kn}\mathbf{H}_{kn,k}$ is Hermitian and positive semidefinite (HPSD) and $\tilde{\mathbf{H}}_{kn,k}^H\tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T}$ is Hermitian and positive definite (HPD), by GEVD algorithm, there exists an invertible matrix $\mathbf{T}_{kn} \in \mathbb{C}^{N_T\times N_T}$ such that

$$\begin{aligned}\mathbf{T}_{kn}^H\mathbf{H}_{kn,k}^H\mathbf{G}_{kn}^H\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{T}_{kn} &= \Lambda_{kn} = \mathrm{diag}(\lambda_1,\cdots,\lambda_{N_T}) \\ \mathbf{T}_{kn}^H(\tilde{\mathbf{H}}_{kn,k}^H\tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T})\mathbf{T}_{kn} &= \mathbf{I}_{N_T}\end{aligned} \tag{9}$$

with $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_{N_T} \geq 0$. Here, the columns of $\mathbf{T}_{kn}$ and the diagonal entries of Λ_{kn} are the generalized eigenvectors and eigenvalues of the pair $\{\mathbf{H}_{kn,k}^H\mathbf{G}_{kn}^H\mathbf{G}_{kn}\mathbf{H}_{kn,k},\ \tilde{\mathbf{H}}_{kn,k}^H\tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T}\}$ respectively. It is then shown in [4], [9] that the optimal precoder which is able to maximize the objective function (8) can be obtained by extracting the leading m columns of $\mathbf{T}_{kn}$ as

$$\mathbf{W}_{kn} = \beta_{kn}[\mathbf{T}_{kn}]_{1:m} \tag{10}$$

where β_{kn} is chosen to satisfy the power constraint. And the resulting maximum SLNR value is given by

$$\mathrm{SLNR}_{kn}^{\max} = \sum_{i=1}^{m}\lambda_i / m \tag{11}$$

What causes computational complexity with this approach is the matrix product $\mathbf{H}_{kn,k}^H\mathbf{G}_{kn}^H\mathbf{G}_{kn}\mathbf{H}_{kn,k}$ and the inversion of matrix $\tilde{\mathbf{H}}_{kn,k}^H\tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T}$. Besides, the system performance will significantly degrade when each user transmits data stream m is larger than one, because the overall performance of a user with multiple streams is dominated by the stream with the worst channel condition. The proposed GSVD-ISP method can solve these problems.

Let $\mathbf{K}_{kn} = [\mathbf{G}_{kn}\mathbf{H}_{kn,k};\tilde{\mathbf{H}}_{kn,k};\sqrt{N_{R,kn}}\mathbf{I}_{N_T}] \in \mathbb{C}^{(M+N_T)\times N_T}$. Firstly we compute the QR decomposition (QRD) of $\mathbf{K}_{kn}$, that is

$$\mathbf{K}_{kn} = \mathbf{P}_{kn}\mathbf{R}_{kn}, \mathbf{P}_{kn} \in \mathbb{C}^{(M+N_T)\times N_T}, \mathbf{R}_{kn} \in \mathbb{C}^{N_T\times N_T} \tag{12}$$

where $\mathbf{P}_{kn}^H\mathbf{P}_{kn} = \mathbf{I}_{N_T}$ and $\mathbf{R}_{kn}$ is upper triangular. Then proceeding to partition $\mathbf{P}_{kn}$ as

$$\begin{aligned}&\mathbf{P}_{kn} = [\mathbf{P}_{kn1};\mathbf{P}_{kn2}] \\ &\mathbf{P}_{kn1} \in \mathbb{C}^{N_{R,kn}\times N_T}, \mathbf{P}_{kn2} \in \mathbb{C}^{(M+N_T-N_{R,kn})\times N_T}\end{aligned} \tag{13}$$

Then we compute the SVD of $\mathbf{P}_{kn1}$ as $\mathbf{U}_{kn}^H\mathbf{P}_{kn1}\mathbf{V}_{kn} = \Sigma_{kn}$, where $\mathbf{U}_{kn} \in \mathbb{C}^{N_{R,kn}\times N_{R,kn}}$ and $\mathbf{V}_{kn} \in \mathbb{C}^{N_T\times N_{R,kn}}$ have orthonormal columns and

$$\Sigma_{kn} = \mathrm{diag}\{\sigma_{kn}^{(1)},\ldots,\sigma_{kn}^{(N_{R,kn})}\}, \sigma_{kn}^{(1)} \geq \ldots \geq \sigma_{kn}^{(N_{R,kn})} \tag{14}$$

Next, we decompose $\mathbf{P}_{kn2}\mathbf{V}_{kn}$ as $\mathbf{P}_{kn2}\mathbf{V}_{kn} = \tilde{\mathbf{U}}_{kn}\mathbf{L}_{kn}$, where $\tilde{\mathbf{U}}_{kn} \in \mathbb{C}^{(M+N_T-N_{R,kn})\times(M+N_T-N_{R,kn})}$ is unitary and $\mathbf{L}_{kn} \in \mathbb{C}^{(M+N_T-N_{R,kn})\times N_{R,kn}}$ is lower triangular, which can be obtained in a similar manner as in the ordinary upper-triangular QRD. Since $\mathbf{P}_{kn}^H\mathbf{P}_{kn} = \mathbf{I}_{N_T}$, we can get

$$\begin{aligned}\mathbf{P}_{kn1}^H\mathbf{P}_{kn1} + \mathbf{P}_{kn2}^H\mathbf{P}_{kn2} &= \mathbf{I}_{N_T} \\ (\mathbf{U}_{kn}\Sigma_{kn}\mathbf{V}_{kn}^H)^H(\mathbf{U}_{kn}\Sigma_{kn}\mathbf{V}_{kn}^H) + (\tilde{\mathbf{U}}_{kn}\mathbf{L}_{kn}\mathbf{V}_{kn}^H)^H(\tilde{\mathbf{U}}_{kn}\mathbf{L}_{kn}\mathbf{V}_{kn}^H) &= \mathbf{I}_{N_T} \\ \Sigma_{kn}^H\Sigma_{kn} + \mathbf{L}_{kn}^H\mathbf{L}_{kn} &= \mathbf{I}_{N_{R,kn}}\end{aligned} \tag{15}$$

which implies

$$\mathbf{L}_{kn} = \mathrm{diag}(\tilde{\sigma}_{kn}^{(1)},\ldots,\tilde{\sigma}_{kn}^{(N_{R,kn})})$$
$$(\sigma_{kn}^{(i)})^2 + (\tilde{\sigma}_{kn}^{(i)})^2 = 1, 1 \le i \le N_{R,kn} \tag{16}$$

Organizing the above results as

$$\mathbf{K}_{kn} = \begin{bmatrix} \mathbf{P}_{kn1} \\ \mathbf{P}_{kn2} \end{bmatrix} \mathbf{R}_{kn} = \begin{bmatrix} \mathbf{U}_{kn} \Sigma_{kn} \mathbf{V}_{kn}^H \mathbf{R}_{kn} \\ \tilde{\mathbf{U}}_{kn} \mathbf{L}_{kn} \mathbf{V}_{kn}^H \mathbf{R}_{kn} \end{bmatrix} \tag{17}$$

We can get

$$\frac{(\mathbf{R}_{kn}^{-1}\mathbf{V}_{kn})^H \mathbf{H}_{kn,k}^H \mathbf{G}_{kn}^H \mathbf{G}_{kn} \mathbf{H}_{kn,k} (\mathbf{R}_{kn}^{-1}\mathbf{V}_{kn})}{(\mathbf{R}_{kn}^{-1}\mathbf{V}_{kn})^H (\tilde{\mathbf{H}}_{kn,k}^H \tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T})(\mathbf{R}_{kn}^{-1}\mathbf{V}_{kn})} = \frac{\Sigma_{kn}^H \Sigma_{kn}}{\mathbf{L}_{kn}^H \mathbf{L}_{kn}} \tag{18}$$

The precoding matrix $\mathbf{W}_{kn}$ is given as $\mathbf{W}_{kn} = \alpha_{kn}[\mathbf{R}_{kn}^{-1}\mathbf{V}_k]_{1:m}$, where α_{kn} is chosen to satisfy the power constraint. The decoding matrix for the kn-th user is then given as $\mathbf{D}_{kn} = \mathbf{W}_{kn}^H \mathbf{H}_{kn,k}^H \mathbf{G}_{kn}^H$ because $\mathbf{W}_{kn}^H \mathbf{H}_{kn,k}^H \mathbf{G}_{kn}^H \mathbf{G}_{kn} \mathbf{H}_{kn,k} \mathbf{W}_{kn}$ becomes a diagonal matrix. From (9), (18), it is easy to see that both λ_i and $(\sigma_{kn}^{(i)})^2 / (\tilde{\sigma}_{kn}^{(i)})^2$ are the generalized eigenvalues of the pair $\left\{ \mathbf{H}_{kn,k}^H \mathbf{G}_{kn}^H \mathbf{G}_{kn} \mathbf{H}_{kn,k}, \tilde{\mathbf{H}}_{kn,k}^H \tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T} \right\}$, so we can get

$$\lambda_i = (\sigma_{kn}^{(i)})^2 / (\tilde{\sigma}_{kn}^{(i)})^2, i = 1,2,\cdots,N_{R,kn} \tag{19}$$

with $\{\lambda_1,\lambda_2,\ldots,\lambda_{N_T}\}$ and $\{\sigma_{kn}^{(1)},\sigma_{kn}^{(2)},\ldots,\sigma_{kn}^{(N_{R,kn})}\}$ being sorted in descending order while $\{\tilde{\sigma}_{kn}^{(1)},\tilde{\sigma}_{kn}^{(2)},\ldots,\tilde{\sigma}_{kn}^{(N_{R,kn})}\}$ being sorted in ascending order. In the GSVD-ISP scheme, it has

$$\begin{aligned} \mathrm{SLNR}_{kn} &= \sum_{i=1}^{m} (\sigma_{kn}^{(i)})^2 \Big/ \sum_{i=1}^{m} (\tilde{\sigma}_{kn}^{(i)})^2 \\ &= \sum_{i=1}^{m} (\sigma_{kn}^{(i)})^2 \Big/ \sum_{i=1}^{m} (1 - (\sigma_{kn}^{(i)})^2) \end{aligned} \tag{20}$$

compared with (12), SLNR in GSVD-ISP scheme is somewhat smaller.

It is mentioned in [11] that the ultimate system performance is decided by the worst SINR of multiple data streams. Clearly, the decoded signal should take the form as

$$\tilde{\mathbf{S}}_{kn} = \mathbf{D}_{kn}\mathbf{G}_{kn}\mathbf{H}_{kn,k}\mathbf{W}_{kn}\mathbf{S}_{kn} + \mathbf{D}_{kn}\mathbf{G}_{kn}\mathbf{H}_{kn,k}\sum_{j=1, j\ne n}^{N} \mathbf{W}_{kj}\mathbf{S}_{kj} + \mathbf{D}_{kn}\mathbf{G}_{kn}\mathbf{Z}_{kn} \tag{21}$$

Thanks to diagonal form in (18), the covariance matrix of decoded inter-cell interference plus noise is given by

$$\mathbb{E}\left(\mathbf{D}_{kn}\mathbf{G}_{kn}\mathbf{Z}_{kn}\mathbf{Z}_{kn}^H\mathbf{G}_{kn}^H\mathbf{D}_{kn}^H\right) = \alpha_{kn}^2 diag((\sigma_{kn}^{(1)})^2,\ldots,(\sigma_{kn}^{(m)})^2) \tag{22}$$

Furthermore, it can be verified through numerical results that the CCI is much smaller than the inter-cell interference plus noise at high SNR. As such, the SINR on the l-th stream, η_l can be approximately calculated as

$$\eta_l = (\alpha_{kn}^4 (\sigma_{kn}^{(l)})^4) / (\alpha_{kn}^2 (\sigma_{kn}^{(l)})^2) = \alpha_{kn}^2 (\sigma_{kn}^{(l)})^2 \tag{23}$$

Then, for the l-th and l'-th stream with $l < l'$, the effective SINR margin between these two streams in the terms of decibel (dB) can be expressed as

$$\Delta_{l,l'} = 10\log_{10}(\eta_l / \eta_{l'}) = 10\log_{10}((\sigma_{kn}^{(l)})^2 / (\sigma_{kn}^{(l')})^2) \tag{24}$$

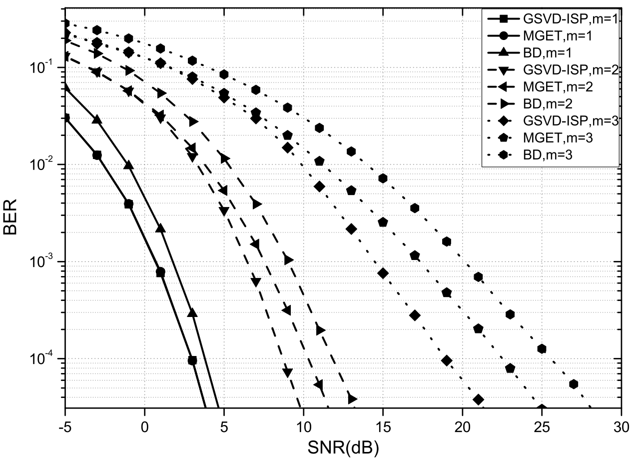

Fig.2 Uncoded BER versus SNR with INR = 0dB, for $N_T = 8$ transimit amtennas at BS and $K = 2$ users each with $N_{R,k1} = \cdots = N_{R,kN} = 3$ receive antennas

Following the same analysis, the margin of $\Delta'_{l,l'}$ for the MGET scheme can be analogously calculated as

$$\Delta'_{l,l'} = 10\log_{10}(\eta'_l / \eta'_{l'}) = 10\log_{10}(\lambda_l / \lambda_{l'}) \tag{25}$$

According to (19), we have $\lambda_l / \lambda_{l'} = (\sigma_{kn}^{(l)}\tilde{\sigma}_{kn}^{(l')})^2 / (\sigma_{kn}^{(l')}\tilde{\sigma}_{kn}^{(l)})^2$, with $\tilde{\sigma}_{kn}^{(l')} > \tilde{\sigma}_{kn}^{(l)}$. So it ensures that $\Delta_{l,l'} < \Delta'_{l,l'}$, in other words, the effective channel gains between the multiple streams are now less unbalanced and the system QoS can be improved.

On the other hand, the GSVD-ISP method avoids the matrix product and the inversion of $\tilde{\mathbf{H}}_{kn,k}^H \tilde{\mathbf{H}}_{kn,k} + N_{R,kn}\mathbf{I}_{N_T}$, resulting in computational complexities reduction.

IV. Simulation Results

Computer simulations are performed to evaluate the performance of GSVD-ISP approach. In all simulations, each user's data are modulated by quadrature phase shift keying (QPSK) signaling. We assume the channel matrix and the interference channel matrix are perfectly known both at the transmitter and the receiver.

Fig.2 compares the simulated bit error rate (BER) per user in a MU-MIMO systems with different system configurations. Here, GSVD-ISP denotes the proposed scheme, BD denotes the scheme proposed in [8] and MGET denotes the scheme proposed in [9]. From the BER curves versus the transmit SNR, it can be seen that GSVD-ISP achieves the same BER performance as MGET when data stream is one. For multiple data streams, GSVD-ISP outperforms the MGET with sizeable gains, for example, GSVD-ISP obtains about 3dB SNR gains around BER is 10-4 when there are 3 data streams. And no matter how many data streams are transmitted, GSVD-ISP and MGET have better performance than BD scheme.

Fig.3 and Fig.4 compare the sum-rate of proposed GSVD-ISP scheme and MGET, BD scheme in the presence of other cell interference with data stream number $m = 1$ and $m = 3$, respectively. We can observe from the figures when $m = 1$, GSVD-ISP has the same sum-rate as the MGET and

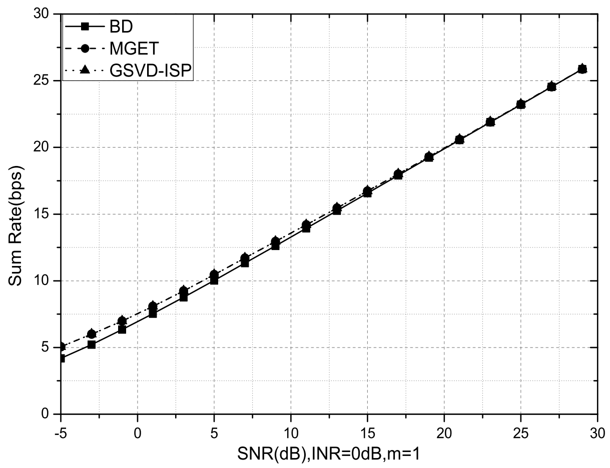

Fig.3 Average sum rate versus SNR with INR = 0dB, for $m=1$, $N_T=8$ antennas at BS and $K=2$ users each with $N_{R,k1}=\cdots=N_{R,kN}=3$ receive antennas

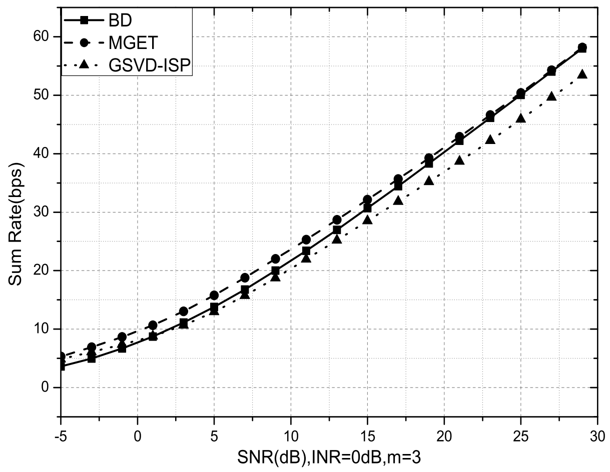

Fig.4 Average sum rate versus SNR with INR = 0dB, for $m=3$, $N_T=8$ antennas at BS and $K=2$ users each with $N_{R,k1}=\cdots=N_{R,kN}=3$ receive antennas

outperforms the BD scheme in the low SNR. In the high SNR, the sum-rate of BD scheme approaches the GSVD-ISP and MGET. While $m=3$, GSVD-ISP suffers more sum-rate loss comparing to that of the MGET and BD, but this loss is no more than 4bps. This indicates that GSVD-ISP is more suitable for edge UEs in MU-MIMO transmission.

V. CONCLUSIONS

In this paper, a new interference-aware precoding algorithm is proposed which is an enhancement to SLNR precoding scheme for downlink multi-stream MU-MIMO channel. SLNR is a promising criterion for linear precoder design in MU-MIMO broadcast channel that sends data to different users in the same cell. Unfortunately, it neglects ICI which may limits the performance of user at the edge of cell. MGET scheme take ICI into account, but the BER performance get worse when each user transmits multi-stream data simultaneously. The proposed GSVD-ISP scheme addresses the shortcoming of MGET method by using the inter-cell interference plus noise covariance matrix for interference suppression and applying GSVD algorithm to get the novel precoder. The performance of this method is evaluated. The results show the GSVD-ISP scheme keeps the same performance as MGET when data stream number $m=1$ and achieves considerable gains in BER performance for multi-stream transmission while maintaining almost the same achievable sum-rate, and it obtains better performance over traditional interference-aware BD algorithm for all conditions.

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