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A Leakage-based Nonlinear Precoder for the Multi-user Multi-stream MIMO Broadcast Channel

Yinghong Cao, Zhe Chen and Fuliang Yin
School of Information and Communication Engineering, Dalian University of Technology, Dalian, China

Abstract: In multi-user Multiple-Input Multiple-Output (MIMO) broadcast systems, it is essential to design the precoder for co-channel interference suppression. In this study, we propose a leakage-based nonlinear precoding scheme for the MIMO broadcast system, wherein each mobile user may receive multiple data streams. In this proposed precoding scheme, the Inter-User Interference (IUI) is minimized by maximizing the Signal-to-Leakage-plus-Noise Ratio (SLNR), and the Inter-Stream Interference (ISI) is mitigated by extending the Tomlinson-Harashima Precoding (THP) algorithm into the stream domain. Since both the IUI and the ISI are mitigated at the Base Station (BS) transmitter, this precoder achieves a very simple receiver at each user, and only a power scaling factor needs to be additionally transmitted to the receiver. Moreover, it is also proved that this proposed precoder supports the multiple data streams within one user equally. Simulation results demonstrate that the proposed scheme can eliminate the interference efficiently and achieve better Bit Error Rate (BER) performance.

Key words: Multi-user MIMO, multi-stream transmission, interference cancellation, nonlinear precoding, broadcast channel, leakage

INTRODUCTION

Multi-user multiple-input multiple-output (MU-MIMO) systems have attracted considerable interest due to the potential of provide large system capacity and high spectral efficiency in recent years (Goldsmith *et al*., 2003; Yu and Cioffi, 2004; Hassibi and Sharif, 2007). In the broadcast channel of these MU-MIMO systems, a Base Station (BS) communicates with multiple co-channel mobile users simultaneously, and thereby a high system throughput is achieved. This broadcast system is also known as the downlink of MU-MIMO system. Since the transmitted signal intends for a particular user also acts as interference to the other users, the main challenge for this system is the mitigation of this Co-Channel Interference (CCI) to ensure the simultaneous transmission of independent messages to different users (Spencer *et al*., 2004a). However, due to the lack of coordination among the decentralized mobile users, the CCI suppression is hard to handle at the receiver side. Furthermore, motivated by the expectation of cheap mobile terminals with low power consumption, the systems with complex signal processing performed at the BS transmitter is preferred (Gibbard and Sesay, 1999). Therefore, it is essential to design the precoding scheme at the BS transmitter for CCI suppression.

Most research on multi-user downlink precoding has tended to assume a single stream transmission to each user (Spencer *et al*., 2004a; Schubert and Boche, 2004; Windpassinger *et al*., 2004; Tarighat *et al*., 2005). This assumption, however, restricts the possibility of gains from additional antennas at the mobile terminals. In next generation wireless communication systems, it is possible to employ antenna arrays at the mobile terminals. This allows the mobile users to receive multiple spatially multiplexed data streams and thereby results in very high data rates (Stankovic and Haardt, 2008; Cheng *et al*., 2010). In the meantime, however, these simultaneously transmitted data streams to a particular user introduce additional Inter-Stream Interference (ISI) at the receiver input. In this scenario, the system CCI contains the interference between different users (IUI) and the interference among the spatially multiplexed streams direct to a certain user (ISI). In order to recover the transmitted data streams, it is essential to mitigate both the Inter-User Interference (IUI) and the ISI at the transmitter. Therefore, compared to the single stream MU-MIMO system, the precoder design for multi-stream MU-MIMO system is more challenging (Liu and Krzymien, 2008). In this study, we concentrate on the multi-user precoder design for the MIMO broadcast channel that allows multi-stream transmission per user.

Corresponding Author: Yinghong Cao, School of Information and Communication Engineering, Dalian University of Technology, Dalian City, Liaoning Province, People Republic of China Tel/Fax: +86-411-8470-7049

One usual linear precoding algorithm that supports multi-stream transmission is Block Diagonalization (BD) (Spencer *et al.*, 2004b). At the expense of dimensionality constraint, this algorithm ensures zero IUI and ISI at the receiver of each user. To perform symbol detection, however, conventional BD requires global Channel State Information (CSI) at each receiver. Due to the lack of coordination among the spatially separated mobiles, additional-transmitted information is needed to find the decoding matrix at every receiver. This is a limitation for BD. An alternative linear approach is to design the precoding matrix by maximizing the Signal-to-Leakage-plus-Noise Ratio (SLNR) (Sadek *et al.*, 2007; Park *et al.*, 2009; Cheng *et al.*, 2010). This leakage based multi-user precoder relaxes the dimensionality constraint in BD, and carries out an analytical closed-form solution for the precoding matrix. However, the precoding matrix, as the additional-transmitted information, is still required at each receiver to decouple the multiple streams. For the linear precoding systems employing original SLNR maximization and the BD algorithm, the additional-transmitted information are used to perform equalization at the receiver. This linear equalization makes the system suffer from noise enhancement, and results in poor power efficiency. To avoid noise enhancement at the decoders and reduce system cost, simple receivers with little additional-transmitted information are preferred.

Nonlinear precoding algorithms can achieve better performance (Windpassinger *et al.*, 2004; Liu and Krzymien, 2008). Since no cooperation among the spatially separated receivers is possible in the multi-user MIMO broadcast system, the Tomlinson-Harashima Precoding (THP) algorithms, which is applicable to broadcast transmission, should move both the backward filter and the forward filter to the transmitter. This architecture enables very simple receivers and the noise enhancement at the receiver is avoided. In general, according to the positions of the diagonal scaling filter, there are two basic THP structures in downlink multi-user MIMO systems (Huang *et al.*, 2008). The diagonal scaling filter decentralized at the receivers (Windpassinger *et al.*, 2004) and the diagonal scaling filter centralized at the transmitter (Windpassinger, 2004). Under a dimensionality constraint, these THP-based solutions achieve complete equalization at the transmitter. However, the THP algorithm incurs high complexity due to the nonlinear nature and the combinatorial problem of user order selection. For a large number of receivers, the complexity at the transmitter becomes very high.

In this study, a leakage-based nonlinear precoder is proposed for the multi-stream MIMO broadcast channel. We extend the THP algorithm to the stream domain; it is performed per user to eliminate the interference between the data streams directed to that user. The interference between users is minimized based on SLNR maximization. Since the THP structure with diagonal scaling filter centralized at the transmitter (Windpassinger, 2004) is considered during the precoder design, this proposed precoding scheme achieves a very simple receiver at each user and only the information of a power scaling factor is needed at the receiver. Unlike the conventional THP-based nonlinear precoding techniques (Windpassinger *et al.*, 2004; Doostnejad *et al.*, 2005; Stankovic and Haardt, 2008; Windpassinger, 2004; Liu and Krzymien, 2008), wherein the THP is performed in user domain, the implementation of THP in this proposed precoder requires much smaller dimension, and the dimensionality constraint is also relaxed. Moreover, we also prove that our scheme supports the data steams within one user equally. Thereby, our scheme overcomes the inherent drawback of the original SLNR maximization scheme. Simulations demonstrate the performance of the proposed scheme.

MULTI-USER MIMO BROADCAST SYSTEM MODEL

Consider a MIMO broadcast channel with K decentralized users and a single Base Station (BS). The BS has N transmit antennas, and user k is equipped with M_k receive antennas.

For the case of multi-stream transmission, let $\mathbf{s}_k = [s_k(1), s_k(2), \ldots, s_k(L_k)]^T$ denotes the data vector transmitted to the k th user, where $L_k (\le M_k)$ is the number of streams for user k and $(\bullet)^T$ denotes the transpose operator. The modulated symbols in $\mathbf{s}_k$ are assumed to be independent and have the variance σ_s^2. For notational simplicity, the time index is dropped.

The channel from the BS to user k is assumed to be flat fading and denoted by a $M_k \times N$ matrix H_k. The elements of H_k are samples of independently and identically distributed (i.i.d.) complex Gaussian process with zero mean and unitary variance.

At the kth user, the received signal vector is given by:

$$y_k = H_k x_k + H_k \sum_{j=1, j\neq k}^{K} x_j + n_k \tag{1}$$

where, x_k is the N×1 transmitted vector corresponding to user k, which is generated by precoding the data vector s_k; n_k is the $M_k \times 1$ additive complex white Gaussian noise (AWGN) vector, whose elements are i.i.d. samples distributed as $CN(0, \sigma_n^2)$.

LEAKAGE-BASED PRECODER FOR MULTI-STREAM MIMO BROADCAST SYSTEM

For the multi-stream MIMO broadcast system, a multi-user precoding algorithm is designed to combat the IUI between users and to decouple the multiple streams within each user.

Original SLNR maximization algorithm: In (Sadek *et al*., 2007), a linear precoder based on Signal to Leakage-plus-Noise Ratio (SLNR) maximization is presented for the multi-stream MIMO broadcast channel.

At the transmitter, the data vector s_i is multiplied by the precoding matrix W_i to generate the transmitted vector x_i, i.e. $x_2 = W_2s_2$. To suppress the IUI, the $N\times L_i$ precoding matrix W_i is chosen to maximize the SLNR of user i = 1, ..., K. The total power leaked from user i to all the other users is defined as $\sum_{k=1,k\neq i}^{K} \|H_k W_i\|_F^2$ and then the SLNR of user i is defined as:

$$\mathrm{SLNR}_i = \frac{\|H_i W_i\|_F^2}{\sum\limits_{k=1,k\neq i}^{K} \|H_k W_i\|_F^2 + \frac{M_i\sigma_n^2}{\sigma_s^2}} = \frac{\mathrm{Tr}(W_i^H H_i^H H_i W_i)}{\mathrm{Tr}\left[W_i^H \left(\frac{M_i\sigma_n^2}{L_i\sigma_s^2} I_N + \tilde{H}_i^H \tilde{H}_i\right) W_i\right]} \tag{2}$$

where, $\tilde{H}_i = [H_1^H \cdots H_{i-1}^H\ H_{i+1}^H \cdots H_K^H]^H$, $(\bullet)^H$ denotes the conjugate transpose operator, Tr (•) stands for trace, $\|\bullet\|_F$ represents the Frobenius norm, and I_N stands for an $N\times N$ identity matrix. To perform power control, the precoding matrix W_i should ensure the constraint $\mathrm{Tr}(W_i^H W_i) = L_i$.

At the receiver, a matched filter is used to decode the signal vector, i.e. the decoded signal is given by:

$$\hat{s}_i = \frac{W_i^H H_i^H}{L_i \|H_i W_i\|_F} y_i \tag{3}$$

In order to decouple the multiple streams sent to a given user, the following constraint should be satisfied while designing the precoder:

$$W_i^H H_i^H H_i W_i = D_i, \quad i = 1, \ldots, K \tag{4}$$

where D_i is a diagonal matrix.

Since, $\frac{M_i\sigma_n^2}{L_i\sigma_s^2} I_N + \tilde{H}_i^H \tilde{H}_i$ is symmetric positive definite, there exists a nonsingular matrix $T_i \in \mathbb{C}^{N\times N}$, which satisfies:

$$\begin{cases} T_i^H H_i^H H_i T_i = \Lambda_i \\ T_i^H (\frac{M_i\sigma_n^2}{L_i\sigma_s^2} I_N + \tilde{H}_i^H \tilde{H}_i) T_i = I_N \end{cases} \tag{5}$$

where, Λ_i is $N\times N$ diagonal matrix with nonnegative entries.

By means of the character of generalized eigenvalue decomposition and singular value decomposition, the optimal W_i, which maximizes the SLNR_i (2) and satisfies the constraint (4), is given by:

$$W_i^{SLNR} = \gamma_i T_i [I_{L_i} \quad 0]^H \tag{6}$$

where, γ_i is used to ensure the power constraint $\mathrm{Tr}(W_i^H W_i) = L_i$ and the columns of T_i are the generalized eigenvectors of $(H_i^H H_i, (\frac{M_i\sigma_n^2}{L_i\sigma_s^2} I_N + \tilde{H}_i^H \tilde{H}_i))$ that corresponding to the L_i maximum generalized eigenvalues.

SLNR is a promising criterion for linear precoder design in multi-user MIMO broadcast system (Park *et al*., 2009; Cheng *et al*., 2010). It decouples the precoder design problem and makes the analytical closed-form solution available. This original SLNR maximization algorithm assumes a perfect knowledge of CSI at the BS. To decouple the multiple streams, the knowledge of H_i and W_2/i should be available at the receiver of user i. Since no cooperation among the mobiles is possible, the $N\times L_i$ precoding matrix W_i needs to be additionally transmitted to user i. The main challenge with this scheme is that the use of matched filter at each receiver limits the BER performance due to noise enhancement, and brings in additional system planning to find the decoding matrix at every receiver. Moreover, from the Eq. 3-6, it is easy to see that the sub-streams within one user have different SINRs. This imbalance among the sub-streams can be seen as an inherent drawback of the original SLNR precoing scheme, since the overall performance of a user with multiple data streams is limited by the stream with worst channel condition (Cheng *et al*., 2010).

The proposed leakage-based nonlinear algorithm

Precoder design: In this section, we propose a leakage-based nonlinear precoder for the multi-stream MIMO broadcast system. Assuming perfect knowledge of CSI at the BS, this proposed precoder mitigates both the IUI and the ISI at the transmitter. Therefore, a very simple receiver is achieved at every user, and only a power scaling factor needs to be additionally transmitted at the transmitter.

Since the THP algorithm is imposed to operate in the stream domain, this proposed precoding scheme encodes the data streams of each user independently at the transmitter. Therefore, the realization of parallel processing at the transmitter is available. The proposed precoding system is shown in Fig. 1.

At the transmitter, to separate the data streams within one user, the nonlinear THP algorithm is introduced. Let s_i denotes the modulated data vector for user I.

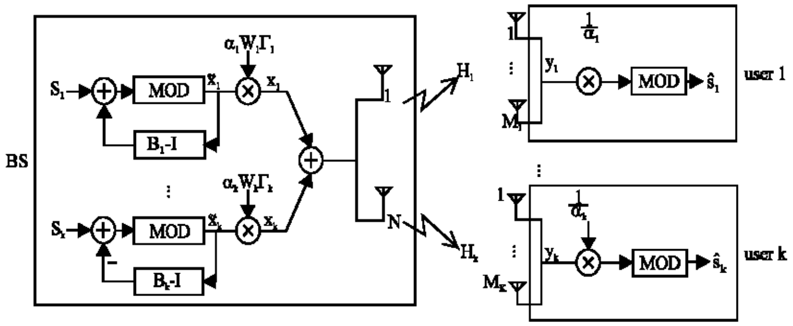

Fig. 1: The proposed precoding system for multi-stream MIMO broadcast channel

The symbols of s_i pass through the backward filter B_i and the modulo operator MOD (•) iteratively. Then a symbol vector is generated, i.e. the l th element of vector is given by:

$$\tilde{x}_i(l) = \mathrm{MOD}[s_i(l) - \sum_{j=1}^{l-1}[B_i]_{lj}\tilde{x}_i(j)] \qquad (7)$$

where s_i (l) denotes the l th element of vector s_i,$[B_i]_{lj}$ denotes the (l, j) th element of B_i. The modulo operator is introduced to reduce the signal power increased by B_i. The modulo operator for a complex variable a is defined as:

$$\mathrm{MOD}(a) = a - A\left\lfloor (\mathrm{Re}(a) + \frac{A}{2}) / A \right\rfloor - jA\left\lfloor (\mathrm{Im}(a) + \frac{A}{2}) / A \right\rfloor \qquad (8)$$

where $\lfloor \bullet \rfloor$ is the floor operator, which gives the integer smaller than or equal to the argument; Re (a) denotes the real part of a, and Im (a) denotes the image part of a; the constant A is determined by the modulation signal constellation used.

At the transmitter, the output vector $\tilde{x}_i$ from the feedback section is subsequently multiplied by a precoding matrix W_i before the transmission over channel. In this proposed precoder, we design the precoding matrix W_i as a cascade of two matrices G_i and F_i, i.e., $W_i = G_iF_i$. The matrix G_i is designed to suppress the IUI, and the matrix F_i works as the forward filter matrix of THP for the mitigation of ISI.

To perform THP over the data streams within one user, the processing matrices B_i, F_i and Γ_i directly depend on the effective channel matrix, which is considered as:

$$H_{eff,i} = H_i G_i \qquad (9)$$

Thereby, the N×L_i matrix G_i, which maximizes the SLNR of user, should be carried out firstly. With the backward filter B_i and the forward filter F_i deployed at the transmitter, the SLNR of user i can be written as:

$$\mathrm{SLNR}_i = \frac{\|H_i W_i \tilde{x}_i\|_F^2}{\sum_{k=1,k\neq i}^{K}\|H_k W_i \tilde{x}_i\|_F^2 + M_i\sigma_n^2} \qquad (10)$$

Consider the output vector $\tilde{x}_i$ from the feedback section. As shown in Eq. 7, using THP, the symbols $\tilde{x}_i$ of is no longer taken from the signal constellation. The values of these symbols are (approximately) uniformly distributed over the boundary region of the signal constellation. This leads to a somewhat increased transmit power. This increment is negligible for moderate modulation sizes, because it decreases rapidly as the modulation size increases and vanishes as the modulation size goes to infinity. For square M-QAM constellations, this increment is found to be $\frac{M}{M-1}$. In Fig. 1, this slight transmit power increase is not compensated, however, in our simulations we do take this into account. Therefore, it can be considered that the symbols of vector $\tilde{x}_i$ have the same power as that in s_i. Moreover, the symbols of $\tilde{x}_i$ can be assumed to be mutually uncorrelated (Windpassinger *et al*., 2004). Thus, the SLNR expression in (10) can be simplified as:

$$\mathrm{SLNR}_i = \frac{\|H_i G_i F_i\|_F^2}{\sum_{k=1,k\neq i}^{K}\|H_k G_i F_i\|_F^2 + \frac{M_i\sigma_n^2}{\sigma_s^2}} \qquad (11)$$

According to THP algorithm, the forward matrix F_i is a unitary matrix. Then Eq. 11 can be written as:

$$\mathrm{SLNR}_i = \frac{\mathrm{Tr}(G_i^H H_i^H H_i G_i)}{\mathrm{Tr}[G_i^H(\frac{M_i\sigma_n^2}{L_i\sigma_s^2} I_N + \tilde{H}_i^H \tilde{H}_i)G_i]} \qquad (12)$$

It is obvious that the forward filter matrix F_i of THP has no effect on SLNR_i and the SLNR_i in Eq. 12 has the same expression as that in the original SLNR maximization algorithm. Therefore, the SLNR_i optimal precoding matrix G_i which maximizes the Eq. 12 can also be carried out by Eq. 6.

Since simple receivers with little additional-transmitted information are preferred, the diagonal scaling matrix Γ_i of THP is also located at the transmitter in our precoding scheme. It should be noted that, placing Γ_i at the transmitter will affect the SLNR of user i, however, this influence to SLNR_i will not considered in our scheme. This is because that, the causality between Γ_i and G_i makes it difficult to find the optimal solutions based on SLNR maximization. Then, the processing matrices for THP can be obtained by performing LQ decomposition (Windpassinger *et al.*, 2004) on the effective channel matrix $H_{\text{eff},i}$, i.e.:

$$H_{\text{eff},i} = S_i Q_i^H \tag{13}$$

where, S_i is a lower triangular matrix, Q_i is a unitary matrix. And:

$$\Gamma_i = \text{diag}([S_i]_{11}^{-1}, [S_i]_{22}^{-1}, \cdots, [S_i]_{L_iL_i}^{-1}) \tag{14}$$

$$B_i = S_i \Gamma_i \tag{15}$$

$$F_i = Q_i \tag{16}$$

where, $[S_i]_{mn}$ denotes the element at the m row and the n column of S_i.

With all these processing matrices placed at the transmitter, complete transmitter side equalization is achieved in our scheme, and this enables very simple receivers at every user. At the receiver, a modulo operation MOD (•) is applied to remove the effect of the modulo operation at the transmitter. To keep transmit power constant, a scaling factor:

$$\alpha_i = \frac{\sqrt{L_i}}{\| W_i \Gamma_i \|_F} \tag{17}$$

is required at the transmitter, and this gain is compensated at the receiver correspondingly.

In this proposed precoding scheme, both the IUI and the AWGN is pre-eliminated at the transmitter based on SLNR maximization. Specially, the multiple sub-streams within one user are also pre-decoupled at the transmitter by performing the THP algorithm in stream domain. Then, the additional-transmitted information in this scheme is decreased to one real scalar Eq. 17 for every user. At each receiver, the residual IUI and noise interference are truncated into a fundamental region due to the nonlinear modulo operation. Thereby, the noise enhancement suffered in linear precoding schemes is avoided.

Performace discussion: In this proposed leakage-based nonlinear precoding scheme, we extend the THP algorithm to the stream domain, the THP algorithm is therefore implemented with a much smaller dimension, and the dimensionality constraint to the system is also relaxed. In conventional THP-based precoding schemes, THP is performed within user domain to ensure the transmission of $\sum_{i=1}^{K} L_i$ independent data streams, which results in the dimensionality constraint of $N \geq \sum_{i=1}^{K} L_i$ and an implementation of $\sum_{i=1}^{K} L_i$ dimension THP. However, as for this proposed precoding system, the dimensionality constraint is relaxed to $N \geq \max(L_i, I = 1, \ldots, K)$ and the THP implementation dimension is reduced to L_i.

Furthermore, the proposed precoding scheme supports the multiple sub-streams within one user equally in contrast to the original SLNR maximization algorithm. At the decoder, the scalar weight α_i is applied at all data streams within user i. It is proved as following that the sub-streams within one user have the identical SINRs.

Consider the proposed precoding system, the transmitted signal is given by:

$$x = \sum_{j=1}^{K} \alpha_j W_j \Gamma_j \tilde{x}_j \tag{18}$$

Clearly, as an input signal to the modulo operator at user i, the received signal after scaling should take the form:

$$y_i' = \frac{1}{\alpha_i}(H_i \sum_{j=1}^{K} \alpha_j W_j \Gamma_j \tilde{x}_j) + n_i) \tag{19}$$

For user i the output vector $\tilde{x}_i$ from the feedback section satisfies that $\tilde{x}_i = B_i^{-1}(s_i + p_i)$, where $\mathbf{p}_i$ is the modulo factor vector (Windpassinger *et al.*, 2004). Applying Eq. 9 and 13-16, we obtain:

$$\begin{aligned} y_i' &= s_i + p_i + H_i \sum_{j=1, j\neq i}^{K} \frac{\alpha_j}{\alpha_i} W_j \Gamma_j \tilde{x}_j + \frac{1}{\alpha_i} n_i \\ &= s_i + p_i + \tilde{I}_i + \tilde{n}_i \end{aligned} \tag{20}$$

where:

$$\tilde{I}_i = H_i \sum_{j=1, j\neq i}^{K} \frac{\alpha_j}{\alpha_i} W_j \Gamma_j \tilde{x}_j$$

is the residual interference in the received signal of user $\tilde{n}_i = \frac{1}{\alpha_i} n_i$ i, is the received noise.

Since the modulo factor vector $\mathbf{p}_i$ in Eq. 20 will be removed by passing $\mathbf{y}'_i$ through the modulo operator, $s_i + p_i$ in (20) can be seen as the desired signal for user i. Then, it is clear that the desired signal power for each sub-stream within user i is identical.

The power of the residual interference and the received noise for each sub-stream of user are further investigated as following.

Let $\mathbf{h}_{i,1}$ represents the l th row of matrix H_i, and then the power of the residual interference in the l th sub-stream of user i is given by:

$$E\{|\tilde{I}_i(l)|^2\} = E\{|h_{i,l} \sum_{j=1, j\neq i}^{K} \frac{\alpha_j}{\alpha_i} W_j \Gamma_j \tilde{x}_j |^2\} \tag{21}$$

where, E{•} stands for expectation, |•|stands for norm operation. Since the symbols of vector $\tilde{x}_i$ has the same power as that in $\mathbf{s}_i$ and they are assumed to be mutually uncorrelated (Windpassinger *et al.*, 2004), Eq. 21 can be written as:

$$E\{|\tilde{I}_i(l)|^2\} = \frac{\sigma_s^2}{\alpha_i^2} \sum_{j=1, j\neq i}^{K} \alpha_j^2 \mathrm{Tr}(\Gamma_j^2 W_j^H h_{i,l}^H h_{i.l} W_j) \tag{22}$$

Applying the Singular Value Decomposition (SVD) to the channel matrix of user i, i.e., $H_i = U_i \Sigma_i V_i$ we have:

$$h_{i,1} = u_{i,1} \Sigma_i V_i \tag{23}$$

where, $u_{i,1}$ is the l th row of matrix U_i. Then Eq. 22 can be written as:

$$E\{|\tilde{I}_i(l)|^2\} = \frac{\sigma_s^2}{\alpha_i^2} \sum_{j=1, j\neq i}^{K} \alpha_j^2 \mathrm{Tr}(\Gamma_j^2 W_j^H V_i^H \sum\nolimits_i^2 V_i W_j) \tag{24}$$

Then, it is easy to see that each sub-stream of user i has the same power of the residual interference.

Moreover, from the system model, n_i is the additive complex white Gaussian noise vector, whose elements are i.i.d. samples distributed as CN $(0, \sigma^2_n)$. Therefore, the power of the received noise $\tilde{n}_i(l)$ for the l th sub-stream of user i is given by:

$$E\{|\tilde{n}_i(l)|^2\} = \frac{\sigma_n^2}{\alpha_i^2} \tag{25}$$

Thus, from Eq. 20, 24 and 25, we ensure that all the sub-streams within one user have the same SINRs; the drawback of the original SLNR maximization precoding scheme is overcame.

SIMULATION RESULTS

Here, simulation results are presented to demonstrate the performance of the proposed leakage-based nonlinear precoder.

Let $(N, M_l ,..., M_k)$ denotes a multi-user MIMO system with a base station and K users, where the base station employs N transmit antennas and the kth user is equipped with M_k receive antennas. In view of the demand of high transmission rates, we focus on high spectral efficiencies. Thus the number of data streams transmitted to user k is assumed to be equal to M_k. Without loss of generality, the same number of receive antennas is assumed for all users. A quasi-static flat fading channel is assumed in this multi-user MIMO system. The channel matrix is known at the transmitter. In the simulations, the channel matrix is the same for every 100 symbols, and alternate independently during different periods. The simulation results are averaged over 10000 channel realizations for BER curves. The range of SNR considered in our simulation is between 0 dB and 30 dB. The SNR is the ratio of the average power of the precoded symbols to noise variance, i.e. the SNR of user i is defined as:

$$\mathrm{SNR}_i = \frac{E\{\|x_i\|^2\}}{M_i \sigma_n^2} \tag{26}$$

Consider a 3-user system with 4 receive-antennas per user and 12 transmit antennas. Figure 2 shows the performance comparison of the proposed leakage-based nonlinear precoder, the original SLNR maximization approach (Sadek *et al.*, 2007), the conventional BD algorithm without power allocation (Spencer *et al.*, 2004b) and the THP-based precoding algorithms in (Windpassinger, 2004). 16-QAM or 16-PSK modulation with Gray mapping is used throughout the simulation. The BER in the figure is the average over all users.

From the simulation results shown in Fig. 2, it can be seen that, with the same antenna configuration and data rate, the proposed precoder outperforms the linear precoding schemes and the THP algorithms without ordering or with sub-optimal ordering.

The original SLNR maximization approach performs poorly with M-QAM modulation. Since the use of matched filter at each receiver results in noise and residual IUI enhancement, whereas the detection of QAM symbols is sensitive to amplitude. The proposed precoder performs significantly better than the original SLNR maximization and the BD algorithm. With a simple receiver, this proposed precoder avoids the noise enhancement suffered in the original SLNR maximization and the BD algorithm.

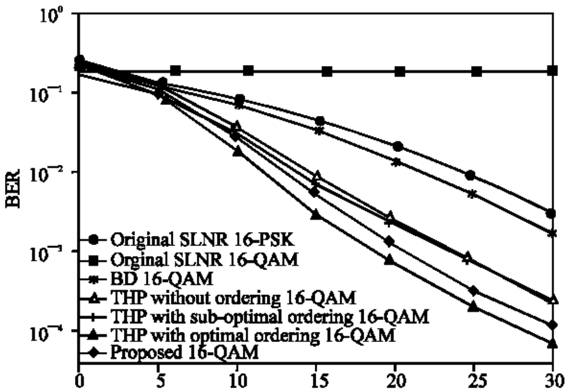

Fig. 2: Performance comparison of the proposed leakage-based nonlinear precoder, original SLNR maximization, BD, THP without ordering (Windpassinger, 2004), THP with sub-optimal ordering (Doostnejad *et al.*, 2005) and THP with optimal ordering in (12, 4, 4, 4) system

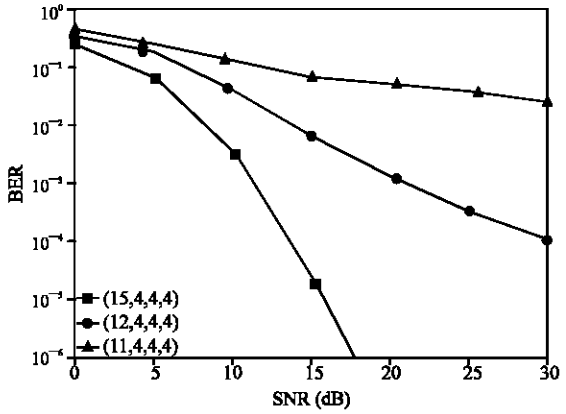

Fig. 3: BER performance of the proposed precoder in a 3-user system with 4 receive antennas per user and a varying number of transmit antennas

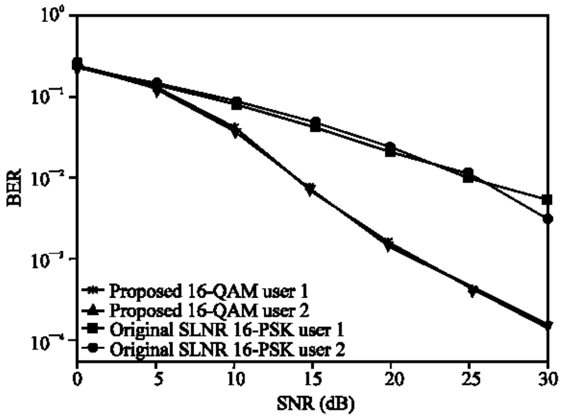

Fig. 4: BER performance of every user in (12, 6, 6) system with the proposed precoder, 16-QAM, and the original SLNR maximization, 16-PSK

The performance of the proposed precoder is also better than the nonlinear THP algorithm without ordering and the THP with sub-optimal ordering presented (Doostnejad *et al.*, 2005). From Fig. 2, it can be observed that the performance of the conventional THP algorithm greatly depends on the user order selection. With THP algorithm, system performance can be significantly improved by ordering the channel matrices of different mobiles properly (Doostnejad *et al.*, 2005). Although the THP-based precoding system with optimal ordering outperforms the other methods, the computational complexity of this method is much higher. While finding the optimal ordering, the THP-based nonlinear precoding algorithm (Windpassinger, 2004) has to be examined over K! rearrangements, which is not practical. For a large number of receivers, the complexity at the transmitter becomes very high. The sub-optimal ordering method presented (Doostnejad *et al.*, 2005) is a low complexity solution; however, the performance with this sub-optimal ordering method improves slightly than that without ordering. From Fig. 2, the proposed precoder achieves satisfactory performance with a greatly reduced computational complexity compared to the optimal ordered THP algorithm. Although the ordering problem is not considered, the proposed precoder performs much closer to the optimal ordered THP than the THP without ordering and with sub-optimal ordering. Since considerable performance improvement is achieved, the proposed precoder is promising.

In Fig. 3-5, we concentrate on the performance of the proposed leakage-based nonlinear precoder.

From Fig. 3, the performance of the proposed scheme improves significantly with the increase of transmit antennas. For (11, 4, 4, 4) system, both the BD algorithm and the THP-based precoding algorithms can not work due to the dimensionality constraint. Based on SLNR maximization, this proposed precoding scheme relaxes the dimensionality constraint; whereas it performs flat in the high SNR region due to the fact that the total number of data streams has exceeded the number of transmit antennas.

In Fig. 4 and 5, we examine the performance of each user within the system and the performance of each sub-stream directed to a given user. The proposed precoder is simulated under a (12, 6, 6) system with 16-QAM. It is shown in Fig. 5 that, as proven in the performance discussion section, this proposed algorithm gains uniform performance in stream domain. This merit

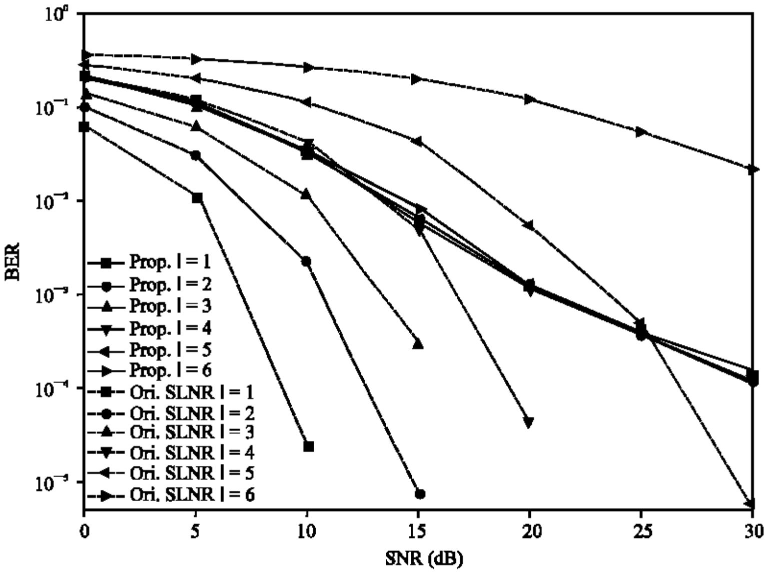

Fig. 5: BER performance of every sub-stream for user 1 in (12, 6, 6) system with the proposed precoder, 16-QAM and the original SLNR maximization, 16-PSK

guarantees a better performance of each user within this system. Moreover, from Fig. 3, this proposed algorithm can achieve equivalent performance between users within the system.

For comparison, the performance of the original SLNR maximization approach is also presented in Fig. 4 and 5. The (12, 6, 6) system with 16-PSK is used. As shown in Fig. 5, with the original SLNR precoding scheme, the sub-stream gains within one user are severely unbalanced. Thus, the overall performance of a user, given in Fig. 4, is dramatically limited by the stream with worst channel condition.

CONCLUSION

A leakage-based nonlinear precoding scheme was proposed for the multi-stream MIMO broadcast channel. In this precoding scheme, the nonlinear THP algorithm was extended to operate in stream domain, both the IUI and the ISI were mitigated at the transmitter, the additional-transmitted information was decreased to a scaling factor, and the noise enhancement was avoided with a very simple receiver. Simulation results shown that, without order selection, this proposed precoding scheme achieved satisfactory performance with relative lower computational complexity. Therefore, this proposed precoder is promising for high rate transmission.

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