Blockwise-Lattice-Reduction Aided Precoders for Multiuser MIMO with Clusters of Correlated Users

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Abstract—This paper presents a new class of Blockwise-Lattice-Reduction (BLR) aided Tomlinson-Harashima precoders (BLR-THPs) for multiuser multiple-input-multiple-output (MU-MIMO) downlink communications with clusters of correlated channels. The proposed BLR-THPs take the clustering information into account by first decoupling the overall downlink channel into multiple subchannels (one for each cluster) before applying the lattice-reduction technique to each subchannel. In comparison to the conventional LR-THPs, the proposed BLR-THPs require much lower complexity as the computationally intensive LR procedure in the LR-THPs is now effectively approximated by multiple LR procedures with much lower dimensionality. We present a number of new precoders that belong to this class and then compared them with the existing THPs with or without LR through extensive computer simulations.

Index Terms—MU-MIMO, lattice-reduction, precoder, leakage.

I. INTRODUCTION

In multi-user (MU) multiple-input multiple-output (MIMO) communications, a base station (BS) equipped with multiple antennas simultaneously communicates with a number of mobile stations (MS’s). As the signals are allowed to occupy the same frequency band and time slot, signal of different user naturally interferes with each other and results in the co-channel interference (CCI). Since the MS’s are all geometrically separated and no user collaboration is possible in general, it is necessary for the BS to apply some precoding schemes so that the CCI at each MS can be effectively suppressed [1]–[5]. For scenarios where the CCI is severe, lattice-reduction (LR) aided schemes [6]–[9] have shown to be effective in improving the error rate performance at the expense of increased computational complexity.

In some practical scenarios, the MS’s tend to be clustered around some hot-spots of the cities such as malls or auditorium, in which case the inter-cluster CCI is usually much higher than the intra-cluster CCI. This prior clustering information can be exploited to mitigate the complexity of LR-aided precoders as is first shown by [10], in which a LR-aided precoding scheme combined with generalized eigenvalue decomposition (GEVD) based spatial division multiplexing (LR-GEVD-SDM) was proposed. The LR-GEVD-SDM has shown to require much lower computational complexity in comparison to the LR-aided zero-forcing (ZF) THP with only slight performance degradation.

In this paper, we first present our BLR-SLNR-THP design, which subsumes the LR-GEVD-SDM [10] as a special case under the ZF criterion. Then we propose a new BLR-SSLNR-THP which consistently outperform their BLR-SLNR-THP counterparts. Computationally efficient inter-cluster ordering algorithm can be derived to further improve the error rate performance of the BLR-SLNR-THP as is shown by the computer simulations.

Notations: Throughout this paper, matrices and vectors are set in boldface, with uppercase letters for matrices and lowercase letters for vectors. The superscripts $^T$, $^H$, $^{-1}$ and $^†$ denote the transpose, conjugate transpose, inverse, and pseudo-inverse of a matrix, respectively. The operator $\| \cdot \|$ denotes the 2-norm of a vector, while $\| \cdot \|_F$ denotes the Frobenius norm of a matrix. tr{\cdot} and det{\cdot} represent the trace and determinant of a matrix, respectively. The operator diag{x_1,...,x_K} denotes the diagonal matrix with diagonal elements {x_1,...,x_K}, while blkdiag{X_1,X_2,...,X_K} denotes the block diagonal matrix with submatrices X_1, X_2, ..., X_K along the diagonal. I_N is the $N \times N$ identity matrix.

II. CHANNEL MODEL

Consider a MU-MIMO system where the BS simultaneously communicates with $N$ single-antenna mobile MS’s over a downlink channel via its $N_T \geq N$ transmit antennas. Without loss of generality, we assume the MS’s in the system has been divided into $K$ clusters (CL’s) with the $k$th cluster containing $N_k$ MS’s, for all $k = 1, ..., K$. Under non-line-of-sight (NLOS) propagation, the downlink channel for the $k$th cluster (CL_k) follows the semi-correlated Rayleigh flat fading model [11, 12] $H_k = \Psi_k A_k$, where $\Psi_k \in \mathbb{C}^{N_k \times D_k}$ consists of elements of independent and identically distributed (i.i.d.), circularly symmetric complex Gaussian random variables with zero-means and unit variances. $A_k \in \mathbb{C}^{D_k \times N_T}$ is the steering matrix corresponding to the DODs of the $k$th cluster, which can be expressed as $A_k = \frac{1}{\sqrt{D_k}} [a(\theta_{k,1}), ..., a(\theta_{k,D_k})]^T$ with $a(\theta_{k,\ell}) \in \mathbb{C}^{N_T \times 1}$ being the steering vector associated to the
\[ a(\theta) = \left[ 1, e^{j2\pi \frac{d\sin \theta}{\lambda}}, \ldots, e^{j2\pi (N_v - 1) \frac{d\sin \theta}{\lambda}} \right]^T, \]

where \( d \) denotes the inter-element spacing of the ULA, and \( \lambda \) denotes the wavelength of the carrier. For notational conveniences, we denote \( H = [H_1^T, \ldots, H_K^T]^T \in \mathbb{C}^{N \times N_v} \), \( \bar{H}_k = [H_{k1}^T, \ldots, H_{k(N_k-1)}^T]^T \in \mathbb{C}^{(N - N_k) \times N_v} \), and \( \tilde{H}_k = [H_{k1}^T, \ldots, H_{k1}^T]^T \in \mathbb{C}^{\sum_{i=1}^{N} N_k \times N_v} \), where \( N = \sum_{k=1}^{K} N_k \). Assuming no two DODs are identical, then from the Vandermonde structure of \( \{A_k\}_{k=1}^{K} \) and also the fact that \( \{\Psi_k\}_{k=1}^{K} \) are independent random matrices with i.i.d. elements, it is clear that \( \{H_{k1}\}_{k=1}^{K} \), \( \{\bar{H}_k\}_{k=1}^{K} \), and \( \{\tilde{H}_k\}_{k=2}^{K} \) are all full rank with probability one.

### III. Proposed Blockwise Lattice-Reduction-Aided Precoders Design

#### A. Transceiver Architecture

The overall transceiver architecture of the proposed precoded system is shown in Fig. 1. Let \( z_k \in \mathbb{Q}^{N_k} \) be the symbol vector being transmitted from the BS to the \( k \)-th cluster, with each element drawn i.i.d. from the \( M \)-ary rectangular QAM constellation \( \mathbb{Q} = \{Q_0 + jQ_1, \ldots, Q_{M-1} \} \). Here the constant \( a = \sqrt{\frac{6}{M-1}} \) is introduced in order to normalize the average energy of the symbols in the constellation set \( \mathbb{Q} \) to unity [13]. It follows that the concatenated symbol vector \( z = [z_1^T, \ldots, z_K^T]^T \) satisfies \( \mathbb{E}\{zz^H\} = I_N \).

In the proposed architecture shown in Fig. 1, the concatenated symbol vector \( z \) is first transformed to \( \tilde{z} \) by a block-diagonal matrix \( B = \text{blkdiag}\{B_1, \ldots, B_K\} \), where \( B_k \) is of dimension \( N_k \times N_k \) and is unimodular for all \( k = 1, \ldots, K \). Since a matrix is unimodular if and only if all its elements are complex integers and has determinant equals \( \pm 1 \), it is clear that the transformation matrix \( B \) is also unimodular. Each block \( B_k \) can be constructed using standard lattice reduction algorithms such as the LLL algorithm or its variants. Because \( B \) has a block-diagonal structure, we refer to the construction of \( B \) as blockwise lattice reduction (BLR) to differentiate it from the conventional full lattice reduction.

After \( \tilde{z} \) is obtained, a block-diagonal permutation matrix \( P = \text{blkdiag}\{P_1, P_2, \ldots, P_K\} \) is then applied, where \( P_k \in \mathbb{C}^{N_k \times N_k} \) is referred to as the intra-cluster user permutation matrix associated to the \( k \)-th cluster. The transformed symbol vector after permutation \( P^T \bar{z} \) is then processed by the Tomlinson-Harashima precoder which consists of a modulo device and a strictly lower triangular feedback matrix \( C \). For notational convenience, we denote

\[ C = \begin{bmatrix} C_{1,1} & \ldots & C_{1,K} \\ \vdots & \ddots & \vdots \\ C_{K,1} & \ldots & C_{K,K} \end{bmatrix}, \]

where \( C_{i,j} \in \mathbb{C}^{N_i \times N_j} \), \( C_{i,j} = 0 \), \( \forall 1 \leq i < j \leq K \), and \( \text{diag}(C_{k,k}) = 1 \). The THP precoded vector \( \tilde{x} = [\tilde{x}_1^T, \ldots, \tilde{x}_K^T]^T \) is then processed by the linear precoder \( T = [T_1, \ldots, T_K] \), with \( \tilde{x}_k \in \mathbb{C}^{N_k} \) and \( T_k \in \mathbb{C}^{N_T \times N_k} \) for all \( k = 1, \ldots, K \). Without loss of generality, we assume the linear precoder \( T \) is properly scaled such that the transmitted signal vector \( x \) follows the power constraint \( \mathbb{E}\{\text{tr}(xx^H)\} = N \).

At the receiver side, the data vector received by the MSs in the \( k \)-th cluster is given by

\[ y_k = H_k T_k \tilde{x}_k + H_k \sum_{\ell=1}^{k-1} T_\ell \tilde{x}_\ell + H_k \sum_{\ell=k+1}^{K} T_\ell \tilde{x}_\ell + u_k, \]

where the second and the third term on the right hand side of (3) correspond to the precursor CCI and postcursor CCI, respectively. \( u_k \in \mathbb{C}^{N_k \times 1} \) denotes the receiver noise vector, and is modelled as a zero-mean, circularly-symmetric complex Gaussian vector with covariance matrix \( \sigma^2 I_{N_k} \).

#### B. Proposed BLR-SLNR-THP Design

We first derive a new BLR-Tomlinson-Harashima precoder with SLNR-based decoupling filter under the MMSE criterion (BLR-SLNR-MMSE-THP). In this design, the linear filter \( T_k \) is designed as

\[ T_k = \beta W_k F_k, \]

where \( W_k \) is the decoupling filter obtained by maximizing the SLNR of the \( k \)-th cluster. \( F_k \) is an \( N_T \times N_k \) matrix to be optimized according to the MMSE criterion, and \( \beta \) is the scaling factor used to enforce the power constraint. From [14], the SLNR associated to the \( k \)-th cluster can be defined as

\[ \text{SLNR}_k = \frac{\text{tr}(W_k^H H_k^H H_k W_k)}{\text{tr}(W_k^H (H_k^H H_k + \sigma^2 I_{N_T}) W_k)}, \]

and the optimal \( W_k \) that maximizes (5) can be obtained as

\[ W_k = \rho_k \tilde{W}_k \begin{bmatrix} I_{N_k} \\ 0 \end{bmatrix}, \]

using the Rayleigh-Ritz theorem [15]. Here \( \tilde{W}_k \in \mathbb{C}^{N_T \times N_k} \) corresponds to the generalized eigenvectors of \((H_k^H H_k, \tilde{H}_k^H \tilde{H}_k + \sigma^2 I_{N_T})\) with the generalized eigenvalues sorted in non-increasing order. As in [14], a scaling constant \( \rho_k \) is introduced to ensure \( \text{tr}(W_k W_k^H) = N_k \). The purpose of \( W_k \) is to suppress the leakage plus noise from the \( k \)-th cluster to all the other clusters. With the use of such decoupling filters in the whole system, the CCI from all the other clusters to the \( k \)-th cluster is also suppressed [14]. The signal model
in (3) is therefore approximately \( y_k \approx H_k T_k \tilde{x}_k + u_k = \beta H_k W_k F_k \tilde{x}_k + u_k \), for all \( k = 1, \ldots, K \). As a result, the overall MU-MIMO downlink channel is therefore essentially decoupled into \( K \) parallel subchannels, where \( H_k W_k \) can be interpreted as the effective subchannel associated to the \( k \)th cluster after decoupling.

After \( W_k \) is obtained, we can then apply the standard LR procedure such as the LLL algorithm [16] to the extended effective subchannel for the \( k \)th cluster \( [H_k W_k, \sigma I_{N_k}]^H \) to generate a reduced matrix \( \Gamma_k = \begin{bmatrix} (H_k W_k)^H & \sigma I_{N_k} \end{bmatrix} B_k \), where

\[
\Gamma_k = \begin{bmatrix} (H_k W_k)^H \\ \sigma I_{N_k} \end{bmatrix} B_k, \tag{7}
\]

The reduced-matrix \( \Gamma_k \) is then permuted by \( P_k \) using V-BLAST ordering [17] as in [18, 19], and decomposed using the QR factorization [15]

\[
\Gamma_k P_k = Q_k R_k = \begin{bmatrix} Q_{k,(1)} \\ Q_{k,(2)} \end{bmatrix} R_k, \tag{8}
\]

where \( Q_k \in \mathbb{C}^{2N_k \times N_k} \) is semi-unitary with \( Q_{k,(1)} \in \mathbb{C}^{N_k \times N_k} \) and \( Q_{k,(2)} \in \mathbb{C}^{N_k \times N_k} \) being its submatrices, and \( R_k \in \mathbb{C}^{N_k \times N_k} \) is upper triangular. The linear filter \( F_k \) and the feedback matrix \( C_{k,k} \) are then obtained as

\[
F_k = Q_{k,(1)} G_k, \tag{9}
\]

\[
C_{k,k} = R_k^H G_k - I_{N_k}, \tag{10}
\]

\[
G_k = \text{diag} \left\{ \frac{1}{[R_k]_{1,1}}, \ldots, \frac{1}{[R_k]_{N_k,N_k}} \right\}, \tag{11}
\]

for all \( k = 1, \ldots, K \). Since all the CCI has been suppressed, no CCI remains to be pre-subtracted from the THP and hence we have \( C_{i,j} = 0 \) for all \( i \neq j \), and consequently \( C = \text{blkdiag}\{C_{1,1}, \ldots, C_{K,K}\} \). Due to this block-diagonal nature of \( C \), the THPs in the precoder design can therefore be implemented in parallel and hence enjoys lower precoding latency. The proposed BLR-SLNR-THP can also be derived under the ZF criterion, to which we will refer as the BLR-SLNR-ZF-THP. After applying the LR procedure to the effective channel \( (H_k W_k)^H \), and performing the QR factorization to the permuted reduced channel matrix, we obtain the following expression

\[
\Gamma_k = (H_k W_k)^H B_k, \tag{12}
\]

\[
\Gamma_k P_k = Q_k R_k, \tag{13}
\]

respectively, where \( Q_k \in \mathbb{C}^{N_k \times N_k} \) is unitary and \( R_k \in \mathbb{C}^{N_k \times N_k} \) is upper triangular. Setting \( F_k = Q_k G_k \), and using the same expressions as (10) and (11), the BLR-SLNR-ZF-THP design is similarly obtained. It is worthwhile noting that the BLR-SLNR-ZF-THP is essentially the same as the (LR-GEVD-SDM) proposed in [10]. As a result, our proposed BLR-SLNR-THP subsumes the LR-GEVD-SDM as a special case under the ZF criterion.

C. Proposed BLR-SLNR-THP Design

In this subsection, we derive a new BLR-Tomlinson-Harashima precoder with successive-SLNR-based decoupling filter, which will be referred to as the BLR-SLNR-THP. In contrast to the the BLR-SLNR-THP, the decoupling filter \( W_k \) in \( T_k \) (4) is now obtained by maximizing the SSLNR [20] associated to the \( k \)th cluster, defined as

\[
\text{SSLNR}_k = \frac{\text{tr}\{W_k^H H_k^H H_k W_k\}}{\text{tr}\{W_k^H (H_k^H H_k + \sigma^2 I_{N_k}) W_k\}}. \tag{14}
\]

The optimal \( W_k \) has a similar form as in (6), except that \( W_k \in \mathbb{C}^{N_k \times N_k} \) now corresponds to the generalized eigenvectors of \( (H_k^H H_k, \hat{H}_k^H \hat{H}_k + \sigma^2 I_{N_k}) \) with the generalized eigenvalues sorted in non-increasing order. In contrast to the BLR-SLNR-THP, here the decoupling filter \( W_k \) only suppresses the leakage plus noise from the \( k \)th cluster to all the other clusters with smaller indices. With the use of such decoupling filters in the whole system, only the post-cursor CCI is suppressed. It follows that the signal model in (3) is approximately

\[
y_k \approx H_k T_k \tilde{x}_k + H_k \sum_{\ell=1}^{K} T_{\ell} \tilde{x}_\ell + u_k, \quad \text{for all} \quad k = 1, \ldots, K. \]

Clearly, the signal model is not yet completely decoupled by \( T_k \) except for \( k = 1 \).

Once the decoupling filters \( \{W_k\}_{k=1}^{K} \) have been obtained, the designs for \( \{B_k\}_{k=1}^{K}, \{P_k\}_{k=1}^{K}, \{F_k\}_{k=1}^{K}, \text{ and } \{C_{k,k}\}_{k=1}^{K} \) in the proposed BLR-SLNR-THP under the MMSE criterion (BLR-SLNR-MMSE-THP) can be obtained by applying the same design procedure on the extended effective channel \( [H_k W_k, \sigma I_{N_k}]^H \) as in (7)-(11). However, due to the presence of the precusor CCI, the feedback matrix \( C \) is no longer block diagonal in the BLR-SLNR-THP, and hence we need to design the lower triangular parts of \( C \) so that the precusor CCI can be perfectly removed from the system.

We first note that the concatenation of the channel matrix \( H \) and the linear precoder \( T \) can be expressed as

\[
HT = \beta \begin{bmatrix} H_1 W_1 F_1 & \tilde{0} & \tilde{0} \\ H_2 W_1 F_1 & \ddots & \tilde{0} \\ \vdots & \ddots & \ddots \end{bmatrix}, \tag{15}
\]

where the elements in the strictly upper triangular part are all suppressed to some small numbers (denoted as \( \tilde{0} \)’s) by construction. Rewriting \( H_k W_k \) in terms of \( B_k, Q_{k,(1)}, R_k, P_k \) for all \( k = 1, \ldots, K \), and factoring out \( B^{-H} P \), we have

\[
HT = \beta B^{-H} P \begin{bmatrix} R_k^H Q_{k,(1)}^H F_1 & \tilde{0} & \tilde{0} \\ \vdots & \ddots & \ddots \end{bmatrix}. \tag{16}
\]

From (16), it is clear that one requires

\[
C_{i,j} = P_k^T B_k^H H_k W_k F_j, \tag{17}
\]
for all $1 \leq j < i \leq K$ in order to completely remove the precursor CCI.

The BLR-SSLNR-THP can also be derived under the ZF criterion, to which we will refer as the BLR-SSLNR-ZF-THP. After obtaining $\mathbf{W}_k$ by maximizing the SSLNR$_k$, we apply the LR procedure to the effective channel $(\mathbf{H}_k \mathbf{W}_k)^H$, and also the QR factorization to the permuted channel matrix as in (12)-(13). Setting $\mathbf{F}_k = \mathbf{Q}_k \mathbf{G}_k$ with $\mathbf{G}_k$ defined as in (11), and following (10) and (17), we obtain the proposed BLR-SSLNR-ZF-THP design.

It is worthwhile noting that the performance of the proposed BLR-SSLNR-THP can be further improved by optimizing the cluster ordering. The resulting precoder will be referred to as the BLR-OSSLNR-THP. A new suboptimal cluster ordering algorithm has been derived, while the details are omitted due to the page limit.

IV. Complexity Analysis

In this section, we analyze the complexity of our proposed BLR-THP, and compare it with the existing THP designs with and without lattice reduction. We assume the use of the LLL algorithm for lattice reduction throughout the analysis. For simplicity, we consider the scenario where there are $K$ clusters of correlated MS’s, with each cluster containing $N_R = N/K$ MS’s.

In our proposed BLR-THP, the design problem is decoupled into $K$ subproblems with smaller dimensions, where each subproblem requires computing the decoding filter $\mathbf{W}_k$, and also performing lattice reduction on the effective channel $(\mathbf{H}_k \mathbf{W}_k)^H$ or $[\mathbf{H}_k \mathbf{W}_k, \sigma \mathbf{I}_{N_k}]^H$. For the computation of leakage-based decoding filters, the main complexity burden lies in the computation of $\mathbf{H}_k^H \mathbf{H}_k$ or $\mathbf{H}_k^H \bar{\mathbf{H}}_k$ as well as the generalized eigen-decomposition, which can be performed with complexity $O(N_T^3)$ [21]. In contrast of the $O(N_T^3)$ complexity required in computing the decoding filters, the computational complexity of the LLL reduction in each subproblem is around $O(N_T^3 \log \gamma_k)$ [22], with $\gamma_k$ being the norm of the longest column vector in the effective channel matrix of the $k$th cluster. As a result, the overall complexity of the BLR-THP is approximately $O(\max(KN_T^3, K N_R^3 \log \gamma))$.

On the contrary, conventional LR-THP schemes [7]-[9] require performing full lattice-reduction over the concatenated channel matrix $\mathbf{H}$ and hence result in an overall complexity of $O(N_T^4 \log \gamma')$, where $\gamma'$ is the norm of the longest column vector in $\mathbf{H}$. Since $N_T^4 \log \gamma' \gg \max(KN_T^3, K N_R^3 \log \gamma)$ for $N_T > K$ and $K \geq 2$, it is clear that the proposed BLR-THP is computationally more efficient comparing to the conventional LR-THPs. Nonetheless, the proposed BLR-THPs generally require higher complexity than the conventional THPs [23, 24], as the latter schemes can be implemented with complexity around $O(N_T^3)$ [24, 25].

V. Simulation Results

In this section, we compare the error rate performance of the proposed BLR-THP designs with the conventional THP [23, 24] and LR-aided THP [7]-[9] under the setting of a MU-MIMO system with 6 antennas at the BS, 2 clusters of mobile users, and 3 MS’s in each cluster. A uniform linear array with antenna spacing $d = \lambda/2$ is assumed at the BS, and the semi-correlated Rayleigh fading channel introduced in Section II is simulated. We assume $D_k = 15$ departure waves for all clusters, with $\theta_{1,1}$ and $\theta_{2,1}$ drawn from a uniform distribution within the interval $[\theta_{1,1}^L, \theta_{1,1}^U] = [45^\circ, 60^\circ]$ and $[\theta_{2,1}^L, \theta_{2,1}^U] = [60^\circ, 45^\circ]$, respectively. After $\theta_{k,1}$ has been determined, $\theta_{k,2}, \ldots, \theta_{k,D_k}$ are then generated i.i.d. from a Gaussian distribution with mean $\theta_{k,1}$ and standard deviation $\sigma_{AS} = 10$, for both $k = 1$ and 2. Throughout the simulation, we assume the data symbols are modulated by 16-QAM, and the LR procedure is performed using the LLL algorithm.

The simulation results of various precoders designs under the ZF and MMSE criteria are shown in Fig. 2 and Fig. 3, respectively. The notations (sorted) or (unsorted) in the legends denote the precoder designs with or without intra-cluster user ordering for the proposed BLR-THP schemes, and with or without user ordering for the conventional THPs and LR-aided THPs. The BLR-subOSSLNR denotes the BLR-OSSLNR precoder with the proposed suboptimal cluster ordering, while BLR-optOSSLNR denotes the BLR-OSSLNR precoder with the optimal cluster ordering using exhaustive search.

From Fig. 2 and Fig. 3, it is observed that all the MMSE precoders provide better performance in comparison to their
ZF counterparts. It is also noted that the user ordering for the proposed BLR-THPs only marginally improves the error rate performance in contrast to that for the conventional THP precoders. The same behaviour is also observed in the LR-THP schemes as shown in the figures. This phenomenon is due to the fact that the technique of lattice reduction has already exploited most of the degrees-of-freedom embedded in the permutation ordering and hence leaves little to be further extracted. On the contrary, by comparing the BLR-SSLNR-THP with the BLR-OSSLNR-THP and BLR-subOSSLNR-THP, it is noted that significant performance gain can be acquired by exploiting the degrees-of-freedom in the inter-cluster-ordering. Furthermore, the proposed suboptimal cluster ordering algorithm performs almost identically with the optimal ordering using exhaustive search in this simulation scenario. Among all the simulated precoders, the LR-MMSE-THP (sorted) attains the best error rate performance at the expense of highest computational complexity as noted in the complexity analysis, while the ZF-THP (unsorted) has the lowest complexity but the worst error rate performance. The proposed BLR-based precoders generally achieve error rate performances between these two extremities while having only moderate complexity. At the BER = $10^{-4}$, the proposed BLR-subOSSLNR-MMSE-THP is roughly 1.9 dB worse than the optimal LR-MMSE-THP, but provides 3.5 dB gain over the BLR-SSLNR-MMSE-THP, 7.1 dB over the BLR-SSLNR-MMSE-THP, and 9.0 dB over the MMSE-THP (sorted). When compared with the ZF designs, the proposed BLR-subOSSLNR-MMSE-THP is roughly 3.4 dB better than the BLR-subOSSLNR-THP, 5 dB better than the LR-ZF-THP, and 10 dB better than the BLR-SSLNR-ZF THP.

VI. Conclusion

In this paper, a new class of precoders has been proposed. In contrast to the conventional THPs with full lattice-reduction, the proposed BLR-THP exploits the clustering information to decouple the downlink channels before applying the lattice reduction and hence results in much lower computational complexity. Precoder designs using SLNR and SSLNR decoupling filters have been proposed. The proposed BLR-SSLNR-THP has a parallel THP structure and hence has lower precoding latency, while the BLR-SSLNR-THP can provide better performance. The performance of the BLR-SSLNR-THP can be further improved by exploiting the inter-cluster ordering to achieve an error rate performance very close to the LR-MMSE-THP with much lower computational complexity.

VII. Acknowledgments

This work was supported in part by the National Science Council under the Grants NSC 100-2221-E-194-032-MY2.

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