Blockwise Uniform Channel Decomposition for MIMO Systems

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Abstract— **In this paper, we investigate spatial multiplexing schemes for closed-loop multiple-input multiple-output (MIMO) systems. The performance of the singular value decomposition (SVD) scheme is limited by the smallest singular value. When all the subchannels are utilized, uniform channel decomposition (UCD) was recently proposed to obtain a performance gain by making subchannels have equal gains. The UCD requires a successive interference cancelation (SIC) receiver, and thus it suffers from the error propagation inherent in the SIC receiver. We propose the blockwise UCD (BL-UCD) scheme which increases the minimum subchannel gain by pairing two singular values. The proposed scheme allows single-symbol decodable maximum-likelihood detection (MLD) instead of the SIC receiver. The simulation results demonstrate that the proposed BL-UCD scheme outperforms the SVD scheme and the conventional UCD at full spatial multiplexing for four transmit antennas and four receive antennas by 8dB and 5dB, respectively.**

I. Introduction

Wireless multiple-input multiple-output (MIMO) systems are capable of improving the system performance as the number of antennas grows [1] [2]. The expected benefits include higher system capacity and improved quality of service as a result of spatial multiplexing and diversity gain. In order to fully exploit both potentials of multiple antennas, we can apply full channel state information (CSI) knowledge to the transmit side to optimize the transmission scheme according to instant channel conditions. Singular value decomposition (SVD) converts the MIMO channel into parallel subchannels on which multiple streams are transmitted. Although the SVD scheme with the water-filling is optimal from an information theoretic point of view, it is necessary to employ complex bit allocation schemes [3] because of vastly different signal-to-noise ratios (SNRs) of the subchannels.

If the same constellation is to be used for each subchannel to avoid the adaptive modulation and coding (AMC) operation, the SVD scheme should be combined with the optimized interleaver and the proper channel coding to obtain diversity gain when all the subchannels are utilized [4]. However, the performance of the coded SVD scheme with the optimized interleaver is still limited by the smallest singular value.

Recently, uniform channel decomposition (UCD) has been proposed for uncoded systems where a successive interference cancelation (SIC) method is employed at the receiver [5]. The UCD scheme attains both full diversity gain and full multiplexing gain by making all the subchannels have equal gain. As a result, the UCD scheme exhibits a better performance than SVD when all the subchannels are utilized. Also, AMC procedure becomes simpler, since all the subchannels have the same quality. However, in practical wireless links the conventional UCD scheme may not work well when channel coding is applied, since the decoder performance substantially degrades due to the error propagation inherent in the decision feedback process in the SIC operation [6].

In this paper, we propose a new blockwise scheme which applies the UCD to subblocks of the effective channel matrix, which we refer to as the blockwise UCD (BL-UCD). In the proposed scheme, a simple maximum-likelihood detection (MLD) is possible utilizing the block diagonal property of the equivalent channel matrix. As a result, the proposed scheme attains single-symbol decodability, and is able to exploit the effective channel of the UCD without the problem of error propagation. In this scheme, we combine two subchannels of a large singular value and a small singular value. Then the proposed BL-UCD scheme generates parallel subchannels which have smaller deviations in channel gains compared to the SVD scheme. The improved minimum channel gain of subchannels results in the enhanced performance. Simulation results show that the proposed BL-UCD scheme outperforms both the SVD and the conventional UCD in terms of error probability.

The paper is organized as follows: Section II describes the system model for the spatial multiplexing scheme in closed-loop MIMO systems. We briefly review the SVD and the conventional UCD in Section III. In Section IV, the BL-UCD scheme is proposed by applying the UCD to subblocks, and it is shown that our scheme achieves symbol-by-symbol decodability. Section V presents the simulation results and compares the proposed method with the conventional schemes. Finally, the paper is terminated with conclusions in Section VI.

II. System Model

In this section, we consider a coded spatial multiplexing scheme with N_t transmit and N_r receive antennas for closed-loop systems. We assume that both the transmitter and the receiver have perfect CSI. The channel encoding is employed by means of bit-interleaved coded modulation (BICM) [7] at

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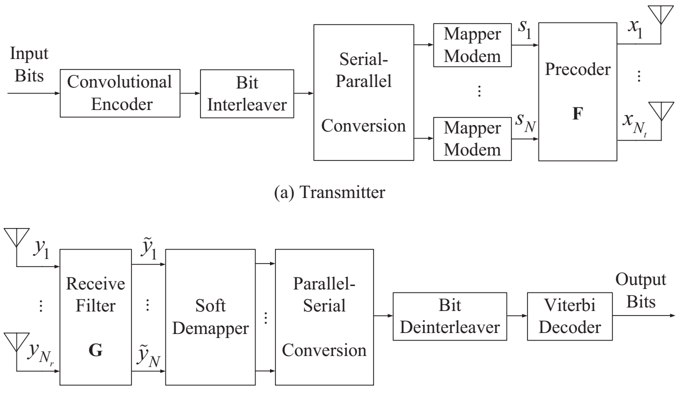

(a) Transmitter

(b) Recevier

Fig. 1. Schematic diagram of a closed-loop spatial multiplexing scheme for N_t transmit and N_r receive antennas

the transmitter, where a single channel encoder supports all transmit antennas as shown in Figure 1 (a). At the transmitter, the information bits are encoded, bit-wise interleaved, and modulated to produce the N dimensional complex symbol vector $\mathbf{s} = [s_1\ s_2 \cdots s_N]^T$, where $s_i \triangleq s_{i,I} + js_{i,Q}$. Here the subscripts I and Q denote inphase and quadrature components, respectively, and j indicates $\sqrt{-1}$. We use M-QAM modulation systems with $s_{i,I}$ and $s_{i,Q}$ chosen from a $\sqrt{M}$-PAM constellation set $\mathcal{X}_{\sqrt{M}}$.

Defining $\mathbf{F}$ as the N_t by N precoder matrix, the data symbol vector $\mathbf{s}$ is precoded by $\mathbf{F}$ to form the N_t dimensional complex transmit signal vector $\mathbf{x} = [x_1\ x_2 \cdots x_{N_t}]^T$. At the receiver, the receive filter $\mathbf{G}$ is applied and then its output is converted to soft values in the soft demapper as shown in Figure 1 (b).

We assume flat fading channels, and also the channel is fixed during one frame and varies independently from frame to frame. The N_r dimensional complex received signal vector $\mathbf{y}$ is given as

$$\begin{aligned}\mathbf{y} &= [y_1\ y_2\ \cdots\ y_{N_r}]^T \\ &= \mathbf{H}\,\mathbf{x} + \mathbf{w} = \mathbf{H}\,\mathbf{F}\,\mathbf{s} + \mathbf{w}\end{aligned}$$

where $\mathbf{H}$ is the N_r by N_t channel matrix whose elements have independent and identically distributed (i.i.d.) complex Gaussian distribution with unit variance and $\mathbf{w}$ denotes the additive white Gaussian noise vector with zero mean and the covariance matrix $\sigma_w^2 \mathbf{I}_{N_r}$. Here $\mathbf{I}_d$ indicates an identity matrix of size d. The autocorrelation matrix of $\mathbf{s}$ is assumed to be $E[\mathbf{s}\mathbf{s}^\dagger] = \sigma_s^2 \mathbf{I}_N$, where $E[\cdot]$ accounts for expectation and $(\cdot)^\dagger$ denotes the complex conjugate transpose of a vector or matrix. We also assume $\text{Tr}(\mathbf{F}^\dagger\mathbf{F}) = N$, where $\text{Tr}(\cdot)$ indicates the trace of a matrix. The received SNR ρ is defined as

$$\rho = \frac{E[\mathbf{s}^\dagger\mathbf{F}^\dagger\mathbf{F}\mathbf{s}]}{\sigma_w^2} = \frac{\sigma_s^2}{\sigma_w^2}\text{Tr}(\mathbf{F}^\dagger\mathbf{F}) = \frac{1}{\alpha}N$$

where we define $\alpha \triangleq \sigma_w^2/\sigma_s^2$.

III. Review of SVD and UCD

In this section, we briefly review two conventional schemes in closed-loop systems, which build up the foundation of the proposed BL-UCD.

A. SVD scheme

The SVD technique generates independent parallel substreams with gains equal to singular values. The SVD of $\mathbf{H}$ is given by

$$\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^\dagger \triangleq [\mathbf{u}_1\mathbf{u}_2\cdots\mathbf{u}_K]\mathbf{\Lambda}[\mathbf{v}_1\mathbf{v}_2\cdots\mathbf{v}_K]^\dagger \tag{1}$$

where $\mathbf{U} \in \mathbb{C}^{N_r\times K}$ and $\mathbf{V} \in \mathbb{C}^{N_t\times K}$ are semi-unitary matrices, and $\mathbf{\Lambda} \in \mathbb{R}^{K\times K}$ denotes a nonnegative diagonal matrix $\text{diag}\{\lambda_1, \lambda_2, \cdots, \lambda_K\}$. Here the singular values are placed in a decreasing order such that $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_K$ and K represents the rank of $\mathbf{H}$. Throughout the paper, we assume that all K streams are transmitted to achieve full spatial multiplexing ($N = K$). The optimal precoder from an information theoretic point of view is then given as $\mathbf{F}_{\text{SVD}} = \mathbf{V}\mathbf{\Phi}$ where $\mathbf{\Phi} \in \mathbb{R}^{N\times N}$ denotes a diagonal matrix as $\mathbf{\Phi} \triangleq \text{diag}\{\phi_1, \phi_2, \cdots, \phi_N\}$ and ϕ_k is found via the water filling process as [2]

$$\phi_k = \left(\mu - \frac{\alpha}{\lambda_k^2}\right)_+^{\frac{1}{2}}.$$

Here μ is chosen such that $\sum_{k=1}^{N}\phi_k^2 = N$ and $(a)_+ \triangleq \max\{0, a\}$.

Denoting $\tilde{\mathbf{y}}_{\text{SVD}}$ as the output of the receive filter $\mathbf{G}_{\text{SVD}} = \mathbf{U}^\dagger$, the filter output signal $\tilde{\mathbf{y}}_{\text{SVD}} \triangleq \mathbf{U}^\dagger\mathbf{y}$ is then written as

$$\begin{aligned}\tilde{\mathbf{y}}_{\text{SVD}} &= [\tilde{y}_{\text{SVD},1}\,\tilde{y}_{\text{SVD},2}\cdots\tilde{y}_{\text{SVD},N}]^T \\ &= \mathbf{U}^\dagger\mathbf{H}\mathbf{F}_{\text{SVD}}\mathbf{s} + \mathbf{U}^\dagger\mathbf{w} = \mathbf{\Sigma}\mathbf{s} + \tilde{\mathbf{w}}\end{aligned} \tag{2}$$

where $\mathbf{\Sigma} \triangleq \mathbf{\Lambda}\mathbf{\Phi}$ denotes an N by N nonnegative diagonal matrix as $\mathbf{\Sigma} = \text{diag}\{\sigma_1, \sigma_2, \cdots, \sigma_N\}$ and $\tilde{\mathbf{w}} \triangleq \mathbf{U}^\dagger\mathbf{w} = [\tilde{w}_1\,\tilde{w}_2\cdots\tilde{w}_N]^T$. In the above equation, the resulting subchannels are given by

$$\tilde{y}_{\text{SVD},k} = \sigma_k s_k + \tilde{w}_k \quad \text{for } k = 1, 2, \cdots, N$$

where σ_k is defined as $\lambda_k\phi_k$.

The error performance of the SVD scheme is mainly limited by the subchannel with the smallest singular value gain. When the BICM structure is employed, the effect of the worst subchannel can be compensated by applying proper error correcting codes. In this case, the performance can be optimized by an interleaver where consecutive bits are mapped over different symbols and transmitted over different subchannels [4]. Although the combination of SVD and BICM may provide a considerable diversity gain, the performance of the SVD scheme still degrades especially when high rate codes are adopted.

B. UCD scheme

The UCD scheme combined with the SIC operation is introduced in [5] to achieve the diversity gain. First consider the effective channel of SVD $\mathbf{H}\mathbf{F}_{\text{SVD}} = \mathbf{U}\boldsymbol{\Sigma}$. Then the (N_r+N) by N matrix $\mathbf{J}$ consisting of $\mathbf{U}\boldsymbol{\Sigma}$ can be decomposed by geometric mean decomposition (GMD) introduced in [8] as

$$\mathbf{J} \triangleq \begin{bmatrix} \mathbf{U}\boldsymbol{\Sigma} \\ \sqrt{\alpha}\mathbf{I}_N \end{bmatrix} = \mathbf{Q}\mathbf{R}\mathbf{P}^{\dagger} \tag{3}$$

where $\mathbf{R} \in \mathbb{R}^{N\times N}$ denotes an upper triangular matrix whose all diagonal elements equal the geometric mean value of the singular values of the matrix $\mathbf{J}$ as

$$r_{ii} = \left(\prod_{n=1}^{N} \sqrt{\sigma_n^2 + \alpha}\right)^{\frac{1}{N}} \quad \text{for } i = 1, 2, \cdots, N,$$

$\mathbf{Q} \in \mathbb{C}^{(N_r+N)\times N}$ is a semi-unitary matrix which consists of a N_r by N submatrix $\tilde{\mathbf{Q}}_u$ and a N by N submatrix $\tilde{\mathbf{Q}}_l$ as $\mathbf{Q} \triangleq \left[\tilde{\mathbf{Q}}_u^T \ \tilde{\mathbf{Q}}_l^T\right]^T$, and $\mathbf{P} \in \mathbb{C}^{N\times N}$ indicates a unitary matrix.

Applying the precoder $\mathbf{F}_{\text{UCD}} = \mathbf{V}\boldsymbol{\Phi}\mathbf{P}$ and the receive filter $\mathbf{G}_{\text{UCD}} = \tilde{\mathbf{Q}}_u^{\dagger}$ yields

$$\begin{aligned} \tilde{\mathbf{y}}_{\text{UCD}} &= \tilde{\mathbf{Q}}_u^{\dagger}\mathbf{H}\mathbf{V}\boldsymbol{\Phi}\mathbf{P}\mathbf{s} + \tilde{\mathbf{Q}}_u^{\dagger}\mathbf{w} \\ &= \mathbf{R}\mathbf{s} - \sqrt{\alpha}\tilde{\mathbf{Q}}_l^{\dagger}\mathbf{P}\mathbf{s} + \tilde{\mathbf{Q}}_u^{\dagger}\mathbf{w}. \end{aligned}$$

The transmitted symbols are detected by applying the SIC operation to the upper triangular matrix $\mathbf{R}$. The UCD operation results in the equal subchannel gains for all diagonal elements of $\mathbf{R}$. However, the UCD scheme suffers from the error propagation inherent in the SIC process, and this loss becomes more pronounced when channel coding is applied. In the following section, we propose a new structure based on UCD which does not need the SIC receiver.

IV. Blockwise Uniform Channel Decomposition

In this section, we will present the BL-UCD scheme which employs the blockwise MLD to avoid the error propagation. Subblocks are formed by grouping two subchannels in order to increase the minimum value of the subchannel gains, and then are precoded by the UCD. The effective channel allows the blockwise MLD which achieves a symbol-by-symbol decodability.

For simplicity, we assume that the number of nonzero singular values is even and equal to the number of the transmitted streams ($N = K$). By rearranging the order of the singular values in (1), the SVD of $\mathbf{H}$ can be rewritten as $\mathbf{H} = \bar{\mathbf{U}}\bar{\boldsymbol{\Lambda}}\bar{\mathbf{V}}^{\dagger}$ where $\bar{\mathbf{U}} \triangleq [\mathbf{u}_1\ \mathbf{u}_N\ \mathbf{u}_2\ \mathbf{u}_{N-1} \cdots \mathbf{u}_{N/2}\ \mathbf{u}_{N/2+1}]$, $\bar{\mathbf{V}} \triangleq [\mathbf{v}_1\ \mathbf{v}_N\ \mathbf{v}_2\ \mathbf{v}_{N-1} \cdots \mathbf{v}_{N/2}\ \mathbf{v}_{N/2+1}]$ and $\bar{\boldsymbol{\Lambda}} \triangleq \text{diag}\{\lambda_1, \lambda_N, \lambda_2, \lambda_{N-1}, \cdots, \lambda_{N/2}, \lambda_{N/2+1}\}$.

The proposed BL-UCD scheme employs the precoder $\mathbf{F}_{\text{BL}} = \bar{\mathbf{V}}\bar{\boldsymbol{\Phi}}\mathbf{P}_{\text{BL}}$ where $\bar{\boldsymbol{\Phi}}$ indicates the N by N diagonal matrix with power loading parameters as $\bar{\boldsymbol{\Phi}} \triangleq \text{diag}\{\phi_1, \phi_N, \phi_2, \phi_{N-1}, \cdots, \phi_{N/2}, \phi_{N/2+1}\}$. Here our goal is to find the proper unitary matrix $\mathbf{P}_{\text{BL}}$ which improves the performance of the UCD with a single-symbol decodable MLD.

Applying the reordered left singular vectors $\bar{\mathbf{U}}^{\dagger}$ at the receiver, equation (2) is then rewritten as

$$\begin{aligned} \tilde{\mathbf{y}} &= \bar{\mathbf{U}}^{\dagger}\mathbf{H}\mathbf{F}_{\text{BL}}\mathbf{s} + \bar{\mathbf{U}}^{\dagger}\mathbf{w} \\ &= \bar{\boldsymbol{\Sigma}}\,\mathbf{P}_{\text{BL}}\,\mathbf{s} + \tilde{\mathbf{w}} \end{aligned} \tag{4}$$

where the N by N diagonal matrix $\bar{\boldsymbol{\Sigma}} \triangleq \bar{\boldsymbol{\Lambda}}\bar{\boldsymbol{\Phi}}$ equals $\text{diag}\{\sigma_1, \sigma_N, \sigma_2, \sigma_{N-1}, \cdots, \sigma_{N/2}, \sigma_{N/2+1}\}$.

Define the ith effective channel submatrix $\bar{\boldsymbol{\Sigma}}_i$ as $\bar{\boldsymbol{\Sigma}}_i \triangleq \text{diag}\{\sigma_i, \sigma_{N-i+1}\}$ for $i = 1, 2, \cdots, N/2$. Then $\bar{\boldsymbol{\Sigma}}$ can be expressed as $\bar{\boldsymbol{\Sigma}} = \text{diag}\{\bar{\boldsymbol{\Sigma}}_1, \bar{\boldsymbol{\Sigma}}_2, \cdots, \bar{\boldsymbol{\Sigma}}_{N/2}\}$.

For the ith subblock, we apply the GMD operation [8] to the matrix $\mathbf{J}_i$ which consists of $\bar{\boldsymbol{\Sigma}}_i$ as

$$\mathbf{J}_i \triangleq \begin{bmatrix} \bar{\boldsymbol{\Sigma}}_i \\ \sqrt{\alpha}\mathbf{I}_2 \end{bmatrix} = \mathbf{Q}_i\mathbf{R}_i\mathbf{P}_i^{\dagger}$$

where $\mathbf{Q}_i \in \mathbb{R}^{4\times 2}$ is a semi-orthogonal matrix, $\mathbf{P}_i \in \mathbb{R}^{2\times 2}$ represents a orthogonal matrix and $\mathbf{R}_i \in \mathbb{R}^{2\times 2}$ denotes an upper triangular matrix with diagonal elements equal to the geometric mean value of the singular values of the matrix $\mathbf{J}_i$ (i.e., $r_{i,11} = r_{i,22} = \sqrt[4]{(\sigma_i^2+\alpha)(\sigma_{N-i+1}^2+\alpha)}$).

Then, the precoding matrix for the ith subblock $\mathbf{P}_i$ is given by [8]

$$\mathbf{P}_i = \begin{bmatrix} \mathcal{C}_i & \mathcal{S}_i \\ -\mathcal{S}_i & \mathcal{C}_i \end{bmatrix} \quad \text{for } i = 1, 2, \cdots, \frac{N}{2} \tag{5}$$

where

$$\mathcal{C}_i = \sqrt{\frac{\sqrt{(\sigma_i^2+\alpha)(\sigma_{N-i+1}^2+\alpha)} - (\sigma_{N-i+1}^2+\alpha)}{\sigma_i^2 - \sigma_{N-i+1}^2}}$$

and

$$\mathcal{S}_i = \sqrt{1 - \mathcal{C}_i^2}.$$

Denoting the N by N matrix $\mathbf{P}_{\text{BL}}$ as

$$\mathbf{P}_{\text{BL}} \triangleq \text{diag}\left\{\mathbf{P}_1, \mathbf{P}_2, \cdots, \mathbf{P}_{\frac{N}{2}}\right\}, \tag{6}$$

the precoder and the receive filter of the proposed BL-UCD are designed as $\mathbf{F}_{\text{BL}} = \bar{\mathbf{V}}\bar{\boldsymbol{\Phi}}\mathbf{P}_{\text{BL}}$ and $\mathbf{G}_{\text{BL}} = \bar{\mathbf{U}}^{\dagger}$, respectively. Applying the orthogonal matrix $\mathbf{P}_{\text{BL}}$ defined in (6) to Equation (4) yields

$$\begin{bmatrix} \tilde{\mathbf{y}}_1 \\ \tilde{\mathbf{y}}_2 \\ \vdots \\ \tilde{\mathbf{y}}_{\frac{N}{2}} \end{bmatrix} = \begin{bmatrix} \mathbf{B}_1 & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{B}_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{B}_{\frac{N}{2}} \end{bmatrix} \begin{bmatrix} \mathbf{s}_1 \\ \mathbf{s}_2 \\ \vdots \\ \mathbf{s}_{\frac{N}{2}} \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{w}}_1 \\ \tilde{\mathbf{w}}_2 \\ \vdots \\ \tilde{\mathbf{w}}_{\frac{N}{2}} \end{bmatrix} \tag{7}$$

where $\tilde{\mathbf{y}}_i \triangleq [\tilde{y}_{2i-1}\ \tilde{y}_{2i}]^T$, $\mathbf{s}_i \triangleq [s_{2i-1}\ s_{2i}]^T$, $\tilde{\mathbf{w}}_i \triangleq [\tilde{w}_{2i-1}\ \tilde{w}_{2i}]^T$ and the two by two subblock matrix $\mathbf{B}_i$ is denoted by $\mathbf{B}_i \triangleq \bar{\boldsymbol{\Sigma}}_i\mathbf{P}_i$. Note that the effective channel of the proposed scheme is easily separated into $N/2$ subblock channels as

$$\tilde{\mathbf{y}}_i = \mathbf{B}_i\mathbf{s}_i + \tilde{\mathbf{w}}_i \quad \text{for } i = 1, 2, \cdots, \frac{N}{2}.$$

Since $\mathbf{B}_i$ has real elements, the real-valued representation for the above ith subblock channel expression can be equivalently written as [9] [10]

$$\begin{bmatrix} \tilde{\mathbf{y}}_{i,I} \\ \tilde{\mathbf{y}}_{i,Q} \end{bmatrix} = \begin{bmatrix} \mathbf{B}_i & \mathbf{0} \\ \mathbf{0} & \mathbf{B}_i \end{bmatrix} \begin{bmatrix} \mathbf{s}_{i,I} \\ \mathbf{s}_{i,Q} \end{bmatrix} + \begin{bmatrix} \tilde{\mathbf{w}}_{i,I} \\ \tilde{\mathbf{w}}_{i,Q} \end{bmatrix}$$

where the subscripts I and Q for a complex vector indicate the inphase and the quadrature parts of the vector, respectively (i.e., $\mathbf{b}_I \triangleq \Re\{\mathbf{b}\}$ and $\mathbf{b}_Q \triangleq \Im\{\mathbf{b}\}$).

Utilizing the block diagonality of the real equivalent channel, the ML solutions $\hat{\mathbf{s}}_i = \hat{\mathbf{s}}_{i,I} + j\hat{\mathbf{s}}_{i,Q}$ for $i = 1, 2, \cdots, N/2$ for equation (7) can be individually found as

$$\hat{\mathbf{s}}_{i,I} = \arg \min_{\mathbf{s}_{i,I} \in \mathcal{X}^2_{\sqrt{M}}} \left|\left| \tilde{\mathbf{y}}_{i,I} - \mathbf{B}_i \ \mathbf{s}_{i,I} \right|\right|^2 \tag{8}$$

and

$$\hat{\mathbf{s}}_{i,Q} = \arg \min_{\mathbf{s}_{i,Q} \in \mathcal{X}^2_{\sqrt{M}}} \left|\left| \tilde{\mathbf{y}}_{i,Q} - \mathbf{B}_i \ \mathbf{s}_{i,Q} \right|\right|^2 \tag{9}$$

where $\hat{\mathbf{s}}_{i,I} \triangleq [\hat{s}_{2i-1,I} \ \hat{s}_{2i,I}]^T$ and $\hat{\mathbf{s}}_{i,Q} \triangleq [\hat{s}_{2i-1,Q} \ \hat{s}_{2i,Q}]^T$.

The proposed BL-UCD generates N independent parallel streams for the pair of two real components, which are separated from two complex symbols. The size of search candidates in (8) and (9) is the same as the M-QAM constellation size. Hence, the proposed BL-UCD method accomplishes both single-symbol decodability and the optimal ML performance for the effective channel produced by the UCD scheme. Note that the conventional UCD fails to achieve the ML performance, since the suboptimal SIC receiver is employed. If N is odd, the last symbol s_N does not have any pair. In this case, s_N can be independently detected without coupling with another stream.

Consequently, the worst effective SNR of the parallel subchannels in the proposed BL-UCD is larger than that of the subchannels obtained from the SVD, since the ith largest singular value and the ith smallest singular value are combined by the precoder of the BL-UCD in the ith subblock in (7). Two parallel subchannels in each subblock have equal channel gains as a result of the UCD process, and the fluctuation of the channel gains in the BL-UCD becomes smaller compared to the SVD. Since the worst SNR of subchannels increases, the proposed scheme provides the improved error probability.

As a special case with no power loading ($\bar{\mathbf{\Phi}} = \mathbf{I}_N$) and the zero regularization factor ($\alpha = 0$) in the proposed BL-UCD, the blockwise GMD (BL-GMD) is obtained which corresponds to the conventional GMD scheme proposed in [11]. The proposed technique and the conventional schemes are summarized in Table I. Since the water filling operation in the SVD scheme is not optimal in terms of error probability, no power loading ($\mathbf{\Phi} = \mathbf{I}_N$) is considered for $\mathbf{F}_{\text{SVD}}$ in (2).

The proposed blockwise schemes need to compute $N/2$ two by two matrices $\mathbf{P}_1, \mathbf{P}_2, \cdots, \mathbf{P}_{N/2}$ from (5) in order to obtain $\mathbf{P}_{\text{BL}}$, while the conventional UCD should calculate the N by N matrix $\mathbf{P}$ and the N_r by N matrix $\tilde{\mathbf{Q}}_u$ using the GMD operation in (3). Hence, the computational complexities of the blockwise schemes are smaller than the conventional UCD.

TABLE I

COMPARISON OF CLOSED-LOOP MIMO SYSTEMS

	SVD	BL-UCD	Conv. UCD
Precoder $\mathbf{F}$	$\mathbf{V}$	$\bar{\mathbf{V}}\bar{\mathbf{\Phi}}\mathbf{P}_{\text{BL}}$	$\mathbf{V}\mathbf{\Phi}\mathbf{P}$
Filter $\mathbf{G}$	$\mathbf{U}^\dagger$	$\bar{\mathbf{U}}^\dagger$	$\tilde{\mathbf{Q}}_u^\dagger$
Complexity	$O(N^3)$	$O(N^3{+}2N^2{+}6N)$	$O(N^3{+}7N^2{+}2N)$
Effective Channel	diagonal	block diagonal	upper triangular
Detection Method	single-symbol decodable MLD	single-symbol decodable MLD	SIC

For the case of $N = K = N_t = N_r$, the computation complexity to obtain the precoder and the receive filter is counted in Table I.

V. Simulation Results

In this section, we present simulation results for the proposed blockwise schemes in flat fading channels and compare them with conventional systems. The spectral efficiency is given by $R_T = R_c \cdot N \cdot \log_2 M$ bps/Hz, where R_c is the rate of the channel codes used. Throughout the paper, we employ a 64 state convolutional encoder with polynomials $(133, 171)$ in octal notation with $R_c = 1/2$ and $R_c = 3/4$, where the rate $3/4$ code is obtained by puncturing [12]. To make a fair comparison, we use the interleaver optimized for the SVD scheme for all simulations as suggested in [4]. The size of the interleaver is determined by $L \cdot N \cdot \log_2 M$, where L denotes the frame length and is set to 64 in all simulations.

In Figures 2 and 3, the performance comparison for 4QAM is presented with four transmit and four receive antennas when using $R_c = 1/2$ and $3/4$, respectively. The plot in Figure 2 shows that the proposed BL-UCD scheme outperforms the SVD scheme and the conventional UCD technique by 1.3dB and 4.2dB at a frame error rate (FER) of 10^{-2}, respectively. The performance of the conventional UCD suffers from the error propagation in a SIC detector. In Figure 3, the SVD exhibits the diversity loss when punctured codes with rate $3/4$ is employed. Hence, the SNR gain of the proposed blockwise schemes over the SVD technique increases to 8dB for the BL-UCD and 5.8dB for the BL-GMD, respectively.

In Figure 4, the effect of the optimal interleaver introduced in [4] is evaluated, and the BL-UCD still outperforms the SVD scheme with the optimized interleaver. This plot shows that the proposed scheme is not as sensitive to the choice of interleavers as the SVD.

VI. Conclusion

In this paper, we have proposed a new blockwise scheme based on the UCD operation in closed-loop MIMO systems. The blockwise structure of the proposed scheme increases the minimum gain of subchannels which dominates the error performance. Furthermore, we show that single-symbol decodable MLD is possible by utilizing the block diagonality for each substream of paired subblocks. The simulation results show that the proposed blockwise scheme substantially improves

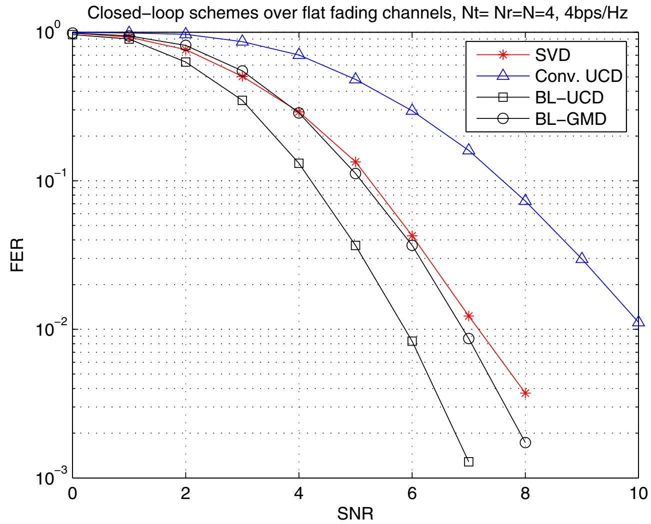

Fig. 2. Performance comparison for 4QAM and $R_c = 1/2$

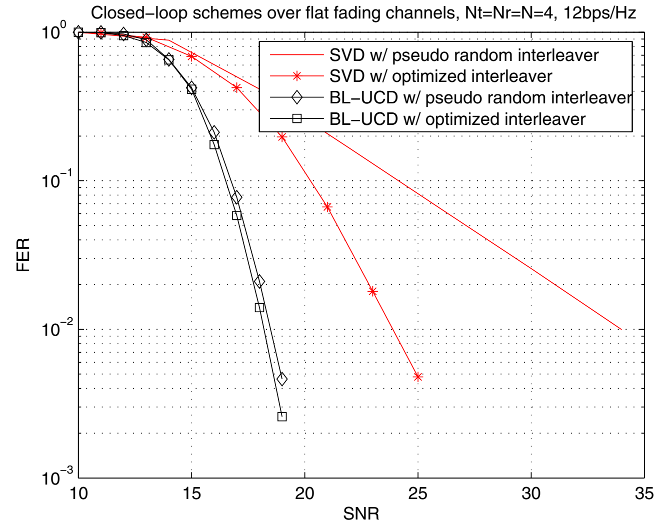

Fig. 4. Effect of interleaver design for 16QAM and $R_c = 3/4$

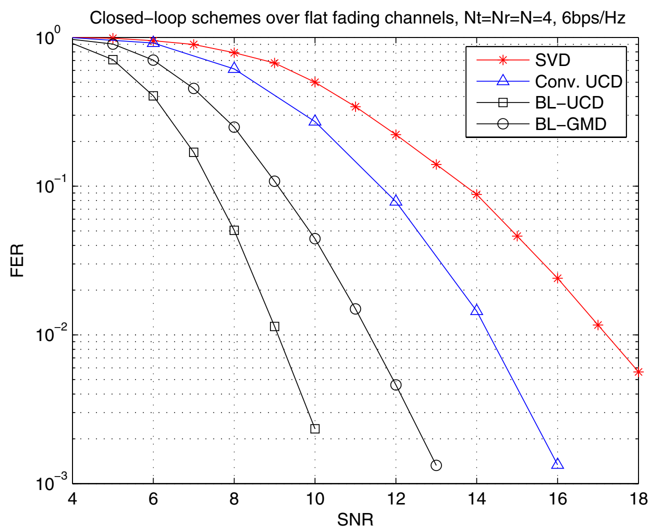

Fig. 3. Performance comparison for 4QAM and $R_c = 3/4$

the performance of the conventional UCD with SIC. We also demonstrate that our techniques are quite effective in achieving the diversity gain when transmitting full spatial streams with high code rates.

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