***Communications and Network*, 2013, 5, 119-126**
http://dx.doi.org/10.4236/cn.2013.53B2023 Published Online September 2013 (http://www.scirp.org/journal/cn)

One-User/One-Group Soft-Decision Aided Multiuser Detection for 2D Spread MC DS-CDMAs

Hoang-Yang Lu, I-Hsuan Lai
Dept. of Electrical Engineering, National Taiwan Ocean University.
Email: hylu@mail.ntou.edu.tw, rockrice043@gmail.com

Received June, 2013

ABSTRACT

We consider the uplink of a multiuser, multiple-input multiple-output (MIMO), frequency-time-domain spread, multi-carrier (MC), direct sequence code division multiple access (DS-CDMA) system. As other CDMA-like systems, the multiple access interference (MAI) effect still exists in such an MC DS-CDMA system. To mitigate the MAI effect, we propose user-based and group-based layered detection schemes. Specifically, to enable a trade-off between the performance and the computational complexity, the schemes only use one user's/group's soft decisions for user-based/group-based layered detection. The results of simulations demonstrate that the proposed schemes outperform existing approaches, and their computational complexity is modest.

Keywords: Multiuser detection, MC DS-CDMA, VBLAST, MIMO

1. Introduction

The rapidly increasing demand for better quality of service (QoS) in wireless systems has motivated the development of several promising approaches to improve system capacity and transmission reliability. One promising multiple access approach for sharing valuable bandwidth resources is called multi-carrier (MC) direct sequence code division multiple access (DS-CDMA) [1,2]. Recently, a new MC scheme, called frequency-time-domain (FT-domain) spread MC DS-CDMA, was proposed in [3]. The scheme first spreads the transmitted symbol by a time-domain (T-domain) signature code. Then, the T-domain spreading signal is copied to each subcarrier to be spread by a frequency-domain (F-domain) signature code. In addition to providing the superior capacity performance gain, FT-domain spread MC DS-CDMA systems have other attractive features, such as short and low-chip-rate signature codes for realizing low-rate signal processing [4].

It has been shown that multiple-input multiple output (MIMO) systems, which deploy multiple antennas on the transmitter side and the receiver side, can yield a significant performance gain for wireless communications [5]. Spatial multiplexing (SM), one of the key MIMO technologies [5], uses multiple transmit antennas in parallel to send multiple symbols to the receiver. In particular, to facilitate symbol detection in SM-based MIMO systems, an effective layered detection scheme, called Vertical Bell Laboratories Layered Space-Time (VBLAST), was proposed in [5,6]. Because of VBLAST's efficiency and feasibility, SM-based MIMO systems can provide high throughput, and they have motivated a considerable amount of research on applications and extensions of VBLAST [7,8]. For example, Sfar et al. extended the SM-based MIMO systems to SM-based MIMO CDMA systems and presented a layered space-time (LAST) MUD that detects transmitted messages symbol by symbol [7]. The symbol-based LAST MUD is actually a variant of VBLAST; however, its computational complexity is very high, so it is not feasible in practice. To reduce the computational complexity, a user-based LAST MUD was proposed in [8]. The mechanism is similar to the symbol-based LAST MUD, but it performs layered symbol detection user by user. In contrast to the symbol-based LAST MUD, the user-based LAST MUD reduces the computational complexity at the expense of performance degradation. Furthermore, like VBLAST, both of the LAST MUD schemes need to rank the detection order of the residual layered signals before detecting the symbols in each layer. Hence, they inevitably incur an extra computational overhead and also suffer from serious latency problems. Furthermore, the results reported in [7,8] demonstrate that the performance of MUDs degrades substantially when the length of the signature codes decreases. To resolve the above problems, it is necessary to develop advanced layered detection schemes for such CDMA-like systems.

In this paper, our objective is to exploit the advantages of FT-domain spread MC DS-CDMA and MIMO systems in order to provide advanced QoS in future wireless communications. To this end, we investigate the uplink of a multiuser MIMO FT-domain spread MC DS-CDMA system, which is an extension of the MIMO CDMA system considered in [7,8]. In the proposed FT-domain spread MC DS-CDMA system, users are also arranged in groups; and each user is assigned a unique T-domain signature code and shares an F-domain signature code with users in the same group. Furthermore, like the SM method, each user employs his/her T-domain and F-domain signature codes to spread the multiple symbols. The spreading signals are then transmitted in parallel from the corresponding multiple antennas over fading channels to the antenna array at the base station. However, the MAI effect, which is caused by the non-orthogonality of signature codes and is the main performance limitation, also affects the investigated MC DS-CDMA system. To mitigate the MAI effect, we propose a one-user soft-decision aided user-based layered (OUSDA-UL) MUD. Our approach ranks the detection order by exploiting users' effective code correlation matrices, and then performs layered symbol detection with the assistance of the previous user's soft decisions [9]. That is the proposed OUSDA-UL scheme sequentially detects a subset of all transmitted symbols stage by stage (i.e. user by user). Moreover, in each stage, the soft decisions for the corresponding transmitted symbols are estimated in parallel and collected for use in the next stage's symbol detection operation. To further reduce the computational complexity, we propose a one-group soft-decision aided group- based layered (OGSDA-GL) MUD. It estimates more transmitted symbols in parallel than the proposed OUSDA-UL scheme; hence, its computational complexity is lower. To enable a trade-off between the system performance and computational complexity, the two schemes only utilize one user's (or one group's) soft decisions to facilitate user-based/group-based layered detection. The soft mechanisms incorporated by existing works usually enhance the system performance at the expense of high computational complexity. Under the trade-off between the performance and computational complexity, the proposed schemes only return partial soft decisions (i.e. one-user's soft-decisions or one-group's soft-decisions) to mitigate interference in the next stage. Finally, the results of extensive simulations show that the proposed MUDs outperform existing approaches and their computational complexity is modest.

Before discussing the system model, we introduce the notations used throughout the paper: $E\{\cdot\}$, $(\cdot)^T$, $(\cdot)^H$, and $FFT(\cdot)$ denote the expectation, the transpose, the Hermitian, and the fast Fourier transform (FFT) operations respectively [10]; $\otimes$ denotes the Kronecker product operator [10]; $\|\cdot\|$ and $\|\cdot\|_F$ represent the Euclidean norm and the Frobenius norm respectively [10]; and $\mathbf{I}_M$, $\bar{\mathbf{0}}_P$, and $\mathbf{0}_L$ denote the $M \times M$ identity matrix, the $P \times 1$ zero vector, and the $L \times L$ zero matrix respectively. The ranges of the indices $i, l, k,$ and g are $1 \le i \le M_R$, $1 \le l \le M_T$, $1 \le k \le K$, and $1 \le g \le G$ respectively. We explain M_R, M_T, K, and G in Section II.

2. Signal Model

Consider a synchronous uplink multiuser MIMO FT-domain spread MC DS-CDMA system. Each user is assigned a unique T-domain signature code and M_T transmit antennas, which are deployed under the SM-based symbol transmission method. In addition, as in [7, 8], users are organized into G groups, and users in the same group share a unique F-domain signature code. For ease of presentation, we assume that the number of users in each group is K. Denote $\mathbf{t}_{g_k} = [t_{g_k,1}\, t_{g_k,2} \cdots t_{g_k,N_t}]^T$ and $\mathbf{f}_g = [f_{g,1}\ f_{g,2} \cdots f_{g,N_f}]^T$, respectively, as the T-domain and F-domain signature codes of the *k*th user in the *g*th group. Here, N_t and N_f are the processing gains of the corresponding signature codes. Each user employs his unique T-domain signature code to spread the M_T binary phase shift keying (BPSK) modulated symbols. Then, the T-domain spreading signals are copied to N_f sub-carriers, and spread by using the corresponding F-domain signature code. After spreading the symbols in the T-domain and F-domain, applying the inverse FFT algorithm, and inserting a cyclic prefix (CP) [2], the user's M_T spreading signals are transmitted in parallel by the M_T transmit antennas over the complex-valued, frequency selective Rayleigh fading channels to the base station. Let M_R receive antennas be deployed at the base station. For simplicity, we assume that the length of all fading channels available to all users is equal to Q [11]. In addition, the complex-valued channel coefficients between the *i*th receive antenna and the *l*th transmit antenna of the *k*th user in the *g*th group are denoted as $\{h^i_{g_k,l}(1), \cdots h^i_{g_k,l}(Q)\}$. We also assume that after removing the CP and performing the FFT operation, the signal will be received successfully. As a result, at the base station's receiver, the corresponding $N_f \times N_f$ diagonal matrix of the F-domain channel's transfer function is

$$\mathbf{H}^i_{g_k,l} = diag(FFT[h^i_{g_k,l}(1), \cdots h^i_{g_k,l}(Q), \bar{\mathbf{0}}^T_{N_f - Q}]);$$

Hence, the associative $N_f \times 1$ effective F-domain signature code is $\tilde{\boldsymbol{f}}^i_{g_k,l} = \boldsymbol{H}^i_{g_k,l} \boldsymbol{f}_g$. Now, the signal received at the base station's *i*th receive antenna can be expressed as follows:

$$\mathbf{r}^i = \sum_{g=1}^{G} \sum_{k=1}^{K} \sum_{l=1}^{M_T} \mathbf{c}^i_{g_k,l} \mathrm{b}_{g_k,l} + \mathbf{n}^i, \tag{1}$$

where $\mathbf{c}^i_{g_k,l} = \mathbf{f}^i_{g_k,l} \otimes \mathbf{t}_{g_k}$ is the effective $N_f N_t \times 1$ FT-domain signature code between the base station's *i*th receive antenna and the *l*th transmit antenna of the *k*th user in the *g*th group; and $\mathbf{n}^i$ is the corresponding $N_f N_t \times 1$ additive white Gaussian noise (AWGN) vector with each entry $\sim \mathcal{CN}(0,\sigma^2)$. For ease of expression, we stack the M_T transmitted BPSK symbols of the *k*th user in the *g*th group to form the user-based transmitted symbol vector $\mathbf{b}_{gk} = [b_{gk,1}, b_{gk,2}, \cdots, b_{gk,M_T}]^T$ and then re-express (1) as follows:

$$\mathbf{r}^i = \sum_{g=1}^{G}\sum_{k=1}^{K}\mathbf{C}^i_{gk}\mathbf{b}_{gk} + \mathbf{n}^i. \tag{2}$$

Here, $\boldsymbol{C}^i_{gk} = [\boldsymbol{c}^i_{gk,1}\, \boldsymbol{c}^i_{gk,2} \cdots \boldsymbol{c}^i_{gk,M_T}]$ is the corresponding $N_f N_t \times M_T$ user-based effective FT-domain spreading matrix between the *i*th receive antenna and the *k*th user in the *g*th group. Similarly, we can stack the *K* transmitted symbol vectors $\mathbf{b}_{gk}$ of the *g*th group as a $KM_T \times 1$ group-based transmitted symbol vector

$$\mathbf{b}_g = [\mathbf{b}^T_{g1}, \mathbf{b}^T_{g2}, \cdots, \mathbf{b}^T_{gK}]^T .$$

Then, (2) can be re-written as follows:

$$\mathbf{r}^i = \sum_{g=1}^{G}\mathbf{C}^i_g\mathbf{b}_g + \mathbf{n}^i, \tag{3}$$

where $\mathbf{C}^i_g = [\mathbf{C}^i_{g1}\, \mathbf{C}^i_{g2} \cdots \mathbf{C}^i_{gK}]$ is the effective associative $N_f N_t \times KM_T$ group-based FT-domain spreading matrix between the *i*th receive antenna and the *g*th group. Then, by stacking the *G* group-based symbol vectors, $\mathbf{b}_1, \cdots \mathbf{b}_G$, we can re-express (3) as follows: $\mathbf{r}^i = \mathbf{C}^i\,\mathbf{b} + \mathbf{n}^i$, where $\mathbf{b} = [\mathbf{b}^T_1\, \mathbf{b}^T_2 \cdots \mathbf{b}^T_G]^T$ and $\mathbf{C}^i = [\mathbf{C}^i_1\, \mathbf{C}^i_2 \cdots \mathbf{C}^i_G]$ are the corresponding $GKM_T \times 1$ transmitted symbol vector and the effective $N_f N_t \times GKM_T$ FT-domain spreading matrix between the *i*th receive antenna and all the transmit antennas. Finally, following [7,8], we use the effective M_R FT-domain spreading matrices, $\mathbf{C}^i$, to match the corresponding signals received by the base station's M_R receive antennas. Then, the sufficient statistics for the received signal at the base station can be formulated as follows:

$$\mathbf{z} = \sum_{i=1}^{M_R}\mathbf{C}^{iH}\mathbf{r}^i = \mathbf{R}\,\mathbf{b} + \mathbf{u}, \tag{4}$$

where $\mathbf{R} = \sum_{i=1}^{M_R}\mathbf{C}^{iH}\mathbf{C}^i$ is the effective spatial-frequency-time (SFT) code correlation matrix; and *u* is the corresponding complex Gaussian noise vector with $\mathcal{CN}(0,\sigma^2 R)$.

3. The Proposed One-User-Soft-Decision Aided User-Based Layered MUD

The proposed OUSDA-UL MUD first ranks the detection order based on the users' effective code correlation matrices. Then, it utilizes the ordered results to successively implement the corresponding user-based MMSE layered detectors and estimate the transmitted symbols.

3.1. User-based Ordering

To avoid a large computational overhead for ranking the detection order, the proposed OUSDA-UL MUD computes the Frobenius norm [10] of the users' effective SFT code correlation matrices and then sorts the matrices in a descending order. For the *k*th user in the *g*th group, the Frobenius norm is formulated as follows:

$$\|\mathbf{R}_{gk}\|_F = \|\sum_{i=1}^{M_R}\mathbf{C}^{iH}_{gk}\mathbf{C}^i_{gk}\|_F, \tag{5}$$

where $\mathbf{R}_{gk}$ is the effective SFT code correlation matrix of the *k*th user in the *g*th group. Note that we assume the coefficients of the user's fading channels are fixed in a frame and change frame by frame [5]. Hence, for each user, (5) is computed in just one pass per frame. As a result, the proposed scheme avoids the ordering problem observed in [6-8], which affects VBLAST-like schemes. In [6-8], the ordering mechanisms compute undetected symbols stage by stage (i.e. symbol by symbol, or user by user) by searching the maximization post signal-to-noise-ratio outputs of the corresponding detectors. However, because the detectors for the undetected symbols need to be computed stage by stage, the computational complexity is usually prohibitive.

3.2. User-based Interference Cancellation and Layered Symbol Detection

Without loss of generality, we assume that (1) after the user-based ordering step, the indices of the detection order are $1_1, 1_2, \cdots, g_k, \cdots, G_K$; and (2) the interference caused by users $1_1, 1_2, \cdots, g_{k-2}$ has been estimated precisely and removed from the received signal. Then, in this step, we perform user-based layered symbol detection and interference cancellation (IC) to estimate the transmitted symbols for the *k*th user in group *g*. Using $()$, the residual sufficient statistics of the corresponding signal $\bar{\mathbf{z}}_{g_{k-1}}$ can be formulated as

$$\bar{\mathbf{z}}_{g_{k-1}} = \bar{\mathbf{R}}_{g_{k-1}}\bar{\mathbf{b}}_{g_{k-1}} + \bar{\mathbf{u}}_{g_{k-1}}, \tag{6}$$

where $\bar{\mathbf{R}}_{g_{k-1}}$ is the sub-block matrix obtained by removing the corresponding rows and columns of the 1_1 th, 1_2 th, $\cdots$, g_{k-2} th users from the effective SFT code correlation matrix *R*; and $u_{g_{k-1}}$ is the corresponding Gaussian noise vector. Then, to estimate the transmitted symbols of the g_k th user b_{g_k}, we utilize the user-based layered MMSE symbol detector with the soft decisions of the g_{k-1} th user and derive

$$arg \min_{\bar{\mathbf{w}}_{g_k},\tilde{\mathbf{b}}_{g_{k-1}}} E\left[\|\mathbf{b}_{g_k} - \bar{\mathbf{W}}^H_{g_k}\bar{\mathbf{z}}_{g_{k-1}} - \tilde{\mathbf{b}}_{g_{k-1}}\|^2\right], \tag{7}$$

where $\bar{\mathbf{W}}_{g_k}$ denotes the g_k th user's $D \times M_T$ layered

MMSE symbol detector in which $D=(G-g)KM_T+(K-k+2)M_T$; $\tilde{\mathbf{b}}_{g_{k-1}}$ is the $M_T\times 1$ soft information vector gleaned from the g_{k-1}th user's soft decisions. From (7), it is clear that the proposed OUSDA-UL MUD attempts to fully exploit the last user's soft information vector $\tilde{\mathbf{b}}_{g_{k-1}}$ in order to enhance the performance of the *k*th user in the *g*th group. Using (7), and after some manipulation, $\overline{\mathbf{W}}_{g_k}$ and $\tilde{\mathbf{b}}_{g_{k-1}}$ can be formulated as follows:

$$\overline{\mathbf{W}}_{g_k}=(E\{\bar{\mathbf{z}}_{g_{k-1}}\bar{\mathbf{z}}^H_{g_{k-1}}\})^{-1}(E\{\bar{\mathbf{z}}_{g_{k-1}}\mathbf{b}^T_{g_k}\}-E\{\bar{\mathbf{z}}_{g_{k-1}}\}\tilde{\mathbf{b}}^H_{g_{k-1}}), \quad (8)$$

and

$$\tilde{\mathbf{b}}_{g_{k-1}}=-\overline{\mathbf{W}}^H_{g_k}E\{\bar{\mathbf{z}}_{g_{k-1}}\}, \quad (9)$$

respectively. Furthermore, we assume that the transmitted symbols and noise are mutually uncorrelated and the transmitted symbols are BPSK modulated and i.i.d. [11]. We also assume that the transmitted symbols are BPSK modulated because of the ease of derivation. In addition, we assume that the transmission signals of the 1_1th, 1_2th, $\cdots$, g_{k-2}th users have been estimated exactly and removed from $\mathbf{z}$ in (4). Hence, the residual sufficient statistics $\bar{\mathbf{z}}_{g_{k-1}}$ in (6) contain the transmission signals of the g_{k-1}th, g_kth, $\cdots$, and G_K th users. Note that, because we utilize the g_{k-1}th user's soft decisions when estimating the g_kth user's transmitted symbols $\mathbf{b}_{g_k}$ in (7), $\bar{\mathbf{z}}_{g_{k-1}}$ must contain the g_{k-1}th user's transmitted signal. Based on the above assumptions and after some manipulations of (9) and (10), we have

$$E\{\bar{\mathbf{z}}_{g_{k-1}}\}=\overline{\mathbf{R}}_{g_{k-1}}E\{\bar{\mathbf{b}}_{g_{k-1}}\}, \quad (10)$$

$$E\{\bar{\mathbf{z}}_{g_{k-1}}\mathbf{b}^T_{g_k}\}=\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}}, \quad (11)$$

$$E\{\bar{\mathbf{z}}_{g_{k-1}}\bar{\mathbf{z}}^H_{g_{k-1}}\}=\overline{\mathbf{R}}_{g_{k-1}}E\{\bar{\mathbf{b}}_{g_{k-1}}\bar{\mathbf{b}}^T_{g_{k-1}}\}\overline{\mathbf{R}}^H_{g_{k-1}}+\sigma^2\overline{\mathbf{R}}_{g_{k-1}}, \quad (12)$$

where $E\{\bar{\mathbf{b}}_{g_{k-1}}\}=[\hat{b}_{g_{k-1},1},\hat{b}_{g_{k-1},2},\cdots,\hat{b}_{g_{k-1},M_T},\bar{\mathbf{0}}^T_{D-M_T}]^T$. Here,

$$\hat{b}_{g_{k-1},l}=\tanh(\frac{1}{2}\bar{\lambda}(b_{g_{k-1},l})), \quad \text{and} \quad \bar{\lambda}(b_{g_{k-1},l})$$

is the soft decision [9] for the BPSK symbol of the $(k-1)$th user in the *g*th group transmitted by the *l*th transmit antenna; $\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}}$ is the $D\times M_T$ sub-block matrix of the SFT code correlation matrix $\mathbf{R}_{g_{k-1}}$ for the *k*th user of the *g*th group; and

$$E\{\bar{\mathbf{b}}_{g_{k-1}}\bar{\mathbf{b}}^T_{g_{k-1}}\}=\begin{bmatrix} E\{\mathbf{b}_{g_{k-1}}\mathbf{b}^T_{g_{k-1}}\} & \mathbf{0}_{M_T} & \cdots & \mathbf{0}_{M_T} \\ \mathbf{0}_{M_T} & \mathbf{I}_{M_T} & \ddots & \vdots \\ \vdots & \vdots & \cdots & \mathbf{I}_{M_T} \end{bmatrix}, \quad (13)$$

where

$$[E\{\mathbf{b}_{g_{k-1}}\mathbf{b}^T_{g_{k-1}}\}]_{i,j}=\begin{cases} \hat{b}_{g_{k-1},i}\hat{b}_{g_{k-1},j}, & i\neq j, \\ 1, & otherwise, \end{cases} \quad (14)$$

where $[\mathbf{X}]_{i,j}$ denotes the (i,j)th entry of matrix $\mathbf{X}$. After some manipulations (described in the Appendix) we have

$$\overline{\mathbf{W}}_{g_k}=(\mathbf{I}_{D\times D}-\mathbf{A}^{-1}\mathbf{B}\mathbf{B}^H)^{-1}\mathbf{A}^{-1}\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}}, \quad (15)$$

where we let $\mathbf{A}=\overline{\mathbf{R}}_{g_{k-1}}E\{\bar{\mathbf{b}}_{g_{k-1}}\bar{\mathbf{b}}^T_{g_{k-1}}\}\overline{\mathbf{R}}^H_{g_{k-1}}+\sigma^2\overline{\mathbf{R}}_{g_{k-1}}$ and $\mathbf{B}=\overline{\mathbf{R}}_{g_{k-1}}E\{\bar{\mathbf{b}}_{g_{k-1}}\}$. Using (15) to find $\bar{\mathbf{b}}_{g_{k-1}}$, (9) can be rewritten as follows:

$$\tilde{\mathbf{b}}_{g_{k-1}}=\mathbf{Y}\times\overline{\mathbf{R}}_{g_{k-1}}E\{\bar{\mathbf{b}}_{g_{k-1}}\}. \quad (16)$$

where $\mathbf{Y}=-((\mathbf{I}_{D\times D}-\mathbf{A}^{-1}\mathbf{B}\mathbf{B}^H)^{-1}\mathbf{A}^{-1}\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}})^H$. We also derive the expression of the above soft decision $\bar{\lambda}(b_{g_{k-1},l})$ in (10). For this, we denote the lth column of $\overline{\mathbf{W}}_{g_k}$ as $[\overline{\mathbf{W}}_{g_k}]_{:,l}$, which is the layered MMSE symbol detector for the *k*th user in the *g*th group transmitted from the *l*th transmit antenna. In addition, we let $\tilde{b}_{g_{k-1},l}$, be the corresponding soft information of the $(k-1)$th user in the *g*th group, which is the *l*th entry of $\tilde{\mathbf{b}}_{g_{k-1}}$ in (16). Then, we can express the corresponding output of the layered MMSE symbol detector as follows:

$$\bar{y}_{g_k,l}=[\overline{\mathbf{W}}_{g_k}]^H_{:,l}\bar{\mathbf{z}}_{g_{k-1}}+\tilde{b}_{g_{k-1},l}, \quad (17)$$

Furthermore, following [9], we regard the output of the layered MMSE detector, $\bar{y}_{g_{k-1},l}$, as approximately Gaussian. Hence, the corresponding soft decision can be represented as

$$\bar{\lambda}(b_{g_k,l})=\log\frac{p(\bar{y}_{g_k,l}|b_{g_k,l}=+1)}{p(\bar{y}_{g_k,l}|b_{g_k,l}=-1)}=\frac{2\times\bar{y}_{g_k,l}\times\bar{m}_{g_k,l}}{\bar{\sigma}^2_{g_k,i}}, \quad (18)$$

where $\bar{m}_{g_k,i}$ and $\bar{\sigma}^2_{g_k,i}$ are the corresponding equivalent mean and variance of the layered MMSE detector's output, expressed as

$$\bar{m}_{g_k,l}=E\{\bar{y}_{g_k,l}b_{g_k,l}\}=[\overline{\mathbf{W}}_{g_k}]^H_{:,l}[\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}}]_{:,l},$$
$$\bar{\sigma}^2_{g_k,l}=var\{[\overline{\mathbf{W}}_{g_k}]^H_{:,l}\bar{\mathbf{u}}_{g_{k-1}}\}=\sigma^2[\overline{\mathbf{W}}_{g_k}]^H_{:,l}\overline{\mathbf{R}}_{g_{k-1}}[\overline{\mathbf{W}}_{g_k}]_{:,l},$$

where $[\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}}]_{:,l}$ is the *l*th column vector of $\overline{\mathbf{R}}^{(g_k)}_{g_{k-1}}$. Note that, for the *k*th user in the *g*th group, we use (15) and (16) to apply the M_T layered MMSE symbol detectors $[\overline{\mathbf{W}}_{g_k}]_{:,l}, l=1\cdots M_T$, concurrently. Then, we utilize the corresponding M_T soft decisions in (18) to help detect the M_T symbols of the $(k+1)$th user in the *g*th group. In other words, the proposed OUSDA-UL MUD estimates the M_T transmitted symbols user-layer by user-layer.

4. The Proposed One-Group-Soft-Decision Aided Group-Based Layered MUD

To reduce the computational complexity of estimating transmitted signals, we propose the OGSDA-GL MUD scheme. It is similar to the OUSDA-UL MUD scheme, but it detects transmitted symbols in a group-layer by group-layer manner. The steps of OGSDA-GL MUD are detailed below.

4.1. Group-based Ordering

Similar to the OUSDA-UL MUD, the signals of the group-layers are ordered by using the Frobenius norms of the groups' effective SFT code correlation matrices, given by

$$\|\mathbf{R}_g\|_F=\|\sum_{i=1}^{M_R}\mathbf{C}_g^{iH}\mathbf{C}_g^i\|_F, \tag{19}$$

where $\mathbf{R}_g$ is the gth group's effective SFT code correlation matrix. Here, $\mathbf{C}_g^i$ is the corresponding effective FT-domain signature matrix defined in (3).

4.2. Group-based IC and Layered Symbol Detection

Without loss of generality, we assume that after the group-based ordering step, the order of the indices is 1, 2, $\cdots$, G. We also assume that the interference caused by the transmitted signals of the 1st, 2nd, $\cdots$, $(g-2)$th groups was estimated precisely and removed from the received signal in (4). Then, as in (6), the sufficient statistics of the corresponding residual signal, $\mathbf{z}_{g-1}$, can be expressed as follows:

$$\breve{\mathbf{z}}_{g-1}=\breve{\mathbf{R}}_{g-1}\breve{\mathbf{b}}_{g-1}+\breve{\mathbf{u}}_{g-1}, \tag{20}$$

where $\breve{\mathbf{R}}_{g-1}$ is the sub-block matrix derived by removing the corresponding rows and columns of the 1st, 2nd, $\cdots$, $(g-2)$th groups from the SFT code correlation matrix $\mathbf{R}$; and $\breve{\mathbf{b}}_{g-1}=[\mathbf{b}_{g-1}^T,\mathbf{b}_g^T,\cdots,\mathbf{b}_G^T]^T$ and $\breve{\mathbf{u}}_{g-1}$ are the associative residual symbol vector and noise vector respectively. Furthermore, similar to (7)-(16) and based on the MMSE method, the group-based layered MMSE detector $\breve{\mathbf{W}}_g$ and the corresponding soft information vector $\breve{\mathbf{b}}_{g-1}$ of the $(g-1)$th group can be expressed as

$$\breve{\mathbf{W}}_g=(\mathbf{I}_{\breve{D}\times\breve{D}}-\breve{\mathbf{A}}^{-1}\breve{\mathbf{B}}\breve{\mathbf{B}}^H)^{-1}\breve{\mathbf{A}}^{-1}\breve{\mathbf{R}}_{g-1}^{(g)}, \tag{21}$$

and

$$\tilde{\mathbf{b}}_{g-1}=-((\mathbf{I}_{\breve{D}\times\breve{D}}-\breve{\mathbf{A}}^{-1}\breve{\mathbf{B}}\breve{\mathbf{B}}^H)^{-1}\breve{\mathbf{A}}^{-1}\breve{\mathbf{R}}_{g-1}^{(g)})^H\breve{\mathbf{R}}_{g-1}E\{\breve{\mathbf{b}}_{g-1}\}, \tag{22}$$

respectively, where we let

$$\breve{\mathbf{A}}=\breve{\mathbf{R}}_{g-1}E\{\breve{\mathbf{b}}_{g-1}\breve{\mathbf{b}}_{g-1}{}^T\}\breve{\mathbf{R}}_{g-1}^H+\sigma^2\breve{\mathbf{R}}_{g-1} \text{ and } \breve{\mathbf{B}}=\breve{\mathbf{R}}_{g-1}E\{\breve{\mathbf{b}}_{g-1}\}.$$

In addition, $\breve{D}=(G-g+2)KM_T$;

$$E\{\breve{\mathbf{b}}_{g-1}\}=[E\{b_{(g-1)_1,1}\},E\{b_{(g-1)_1,2}\},\cdots,E\{\tilde{b}_{(g-1)_K,M_T}\},\bar{\mathbf{0}}_{\breve{D}-KM_T}^T]^T$$

and

$$E\{\breve{\mathbf{b}}_{g-1}\breve{\mathbf{b}}_{g-1}^T\}=\begin{bmatrix} E\{\mathbf{b}_{g-1}\mathbf{b}_{g-1}^T\} & \mathbf{0}_{KM_T} & \cdots & \mathbf{0}_{KM_T} \\ \mathbf{0}_{KM_T} & \mathbf{I}_{KM_T} & \ddots & \vdots \\ \vdots & \vdots & \cdots & \mathbf{I}_{KM_T} \end{bmatrix}, \tag{23}$$

where

$$[E\{\mathbf{b}_{g-1}\mathbf{b}_{g-1}^T\}]_{m,n}=\begin{cases} \hat{b}_{(g-1)_{k_1,i}}\hat{b}_{(g-1)_{k_2,j}}, & k\neq l \text{ or } i\neq j, \\ 1 & \text{otherwise.} \end{cases} \tag{24}$$

Here, we let $m=(k_1-1)M_T+i$ and $n=(k_2-1)M_T+j$, where k_1 *and* $k_2=1\cdots K$, and i *and* $j=1\cdots M_T$. Finally, we assume that the outputs of the group-based layered MMSE detectors in (21) and (22) are approximately Gaussian [9]. Then, the soft decision, $\breve{\lambda}(b_{g_k,l})$, for the kth user in the gth group transmitted by the lth transmit antenna can be expressed as follows:

$$\breve{\lambda}(b_{g_k,l})=\log\frac{p(\breve{y}_{g_k,l}|b_{g_k,l}=+1)}{p(\breve{y}_{g_k,l}|b_{g_k,l}=-1)}=\frac{2\times\breve{y}_{g_k,l}\times\breve{m}_{g_k,l}}{\breve{\sigma}_{g_k,l}^2}, \tag{25}$$

where $\breve{y}_{g_k,l}$, $\breve{m}_{g_k,l}$, $\breve{\sigma}_{g_k,l}^2$ denote the corresponding group-based layered MMSE detectors' output, the mean of the output, and the noise power of the output. They can be written as

$$\breve{y}_{g_k,l}=[\breve{\mathbf{W}}_g]_{:,p}^H\tilde{\mathbf{z}}_{g-1}+[\tilde{\mathbf{b}}_{g-1}]_p, \tag{26}$$

$$\breve{m}_{g_k,l}=[\breve{\mathbf{W}}_g]_{:,p}^H[\breve{\mathbf{R}}_{g-1}^{(g)}]_{:,p}, \tag{27}$$

$$\breve{\sigma}_{g_k,l}^2=\sigma^2[\breve{\mathbf{W}}_g]_{:,p}^H\breve{\mathbf{R}}_{g-1}[\breve{\mathbf{W}}_g]_{:,p}, \tag{28}$$

respectively, where $p=(k-1)M_T+l$. Note that, based on (20)-(27), the proposed OGSDA-GL MUD estimates the KM_T transmitted symbols of the gth group in parallel. It also exploits the soft decisions of the gth group to help the layered MMSE detectors estimate the transmitted symbols of the $(g+1)$th group. This strategy enables the OGSDA-GL MUD to estimate the transmitted symbols group by group.

5. Simulation Results and Discussion

We conducted computer simulations and a complexity analysis to assess the performance of the proposed schemes. For ease of presentation, we assume the channels are complex-valued, frequency selective Rayleigh fading channels, the channel length Q is 3, and the number of receive antennas, M_R, is 4. In addition, the user concurrently transmits the spreading signals in parallel from the M_T transmit antennas over the fading channels to the base station. In the simulations and complexity analysis, we compared the performance of the following six schemes: the linear MMSE SIC [13], the decorrelating detector (DD) [4], the symbol-based LAST MUD [7], the user-based LAST MUD [8], the proposed OUSDA-UL MUD, and the proposed OGSDA-GL MUD. We use a single user's performance (i.e. the performance when the system settings are $G=1$, $K=1$, $M_T=1$, and $M_R=4$) as the benchmark. **Figures 1-4** show the bit error rate (BER) versus the signal to noise ratio (SNR) result of the compared schemes.

To assess the proposed schemes, we assume the system settings are as follows: the number of groups $G=4$, the number of users in each group $K=3$, and the number of transmit antennas of each user $M_T=2$. In addition, we consider two lengths of F-domain and T-domain signature codes: $(N_f=9, N_t=8)$ and $(N_f=12, N_t=8)$. The simulation results for the six schemes are shown in **Figures 1** and **2**. Interestingly, in **Figure 1**, the BER values of the linear MMSE SIC, the DD, the symbol-based LAST MUD, and the user-based LAST MUD hardly change when the SNR $\geq$ 6 dB. That is, they appear to be error-floor phenomena, which usually occur because the receivers cannot mitigate the interference effectively [12]. The results in **Figure 1** also show the proposed OUSDA-UL and OGSDA-GL MUDs are more robust against the MAI effect than the other four methods; hence, they achieve significantly better performance gains. Next, we change the length of the T-domain signature code N_t from 8 to 12 and leave the other system settings the same as those in **Figure 1**. From the results in **Figure 3**, we observe that the BER performance of the six schemes is significantly better than that shown in **Figure 1**. A possible intuitive explanation for this phenomenon is that is due to a reduction in the load.

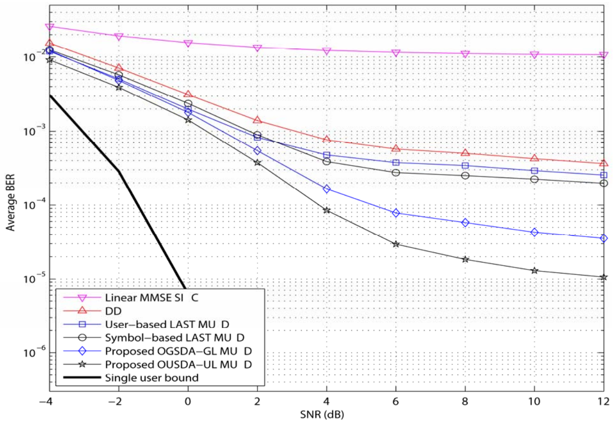

Figure 1. The BER versus the SNR with G = 4, K = 3, M_T = 2, M_R = 4, N_f = 9, N_t = 8.

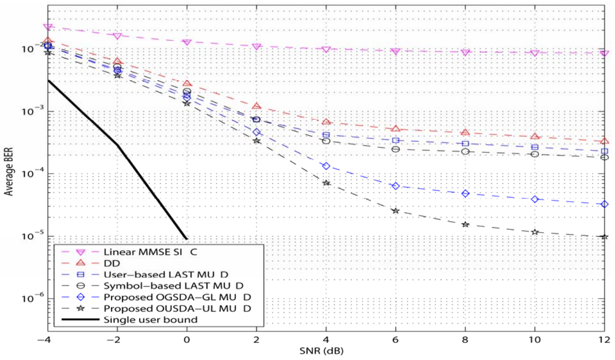

Figure 2. The BER versus the SNR with G = 4, K = 3, M_T = 2, M_R = 4, N_f = 12, N_t = 8.

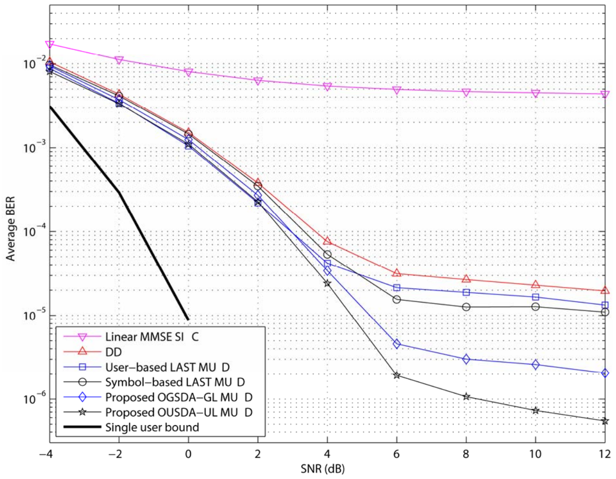

Figure 3. The BER versus the SNR with G = 4, K = 3, M_T = 2, M_R = 4, N_f = 9, N_t = 12.

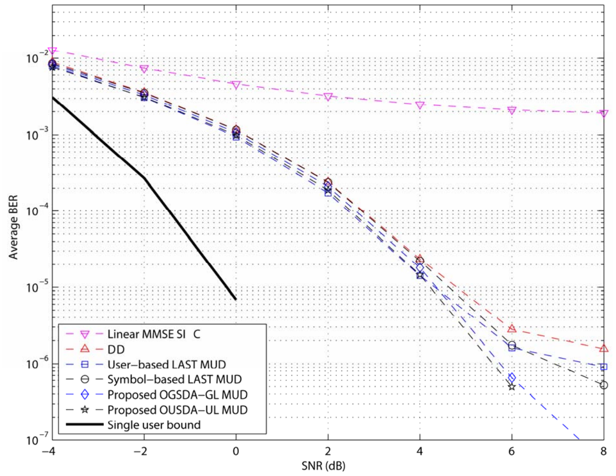

Figure 4. The BER versus the SNR with G = 4, K = 3, M_T = 2, M_R = 4, N_f = 12, N_t = 16.

From the above observations, we conclude that increasing the length of the T-domain signature code in the six schemes is more effective in mitigating the MAI effect than increasing the length of F-domain signature code. Furthermore, as shown in **Figure 3** the proposed OUSDA-UL and OGSDA-GL MUDs also outperform the compared schemes when the length of the T-domain signature code is changed. Overall, the OUSDA-UL MUD achieves the best BER performance. Note that in **Figures 1** and **2**, the error floors of the six schemes occur when the SNR 6 dB. This means that the power of each transmitted symbol is stronger than when the SNR < 6 dB; hence, the interference increases. Since none of the compared schemes can eliminate the interference completely, error floors occur in such scenarios. However, **Figure 1** shows that the proposed schemes outperform the other four schemes.

We also increase the lengths of both types of signature codes from ($N_f=9, N_t=8$) to ($N_f=12, N_t=16$), while maintaining the system settings shown in **Figure 1**. From the results presented in **Figure 4**, we observe that all six schemes perform better than in the scenarios discussed above (i.e., **Figures 1**, **2**, and **3**). This is reasonable because increasing the lengths of the F-domain and the T-domain signature codes individually can mitigate inter-group MAI and inter-user MAI respectively. In this scenario, the proposed OUSDA-UL MUD and OGSDA-GL MUD achieve the best and second best performance gains among the six compared schemes.

Next, we analyze the computational complexity of the six compared schemes. Because computing the inversion of a matrix generally dominates the computational complexity, we focus on that aspect of the schemes. For the proposed OUSDA-UL MUD and OGSDA-GL MUD, we compute the corresponding complex multiplications and additions (CMAs) needed for Equations (15) and (21). Furthermore, approximately P^3 complex CMAs are needed to find the inversion of a $P \times P$ matrix. For ease of reference, we show the expressions of the computational complexity for the six schemes in **Table 1**. For example, in the ($G=4, K=3, M_T=2$) scenario, the linear MMSE SIC, the decorrelating detector (DD), the symbol-based LAST MUD, the user-based LAST MUD, the proposed OUSDA-UL MUD, and the proposed OGSDA-GL MUD require 13844, 13824, 90000, 48672, 97344, and 43200 CMAs respectively. Therefore, the proposed OUSDA- UL MUD needs the largest number of CMAs among the six schemes. This is because it exploits the last user's soft decisions to help improve the BER performance, but the price is an increase in the computational overhead. Meanwhile, the proposed OGSDA-GL MUD needs fewer CMAs than the symbol-based LAST MUD, but more than the user-based LAST MUD. The linear MMSE SIC scheme requires the second lowest amount of computation, but its BER performance is the worst among the six schemes.

Table 1. Comparison of the computational complexity of the proposed schemes.

MUDs	Complex multiplications/additions
Linear MMSE SIC	$(GKM_T)^3 + GKM_T$
DD	$(GKM_T)^3$
Symbol-based LAST	$\sum_{i=0}^{GKM_T-1}(GKM_T - i)^3$
User-based LAST	$\sum_{i=0}^{GK-1}(GKM_T - i * M_T)^3$
Proposed OUSDA-UL	$\sum_{g=1}^{G}\sum_{k=1}^{K}3D^3$
Proposed OGSDA-GL	$\sum_{g=1}^{G}3\breve{D}^3$

7. Conclusions

We have investigated layered symbol detection strategies for the uplink of a multiuser MIMO frequency-time-domain spread MC DS-CDMA system. First, we proposed a scheme called OUSDA-UL MUD, which exploits the last user's soft decisions to help mitigate the MAI effect and improve the BER performance. Second, to reduce the computational complexity, we proposed the OGSDA-GL MUD, which exploits the last group's soft decisions to facilitate layered symbol detection. The results of simulations and a complexity analysis demonstrate that the proposed schemes yield better BER performance gains than existing approaches, but their computational overheads are modest.

8. Acknowledgements

This work was supported by National Taiwan Ocean University of R.O.C. under contract NTOU-101-002.

REFERENCES

[1] M. Jiang and L. Hanzo, "Multiuser MIMO-OFDM for Next-generation Wireless Systems," *Proceedings of IEEE*, Vol. 95, No. 7, 2007, pp. 1430-1469. doi:10.1109/JPROC.2007.898869

[2] M. Guenach and H. Steendam, "Performance Evaluation and Parameter Optimization of MC-CDMA," *IEEE Trans. Vehicular Technology*, Vol. 56, No. 3, 2007, pp. 1165-1175. doi:10.1109/TVT.2007.895605

[3] C. W. You and D. S. Hong, "Multicarrier CDMA Systems Using Time-domain and Frequency-domain Spreading Codes," *IEEE Trans. Commun.*, Vol. 51, No. 1, 2003, pp. 17-21. doi:10.1109/TCOMM.2002.807630

[4] B. Hu, L.-L Yang and L. Hanzo, "Time- and Frquency-Domain-spread Generalized Multicarrier DS-CDMA Using Subspace-based Blind and Group-blind Space-time Multiuser Detection," *IEEE Trans. Vehicular Technology*, Vol. 57, No. 5, 2008, pp. 3235-3241. doi:10.1109/TVT.2008.917231

[5] A. Paulraj, R. Nabar and D. Gore, *Introduction to Space-Time Wireless Communications*, Cambridge University Press, 2003.

[6] G. J. Foschini, G. D. Golden, R. A. Valenzuela and P. W. Wolniansky, "Simplified Processing for High Spectral Efficiency Wireless Communication Employing Multi-element Arrays," *IEEE J. Select. Areas Commun.*, Vol. 17, No. 11, 1999, pp. 1841-1852. doi:10.1109/49.806815

[7] S. Sfar, R. D. Murch and K. B. Letaief, "Layered Space-time Multiuser Detection over Wireless Uplink Systems," *IEEE Transactions Wireless Communications*, Vol. 2, No. 4, 2003, pp. 653-668. doi:10.1109/TWC.2003.814337

[8] S. Sfar and K. B. Letaief, "Layered Group Detection for Multiuser MIMO Wireless CDMA Systems," *IEEE Transactions Wireless Communications*, Vol. 5, No. 9,

2006, pp. 2305-2311. doi:10.1109/TWC.2006.1687748

[9] X. Wang and H. V. Poor, *Wireless Communication Systems.* Pearson Edu., Inc., NJ, 2004.

[10] T. K. Moon and W. C. Stirling, *Mathematical Method and Algorithms for Signal Processing.* Prentice Hall, 2000.

[11] J. G. Proakis and M. Salehi, *Digital Communications.* 5th ed. McGraw-Hill, 2008.

[12] R. C. de Lamare and R. Sampaio-Neto, "Minimum Mean-squared Error Iterative Successive Parallel Arbitrated Decision Feedback Detectors for DS-CDMA Systems," *IEEE Transactions Communications*, Vol. 56, No. 5, 2008, pp. 778-789. doi:10.1109/TCOMM.2008.060209

[13] A. Bentrcia, A. Zerguine, A. U. Sheikh and M. Benyoucef, "A New Linear Group-wise SIC Multiuser Detector," *IEEE Communications Letters*, Vol. 11, No. 2, 2007, pp. 176 - 178. doi:10.1109/LCOMM.2007.061472