Adaptive Mode Selection for Multiuser MIMO Downlink Systems

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***Abstract*— This paper proposes a block diagonalization (BD) method, which nullifies the multiuser interference and, hence, increases the sum capacity in a multiuser multiple-input multiple-output (MU-MIMO) downlink system. The proposed BD scheme employs all users' receive processing as well as channel information. In addition, this paper proposes three adaptive mode selection schemes for the proposed BD: namely, an exhaustive mode search (EMS); an up-tree-based mode search (UTMS); and a down-tree-based mode search (DTMS). The EMS is a greedy search, whereas UTMS and DTMS are simplified searches that reduce the EMS computations significantly but have almost the same performance as the EMS. Simulation results show that the proposed BD method with the proposed adaptive mode selection schemes can increase the sum capacity significantly.**

I. Introduction

This paper considers a multiuser multiple-input multiple-output (MU-MIMO) system, assuming that both a transmitter (TX) and a receiver (RX) have perfect channel information. A dirty paper coding (DPC) was introduced for the MU-MIMO system to maximize channel capacity [1], i.e., the sum capacity (bits/sec/Hz) of all users. However, the DPC is difficult to apply in practice because it is a nonlinear scheme. Hence, as an alternative suboptimal technique, a block diagonalization (BD) method was recently proposed to increase the capacity of a MU-MIMO system [2], [3]. BD is a linear processing at a TX and decomposes a multiuser MIMO channel into multiple single-user MIMO (SU-MIMO) channels.

In [2] and [3], a preprocessing technique for BD at a TX was proposed by using only channel information of all users to cancel inter-user interference (IUI). In [4], an eigenmode selection technique was applied for the BD with a known SU-MIMO technique [5]-[7]. However, in [4], the eigenmode selection was made with only knowledge of channel information, excluding RX processing of users as the other works in [2], [3]. In [8], an enhanced preprocessing technique at a TX was proposed by employing all users' RX processing in addition to all users' channel information. However, the BD technique in [8] requires an iterative processing between a TX and a RX. This iteration can increase the complexity of the system and hence, this is the motivation of the current paper.

An objective of this current paper is to reduce the complexity of a BD processing but maintain performance. Another objective is to propose a method similar to the eigenmode selection in [4], but to include all users' RX processing information to maximize capacity as the one in [8].

Adaptive mode selection that depends on channel information was not considered in [8]. A mode defines a combination of the number of streams for each user. Each stream corresponds to a singular value of SU-MIMO channel after BD of MU-MIMO channel. This current paper proposes to use BD with adaptive mode selection in a MU-MIMO system. It is expected that the proposed adaptive mode selection can have a higher capacity than a fixed mode. In other words, a higher diversity can be achieved if the number of streams is adaptively assigned for each user, depending on channel and SNR. This paper will provide an adaptive mode selection methods for a MU-MIMO system and justify the expected results through simulation, by showing significant improvement of the sum capacity.

Section II describes a MU-MIMO system model. Section III reviews the existing BD methods for a MU-MIMO system. Section IV presents the proposed adaptive mode selection methods. Section V provides simulation results. Section VI concludes the paper.

II. Multiuser MIMO System Model

Fig. 1 shows a block of a MU-MIMO downlink system. Let k denote the index of the kth user mobile station (MS), where the system supports K users. Also let N_T and $N_{R,k}$ denote, respectively, the number of TX antennas at a base station (BS) and the number of RX antennas at the kth user, $k \in \{1, 2, \cdots, K\}$. The $\mathbf{x}_k$ denotes a $L_k \times 1$ symbol vector from the kth user, where L_k is the number of streams. This paper assumes that the minimum number of L_k is one, because the system supports at least one stream per user for fairness. The $\mathbf{x}_k$ can be written as $\mathbf{x}_k = [x_{k,1}, x_{k,2}, \cdots, x_{k,L_k}]^T$, where $x_{k,l}$ is the lth symbol, $l \in \{1, 2, \cdots, L_k\}$, and the superscripts T and H, respectively, denote the transpose and the Hermitian, i.e., the conjugate transpose operation. The symbol vector $\mathbf{x}_k$ is fed into the transmit-preprocessor $\mathbf{T}_k \in$

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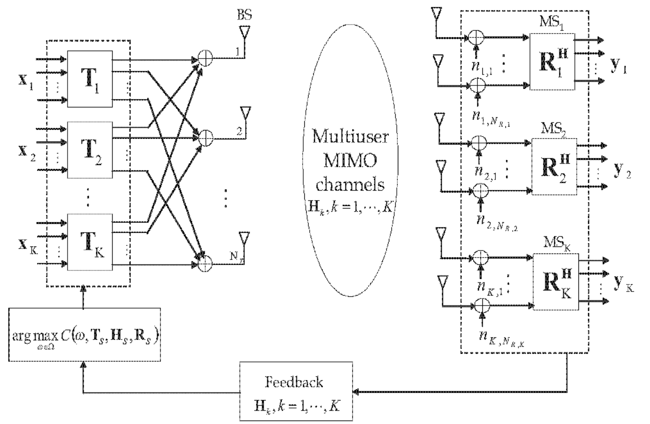

Fig. 1. A block diagram of a multiuser MIMO downlink system with an adaptive spatial mode selection.

$\mathbb{C}^{N_T \times L_k}$. The K output vectors of each dimension $N_T \times 1$ are summed and transmitted through the N_T BS antennas. Let $\mathbf{H}_k \in \mathbb{C}^{N_{R,k} \times N_T}$ denote the channel matrix whose entries are independently identically distributed (i.i.d.) with zero mean complex Gaussian random variables of distribution $\mathcal{CN}(0,1)$. Both a TX and K RXs know $\mathbf{H}_k$. Let $\mathbf{n}_k \in \mathbb{C}^{N_{R,k} \times 1}$ denote a noise vector at the kth RX whose entries are i.i.d. with a zero mean and a variance of σ_n^2. The $\mathbf{n}_k$ can be written as $\mathbf{n}_k = [n_{k,1}, n_{k,2}, \cdots, n_{k,N_{R,k}}]^T$. The received signal vector at the kth RX can be written as $\mathbf{H}_k \sum_{k=1}^{K} \mathbf{T}_k \mathbf{x}_k + \mathbf{n}_k$. Let $\mathbf{R}_k \in \mathbb{C}^{N_{R,k} \times L_k}$ denote the receive-postprocessor at the kth RX. Then, the output vector $\mathbf{y}_k$ from the kth receive-postprocessor can be written as

$$\mathbf{y}_k = \mathbf{R}_k^H \mathbf{H}_k \sum_{k=1}^{K} \mathbf{T}_k \mathbf{x}_k + \mathbf{R}_k^H \mathbf{n}_k \tag{1}$$

where $\mathbf{y}_k \in \mathbb{C}^{L_k \times 1}$ [8].

The transmit-preprocessor $\mathbf{T}_k$ in (1) nullifies the IUI, i.e., $\mathbf{R}_i^H \mathbf{H}_i \mathbf{T}_k = 0$ for all $i \neq k$ and (1) can be rewritten as

$$\mathbf{y}_k = \mathbf{R}_k^H \mathbf{H}_k \mathbf{T}_k \mathbf{x}_k + \mathbf{R}_k^H \mathbf{n}_k \tag{2}$$

which is equivalent to a SU-MIMO system for the kth user [8]. The K users feedback channel information $\mathbf{H}_k, k = 1, \cdots, K$ into the TX. Then the TX finds the best mode ω_{opt} among the set Ω of all the possible modes to maximize the sum capacity as

$$\omega_{opt} = \arg\max_{\omega \in \Omega} C(\omega, \mathbf{T}_S, \mathbf{H}_S, \mathbf{R}_S) \tag{3}$$

where $\mathbf{T}_S$ and $\mathbf{H}_S$ denote the overall transmit-preprocessor and channel matrices, respectively, and $\mathbf{R}_S$ stands for an overall block diagonalized receive-postprocessor matrix. They are, respectively, written as

$$\mathbf{T}_S = [\mathbf{T}_1, \mathbf{T}_2, \cdots, \mathbf{T}_K], \tag{4}$$

$$\mathbf{H}_S = [\mathbf{H}_1^H, \mathbf{H}_2^H, \cdots, \mathbf{H}_K^H]^H, \tag{5}$$

and

$$\mathbf{R}_S = \mathrm{diag}[\mathbf{R}_1, \mathbf{R}_2, \cdots, \mathbf{R}_K]. \tag{6}$$

The next section describes the transmit-preprocessor $\mathbf{T}_k$ and the receive-postprocessor $\mathbf{R}_k$ in [2]-[4] and [8] briefly.

III. Existing Multiuser MIMO Systems

The sum capacity of a MU-MIMO downlink BD system can be written as

$$C_{BD} = \max_{\mathbf{R}_S, \mathbf{T}_S} \log_2 det(\mathbf{I} + \frac{1}{\sigma_n^2} \mathbf{R}_S^H \mathbf{H}_S \mathbf{T}_S \mathbf{T}_S^H \mathbf{H}_S^H \mathbf{R}_S) \tag{7}$$

using (5) in [2] under a BD constraint which will be explained below. After BD, (7) can be rewritten as

$$C_{BD} = \max_{\mathbf{R}_S, \mathbf{T}_S} \sum_{k=1}^{K} \log_2 det(\mathbf{I} + \frac{1}{\sigma_n^2} \mathbf{R}_k^H \mathbf{H}_k \mathbf{T}_k \mathbf{T}_k^H \mathbf{H}_k^H \mathbf{R}_k) \tag{8}$$

because the off-diagonal submatrices $\mathbf{R}_i^H \mathbf{H}_i \mathbf{T}_k$ in matrix $\mathbf{R}_S^H \mathbf{H}_S \mathbf{T}_S$ will be zero matrices due to the BD constraint for all $i \neq k$ and $det(diag(\mathbf{A}, \mathbf{B})) = det(\mathbf{A})det(\mathbf{B})$ for any square matrices $\mathbf{A}$ and $\mathbf{B}$.

Different BD methods have appeared in the literature. A transmit-preprocessing $\mathbf{T}_k$ can be represented as a product of matrices. Let $\mathbf{W}_k$ be the first matrix in the product. In [2]-[4], $\mathbf{W}_k \in \mathbb{C}^{N_T \times (N_T - \sum_{m=1, m\neq k}^{K} N_{R,m})}$ is chosen as

$$\mathbf{W}_k \in null([\mathbf{H}_1^H, \cdots, \mathbf{H}_{k-1}^H, \mathbf{H}_{k+1}^H, \cdots, \mathbf{H}_K^H]^H). \tag{9}$$

The number of columns in $\mathbf{W}_k$ should be larger than 0 to have a nonzero weight matrix. This is why a constraint on the number of TX antennas is established as

$$\sum_{m=1, m\neq k}^{K} N_{R,m} < N_T \tag{10}$$

for the kth user [2]-[4]. This $\mathbf{W}_k$ satisfies $\mathbf{H}_i \mathbf{W}_k = 0$ for all $i \neq k$, which means that $\mathbf{W}_k$ is a nulling weight matrix against IUI. Then, a singular value decomposition (SVD) is applied to $\mathbf{H}_k \mathbf{W}_k$ in [2]-[4] as

$$\mathbf{H}_k \mathbf{W}_k = \mathbf{U}_k \mathbf{D}_k \mathbf{V}_k^H \tag{11}$$

where $\mathbf{U}_k \in \mathbb{C}^{N_{R,k} \times N_{R,k}}$ and $\mathbf{V}_k \in \mathbb{C}^{(N_T - \sum_{m=1, m\neq k}^{K} N_{R,m}) \times N_{R,k}}$ are left and right singular matrices, respectively, and $\mathbf{D}_k \in \mathbb{C}^{N_{R,k} \times N_{R,k}}$ is a diagonal matrix of singular values of $\mathbf{H}_k \mathbf{W}_k$. In [2]-[4] the receive-postprocessor $\mathbf{R}_k$ is chosen as

$$\mathbf{R}_k = \mathbf{U}_k(:, 1 : L_k) \tag{12}$$

where $(:, 1 : L_k)$ denotes the collection of columns from 1 to L_k. Let $\mathbf{E}_k \in \mathbb{C}^{L_k \times L_k}$ denote the power loading matrix for the kth user, where $\mathbf{E}_k = diag(e_{k,1}, \cdots, e_{k,L_k})$. Then (2) can be rewritten as

$$\begin{aligned} \mathbf{y}_k &= \mathbf{R}_k^H \mathbf{H}_k \mathbf{T}_k \mathbf{x}_k + \mathbf{R}_k^H \mathbf{n}_k \\ &= \mathbf{U}_k^H(:, 1 : L_k) \mathbf{H}_k \mathbf{W}_k \mathbf{V}_k(:, 1 : L_k) \mathbf{E}_k \mathbf{x}_k + \mathbf{R}_k^H \mathbf{n}_k \\ &= \mathbf{D}_k(1 : L_k, 1 : L_k) \mathbf{E}_k \mathbf{x}_k + \mathbf{R}_k^H \mathbf{n}_k \end{aligned} \tag{13}$$

where $(1 : L_k, 1 : L_k)$ denotes the collection of rows and columns from 1 to L_k. Therefore, the transmit-preprocessor $\mathbf{T}_k$ can be written as

$$\mathbf{T}_k = \mathbf{W}_k \mathbf{V}_k(:, 1 : L_k) \mathbf{E}_k \tag{14}$$

by comparing the first and the second equations in the right handside of (13). In (13), the noise vector is premultiplied by $\mathbf{R}_k^H$. However, $\mathbf{R}_k$ is a unitary matrix from (12) and, hence, there is no noise enhancement.

In [8], the nulling weight matrix $\mathbf{W}_k \in \mathbb{C}^{N_T \times (N_T - \sum_{m=1,m\neq k}^{K} L_m)}$ is chosen as

$$\mathbf{W}_k \in null([\mathbf{H}_1^H\mathbf{R}_1, \cdots, \mathbf{H}_{k-1}^H\mathbf{R}_{k-1}, \mathbf{H}_{k+1}^H\mathbf{R}_{k+1}, \cdots, \mathbf{H}_K^H\mathbf{R}_K]^H) \tag{15}$$

instead of the one in (9). This $\mathbf{W}_k$ in (15) satisfies $\mathbf{R}_i^H\mathbf{H}_i\mathbf{W}_k = 0$ for all $i \neq k$. A constraint on the number of TX antennas for this BD is established as

$$\sum_{m=1,m\neq k}^{K} L_m < N_T \tag{16}$$

for the kth user [8]. Note that the number of columns of $\mathbf{W}_k$ in (15) is larger than or equal to that of $\mathbf{W}_k$ in (9) as

$$N_T - \sum_{m=1,m\neq k}^{K} N_{R,m} \leq N_T - \sum_{m=1,m\neq k}^{K} L_m. \tag{17}$$

This is because the number of streams L_k can be smaller than the number of RX antennas $N_{R,k}$ for the kth user. Hence, the dimension of the null space in (15) can be larger than that in (9). This implies that a higher diversity gain can be achieved with $\mathbf{W}_k$ in (15) than that in (9). Therefore, this current paper will also consider a $\mathbf{W}_k$ similar to the one in (15). However, an iterative computation is required for $\mathbf{W}_k$ in (15). The number of iterations for this processing is nonnegligible. Therefore, this current paper proposes a method to find a nulling weight matrix without iteration in the next section.

IV. Proposed Multiuser MIMO System with Adaptive Mode Selection

The proposed nulling weight matrix $\mathbf{W}_k \in \mathbb{C}^{N_T \times (N_T - \sum_{m=1,m\neq k}^{K} L_m)}$ is chosen as

$$\mathbf{W}_k \in null([\mathbf{H}_1^H\mathbf{U}_1, \cdots, \mathbf{H}_{k-1}^H\mathbf{U}_{k-1}, \mathbf{H}_{k+1}^H\mathbf{U}_{k+1}, \cdots, \mathbf{H}_K^H\mathbf{U}_K]^H) \tag{18}$$

instead of the one in (15), where $\mathbf{U}_k$ consists of the dominant L_k left singular vectors of $\mathbf{H}_k$ as

$$\mathbf{H}_k = \mathbf{U}_{0,k}\mathbf{D}_k\mathbf{V}_k^H \tag{19}$$

$$\mathbf{U}_k = \mathbf{U}_{0,k}(:, 1:L_k) \tag{20}$$

where $\mathbf{U}_{0,k} \in \mathbb{C}^{N_{R,k} \times N_{R,k}}$, $\mathbf{V}_k \in \mathbb{C}^{N_T \times N_{R,k}}$ are left and right singular matrices, respectively, and $\mathbf{D}_k \in \mathbb{C}^{N_{R,k} \times N_{R,k}}$ is a diagonal matrix of singular values of $\mathbf{H}_k$. This $\mathbf{W}_k$ in (18) satisfies $\mathbf{U}_i^H\mathbf{H}_i\mathbf{W}_k = 0$ for all $i \neq k$, which means that $\mathbf{W}_k$ is a nulling weight matrix against IUI. Then a SVD is applied to $\mathbf{U}_k^H\mathbf{H}_k\mathbf{W}_k$ as

$$\mathbf{U}_k^H\mathbf{H}_k\mathbf{W}_k = \bar{\mathbf{U}}_k\bar{\mathbf{D}}_k\bar{\mathbf{V}}_k^H \tag{21}$$

where $\bar{\mathbf{U}}_k \in \mathbb{C}^{L_k \times L_k}$, $\bar{\mathbf{V}}_k \in \mathbb{C}^{(N_T - \sum_{m=1,m\neq k}^{K} L_m) \times L_k}$ are left and right singular matrices, respectively, and $\bar{\mathbf{D}}_k \in \mathbb{C}^{L_k \times L_k}$ is a diagonal matrix of singular values of $\mathbf{U}_k^H\mathbf{H}_k\mathbf{W}_k$. The receive-postprocessor $\mathbf{R}_k$ is chosen as

$$\mathbf{R}_k = \mathbf{U}_k\bar{\mathbf{U}}_k. \tag{22}$$

Let $\mathbf{E}_k \in \mathbb{C}^{L_k \times L_k}$ denote the power loading matrix for the kth user, where $\mathbf{E}_k = diag(e_{k,1}, \cdots, e_{k,L_k})$. Then (2) can be rewritten as

$$\begin{aligned} \mathbf{y}_k &= \mathbf{R}_k^H\mathbf{H}_k\mathbf{T}_k\mathbf{x}_k + \mathbf{R}_k^H\mathbf{n}_k \\ &= \bar{\mathbf{U}}_k^H\mathbf{U}_k^H\mathbf{H}_k\mathbf{W}_k\bar{\mathbf{V}}_k\mathbf{E}_k\mathbf{x}_k + \mathbf{R}_k^H\mathbf{n}_k \\ &= \bar{\mathbf{D}}_k\mathbf{E}_k\mathbf{x}_k + \mathbf{R}_k^H\mathbf{n}_k. \end{aligned} \tag{23}$$

Therefore the transmit-preprocessor $\mathbf{T}_k$ can be written as

$$\mathbf{T}_k = \mathbf{W}_k\bar{\mathbf{V}}_k\mathbf{E}_k. \tag{24}$$

An SVD has been applied to the effective channels to maximize the sum capacity [9]. The corresponding sum capacity of a MU-MIMO with the proposed BD can be written from (8) as

$$C_{BD} = \max_{\mathbf{E}_S} \sum_{k=1}^{K} \log_2 det(\mathbf{I} + \frac{1}{\sigma_n^2}\bar{\mathbf{D}}_k\mathbf{E}_k\mathbf{E}_k^H\bar{\mathbf{D}}_k^H) \tag{25}$$

by substituting (22) and (24) into (8). Equation (25) can be rewritten as

$$C_{BD} = \max_{\mathbf{E}_S} \log_2 det(\mathbf{I} + \frac{1}{\sigma_n^2}\bar{\mathbf{D}}_S\mathbf{E}_S) \tag{26}$$

where

$$\bar{\mathbf{D}}_S = \begin{bmatrix} \bar{\mathbf{D}}_1^2 & & 0 \\ & \ddots & \\ 0 & & \bar{\mathbf{D}}_K^2 \end{bmatrix} \tag{27}$$

and

$$\mathbf{E}_S = \begin{bmatrix} \mathbf{E}_1^2 & & 0 \\ & \ddots & \\ 0 & & \mathbf{E}_K^2 \end{bmatrix}. \tag{28}$$

The sum capacity C_{BD} in (26) can be maximized by the optimal power loading $\mathbf{E}_S$ from the water-filling under total power constraint P_T, i.e., $P_T = \sum_{k=1}^{K}\sum_{m=1}^{K} e_{k,L_m}^2$ [9]. The sum capacity as indicated by (25) is a function of $\mathbf{U}_k$, $\bar{\mathbf{U}}_k$, $\bar{\mathbf{V}}_k$, $\mathbf{E}_k$, and $\mathbf{W}_k$, which are determined by the mode selected for a given $\mathbf{H}_k$. Hence, the sum capacity depends on the mode selection. This paper proposes two adaptive mode selection algorithms: an exhaustive mode search (EMS); and a tree-based mode search (TMS).

Exhaustive Mode Search

Step 0. Define Ω as the set of all the possible modes under constraints $N_T \geq \sum_{k=1}^{K} L_k$ and $N_{R,k} \geq L_k \geq 1, k = 1, \cdots, K$.

Step 1. Select a candidate mode ω among Ω as $\omega = (L_1, L_2, \cdots, L_K) \in \Omega$.

Step 2. Compute a BD weight matrix $\mathbf{W}_k, k = 1, \cdots, K$, from (18) for ω obtained from Step 1.

Step 3. Compute C_{BD} from (25) with $\mathbf{W}_k$ obtained from Step 2, $k = 1, \cdots, K$. If the current C_{BD} is higher

TABLE I

NUMBER OF ITERATIONS BETWEEN A TX AND A RX REQUIRED FOR THE BD IN [8] AND THE PROPOSED BD FOR A GIVEN FIXED MODE.

	System [8]	Proposed system
$\omega = (1,1,1,1)$	10.692	0
$\omega = (2,2,2,2)$	0	0

than the previous C_{BD}, then go to Step 4 after updating the C_{BD} and ω. Otherwise, go to Step 4.

Step 4. Stop if all modes have been tested, i.e., Ω is a null set. Otherwise, update Ω by excluding the tested ω and go to Step 1.

The cardinality of the set Ω of all the possible modes is a function of N_T, K, and $N_{R,k}$, $k = 1, \cdots, K$. For example, $\Omega = \{(1,1),(1,2),(1,3),(2,1),(2,2),(3,1)\}$ when $N_T = 4$, $K = 2$, and $N_{R,1} = N_{R,2} = 4$. As a special case, when $N_T = \sum_{k=1}^{K} N_{R,k}$, the cardinality of Ω is $\Pi_{k=1}^{K} N_{R,k}$. Thus the computational load of the EMS can be high. Therefore, a TMS of low complexity is proposed below.

Tree-Based Mode Search

Step 1. Select an initial candidate mode ω as $\omega = (L_1, L_2, \cdots, L_K) = (1,1,\cdots,1)$. Compute a BD weight matrix $\mathbf{W}_k, k = 1, \cdots, K$, from (18) and C_{BD} from (25) for ω.

Step 2. Increase the number of streams L_k one by one for each user, and compute a BD weight matrix $\mathbf{W}_k$ and C_{BD} for each mode if the constraints $N_T \geq \sum_{k=1}^{K} L_k$ and $N_{R,k} \geq L_k \geq 1, k = 1, \cdots, K$, are satisfied. Find ω for which C_{BD} is the largest among the possible candidates in Step 2.

Step 3. If the current C_{BD} is higher than the previous C_{BD}, then update C_{BD} and ω, and go to Step 2. Otherwise, stop.

Note that at Step 1 in the TMS, $\omega = (L_1, L_2, \cdots, L_K) = (N_{R,1}, N_{R,2}, \cdots, N_{R,K})$ can be used as an initial candidate mode instead of $\omega = (1,1,\cdots,1)$. Then at Step 1, the next trial candidate mode can be found by decreasing the number of streams one by one for each user instead increasing. Let an up-TMS (UTMS) and a down-TMS (DTMS) denote the corresponding algorithm, respectively, when the number of streams is increased and decreased one by one.

An UTMS is expected to stop earlier than a DTMS when the SNR is relatively low, and vice versa. This expectation is consistent with the fact that in a SU-MIMO system. Therefore, a UTMS or DTMS can be used, depending on SNR. The worst computational complexity happens if the search goes through the maximum number of possible stages. The worst computational complexity of a TMS can be written as $1 + K^2(N_R - 2) + \sum_{m=1}^{K} m$, when $N_T = \sum_{k=1}^{K} N_{R,k}$ and $N_R = N_{R,1} = \cdots = N_{R,K} \geq 2$.

V. SIMULATION RESULTS AND DISCUSSIONS

Simulation results are presented for the sum capacity. Fig. 2 shows the sum capacities of the proposed BD and the BD methods in [2]-[4] and [8] versus SNR per RX antenna in dB with parameters $N_T = 8$, $K = 4$, and $N_{R,k} = 2, k = 1, \cdots, 4$. Two fixed modes $\omega = (1,1,1,1)$ and $\omega = (2,2,2,2)$ were considered.

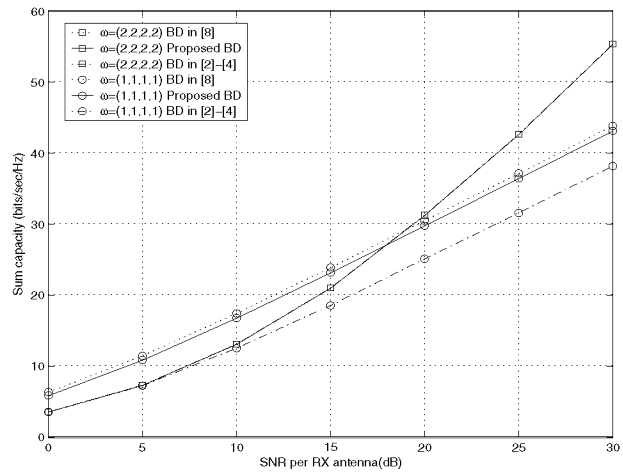

Fig. 2. Sum capacities of the proposed BD and the BD in [2]-[4] and [8] versus SNR per RX antenna in dB for two fixed modes with parameters $N_T = 8$, $K = 4$, and $N_{R,k} = 2, k = 1, \cdots, 4$.

It can be observed in Fig. 2 that all of BD schemes in [2]-[4] and [8], including the proposed scheme, show the same sum capacity when $\omega = (2,2,2,2)$. This is because (17) becomes $N_T - \sum_{m=1,m\neq k}^{K} N_{R,m} = N_T - \sum_{m=1,m\neq k}^{K} L_m$ for all k, which implies that there are no degrees of freedom left at the BS. This means that additional diversity is not possible for any user with mode $\omega = (2,2,2,2)$. Therefore, all BD schemes in [2]-[4] and [8], including the proposed scheme, show the same sum capacity. But a higher diversity can be achieved using the proposed BD scheme than the ones in [2]-[4]. For example, when SNR is 10 dB, as shown in Fig. 2, the sum capacity of the proposed BD scheme with $\omega = (1,1,1,1)$ is 16.8 bits/sec/Hz whereas that of the BD schemes in [2]-[4] is 12.6 bits/sec/Hz, which is a significant improvement.

It is also observed in Fig. 2 that the sum capacity of the proposed BD scheme is almost equal to that of the BD scheme in [8]. However, the BD scheme in [8] requires higher complexity, due to the required iterations, than the proposed BD scheme. Table I lists the required number of iterations for the BD scheme in [8]. When $\omega = (1,1,1,1)$, the BD scheme in [8] requires 10.692 iterations on average whereas the proposed BD scheme requires zero iteration. The computational load for each iteration depends on N_T, $N_{R,k}$, and K. Therefore, the overall computational load of the BD scheme in [8] can be significantly larger than that of the proposed BD scheme when N_T, $N_{R,k}$, and K are large.

The corresponding results of the existing schemes in [2]-[4] and [8] are not shown intentionally in Fig. 3 because they have the same performance when $\omega = (2,2,2,2)$; the schemes in [2]-[4] are worse than the proposed one when $\omega = (1,1,1,1)$; and the scheme in [8] is insignificantly better than the proposed one when $\omega = (1,1,1,1)$, as shown in Fig. 2.

TABLE II

NUMBER OF SEARCHES REQUIRED FOR THE ADAPTIVE MODE SELECTION SUCH AS THE EMS, UTMS, AND DTMS FOR THE RESULTS IN FIG. 3.

SNR (dB)	0	5	10	15	20	25	30
EMS	16	16	16	16	16	16	16
UTMS	5.66	7.56	9.04	10.04	10.55	10.82	10.94
DTMS	10.99	10.92	10.41	9.58	8.73	8.05	7.43

Fig. 3 shows the sum capacities of the proposed adaptive mode selection schemes versus SNR per RX antenna in dB with parameters $N_T = 8$, $K = 4$, and $N_{R,k} = 2, k = 1, \cdots, 4$. The results for two fixed modes with the proposed BD scheme are also shown for comparisons. The proposed adaptive BD scheme with EMS shows a higher sum capacity than that with a fixed mode such as $\omega = (1,1,1,1)$ and $\omega = (2,2,2,2)$. As SNR decreases, the sum capacity with mode $\omega = (1,1,1,1)$ approaches that of the proposed EMS, whereas the sum capacity with mode $\omega = (2,2,2,2)$ approaches that of the proposed EMS as SNR increases. This means that at a low SNR, the diversity mode, i.e., $\omega = (1,1,1,1)$, is preferable over the multiplexing mode, i.e., $\omega = (2,2,2,2)$, and vice versa. At a medium SNR, the adopting hybrid mode can yield a higher sum capacity than a fixed mode. For example, the best-hybrid mode that can be employed by the proposed EMS, UTMS, and DTMS, can improve the sum capacity by $(34.1 - 27.4)/27.4 \times 100 = 25\%$ in bits/sec/Hz at SNR=18 dB, compared to a fixed mode of $\omega = (1,1,1,1)$ or $\omega = (2,2,2,2)$.

Also, Fig. 3 shows that the proposed UTMS and DTMS have the same sum capacity as the proposed EMS, although the computational loads of the UTMS and DTMS are less than that of the EMS. Table II lists the average number of searches required for the proposed EMS, UTMS, and DTMS. This is based on one thousand trial channels. The average number of searches with the UTMS and DTMS is considerably lower than that of the EMS. For example, when SNR is 0 dB, the UTMS can reduce the number of searches by $(16-5.66)/16\times 100 = 65\%$, compared to the EMS. The number of searches required for the UTMS and DTMS, respectively, increases and decreases as the SNR increases. This is because at a low SNR, $\omega = (1,1,1,1)$ is close to the best mode, and the UTMS starts its search with $\omega = (1,1,1,1)$. Therefore, the UTMS terminates with a low number of searches, and vice versa.

VI. CONCLUSIONS

A conventional mode selection method, e.g., [4], employed a block diagonalization (BD) weight matrix $\mathbf{W}_k$ for a multiuser MIMO downlink system. The $\mathbf{W}$ was obtained by using only channel information in [4]. However, a receiver mode structure was also included in addition to channel information for the proposed BD weight matrix in this paper as [8]. This paper found that the proposed BD scheme required no iteration between a TX and a RX; hence, the computational complexity could be significantly reduced, e.g., eleven times reduction, compared to that in [8], when $N_T = 8$, $K = 4$, and $\omega = (1,1,1,1)$.

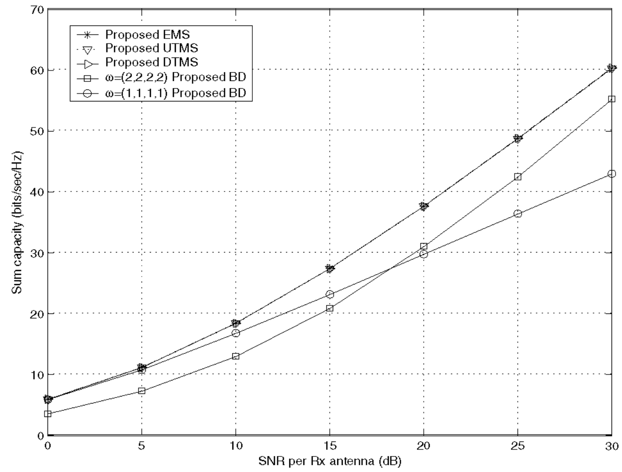

Fig. 3. Sum capacities of adaptive mode selection versus SNR per RX antenna in dB with parameters $N_T = 8$, $K = 4$, $N_{R,k} = 2, k = 1, \cdots, 4$. The results for two fixed modes with the proposed BD scheme are also shown for comparisons.

In addition, this paper presented three adaptive mode selection methods, i.e., the EMS, UTMS, and DTMS, to find a best mode. Then, this paper showed that the proposed adaptive BD schemes could significantly improve the sum capacity with the best mode, e.g., by 6.7 bits/sec/Hz more for $(N_T, K) = (8, 4)$ at SNR=18 dB over the methods in [2]-[4] and [8].

Finally, this paper found that the performance of a mode search with the proposed UTMS and DTMS was equivalent to the EMS, which is a greedy search method, but could reduce the search computation significantly, e.g., 65% of the EMS when $(N_T, K) = (8, 4)$ and SNR=0 dB.

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