Multi-Functional Antenna Array Assisted MC DS-CDMA Using Downlink Preprocessing Based on Singular Value Decomposition

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Abstract— **In this contribution we propose and investigate a transmitter preprocessing scheme designed for downlink transmission in multicarrier direct-sequence code-division multiple-access (MC DS-CDMA) systems using multiple base-station antenna arrays, where each antenna array employs multiple array elements. The transmitter preprocessing scheme is derived based on the singular value decomposition (SVD). Our transmitter preprocessing design is capable of supporting a high number of MC DS-CDMA users, while maintaining a high diversity gain at a low detection complexity at the remote mobile stations (MSs). The characteristics of MC DS-CDMA using the proposed transmitter preprocessing scheme are discussed and the achievable bit-error-rate (BER) performance is investigated, when assuming that each subcarrier experiences flat Rayleigh fading. Our simulation results demonstrate that for a SVD-assisted MC DS-CDMA system using M distinct transmit antenna arrays and time (T)-domain spreading sequences of length N_e chips, the number of users supported can be as high as MN_e, since N_e and M number of users may be distinguished in the T-domain and spatial-or S-domain, respectively. Furthermore, the SVD-assisted MC DS-CDMA system is capable of supporting MN_e number of users at a near single-user BER performance.**

I. INTRODUCTION

Multi-Carrier Direct Sequence Code Division Multiple Access (MC DS-CDMA) constitutes a high-flexibility multiple-access scheme, which is capable of providing a degree of freedom for system designers in comparison to both single-carrier DS-CDMA and frequency (F)-domain spread multicarrier CDMA (MC-CDMA) dispensing with T-domain spreading [1]–[3]. In [4], [5] the authors have proposed and investigated a MC DS-CDMA system, which employs multiple distinct $\lambda/2$-spaced base-station (BS) antenna arrays in order to achieve a high receive diversity [4] for the uplink (UL) or transmit diversity [5] for the downlink (DL) in the spatial or S-domain. Furthermore, as shown in [4], [5], when receiver or transmitter beamforming is employed, the proposed MC DS-CDMA system is capable of suppressing the interfering signals having direction-of-arrivals (DoAs) that are sufficiently different from that of the desired signal. To be more specific, in [5] the performance of multi-functional antenna array assisted MC DS-CDMA has been investigated, where the BS transmitter preprocessed the transmitted signals using steered space-time spreading (SSTS), which makes use of the knowledge of all the downlink users' DOAs, but does not exploit the knowledge of the channel impulse responses (CIRs) of the DL channels. In this case the DL users experience severe multiuser interference (MUI), which may only be mitigated at the remote MSs with the aid of advanced multiuser detection (MUD) or interference cancellation schemes [6].

Recently, transmitter preprocessing techniques have received wide attention [7]–[12]. It has been shown that DL transmit diversity may be readily achieved with the aid of transmitter preprocessing applied in the context of time-division duplexing (TDD), while the DL MUI may be mitigated by carrying out the required signal processing at the BS. Consequently, power-efficient MSs may be designed, which employ low-complexity algorithms. Therefore in this contribution we investigate the performance of the MC DS-CDMA system considered in [4], [5], when assuming TDD-based cellular communications and that the BS transmitter is capable of exploiting the knowledge of both the DoAs and the CIRs in the context of all the DL users. Specifically, we assume that the BS transmitter preprocesses the transmitted DL signals using SVD principles. The transmitter preprocessing scheme was designed for ensuring that the MC DS-CDMA becomes capable of simultaneously supporting a high number of users and of achieving the highest attainable diversity gain with the aid of low-complexity MS detectors. We will demonstrate that the attainable performance of MC DS-CDMA can be significantly enhanced, when our SVD-assisted transmitter preprocessing schemes is employed. Specifically, when using M distinct transmit antenna arrays and T-domain spreading sequences of length N_e, the system becomes capable of supporting upto MN_e users, while achieving a near-single-user BER performance. This is possible, since N_e users may be uniquely identified in the T-domain, while M users in the S-domain. Furthermore, an attractive performance trade-off can be found between the number of users supported and the achievable diversity gain, as detailed in our forthcoming discourse.

II. SYSTEM DESCRIPTION

In this section we consider the transmitter and receiver models of our MC DS-CDMA system using multi-functional antenna arrays at the BS, which employs DL transmitter preprocessing based on the principles of SVD.

A. Transmitter Model

Fig. 1 shows the transmitter schematic of the DL MC DS-CDMA system, where the BS employs M transmit antenna arrays, each of which consists of L array elements. We assume that the M antenna arrays are set sufficiently far apart from each other, in order that their CIRs become independent. By contrast, the spacing of the L array elements of an antenna array is optimized for achieving a beamforming gain, which can be configured for enhancing the signals in certain directions, while simultaneously nulling the MUI in other directions. As shown in Fig. 1, the MC DS-CDMA scheme has a total of UV number of subcarriers. We assume that each of the subcarrier signals experiences flat fading, even though the composite MC DS-CDMA signal experiences frequency-selective fading.

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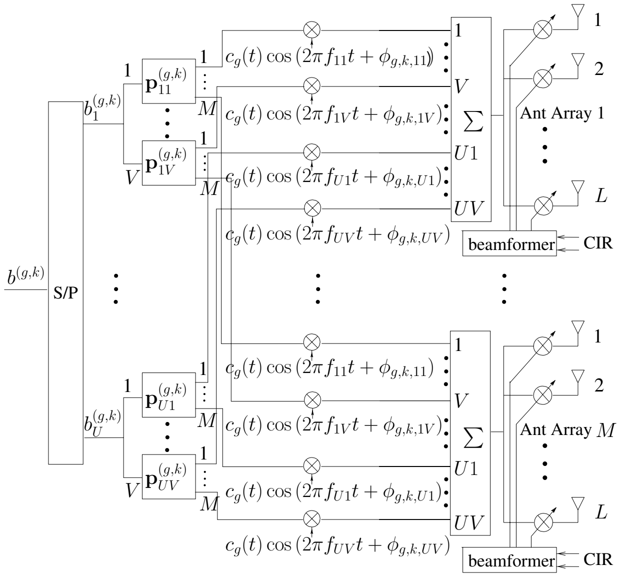

Fig. 1: Downlink transmitter schematic of MC DS-CDMA employing M transmit antenna arrays, each of which has L array elements, when BS transmitter preprocessing is employed.

We assume that the MC DS-CDMA system supports $\mathcal{K}=KG$ DL users, which are divided into G user-groups and each group contains K users. The K users in a given group, say group g, share a common T-domain spreading sequence $\mathbf{c}_g=[c_g[0],\cdots,c_g[N_e-1]]^T$ of length N_e chips. Furthermore, it is assumed that $\mathbf{c}_g$ is orthogonal to $\mathbf{c}_q$. Following the serial-to-parallel (S/P) conversion stage of Fig. 1, the data bits to be transmitted to the kth downlink user in the gth group can be expressed as

$$\mathbf{b}^{(g,k)}=\left[b_1^{(g,k)},b_2^{(g,k)},\ldots,b_U^{(g,k)}\right]^T, \tag{1}$$

where a single bit is mapped to V subcarriers. Therefore, the total number of subcarriers in the MC DS-CDMA system considered is UV. Specifically, the subcarriers invoked for transmitting the uth, $u=1,\ldots,U$, bit of the kth user in the gth group are $\{f_{u1},f_{u2},\ldots,f_{uV}\}$.

As shown in Fig. 1, in the context of the uvth subcarrier, the data bit $b_u^{(g,k)}$ is first preprocessed by an M-length vector $\mathbf{p}_{uv}^{(g,k)}$, yielding M outputs corresponding to the M number of L-element transmit antenna arrays. Following preprocessing, the signals are spread using the T-domain spreading code $c_g(t)=\sum_{n=0}^{N_e-1}c_g[n]P_{T_c}(t-nT_c)$, where $P_{T_c}(t)$ represents the typical rectangular chip waveform of width T_c, while T_c represents the chip-duration, $N_e=T_s/T_c$ denotes the spreading factor, $T_s=UT_b$ is the symbol-duration, while T_b is the bit-duration. As shown in Fig. 1, following T-domain spreading, the resultant signals modulate the carrier and, finally, they are transmitted by the M antenna arrays, where the array elements' signals may be weighted based on certain optimization criteria with the aid of our knowledge concerning the CIRs of the DL channels.

Based on the above discussions, it can be shown that the baseband equivalent signals transmitted to the K users in the gth group can be expressed as

$$\begin{aligned}\mathbf{s}^{(g)}(t)=&\sqrt{\frac{2P}{VL}}\sum_{k=1}^{K}\sum_{u=1}^{U}\sum_{v=1}^{V}\mathbf{W}^{(g,k)}\mathbf{p}_{uv}^{(g,k)}b_u^{(g,k)}\\ &\times c_g(t)\exp\left(2\pi f_{uv}t+\phi_{uv}^{(g,k)}\right)\\ &g=1,2,\ldots,G,\end{aligned} \tag{2}$$

where P represents the power transmitted to each of the K users, VL is a power normalization factor, where the multiplier V is due to the V subcarriers conveying the same data bit, while L represents the number of array elements. Furthermore, in (2) $\mathbf{W}^{(g,k)}$ is the $(ML\times M)$-dimensional transmitter beamforming matrix of the M L-element antenna arrays, which can be expressed as

$$\mathbf{W}^{(g,k)}=\begin{bmatrix}\mathbf{w}_1^{(g,k)} & \mathbf{0} & \cdots & \mathbf{0}\\ \mathbf{0} & \mathbf{w}_2^{(g,k)} & \cdots & \mathbf{0}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{w}_M^{(g,k)}\end{bmatrix}, \tag{3}$$

where $\mathbf{0}$ is an L-length vector having entries of zeros, while $\mathbf{w}_m^{(g,k)}$ is the transmitter's beamforming vector, which can be optimized using various optimization criteria [13]. In this contribution we employ a low-complexity matched-filtering (MF) assisted transmitter beamforming scheme. Furthermore, we assume that the distance between two adjacent array elements of a given antenna array is half of the wavelength of the radio-frequency (RF) carrier. In this case, it can be shown that the weight vector $\mathbf{w}_m^{(g,k)}$ of the MF-assisted transmitter beamforming scheme is given by

$$\begin{aligned}\mathbf{w}_m^{(g,k)}=[1\;\;&\exp\left(-j[\pi\sin(\psi_m^{(g,k)})]\right)\;\;\cdots\\ &\exp\left(-j[(L-1)\pi\sin(\psi_m^{(g,k)})]\right)]^T\\ &m=1,\ldots,M;\;g=1,\ldots,G;\;k=1,\ldots,K,\end{aligned} \tag{4}$$

where $\psi_m^{(g,k)}$ is the DoA in terms of the signals transmitted from the mth antenna array to the kth user in the gth group.

B. Receiver Model

Let the CIR of the uvth subcarrier transmitted from the mth BS antenna array to the kth user of the gth user-group be expressed as

$$\begin{aligned}\bar{\mathbf{h}}_{uv,m}^{(g,k)}=h_{uv,m}^{(g,k)}\cdot[1\;\;&\exp\left(j[\pi\sin(\psi_m^{(g,k)})]\right)\;\;\cdots\\ &\exp\left(j[(L-1)\pi\sin(\psi_m^{(g,k)})]\right)]^T\\ g=1,\ldots,G;\;&k=1,\ldots,K;\;m=1,\ldots,M;\\ &u=1,\ldots,U;\;v=1,\ldots,V,\end{aligned} \tag{5}$$

where, again, $\psi_m^{(g,k)}$ is the DoA in the context of the signals transmitted from the mth antenna array to the kth user of the gth group, $h_{uv,m}^{(g,k)}$ is the complex-valued fading gain of the uvth subcarrier's channel connecting the mth antenna array with the kth user of the gth group. Then, it may be readily shown that we have

$$\bar{\mathbf{h}}_{uv,m}^{(g,k)T}\mathbf{w}_m^{(g,k)}=Lh_{uv,m}^{(g,k)}. \tag{6}$$

Therefore, the transmitter beamforming arrangement described in (2) is a MF-based scheme, which maximizes the output SNR, when communicating over Gaussian channels imposing no multiuser and no inter-channel interference. Let

$$\bar{\mathbf{h}}_{uv}^{(g,k)}=\left[\bar{\mathbf{h}}_{uv,1}^{(g,k)T},\cdots,\bar{\mathbf{h}}_{uv,M}^{(g,k)T}\right]^T, \tag{7}$$

which is an ML-length vector containing the CIRs of the ML array elements. Then, it can be shown that the inner product between $\bar{\mathbf{h}}_{uv}^{(g,k)}$ and $\mathbf{W}^{(g,j)}$ can be expressed as

$$\bar{\mathbf{h}}_{uv}^{(g,k)T}\mathbf{W}^{(g,j)} = L\mathbf{h}_{uv}^{(g,kj)T}, \tag{8}$$

where $\mathbf{h}_{uv}^{(g,kj)}$ is an M-length CIR vector given by

$$\mathbf{h}_{uv}^{(g,kj)} = [h_{uv,1}^{(g,kj)} \;\; h_{uv,2}^{(g,kj)} \;\; \cdots \;\; h_{uv,M}^{(g,kj)}]^T, \tag{9}$$

where $h_{uv,m}^{(g,kj)}$ is given by

$$h_{uv,m}^{(g,kj)} = h_{uv,m}^{(g,k)}\mathbf{w}_m^{(g,k)H}\mathbf{w}_m^{(g,j)}/L, \tag{10}$$

which represents the cross-correlation between the kth and jth users' array vectors, provided that both users are in the gth group.

Without loss of generality, let us focus our attention on the signal received by the first ($k = 1$) user in the first ($g = 1$) user-group, which we refer to as the reference user or signal for convenience. Then, the corresponding received signal can be expressed as

$$r_{uv}(t) = \bar{\mathbf{h}}_{uv}^T \times \sum_{g=1}^{G}\mathbf{s}^{(g)}(t) + n_{uv}(t), \tag{11}$$

where the superscript of the reference user is ignored for convenience. In (11) $\bar{\mathbf{h}}_{uv}^{(g,k)}$ is given by (7), $\mathbf{s}^{(g)}(t)$ is given by (2), while $n_{uv}(t)$ is a complex AWGN noise process, which has a mean of zero and a variance of σ_n^2 per dimension.

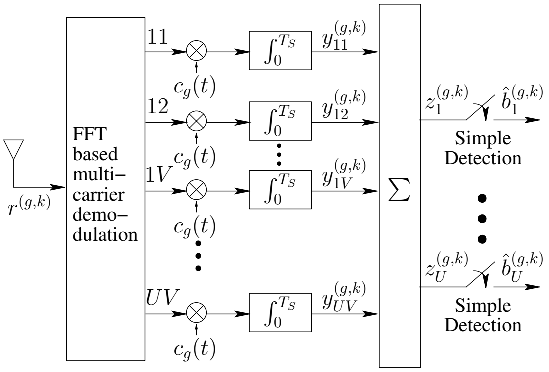

Fig. 2: Receiver schematic of the kth DL user in the gth user-group.

The receiver structure of the kth DL user in the gth group is shown in Fig. 2, where multicarrier demodulation is carried out with the aid of the fast Fourier transform (FFT). The resultant output signals are processed by a bank of UV MFs associated with the spreading code $c_g(t)$, which provide UV observations. Finally, for each of the U bits, say $b_u^{(g,k)}$, the V observations corresponding to the V subcarriers conveying $b_u^{(g,k)}$ are combined, in order to generate the decision variable $z_u^{(g,k)}$ for $b_u^{(g,k)}$.

According to the above discussions and remembering that the G number of T-domain spreading codes and the different subcarrier signals are orthogonal, it can be shown that the MF's output corresponding to the uvth subcarrier of the reference user can be expressed as

$$\begin{aligned} y_{uv} &= \sqrt{\frac{2P}{VL}}\sum_{k=1}^{K}\bar{\mathbf{h}}_{uv}^T\mathbf{W}^{(g,k)}\mathbf{p}_{uv}^{(g,k)}b_u^{(g,k)} + n_{uv} \\ &= \sqrt{\frac{2PL}{V}}\sum_{k=1}^{K}\mathbf{h}_{uv}^{(g,k)T}\mathbf{p}_{uv}^{(g,k)}b_u^{(g,k)} + n_{uv}, \end{aligned} \tag{12}$$

where the elements in $\mathbf{h}_{uv}^{(g,k)}$ are given by (10), while the Gaussian noise sample n_{uv} is given by

$$n_{uv} = \frac{1}{T_s}\int_0^{T_s} n_{uv}(t)c_g(t)\exp\left(-j2\pi f_{uv}t\right)dt, \tag{13}$$

which has a zero mean and a variance of σ_n^2/T_s per dimension.

Finally, the decision variable for $b_u^{(g,1)}$ can be expressed as

$$z_u = \sum_{v=1}^{V} y_{uv}, \tag{14}$$

and $b_u^{(g,1)}$ is decided according to

$$\hat{b}_u^{(g,1)} = \text{sgn}(\Re(z_u)),\; u = 1, 2, \ldots, U, \tag{15}$$

where $\Re(z)$ represents the real part of z.

According to the detection scheme of Fig. 2, the detector consists of a bank of MFs and hence has an extremely low-complexity. Furthermore, as seen in (12), the detector's output is free from multicarrier interference. Furthermore, no MUI is imposed by the users in the other groups. However, when the array vectors of the users in the same group are non-orthogonal, these users may interfere with each other, yielding intra-group MUI. In the next section we will show that the intra-group MUI can be removed with the aid of SVD-assisted transmitter preprocessing.

III. TRANSMITTER PREPROCESSING BASED ON SINGULAR VALUE DECOMPOSITION

In this section we consider the design of the proposed transmitter preprocessing vector $\mathbf{p}_{uv}^{(g,k)}$ seen in (12), so as to achieve two simultaneous design objectives, namely that of removing the intra-group MUI and achieving a transmit diversity order of n_t in the S-domain. We commence by expressing the preprocessing vector $\mathbf{p}_{uv}^{(g,k)}$ as

$$\mathbf{p}_{uv}^{(g,k)} = \mathbf{P}_{uv}^{(g,k)}\mathbf{d}_{uv}^{(g,k)}, \tag{16}$$

where $\mathbf{P}_{uv}^{(g,k)}$ is $(M \times n_t)$-dimensional, which is designed to suppress the intra-group MUI, while $\mathbf{d}_{uv}^{(g,k)}$ is an n_t-length vector used for combining the resultant signals in the S-domain, in order to achieve a diversity order of n_t in the S-domain. Let us first consider the design of $\mathbf{P}_{uv}^{(g,k)}$.

A. Design of $\mathbf{P}_{uv}^{(g,k)}$: Intra-Group MUI suppression

As shown in (12), the intra-group MUI can be entirely removed, if the constituent preprocessing matrices $\left\{\mathbf{P}_{uv}^{(g,j)}\right\}$ are chosen to satisfy

$$\mathbf{h}_{uv}^{(g,k)T}\mathbf{P}_{uv}^{(g,j)} = \mathbf{0}_{n_t}^T,\; \text{for } k \neq j, \tag{17}$$

where $\mathbf{0}_{n_t}$ is an n_t-length all-zero vector. Therefore, according to [7], the constituent preprocessing matrix $\mathbf{P}_{uv}^{(g,j)}$ of user j should lie in the null subspace determined by

$$\begin{aligned} \mathbf{H}_{uv}^{(g,j)T} = \left[\mathbf{h}_{uv}^{(g,1)}, \cdots, \mathbf{h}_{uv}^{(g,j-1)}, \mathbf{h}_{uv}^{(g,j+1)}, \cdots, \mathbf{h}_{uv}^{(g,K)}\right]^T&, \\ j = 1, 2, \ldots, K&, \end{aligned} \tag{18}$$

which is composed by the spatial signatures of the users, except for user j.

Upon carrying out the SVD of $\mathbf{H}_{uv}^{(g,j)}$ [13], we arrive at:

$$\mathbf{H}_{uv}^{(g,j)} = \mathbf{U}_{s,uv}^{(g,j)}\left[\mathbf{D}_{uv}^{(g,j)} \;\; \mathbf{0}\right]\begin{bmatrix} \mathbf{V}_{s,uv}^{(g,j)H} \\ \mathbf{V}_{n,uv}^{(g,j)H} \end{bmatrix}, \tag{19}$$

where $\mathbf{U}_{s,uv}^{(g,j)}$ is a $((K-1) \times (K-1))$ orthonormal matrix, $\mathbf{D}_{uv}^{(g,j)}$ is a $((K-1) \times (K-1))$ diagonal matrix containing the non-zero singular values of $\mathbf{H}_{uv}^{(g,j)}$, $\mathbf{0}$ is a $((K-1)\times(M-K+1))$ all-zero matrix, $\mathbf{V}_{s,uv}^{(g,j)}$ is a $(M\times(K-1))$ orthonormal matrix corresponding to the signal subspace determined by the $(K-1)$ interfering users, while $\mathbf{V}_{n,uv}^{(g,j)}$ is a $(M\times(M-K+1))$ orthonormal matrix corresponding to the orthogonal subspace of $\mathbf{H}_{uv}^{(g,j)}$.

Let $n_t = M-K+1$, wehre n_t represents the transmit diversity order achieved by the MC DS-CDMA system in the S-domain. Hence, n_t is referred to as the effective number of transmit antennas. In this case, the constituent preprocessing matrix $\mathbf{P}_{uv}^{(g,j)}$ can be chosen as

$$\mathbf{P}_{uv}^{(g,j)} = \mathbf{V}_{n,uv}^{(g,j)},\ j=1,2,\ldots,K. \tag{20}$$

Let us now consider the design of the constituent preprocessing matrix $\mathbf{d}_{uv}^{(g,k)}$ in (16).

B. Design of $\mathbf{d}_{uv}^{(g,k)}$: Transmit Diversity Combining

Upon substituting the preprocessing matrices $\left\{\mathbf{p}_{uv}^{(g,j)}\right\}$ of (16) associated with the constituent preprocessing matrices $\left\{\mathbf{P}_{uv}^{(g,j)}\right\}$ of (20) into (12), it can be shown that the intra-group MUI imposed on user 1 is entirely removed. Furthermore, the reference user's signal is projected onto an n_t-dimensional orthogonal subspace. Let

$$\mathbf{e}_{uv}^{(g,1)} = \mathbf{P}_{uv}^{(g,1)T}\mathbf{h}_{uv}^{(g,1)}, \tag{21}$$

where $\mathbf{e}_{uv}^{(g,1)}$ can be expressed as

$$\mathbf{e}_{uv}^{(g,1)} = \left[e_{uv,1}^{(g,1)}\ \cdots\ e_{uv,n_t}^{(g,1)}\right]^T. \tag{22}$$

Consequently, we can express the constituent preprocessing matrix $\mathbf{d}_{uv}^{(g,1)}$ as

$$\mathbf{d}_{uv}^{(g,1)} = \left[d_{uv,1}^{(g,1)}, d_{uv,2}^{(g,1)}, \ldots, d_{uv,n_t}^{(g,1)}\right]^T \tag{23}$$

and let $d_{uv,i}^{(g,1)}$ be formulated as

$$d_{uv,i}^{(g,1)} = e_{uv,i}^{(g,1)*}/\sqrt{E_{uv}^{(g,1)}}, \tag{24}$$

where $e_{uv,i}^{(g,1)*}$ is the conjugate of $e_{uv,i}^{(g,1)}$. Furthermore, we stipulate that

$$E_{uv}^{(g,1)} = \sum_{i=1}^{n_t}\left|e_{uv,i}^{(g,1)}\right|^2 \tag{25}$$

in order to ensure that the total power transmitted to a remote user remains the same both before and after preprocessing.

Finally, upon substituting (16) associated with the constituent preprocessing matrices $\left\{\mathbf{P}_{uv}^{(g,j)}\right\}$ of (20) and $\mathbf{d}_{uv}^{(g,1)}$ of (23) into (12), it can be shown that the decision variable of $b_u^{(g,1)},\ u=1,\ldots,U$ of the reference user can be expressed as

$$y_{uv} = \sqrt{\frac{2PL}{V}}\sqrt{E_{uv}^{(g,k)}}b_{uv}^{(g,k)} + n_{uv}, \qquad u=1,\ldots,U;\ v=1,\ldots,V, \tag{26}$$

which is free from inter-group interference, multicarrier interference and intra-group MUI.

C. Discussion

It is widely recognized that in a conventional single-carrier DS-CDMA system [3] using N_e-chip Walsh-Hadamard (WH) codes as the T-domain spreading sequences, the maximum number of users supported is $\mathcal{K} = N_e$, if no BER degradation is tolerated in comparison to the corresponding single-user DS-CDMA system having the same bandwidth. By contrast, the MC DS-CDMA system considered in this contribution has the following characteristics.

- The achievable diversity order is $Vn_t = V(M-K+1)$, where V represents that in the F-domain, while n_t is the diversity order in the S-domain;
- The number of users supported is $\mathcal{K} = N_eK,\ 1\le K\le M$, where N_e is the length of the T-domain spreading sequences, while K is the number of users per user-group. With the aid of the transmitter preprocessing proposed in Sections III-A and III-B, $\mathcal{K} = N_eK$ number of users can be supported by the MC DS-CDMA system without any significant performance degradation in comparison to the identical-bandwidth single-user MC DS-CDMA system;
- There is a trade-off between the number of users supported and the diversity order achieved. In the extreme case, when the diversity order is V corresponding to $n_t = M-K+1 = 1$, which implies $K=M$, the number of supportable users is as high as $\mathcal{K} = N_eM$. If the MC DS-CDMA system supports only $\mathcal{K} = N_e$ users, implying that each group has only $K=1$ user, then the diversity order achieved is $Vn_t = VM$.

Let us now consider our simulation results in the next section.

IV. SIMULATION RESULT

In this section the BER performance of the MC DS-CDMA system using multiple BS transmit antenna arrays is investigated, when assuming that each subcarrier signal experiences flat Rayleigh fading. In our simulations we assumed that the F-domain diversity order is $V=4$ and that the T-domain spreading sequences were the $N_e = 32$-length WH codes. The BER performance of MC DS-CDMA using the proposed transmitter preprocessing scheme is also compared to that of other MC DS-CDMA systems investigated in the literature, as detailed in our forthcoming discourse.

The legends used in Figs. 3 and 4 are as follows. For MC DS-CDMA using SVD-assisted transmitter preprocessing, the corresponding BER curves are indicated by '$(M(n_t)\times L)$ TP-SVD', where M is the number of transmit antenna arrays, L is the number of array elements of each antenna array and n_t represents the effective number of logical transmit antennas. In Figs. 3 and 4 the legend '$(1,1)$' indicates the MC DS-CDMA system using no preprocessing, '$(1,L)$ BF' corresponds to the MC DS-CDMA system using only the steered beamforming scheme of [5], while '(M,L) SSTS' corresponds to MC DS-CDMA system using both steered beamforming and space-time spreading (STS) [3], which are not detailed here owing to lack of space.

It is observed from the results seen in Figs. 3 and 4 that when assuming orthogonal multicarrier signals and that the subcarrier signals experience flat-fading, conventional MC DS-CDMA using N_e-length T-domain spreading sequences is capable of supporting at most $\mathcal{K} = N_e$ users, when tolerating no significant BER degradation compared to that of the identical-bandwidth single-user system. In [5] the MC DS-CDMA system was assumed to employ both T-domain and F-domain spreading, i.e TF-domain spreading, in order to increase the maximum number of users supported by the system. However, as shown in Figs. 3 and 4, when the MC DS-CDMA system using TF-domain spreading supports $\mathcal{K} = 2N_e = 64$ users instead of $\mathcal{K} = N_e = 32$ users, the resultant BER performance is significantly degraded. By contrast, when the SVD-assisted transmitter preprocessing is employed, the MC DS-CDMA systems supporting $\mathcal{K} = N_e = 32$, $\mathcal{K} = 2N_e = 64$ and $\mathcal{K} = 3N_e = 96$ users are capable of achieving a similar BER performance, as evidenced by Figs. 3 and 4.

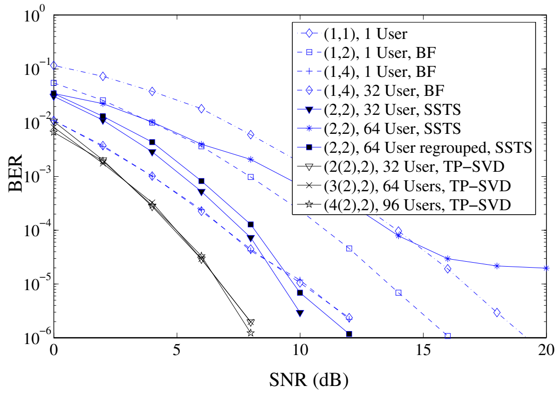

Fig. 3: BER versus SNR performance of the DL MC DS-CDMA system using $V = 4$ subcarriers and $N_e = 32$-chip WH code based T-domain spreading.

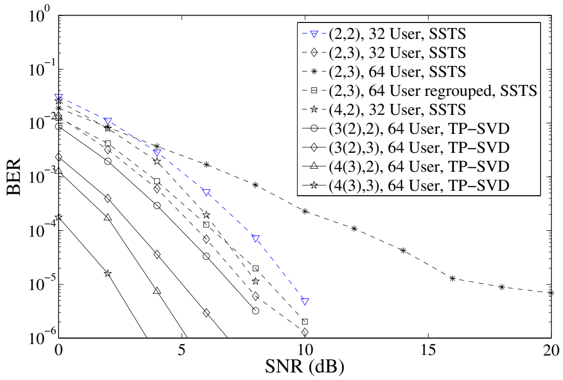

Fig. 4: BER versus SNR performance of the DL MC DS-CDMA systems using $V = 4$ subcarriers and $N_e = 32$-chip WH codes based T-domain spreading.

We can also infer the following observations from the results of Figs. 3 and 4. Firstly, when the MC DS-CDMA system employs only a single transmit antenna array ($M = 1$) using a single array element ($L = 1$), the attainable BER performance is the worst. Secondly, when the MC DS-CDMA system employs $M = 1$ BS antenna arrays, but $L > 1$ array elements, the required SNR is significantly reduced and the corresponding curves are shifted to the left of that corresponding to the case of $L = 1$. Thirdly, when the MC DS-CDMA system employs $M > 1$ BS antenna arrays and each antenna array has $L > 1$ array elements, and when additionaly steered transmitter beamforming combined with STS is applied, the MC DS-CDMA system becomes capable of achieving a transmit diversity order of M, in addition to the SNR reduction achieved by the antenna arrays [5]. Furthermore, as seen in Figs. 3 and 4, when the MC DS-CDMA BS transmitter employs our SVD-assisted transmitter preprocessing scheme denoted by 'TP-SVD', the BER performance is further improved in comparison to the system using pure SSTS in isolation. In contrast to the pure SSTS scheme [5], which does not require the explicit knowledge of the DL CIRs, except for the DoAs necessitated by the steered beamforming scheme, SVD-assisted transmitter preprocessing requires the explicit knowledge of the DL CIRs. However, the SSTS-assisted transmitter scheme typically employs a higher-complexity multiuser detection (MUD) scheme, than SVD-assisted transmitter preprocessing, which requires only low-complexity MF-assisted detection.

V. CONCLUSION

In this contribution we have proposed and investigated a SVD-assisted transmitter preprocessing scheme designed for MC DS-CDMA systems using multiple BS transmit antenna arrays, where each antenna array employs multiple array elements. The SVD-assisted transmitter preprocessing scheme has been designed for supporting the highest possible number of downlink users, while simultaneously achieving the highest possible transmit diversity gain. Our study shows that for a SVD-assisted MC DS-CDMA system using M transmit antenna arrays and length-N_e T-domain spreading sequences, the number of users supported with the aid of both T-domain and S-domain multiplexing can be as high as MN_e . Our simulation results show that the SVD-assisted MC DS-CDMA system is indeed capable of supporting a high number of users, while maintaining a near-single-user BER performance.

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