BUFFER AIDED DISTRIBUTED SPACE TIME CODING TECHNIQUES FOR COOPERATIVE DS-CDMA SYSTEMS

Jiaqi Gu and Rodrigo C. de Lamare*†*

Communications Research Group, Department of Electronics, University of York, U.K.*
CETUC, PUC-Rio, Rio de Janeiro, Brazil†
Email: jg849@york.ac.uk, rodrigo.delamare@york.ac.uk

ABSTRACT

In this work, we propose a buffer-aided distributed space-time coding (DSTC) scheme for cooperative direct-sequence code-division multiple access systems. We first devise a relay selection algorithm that can automatically select the optimum set of relays among both the source-relay phase and the relay-destination phase for DSTC transmission according to the signal-to-interference-plus-noise ratio (SINR) criterion. Multiple relays equipped with buffers are introduced in the network, which allows the relays to store data received from the sources and wait until the most appropriate time for transmission. Simulation results show that the proposed buffer-aided DSTC scheme and algorithm outperform prior art.

***Index Terms*—** DS-CDMA networks, cooperative systems, relay selection, greedy algorithms, space time coding, buffer.

1. INTRODUCTION

The ever-increasing demand for performance and reliability in wireless communication has encouraged the development of numerous innovative techniques. Among them, cooperative diversity is one of the key techniques that has been considered in recent years [1] as an effective tool to improving transmission performance and system reliability. Several cooperative schemes have been proposed [2, 3, 4], and among the most effective ones are Amplify-and-Forward (AF), Decode-and-Forward (DF) [4] and various distributed space-time coding (DSTC) technique [5, 6, 7, 8, 9]. For an AF protocol, relays cooperate and amplify the received signals with a given transmit power amplifying their own noise. With the DF protocol, relays decode the received signals and then forward the re-encoded message to the destination. DSTC schemes exploit spatial and temporal transmit diversity by using a set of distributed antennas. With DSTC, multiple redundant copies of data are sent to the receiver to improve the quality and reliability of data transmission. Applying DSTC at the relays provides multiple processed signal copies to compensate for the fading and noise, helping to achieve the attainable diversity and coding gains so that the interference can be more effectively mitigated. As a result, better performance can be achieved when appropriate signal processing and relay selection strategies are applied.

In cooperative relaying systems, strategies that employ multiple relays have been recently introduced in [10, 11, 12, 13]. The aim of relay selection is to find the optimum relay so that the signal can be transmitted and received with increased reliability. Recently, a new cooperative scheme with buffers equipped at relays has been introduced and analyzed in [14, 15, 16, 17]. The main purpose is to select the best link according to a given criterion. In [14], a brief introduction of the buffer-aided relaying protocols for different networks is carefully described and the some practical challenges are discussed. Consequently, a further study of the throughput and diversity gain of the buffer-aided system is introduced in [15]. In [16], a new selection technique that is able to achieve the full diversity gain by selecting the strongest available link in every time slot is detailed. In [17], a max-max relay selection (MMRS) scheme for half-duplex relays with buffers is proposed. In particular, relays with the optimum source-relay links and relay-destination links are chosen and controlled for transmission and reception, respectively.

In this work, we propose a buffer-aided DSTC scheme and algorithm for cooperative direct-sequence code-division multiple access (DS-CDMA) system. The proposed algorithm automatically selects the optimum set of relays according to the signal-to-interference-plus noise ratio (SINR) criterion. The proposed scheme can be divided into two parts. Initially, a link combination associated with the optimum relay group is selected, which determines if the buffer is ready for transmission or reception. For the second part, DSTC is performed from the selected relay combination to the destination when the buffers are switched to the transmission mode. The direct transmission is conducted between the source and the relay combination when the buffers are in the reception mode. The key advantage of introducing the buffers in the system is their ability to store multiple blocks of data so that the most appropriate ones can be selected at a suitable time instant. The main difference of this proposed work as compared to [14, 15, 16, 17] is the selection of the relay combinations, where the proposed relay selection algorithm chooses the relay pair rather than a single relay as the DSTC transmission needs the cooperation of a pair of antennas. In addition, a greedy [18, 19, 20, 21, 22, 23] relay pair selection technique is also devised in this work so that the high cost brought by the exhaustive search can be avoided when a large number of relays are involved in the transmission.

This paper is organized as follows. In Section 2, the system model is presented. In Section 3, the buffer-aided cooperative DSTC scheme is explained. In Section 4, the greedy relay pair selection strategy is proposed. In Section 5, simulation results are presented and discussed. Finally, conclusions are drawn in Section 6.

2. DSTC COOPERATIVE DS-CDMA SYSTEM MODEL

We consider the uplink of a synchronous DS-CDMA system with K users, flat fading channels, L relays equipped with finite-size buffers capable of storing B packets and N chips per symbol. The system is equipped with a cooperative protocol at each relay and we assume that the transmit data are organized in packets comprising P symbols. The received signals are filtered by a matched filter and sampled at chip rate to obtain sufficient statistics. As shown in Fig.1, in the proposed scenario, the transmission is divided into two phases. In the first phase, the source transmits the data to each of the relay over two consecutive time instants, the decoded data over two time slot-

This work is funded by the ESII consortium under task 26 for low-cost wireless ad hoc and sensor networks

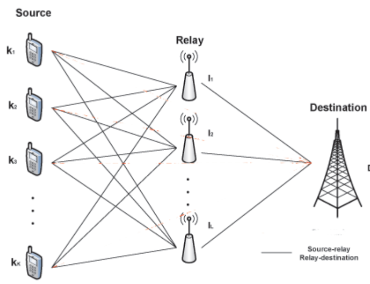

Fig. 1. Uplink of a cooperative DS-CDMA system.

s $[\hat{b}_{r_l d,k}(2i-1), \hat{b}_{r_l d,k}(2i)]$ is stored at relay l and is prepared to send data to the destination. A DSTC scheme is then employed in the following phase, where the corresponding 2×2 Alamouti [24] detected symbol matrix over relay m and relay n for user k among two consecutive time instants is given by

$$\mathbf{B}_k = \begin{bmatrix} \hat{b}_{r_m d,k}(2i-1) & -\hat{b}^*_{r_n d,k}(2i) \\ \hat{b}_{r_n d,k}(2i) & \hat{b}^*_{r_m d,k}(2i-1) \end{bmatrix}. \quad (1)$$

The received signal from relay m and n to the destination over two consecutive time slots yields the $N \times 1$ received vectors described by

$$\mathbf{y}_{r_{m,n} d}(2i-1) = \sum_{k=1}^{K} \mathbf{h}^k_{r_m d} \hat{b}_{r_m d,k}(2i-1) + \mathbf{h}^k_{r_n d} \hat{b}_{r_n d,k}(2i) + \mathbf{n}(2i-1), \quad (2)$$

$$\mathbf{y}_{r_{m,n} d}(2i) = \sum_{k=1}^{K} \mathbf{h}^k_{r_n d} \hat{b}^*_{r_m d,k}(2i-1) - \mathbf{h}^k_{r_m d} \hat{b}^*_{r_n d,k}(2i) + \mathbf{n}(2i), \quad (3)$$

where $\mathbf{h}^k_{r_l d} = a^k_{r_l d} \mathbf{s}_k h_{r_l d,k}$ denotes the channel vector for user k from the l-th relay to the destination with $m, n \in [1, 2, ..., L]$. The quantity $a^k_{r_l d}$ represents the k-th user's amplitude from the l-th relay to the destination, $\mathbf{s}_k = [s_k(1), s_k(2), ...s_k(N)]^T$ is the $N \times 1$ signature sequence for user k and $h_{r_l d,k}$ are the channel fading coefficients for user k from the l-th relay to the destination. The $N \times 1$ noise vectors $\mathbf{n}(2i-1)$ and $\mathbf{n}(2i)$ contain samples of zero mean complex Gaussian noise with variance σ^2, $\hat{b}_{r_l d,k}(2i-1)$ and $\hat{b}_{r_l d,k}(2i)$ are the decoded symbols at the output of relay l after using a cooperative protocol at time instants $(2i-1)$ and $(2i)$, respectively. Equivalently, (2) and (3) can be rewritten as

$$\mathbf{y}_{r_{m,n} d} = \mathbf{H}^k_{r_{m,n} d} \mathbf{b}_{r_{m,n} d,k} + \mathbf{n}_{r_{m,n} d}, \quad (4)$$

where $\mathbf{y}_{r_{m,n} d} = \left[\mathbf{y}^T_{r_{m,n} d}(2i-1), \mathbf{y}^T_{r_{m,n} d}(2i)\right]^T$ represents the received signal from relay m and n over two time instants. $\mathbf{H}^k_{r_{m,n} d} = \begin{bmatrix} \mathbf{h}^k_{r_m d} & \mathbf{h}^k_{r_n d} \\ (\mathbf{h}^k_{r_n d})^* & -(\mathbf{h}^k_{r_m d})^* \end{bmatrix}$ denotes the Alamouti channel matrix for user k and $\mathbf{b}_{r_{m,n} d,k} = \left[\hat{b}_{r_m d,k}(2i-1), \hat{b}_{r_n d,k}(2i)\right]^T$ is the processed symbol when the DF protocol is used at relays m and n at the corresponding time instant, and $\mathbf{n}_{r_{m,n} d} = [\mathbf{n}(2i-1), \mathbf{n}(2i)]^T$ is the noise vector.

3. PROPOSED BUFFER-AIDED DSTC SCHEME

In this section, we present a buffer-aided cooperative DSTC scheme, where each relay is equipped with a buffer so that the processed data can be stored and the buffer can wait until the channel pair associated with the best performance is selected. As shown by Fig. 2, processed data are stored at the corresponding buffer entries and then re-encoded when the appropriate time interval comes. This method effectively improves the quality of the transmission, guarantees that the most suitable signal is selected from the buffer entries and sent to the destination with a higher reliability.

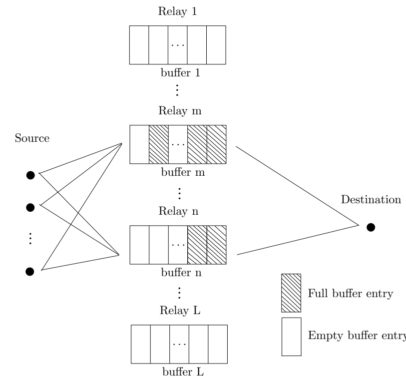

Fig. 2. Proposed buffer-aided cooperative scheme.

The algorithm begins with a SINR calculation for all possible channel combinations. In the case of the Alamouti code, every two relays are combined into a group and all possible lists of corresponding channel pairs are considered. The corresponding SINR is then calculated and recorded as follows:

$$\mathrm{SINR}_{sr_{m,n}} = \frac{\sum\limits_{k=1}^{K} \mathbf{w}^H_{s_k r_m} \mathbf{w}_{s_k r_m} + \mathbf{w}^H_{s_k r_n} \mathbf{w}_{s_k r_n}}{\sum\limits_{k=1}^{K} \sum\limits_{\substack{l=1 \\ l \neq m,n}}^{L} \mathbf{w}^H_{s_k r_l} \mathbf{w}_{s_k r_l} + \sigma^2}, \quad (5)$$

$$\mathrm{SINR}_{r_{m,n} d} = \frac{\sum\limits_{k=1}^{K} (\mathbf{w}^k_{r_m d})^H \mathbf{w}^k_{r_m d} + (\mathbf{w}^k_{r_n d})^H \mathbf{w}^k_{r_n d}}{\sum\limits_{k=1}^{K} \sum\limits_{\substack{l=1 \\ l \neq m,n}}^{L} (\mathbf{w}^k_{r_l d})^H \mathbf{w}^k_{r_l d} + \sigma^2}, \quad (6)$$

In Eq. (5), $\mathrm{SINR}_{sr_{m,n}}$ denotes the SINR for the combined paths from all users to relay m and relay n, $\mathbf{w}_{s_k r_l}$ is the detector used at the relays. When the RAKE receiver is adopted at the corresponding relay, $\mathbf{w}_{s_k r_l}$ is expressed as

$$\mathbf{w}_{s_k r_l} = \mathbf{h}_{s_k r_l}, \quad (7)$$

where $\mathbf{h}_{s_k r_l} = a_{s_k r_l} \mathbf{s}_k h_{s_k r_l}$ is the channel vector from user k to relay l. Similarly, if the linear MMSE receiver is employed at the relays, $\mathbf{w}_{s_k r_l}$ is given by

$$\mathbf{w}_{s_k r_l} = \left(\sum_{k=1}^{K} \mathbf{h}_{s_k r_l} \mathbf{h}^H_{s_k r_l} + \sigma^2 \mathbf{I} \right)^{-1} \mathbf{h}_{s_k r_l}, \quad (8)$$

$\mathbf{h}_{s_k r_l} = a_{s_k r_l} \mathbf{s}_k h_{s_k r_l}$ is the effective signature vector from user k to the relay l. Similarly, in Eq. (6), $\mathrm{SINR}_{r_{m,n} d}$ represents the SINR for the combined paths from relay m and relay n to the destination. $\mathbf{w}^k_{r_l d}$ is the detector used at the destination. When the RAKE receiver is adopted at the destination, $\mathbf{w}^k_{r_l d}$ is expressed as

$$\mathbf{w}^k_{r_l d} = \mathbf{h}^k_{r_l d}. \quad (9)$$

Similarly, if the linear minimum mean-square error (MMSE) receiver is employed at the relays, $\mathbf{w}^k_{r_l d}$ is equal to

$$\mathbf{w}^k_{r_l d} = \left(\sum_{k=1}^{K} \mathbf{h}^k_{r_l d} (\mathbf{h}^k_{r_l d})^H + \sigma^2 \mathbf{I} \right)^{-1} \mathbf{h}^k_{r_l d}. \quad (10)$$

The above equations correspond to a cooperative system under the assumption that all users are transmitted to the selected relays m and n. We then sort all these SINR values in a decreasing order and select the one with the highest SINR as given by

$$\mathrm{SINR_{p,q}} = \arg \max_{m,n \in [1,2,\ldots,L]} \{\mathrm{SINR_{sr_{m,n}}}, \mathrm{SINR_{r_{m,n}d}}\}, \quad (11)$$

where $\mathrm{SINR_{p,q}}$ denotes the highest SINR associated with relay p and relay q. After the highest SINR is selected, two different situations need to be considered as follows.

Source-relay link:

If the highest SINR belongs to the source-relay link, then the signal sent to the target relays p and q over two time instants is given by

$$\mathbf{y}_{sr_l}(2i-1)=\sum_{k=1}^{K}b_k(2i-1)\mathbf{w}_{s_kr_l}+\mathbf{w}_{sr_l}(2i-1), l\in[p,q], \quad (12)$$

$$\mathbf{y}_{sr_l}(2i)=\sum_{k=1}^{K}b_k(2i)\mathbf{w}_{s_kr_l}+\mathbf{w}_{sr_l}(2i), l\in[p,q]. \quad (13)$$

The received signal is then processed by the detectors as the DF protocol is adopted. Therefore, the decoded symbols that are stored and sent to the destination from the l-th relay are obtained as the

$$\hat{b}_{r_ld,k}(2i-1)=Q(\mathbf{w}_{s_kr_l}^H\mathbf{y}_{sr_l}(2i-1)), \quad (14)$$

and

$$\hat{b}_{r_ld,k}(2i)=Q(\mathbf{w}_{s_kr_l}^H\mathbf{y}_{sr_l}(2i)). \quad (15)$$

$Q(\cdot)$ denotes the slicer. After that, the buffers are then switched to the reception mode, the decoded symbol is consequently stored in the corresponding buffer entries. Clearly, these operations are performed when the corresponding buffer entries are not full, otherwise, the second highest SINR is chosen as given by

$$\mathrm{SINR}_{\mathrm{p,q}}^{\mathrm{pre}}=\mathrm{SINR}_{\mathrm{p,q}} \quad (16)$$

$$\mathrm{SINR}_{\mathrm{u,v}}\in\max\{\mathrm{SINR}_{\mathrm{sr_{m,n}}},\mathrm{SINR}_{\mathrm{r_{m,n}d}}\}\setminus\mathrm{SINR}_{\mathrm{p,q}}^{\mathrm{pre}}, \quad (17)$$

where $\mathrm{SINR}_{\mathrm{u,v}}$ denotes the second highest SINR associated with the updated relay pair $\Omega_{u,v}$. $\{\mathrm{SINR}_{\mathrm{sr_{m,n}}},\mathrm{SINR}_{\mathrm{r_{m,n}d}}\}\setminus\mathrm{SINR}_{\mathrm{p,q}}^{\mathrm{pre}}$ denotes a complementary set where we drop the $\mathrm{SINR}_{\mathrm{p,q}}^{\mathrm{pre}}$ from the set of SINR links $\{\mathrm{SINR}_{\mathrm{sr_{m,n}}},\mathrm{SINR}_{\mathrm{r_{m,n}d}}\}$. Consequently, the above process repeats in the following time instants.

Relay-destination link:

If the highest SINR is selected from the relay-destination link, in the following two consecutive time instants, the buffers are switched to transmission mode and the decoded symbol for user k is re-encoded with the Alamouti matrix as in (1) so that DSTC is performed from the selected relays p and q to the destination as given by

$$\mathbf{y}_{r_{p,q}d}(2i-1)=\sum_{k=1}^{K}\mathbf{w}_{r_pd}^k\hat{b}_{r_pd,k}(2i-1)+\mathbf{w}_{r_qd}^k\hat{b}_{r_qd,k}(2i)+\mathbf{n}(2i-1), \quad (18)$$

$$\mathbf{y}_{r_{p,q}d}(2i)=\sum_{k=1}^{K}\mathbf{w}_{r_qd}^k\hat{b}_{r_pd,k}^*(2i-1)-\mathbf{w}_{r_pd}^k\hat{b}_{r_qd,k}^*(2i)+\mathbf{n}(2i). \quad (19)$$

The received signal is then processed by the detectors at the destination. Clearly, the above operation is conducted under the condition that the corresponding buffer entries are not empty, otherwise, the second highest SINR is chosen according to (16) and (17) and the above process is repeated.

Moreover, the size B of the buffers also plays a key role in the performance of the system, which improves with the increase of the size as buffers with greater size allows more data packets to be stored. In this case, extra degrees of freedom in the system or choices for data transmission are available. The key advantage of the proposed scheme is its ability to select the most appropriate symbols before they are forwarded to the next phase. In practice, the performance highly depends on the buffer size B, the number of users K and the accuracy of the detection at the relays.

4. GREEDY RELAY PAIR SELECTION TECHNIQUE

In this section, a greedy relay pair selection algorithm is introduced. For this relay selection problem, the exhaustive search of all possible relay pairs is the optimum way to obtain the best performance. However, the major problem that prevents us from applying this method when a large number of relays involved in the transmission is its considerable computational complexity. When L relays ($L/2$ relay pairs if L is an even number) participate in the transmission, a cost of $L(L-1)$ link combinations is required as both source-relay links and relay-destination links need to be considered.

We propose a greedy relay pair selection algorithm that can approach the global optimum with a reduced computational complexity. The algorithm starts with a single link selection where we examine the SINR for each of the links as given by

$$\mathrm{SINR}_{sr_p}=\frac{\sum_{k=1}^{K}\mathbf{w}_{s_kr_p}^H\mathbf{w}_{s_kr_p}}{\sum_{k=1}^{K}\sum_{\substack{l=1\\l\neq p}}^{L}\mathbf{w}_{s_kr_l}^H\mathbf{w}_{s_kr_l}+\sigma^2}, \quad (20)$$

$$\mathrm{SINR}_{r_pd}=\frac{\sum_{k=1}^{K}(\mathbf{w}_{r_pd}^k)^H\mathbf{w}_{r_pd}^k}{\sum_{k=1}^{K}\sum_{\substack{l=1\\l\neq p}}^{L}(\mathbf{w}_{r_ld}^k)^H\mathbf{w}_{r_ld}^k+\sigma^2}, \quad (21)$$

where SINR_{sr_p} and SINR_{r_pd} denote the SINR from the source to an arbitrary relay p and from relay p to the destination, respectively. We then select the link with the highest SINR and its associated relay q is recorded as the base relay as given by

$$\mathrm{SINR}_{\mathrm{q}}^{\mathrm{base}}=\arg\max_{p\in[1,2,\ldots,L]}\{\mathrm{SINR}_{\mathrm{sr_p}},\mathrm{SINR}_{\mathrm{r_pd}}\}. \quad (22)$$

Consequently, all possible relay pairs involved with base relay q are listed as $\Omega_{p,q}$, where $p\in[1,L], p\neq q$. The SINR for these $(L-1)$ relay pairs are then calculated as in (5) and (6). After that, the optimum relay pair is chosen according to (11) and the algorithm begins if the corresponding buffers are available for either transmission or reception.

Transmission mode

When the buffers are switched to the transmission mode, a buffer space check is conducted firstly to ensure the corresponding buffers are not empty. We then have,

$$\Omega_p^{\mathrm{buffer}}\neq\varnothing,\ p\in[1,2,...,L], \quad (23)$$

and

$$\Omega_q^{\mathrm{buffer}}\neq\varnothing,\ q\in[1,2,...,L], \quad (24)$$

where $\Omega_p^{\mathrm{buffer}}$ and $\Omega_q^{\mathrm{buffer}}$ represents the buffer p and the buffer q associated with the relay pair $\Omega_{p,q}$. In this situation, the DSTC scheme is performed afterwards as in (18) and (19) through the selected relay pair. Conversely, empty buffer entries indicate that the selected relay pair cannot forward the data to the destination. In this case, we drop this relay pair, select another relay pair among the remaining $(L-2)$ candidate pairs with the highest SINR as given by

$$\mathrm{SINR}_{\mathrm{m,q}}=\arg\max_{\substack{l\neq p,q\\l\in[1,2,\ldots,L]}}\{\mathrm{SINR}_{\mathrm{l,q}}\}, \quad (25)$$

The algorithm then repeats the new selected relay pair $\Omega_{m,q}$. Otherwise, if all possible relay pairs $\Omega_{l,q}$ ($l\neq p,q,l\in[1,L]$) are not available, we then reset the base relay associated with the second highest SINR as described by

$$\mathrm{SINR}_{\mathrm{q}}^{\mathrm{pre}}=\mathrm{SINR}_{\mathrm{q}}^{\mathrm{base}}, \quad (26)$$

$$\mathrm{SINR}_{\mathrm{q}}^{\mathrm{base}}=\max\{\mathrm{SINR}_{\mathrm{s_kr_l}},\mathrm{SINR}_{\mathrm{r_ld}}\}\setminus\mathrm{SINR}_{\mathrm{q}}^{\mathrm{pre}}, \quad (27)$$

where $\{\mathrm{SINR}_{\mathrm{s_kr_l}},\mathrm{SINR}_{\mathrm{r_ld}}\}\setminus\mathrm{SINR}_{\mathrm{q}}^{\mathrm{pre}}$ denotes a complementary set where we drop the $\mathrm{SINR}_{\mathrm{q}}^{\mathrm{pre}}$ from the link SINR set $\{\mathrm{SINR}_{\mathrm{s_kr_l}},\mathrm{SINR}_{\mathrm{r_ld}}\}$. After this selection process, a new relay pair is chosen and the transmission procedure repeats as above.

Reception mode

When the buffers are switched to reception mode, similarly, a buffer space check is performed initially to ensure there is enough space for storing the processed data, namely,

$$\Omega_p^{\mathrm{buffer}}\neq\mathrm{U},\ p\in[1,2,...,L], \quad (28)$$

and

$$\Omega_q^{\mathrm{buffer}}\neq\mathrm{U},\ q\in[1,2,...,L], \quad (29)$$

where U represents a full buffer set. In this case, if the buffers are not full, then, the sources send the data to the selected relay pair

$\Omega_{p,q}$ over two time instants according to (12) and (13). Otherwise, the algorithm reselects a new relay pair as in (25), (26) and (27).

The proposed greedy relay pair selection method considers the combination effect of the channel condition so that DSTC can be conducted with a collection of relays. When compared with the exhaustive search, less than $2(L-1)$ types of link combinations are examined as the proposed method explores the link combination when both single relay and relay pair are involved. Specifically, the exhaustive relay pair search requires $(7KNL^3 - 7KNL^2)$ multiplications and $(2KNL^3 - 2KNL^2 + KL^3 - KL^2 - 2L^2 + 2L)$ additions, while the proposed greedy relay pair selection algorithm only requires less than $(21KNL^2 - 7KNL)$ multiplications and $(6KNL^2 + 3KL^2 - 3KL - L + 1)$ additions, which is an order of magnitude less costly. Therefore, when a large number of relays participate in the transmission, with a careful control of the buffer size B, a good balance of complexity and performance is achieved.

Moreover, the improvement of the performance brought by the buffer-aided relays are at the expense of the transmission delay. Hence, it is of great importance to investigate the performance delay trade-off of the proposed buffer-aided DSTC schemes [25] in our following work. Furthermore, a delay is also introduced by the way we encode the data via the DSTC scheme and the processing of relay pairs selection.

5. SIMULATIONS

In this section, a simulation study of the proposed buffer-aided DSTC technique for cooperative systems is carried out. The DS-CDMA network uses randomly generated spreading codes of length $N = 16$. The corresponding channel coefficients are taken as uniformly random variables and are normalized to ensure the total power is unity for all analyzed techniques. We assume perfectly known channels at the receivers. Equal power allocation with normalization is assumed to guarantee no extra power is introduced during the transmission. We consider packets with 1000 BPSK symbols and average the curves over 300 trials.

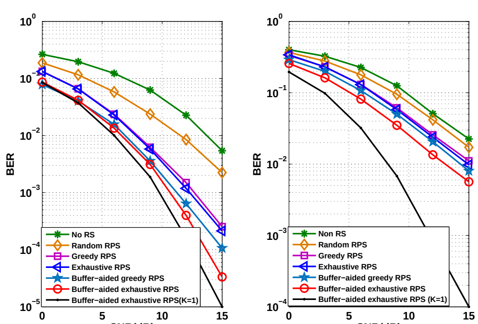

Fig. 3. a) Performance comparison for buffer-aided scheme and non buffer-aided scheme in cooperative DS-CDMA system with perfect decoding at the relay, MF at the destination b) Performance comparison for buffer-aided scheme and non buffer-aided scheme in cooperative DS-CDMA system with MMSE at the relay, MF at the destination

The first example shown in Fig. 3(a) illustrates the performance comparison between the proposed buffer-aided DSTC transmission with different relay pair selection strategies (RPS) and DSTC transmission with relay pair selections and no buffers when better decoding techniques are adopted. The system has 3 users, 6 relays, perfect decoding is assumed at each relay and the matched filter is adopted at the destination. Specifically, for the no relay selection (RS) DSTC technique, all relays participate in the DSTC transmission (every two consecutive relays are working in pairs). Similarly, for the non buffer-aided schemes, the relay pair selection process only occurs during the second phase (relay-destination), where the random selection algorithm chooses an arbitrary relay pair, the proposed greedy algorithm chooses two relays associated with two optimum relay-destination links and the exhaustive relay pair schemes examines all possible relay pairs and selects the one with the highest SINR. In contrast, the proposed buffer-aided scheme automatically selects the relay pair over both source-relay links and relay-destination links. Moreover, with the help of the buffers, the most appropriate data are sent and better overall system performance can be achieved. The performance bounds for a single-user buffer-aided exhaustive RPS DSTC is presented here for comparison purposes. Consequently, the results reveal that our proposed buffer-aided strategies ($B = 6$) perform better than the one without buffers. In particular, Fig. 3(a) also illustrates that our proposed buffer-aided schemes can approach the single user bound very closely.

The second example depicted in Fig. 3(b) compares the proposed buffer-aided DSTC transmission with different relay pair strategies and DSTC transmission with relay pair selections and no buffers. In this scenario, where we apply the linear MMSE receiver at each of the relays and the RAKE at the destination in an uplink cooperative scenario with 3 users, 6 relays and buffer size $B = 6$. Similarly, the performance for a single-user buffer-aided exhaustive RPS DSTC are presented for comparison purposes. The results indicate that our proposed buffer-aided strategies ($B = 6$) perform better than the one without buffers. Furthermore, the BER performance curves of our greedy RPS algorithm approach the exhaustive RPS, while keeping the complexity reasonably low for practical use.

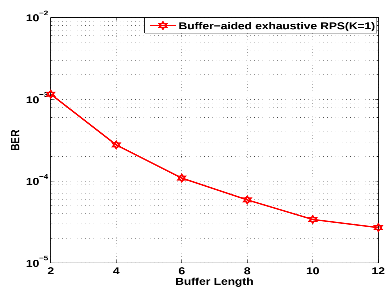

Fig. 4. BER versus size of the buffers for uplink cooperative system

The algorithms are then assessed in terms of the BER versus buffer size B in Fig. 5 with a fixed SNR=15dB. Similarly, we assume perfect decoding at the relays and RAKE at the destination. The results indicate that the overall BER degrades as the size of the buffer increases. It also shows that with larger buffer sizes, the system experiences diminishing returns in performance. In this case, a good balance between the transmission delay and the buffer size can be obtained when the buffer size is carefully considered.

6. CONCLUSIONS

In this work, we have presented a buffer-aided DSTC scheme for cooperative DS-CDMA systems with different relay pair selection techniques. With the help of buffers, this approach effectively improves the transmission performance as decoded symbols are stored in the corresponding buffer entries and wait until the most appropriate time for transmission. Simulation results show that the performance of the proposed scheme and algorithm offer considerable gains as compared to existing non buffer-aided schemes.

7. REFERENCES

[1] J.G.Proakis, *Digital Communications*, McGraw-Hill, Inc, New York, USA, 4th edition, 2011.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity - parts I and II," *IEEE Trans. Communication.*, vol. 51, no. 11, pp. 1927–1948, November 2003.

[3] L. Venturino, X. Wang, and M. Lops, "Multi-user detection for cooperative networks and performance analysis," *IEEE Trans. Signal Processing*, vol. 54, no. 9, pp. 3315–3329, September 2006.

[4] J. N. Laneman and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behaviour," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, December 2004.

[5] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct 2003.

[6] S. Yiu, R. Schober, and L. Lampe, "Distributed space-time block coding," *IEEE Trans. Wireless Commun.*, vol. 54, no. 7, pp. 1195–1206, Jul 2006.

[7] R. C. de Lamare and R. Sampaio-Neto, "Blind adaptive MIMO receivers for space-time block-coded DS-CDMA systems in multipath channels using the constant modulus criterion," *IEEE Trans. on Commun.*, vol. 58, no. 1, pp. 21–27, Jan 2010.

[8] Y. Jing and B. Hassibi, "Distributed space-time coding in wireless relay networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 12, pp. 3524 – 3536, Dec. 2006.

[9] T. Peng, R. C. de Lamare, and A. Schmeink, "Adaptive distributed space-time coding for cooperative MIMO relaying systems," *2012 International Symposium on Wireless Communication Systems (ISWCS)*, pp. 28 – 31, Aug. 2012.

[10] Y. Jing and H. Jafarkhani, "Single and multiple relay selection schemes and their achievable diversity orders," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1084–1098, Mar 2009.

[11] P. Clarke and R. C. de Lamare, "Transmit diversity and relay selection algorithms for multi-relay cooperative MIMO systems," *IEEE Trans. Veh. Technol*, vol. 61, no. 3, pp. 1084–1098, Mar 2012.

[12] Tong Peng, R.C. de Lamare, and A. Schmeink, "Adaptive distributed space-time coding based on adjustable code matrices for cooperative MIMO relaying systems," *IEEE Trans. on Commun.*, vol. 61, no. 7, pp. 2692–2703, July 2013.

[13] S. Talwar, Y. Jing, and S. Shahbazpanahi, "Joint relay selection and power allocation for two-way relay networks," *IEEE Signal Process. Lett*, vol. 18, no. 2, pp. 91–94, Feb 2011.

[14] N. Zlatanov, A. Ikhlef, T. Islam, and R. Schober, "Buffer-aided cooperative communications: opportunities and challenges," *IEEE Communications Magazine*, vol. 52, no. 4, pp. 146–153, May 2014.

[15] N. Zlatanov, R. Schober, and P. Popovski, "Throughput and diversity gain of buffer-aided relaying," *IEEE Globecom*, pp. 1–6, Dec 2011.

[16] I. Krikidis, T. Charalambous, and J. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1592–1967, May 2012.

[17] A. Ikhlef, D. S. Michalopoulos, and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1124–1135, Jan 2012.

[18] M. Ding, S. Liu, H. Luo, and W. Chen, "MMSE based greedy antenna selection scheme for AF MIMO relay systems," *IEEE Signal Process. Lett*, vol. 17, no. 5, pp. 433–436, May 2010.

[19] S. Song and W. Chen, "MMSE based greedy eigenmode selection for AF MIMO relay channels," *IEEE Globecom*, Anaheim, CA, Dec. 2012.

[20] J. Gu and R. C. de Lamare, "Joint parallel interference cancellation and relay selection algorithms based on greedy techniques for cooperative DS-CDMA systems," *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)*, pp. 2754 – 2758, May 2014.

[21] R.C. de Lamare and R. Sampaio-Neto, "Minimum mean-squared error iterative successive parallel arbitrated decision feedback detectors for ds-cdma systems," *IEEE Trans. on Commun.*, vol. 56, no. 5, pp. 778–789, May 2008.

[22] J. Gu and R. C. de Lamare, "Joint interference cancellation and relay selection algorithms based on greedy techniques for cooperative ds-cdma systems," *EURASIP Jounal on Wireless Communications and Networking*, 2016.

[23] R.C. de Lamare and R. Sampaio-Neto, "Adaptive reduced-rank processing based on joint and iterative interpolation, decimation, and filtering," *IEEE Trans. Signal Processing*, vol. 57, no. 7, pp. 2503–2514, July 2009.

[24] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451 – 1458, Oct. 1998.

[25] T. Islam, R. Schober A. Iklef, and V. Bhargava, "Diversity and delay analysis of buffer-aided bicm-ofdm relaying," *IEEE Trans. Wireless Commun.*, vol. 12, no. 11, pp. 5506 – 5519, Nov. 2013.