# JOINT SIC AND MULTI-RELAY SELECTION ALGORITHMS 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[†]
Emails: jg849@york.ac.uk, rodrigo.delamare@york.ac.uk

## ABSTRACT

In this work, we propose a cross-layer design strategy based on a joint successive interference cancellation (SIC) detection technique and a multi-relay selection algorithm for the uplink of cooperative direct-sequence code-division multiple access (DS-CDMA) systems. We devise a low-cost greedy list-based SIC (GL-SIC) strategy with RAKE receivers as the front-end that can approach the maximum likelihood detector performance. We also present a low-complexity multi-relay selection algorithm based on greedy techniques that can approach the performance of an exhaustive search. Simulations show an excellent bit error rate performance of the proposed detection and relay selection algorithms as compared to existing techniques.

***Index Terms*—** DS-CDMA, cooperative systems, relay selection, greedy algorithms, SIC detection.

## 1. INTRODUCTION

In wireless communications, fading induced by multipath propagation has a detrimental effect on the received signals. In order to mitigate this effect, modern diversity techniques like cooperative diversity have been widely considered in recent years [1]. Several cooperative schemes have been proposed [2–4] and among the most effective ones are Amplify-and-Forward (AF) and Decode-and-Forward (DF) [4].

DS-CDMA systems are a multiple access technique that can be incorporated with cooperative systems in ad hoc and sensor networks [5,6]. Due to the multiple access interference (MAI) effect that arises from nonorthogonal received waveforms, the system is adversely affected. To address this issue, multiuser detection (MUD) techniques have been developed in [7] as an effective approach to suppress MAI. The optimal detector, known as maximum likelihood (ML) detector, has been proposed in [7]. However, this method is infeasible for ad hoc and sensor networks considering its computational complexity. Motivated by this fact, several sub-optimal strategies have been developed: the linear detector [8], the successive interference cancellation (SIC) [9], the parallel interference cancellation (PIC) [10] and the minimum mean-square error (MMSE) decision feedback detector [11].

Prior studies on relay selection methods have been recently introduced in [12–15]. Among these approaches, a greedy algorithm is an effective way to approach the global optimal solution. Greedy algorithms have been widely applied in sparse approximation [16], internet routing [17] and arithmetic coding [18]. In cooperative relaying systems, greedy algorithms are used in [14, 15] to search for the best relay combination. However, with insufficient number of combinations considered in the selection process, a significant performance loss is viewed as compared to an exhaustive search.

The objective of this paper is to propose a cross-layer design strategy that jointly considers the optimization of a low-complexity detection and a relay selection algorithm for ad hoc and sensor networks that employ DS-CDMA systems. Cross-layer designs that integrate different layers of the network have been employed in prior work [19, 20] to guarantee the quality of service and help increase the capacity, reliability and coverage of networks. In this work, we devise a low-cost greedy list-based successive interference cancellation (GL-SIC) strategy with RAKE receivers as the front-end that can approach the maximum likelihood detector performance.We also present a low-cost multi-relay selection algorithm based on greedy techniques that can approach the performance of an exhaustive search. A cross-layer design technique that brings together the proposed GL-SIC algorithm and the greedy relay selection is then considered and evaluated by simulations.

The rest of this paper is organized as follows. In Section 2, the system model is described. In Section 3, the GL-SIC detector is presented. In Section 4, the relay selection strategy is proposed. In Section 5, simulation results are presented and discussed. Finally, conclusions are drawn in Section 6.

## 2. COOPERATIVE DS-CDMA SYSTEM MODEL

We consider the uplink of a synchronous DS-CDMA system with $K$ users $(k_1, k_2, ...k_K)$, $L$ relays $(l_1, l_2, ...l_L)$, $N$ chips per symbol and $L_p$ $(L_p < N)$ propagation paths for each link. The system is equipped with a DF 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, sampled at chip rate to obtain sufficient statistics and organized into $M \times 1$ vectors $\mathbf{y}_{sd}$, $\mathbf{y}_{sr}$ and $\mathbf{y}_{rd}$, which represent the signals received from the sources (users) to the destination, the sources to the relays and the relays to the destination, respectively. The proposed algorithms for detection and relay selection are employed at the relays and at the destination. The received signal at the destination comprises the

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

data transmitted during two phases that are jointly processed at the destination. Therefore, the received signal is described by a $2M \times 1$ vector formed by stacking the received signals from the relays and the sources as given by

$$\begin{bmatrix} \mathbf{y}_{sd} \\ \mathbf{y}_{rd} \end{bmatrix} = \begin{bmatrix} \sum\limits_{k=1}^{K} a_{sd}^{k} \mathbf{S}_k \mathbf{h}_{sd,k} b_k \\ \sum\limits_{l=1}^{L} \sum\limits_{k=1}^{K} a_{r_l d}^{k} \mathbf{S}_k \mathbf{h}_{r_l d,k} \hat{b}_{r_l d,k} \end{bmatrix} + \begin{bmatrix} \mathbf{n}_{sd} \\ \mathbf{n}_{rd} \end{bmatrix}, \quad (1)$$

where $M = N + L_p - 1$, $b_k \in \{+1, -1\}$ correspond to the transmitted symbols, $a_{sd}^{k}$ and $a_{r_l d}^{k}$ represent the $k$-th user's amplitude from the source to the destination and from the $l$-th relay to the destination. The $M \times L_p$ matrix $\mathbf{S}_k$ contains the signature sequence of each user shifted down by one position at each column that forms

$$\mathbf{S}_k = \begin{bmatrix} s_k(1) & & \mathbf{0} \\ \vdots & \ddots & s_k(1) \\ s_k(N) & & \vdots \\ \mathbf{0} & \ddots & s_k(N) \end{bmatrix}, \quad (2)$$

where $\mathbf{s}_k = [s_k(1), s_k(2), ...s_k(N)]^T$ is the signature sequence for user $k$. The vectors $\mathbf{h}_{sd,k}$, $\mathbf{h}_{r_l d,k}$ are the $L_p \times 1$ channel vectors for user $k$ from the source to the destination and the $l$-th relay to the destination. The $M \times 1$ noise vectors $\mathbf{n}_{sd}$ and $\mathbf{n}_{rd}$ contain samples of zero mean complex Gaussian noise with variance $\sigma^2$, $\hat{b}_{r_l d,k}$ is the decoded symbol for user $k$ at the output of relay $l$ after using the DF protocol. The received signal in (1) can then be described by

$$\mathbf{y}_d(i) = \sum_{k=1}^{K} \mathbf{C}_k \mathbf{H}_k(i) \mathbf{A}_k(i) \mathbf{B}_k(i) + \mathbf{n}(i), \quad (3)$$

where $i$ denotes the time instant corresponding to one symbol in the transmitted packet and its received and relayed copies. $\mathbf{C}_k$ is a $2M \times (L+1)L_p$ matrix comprising shifted versions of $\mathbf{S}_k$ as given by

$$\mathbf{C}_k = \begin{bmatrix} \mathbf{S}_k & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{S}_k & \dots & \mathbf{S}_k \end{bmatrix}, \quad (4)$$

$\mathbf{H}_k(i)$ denotes a $(L+1)L_p \times (L+1)$ channel matrix between the links. $\mathbf{A}_k(i)$ is a $(L+1) \times (L+1)$ diagonal matrix of amplitudes for user $k$. $\mathbf{B}_k(i) = [b_k, \hat{b}_{r_1 d,k}, \hat{b}_{r_2 d,k}, ..., \hat{b}_{r_L d,k}]^T$ is a $(L+1) \times 1$ vector for user $k$ that contains the transmitted symbol at the source and the detected symbols at the output of each relay, and $\mathbf{n}(i)$ is a $2M \times 1$ noise vector.

## 3. PROPOSED GL-SIC MULTIUSER DETECTION

In this section, we detail the GL-SIC multiuser detector that can be applied in the uplink of a cooperative system. The GL-SIC detector uses the RAKE receiver as the front-end, so that the matrix inversion brought by the MMSE filter can be avoided. The GL-SIC detector exploits the Euclidean distance between the users of interest and their nearest constellation points, with multiple ordering at each stage, all possible lists of tentative decisions for each user are generated. When seeking appropriate candidates, a greedy-like technique is performed to build each list and all possible estimates within the list are examined when unreliable users are detected. Unlike prior work which employs the concept of Euclidean distance with multiple feedback SIC (MF-SIC) [21], GL-SIC jointly considers multiple numbers of users, constellation constraints and re-ordering at each detection stage to obtain an improvement in detection performance.

### 3.1. The proposed GL-SIC design

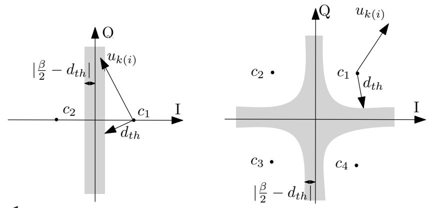

**Fig. 1**. The reliability check in BPSK and QPSK constellations.

In the following, we describe the process for initially detecting $n$ users described by the indices $k_1, k_2, ..., k_n$ at the first stage. Other users can be obtained accordingly. As shown by Fig. 1, $\beta$ is the distance between two nearest constellation points, $d_{th}$ is the threshold. The soft output of the RAKE receiver for user $k$ is then obtained by

$$u_k(i) = \mathbf{w}_k^H \mathbf{y}_{sr_l}(i), \quad (5)$$

where $\mathbf{y}_{sr_l}(i)$ represents the received signal from the source to the $l$-th relay, $u_k(i)$ stands for the soft output of the $i$-th symbol for user $k$ and $\mathbf{w}_k$ denotes the RAKE receiver that corresponds to a filter matched to the effective signature at the receiver. After that, we order all users into a decreasing power level and organize them into a vector $\mathbf{t}_a$. We pick the first $n$ entries $[\mathbf{t}_a(1), \mathbf{t}_a(2), ..., \mathbf{t}_a(n)]$ which denote users $k_1, k_2, ..., k_n$, the reliability of each of the $n$ users is examined by the corresponding Euclidean distance between the desired user and its nearest constellation point $c$.

**Decision reliable**:

If all $n$ users are determined as reliable

$$u_{\mathbf{t}_a(t)}(i) \notin \mathbf{C}_{\text{grey}}, \quad \text{for } t \in [1, 2, ..., n], \quad (6)$$

these soft estimates will then be applied to a slicer $Q(\cdot)$ as

$$\hat{b}_{\mathbf{t}_a(t)}(i) = Q(u_{\mathbf{t}_a(t)}(i)), \ \text{for } t \in [1, 2, ..., n], \quad (7)$$

where $\hat{b}_{\mathbf{t}_a(t)}(i)$ denotes the detected symbol for the $\mathbf{t}_a(t)$-th user, $\mathbf{C}_{\text{grey}}$ is the shadowed area in Fig. 1, it should be noted that the shadowed region would spread along both the vertical and horizontal directions. The cancellation is then performed in the same way as a conventional SIC where we mitigate the impact of MAI brought by these users

$$\mathbf{y}_{sr_l,s+1}(i) = \mathbf{y}_{sr_l,s}(i) - \sum_{t=1}^{n} \mathbf{H}_{sr_l,\mathbf{t}_a(t)}(i) \hat{b}_{\mathbf{t}_a(t)}(i), \quad (8)$$

where $\mathbf{H}_{sr_l,\mathbf{t}_a(t)}(i) = a_{sr_l}^{\mathbf{t}_a(t)} \mathbf{S}_{\mathbf{t}_a(t)}(i) \mathbf{h}_{sr_l,\mathbf{t}_a(t)}(i)$ stands for the desired user's channel matrix associated with the link between the source and the $l$-th relay, $\mathbf{y}_{sr_l,s}$ is the received signal from the source to the $l$-th relay at the $s$-th $(s = 1, 2, ..., K/n)$ cancellation stage. The process is then repeated with another $n$ users being selected from the remaining users at each following stage, and this algorithm changes to the unreliable mode when unreliable users are detected.

**Decision unreliable**:

(a). If part of the $n$ users are determined as reliable, while others are considered as unreliable, we have

$$u_{\mathbf{t}_p(t)}(i) \notin \mathbf{C}_{\text{grey}}, \quad \text{for } t \in [1,2,...,n_p], \tag{9}$$

$$u_{\mathbf{t}_q(t)}(i) \in \mathbf{C}_{\text{grey}}, \quad \text{for } t \in [1,2,...,n_q], \tag{10}$$

where $\mathbf{t}_p$ is a $1 \times n_p$ vector that contains $n_p$ reliable users and $\mathbf{t}_q$ is a $1 \times n_q$ vector that includes $n_q$ unreliable users, subject to $\mathbf{t}_p \cap \mathbf{t}_q = \varnothing$ and $\mathbf{t}_p \cup \mathbf{t}_q = [1,2,...n]$ with $n_p + n_q = n$. Consequently, the $n_p$ reliable users are applied to the slicer $Q(\cdot)$ directly and the $n_q$ unreliable ones are examined in terms of all possible constellation values $c^m$ $(m = 1,2,...,N_c)$ from the $1 \times N_c$ constellation points set $\mathbf{C} \subseteq F$, where $F$ is a subset of the complex field and $N_c$ is determined by the modulation type. The detected symbols are given by

$$\hat{b}_{\mathbf{t}_p(t)}(i) = Q(u_{\mathbf{t}_p(t)}(i)), \text{for } t \in [1,2,...,n_p], \tag{11}$$

$$\hat{b}_{\mathbf{t}_q(t)}(i) = c^m, \quad \text{for } t \in [1,2,...,n_q], \tag{12}$$

At this point, $N_c^{n_q}$ combinations of candidates for $n_q$ users are generated. The detection tree is then split into $N_c^{n_q}$ branches. After this processing, (8) is applied with its corresponding combination to ensure the interference caused by the $n$ detected users is mitigated. Following that, $N_c^{n_q}$ updated $\mathbf{y}_{sr_l}(i)$ are generated, we reorder the remaining users at each cancellation stage and compute a conventional SIC with RAKE receivers for each branch. The following $K \times 1$ different ordered candidate detection lists are then produced

$$\mathbf{b}^j(i) = [\mathbf{s}_{\text{pre}}(i),\ \mathbf{s}_p(i),\ \mathbf{s}_q^j(i),\ \mathbf{s}_{\text{next}}^j(i)]^T,\ j = 1,2,...,N_c^{n_q}, \tag{13}$$

where $\mathbf{s}_{\text{pre}}(i) = [\hat{b}_{\mathbf{t}_a(1)}(i), \hat{b}_{\mathbf{t}_a(2)}(i), ...]^T$ stands for the previous stages detected reliable symbols, $\mathbf{s}_p(i) = [\hat{b}_{\mathbf{t}_p(1)}(i), \hat{b}_{\mathbf{t}_p(2)}(i), ..., \hat{b}_{\mathbf{t}_p(n_p)}(i)]^T$ is a $n_p \times 1$ vector that denotes the current stage reliable symbols detected directly from slicer $Q(\cdot)$ when (9) occurs, $\mathbf{s}_q^j(i) = [c^m_{\mathbf{t}_q(1)}, c^m_{\mathbf{t}_q(2)}, ..., c^m_{\mathbf{t}_q(n_q)}]^T, j = 1,2,...,N_c^{n_q}$ is a $n_q \times 1$ vector that contains the detected symbols deemed unreliable at the current stage as in (10), each entry of this vector is selected randomly from the constellation point set $\mathbf{C}$ and all possible $N_c^{n_q}$ combinations need to be considered and examined. $\mathbf{s}_{\text{next}}^j(i) = [..., \hat{b}^{\mathbf{s}_q^j}_{\mathbf{t}'(1)}(i), ..., \hat{b}^{\mathbf{s}_q^j}_{\mathbf{t}'(n)}(i)]^T$ includes the corresponding detected symbols in the following stages after the $j$-th combination of $\mathbf{s}_q(i)$ is allocated to the unreliable user vector $\mathbf{t}_q$, and $\mathbf{t}'$ is a $n \times 1$ vector that contains the users from the last stage.

(b). If all $n$ users are considered as unreliable

$$u_{\mathbf{t}_b(t)}(i) \in \mathbf{C}_{\text{grey}}, \quad \text{for } t \in [1,2,...,n], \tag{14}$$

where $\mathbf{t}_b = [1,2,...,n]$, then all $n$ unreliable users can assume the values in $\mathbf{C}$. In this case, the detection tree will be split into $N_c^n$ branches to produce

$$\hat{b}_{\mathbf{t}_b(t)}(i) = c^m, \text{ for } t \in [1,2,...,n], \tag{15}$$

Similarly, (8) is then applied and a conventional SIC with different orderings at each cancellation stage is performed via each branch. Since all possible constellation values are tested for all unreliable users, we have the candidate lists

$$\mathbf{b}^j(i) = [\mathbf{s}_{\text{pre}}(i),\ \mathbf{s}_b^j(i),\ \mathbf{s}_{\text{next}}^j(i)]^T,\ j = 1,2,...,N_c^n, \tag{16}$$

where $\mathbf{s}_{\text{pre}}(i) = [\hat{b}_{\mathbf{t}_a(1)}(i), \hat{b}_{\mathbf{t}_a(2)}(i), ...]^T$ are the reliable symbols that are detected from previous stages, $\mathbf{s}_b^j(i) = [c^m_{\mathbf{t}_b(1)}, c^m_{\mathbf{t}_b(2)}, ..., c^m_{\mathbf{t}_b(n)}]^T, j = 1,2,...,N_c^n$ is a $n \times 1$ vector that represents $n$ number of users which are regarded as unreliable at the current stage as shown by (14), each entry of $\mathbf{s}_b^j$ is selected randomly from the constellation point set $\mathbf{C}$. The vector $\mathbf{s}_{\text{next}}^j(i) = [..., \hat{b}^{\mathbf{s}_b^j}_{\mathbf{t}'(1)}(i), ..., \hat{b}^{\mathbf{s}_b^j}_{\mathbf{t}'(n)}(i)]^T$ contains the corresponding detected symbols in the following stages after the $j$-th combination of $\mathbf{s}_b(i)$ is allocated to all unreliable users. After the candidates are generated, lists are built for each group of users, and the ML rule is used to choose the best candidate list as described by

$$\mathbf{b}^{\text{best}}(i) = \min_{\substack{1 \le j \le m, \text{where} \\ m = N_c^{n_q} \text{ or } N_c^n}} \| \mathbf{y}_{sr_l}(i) - \mathbf{H}_{sr_l}(i)\mathbf{b}^j(i) \|^2 . \tag{17}$$

### 3.2. GL-SIC with multi-branch processing

The multiple branch (MB) structure [11, 22] that employs multiple parallel processing branches can help to obtain extra detection diversity. Inspired by this, we change the ordering for $\mathbf{b}^{\text{best}}$ with indices $\mathbf{O} = [1,2,...,K]$ into a group of different detection sequences to form a parallel structure with each branch shares a different detection order. Since it is not practical to test all $L_b = K!$ possibilities due to the high complexity, a reduced number of branches can be tested. With each index number in $\mathbf{O}_{l_b}$ being the corresponding index number in $\mathbf{O}$ cyclically shifted to right by one position, namely: $\mathbf{O}_{l_1} = [K,1,2,...,K-2,K-1], \mathbf{O}_{l_2} = [K-1,K,1,...,K-3,K-2], ..., \mathbf{O}_{l_{K-1}} = [2,3,4,...,K,1]$ and $\mathbf{O}_{l_K} = [K,K-1,...,1]$(reversed order). After that, each of the $K$ parallel branches computes a GL-SIC algorithm with its corresponding order. After obtaining $K+1$ different candidate lists according to each branch, a modified ML rule is applied with the following steps:

**Table 1**. The specific steps for multi-branch selection

| |
|---|
| 1. Obtain the best candidate branch $\mathbf{b}^{O_{l_{\text{base}}}}(i)$ among all $K+1$ ($\mathbf{O}$ included) parallel branches according to the ML rule: $\mathbf{b}^{O_{l_{\text{base}}}}(i) = \min_{0 \le b \le K} \| \mathbf{y}_{sr_l}(i) - \mathbf{H}_{sr_l}\mathbf{b}^{O_{l_b}}(i) \|^2$ . |
| 2. Re-examine the detected value for user $k$ $(k = 1,2,...,K)$ by fixing the detected results of all other unexamined users in $\mathbf{b}^{O_{l_{\text{base}}}}(i)$, then replace the $k$-th user's detection result $\hat{b}_k$ in $\mathbf{b}^{O_{l_{\text{base}}}}(i)$ by its corresponding detected values from all other $K$ branches $\mathbf{b}^{O_{l_b}}(i)$, $(l_b \neq l_{\text{base}}, \mathbf{O} = \mathbf{O}_{l_0})$ with the same index, the combination with the minimum Euclidean distance is selected through the ML rule and the improved estimate of user $k$ is saved and kept. |
| 3. The same process is then repeated with the next user in $\mathbf{b}^{O_{l_{\text{base}}}}(i)$ until all users in $\mathbf{b}^{O_{l_{\text{base}}}}(i)$ are examined. |

## 4. PROPOSED GREEDY MULTI-RELAY SELECTION METHOD

In this section, a greedy multi-relay selection method is introduced. For this problem, the best relay combination is obtained through a costly exhaustive search of all possible subsets of relays. With $L$ relays involved in the transmission, an exponential complexity of $2^L - 1$ is experienced. This fact motivates us to seek other alternative methods. The standard greedy algorithm can be used in the selection process by cancelling the poorest relay-destination link stage by stage, however this method can approach only a local optimum. The proposed greedy multi-relay selection method can go through a reduced number of relay combinations and approach the best one based on previous decisions. In the proposed relay selection, the signal to interference and noise ratio (SINR) is used as the criterion to determine the optimum relay set. The expression of the SINR is

$$\mathrm{SINR_q} = \frac{E[|\mathbf{w}_q^H \mathbf{h}_q|^2]}{E[|\boldsymbol{\eta}|^2] + n}, \quad (18)$$

where $\mathbf{w}_q$ denotes the RAKE receiver for user $q$, $E[|\boldsymbol{\eta}|^2]$is the interference brought by all other users, $n$ is the noise. For the RAKE receiver, the SINR is given by

$$\mathrm{SINR_q} = \frac{|\mathbf{h}_q^H \mathbf{h}_q|^2}{\sum\limits_{\substack{k=1\\k\neq q}}^{K} |\mathbf{h}_q^H \mathbf{h}_k|^2 + \mathbf{h}_q^H \sigma_N^2 \mathbf{h}_q}, \quad (19)$$

where $\mathbf{h}_q$ is the channel vectors for user $q$, $\mathbf{H}$ is the channel matrix for all users. It should be mentioned that in various relay combinations, the channel vectors $\mathbf{h}_q$ for user $q$ ($q = 1, 2, ..., K$) is different as different relay-destination links are involved, and $\sigma_N^2$ is the noise variance. This problem can be then cast as the following optimization

$$\mathrm{SINR}_{\Omega_{\mathrm{best}}} = \max \ \{\min(\mathrm{SINR}_{\Omega_{\mathrm{r(q)}}}), q = 1, ..., K\}, \quad (20)$$

where $\Omega_r$ denotes all possible combination sets ($r \leq L(L+1)/2$) of any number of selected relays, $\mathrm{SINR}_{\Omega_{\mathrm{r(q)}}}$ represents the SINR for user $q$ in set $\Omega_r$, min $(\mathrm{SINR}_{\Omega_{\mathrm{r(q)}}}) = \mathrm{SINR}_{\Omega_{\mathrm{r}}}$ stands for the SINR for relay set $\Omega_r$ and $\Omega_{\mathrm{best}}$ is the best relay set that provides the highest SINR.

### 4.1. Standard greedy relay selection algorithm

The standard greedy relay selection method is operated in stages by cancelling the single relay according to the channel condition, as the channel path power is given by

$$P_{h_{r_l d}} = \mathbf{h}_{r_l d}^H \mathbf{h}_{r_l d}, \quad (21)$$

where $\mathbf{h}_{r_l d}$ is the channel vector between the $l$-th relay and the destination. The selection begins with all $L$ relays participating in the transmission, and the initial SINR is determined when all relays are involved in the transmission. For the second stage, we cancel the poorest relay-destination link and calculate the current SINR for the remaining $L-1$ relays, as compared with the previous SINR, if

$$\mathrm{SINR_{cur}} > \mathrm{SINR_{pre}}, \quad (22)$$

we update the previous SINR as

$$\mathrm{SINR_{pre}} = \mathrm{SINR_{cur}}, \quad (23)$$

and move to the third stage, where we remove the current poorest link and repeat the process. The algorithm stops when $\mathrm{SINR_{cur}} < \mathrm{SINR_{pre}}$ or there is only one relay left. This process is performed once before each packet transmission.

### 4.2. Proposed greedy relay selection algorithm

The proposed method differs from the standard one as we drop each of the relays in turns rather than drop them based on the channel condition. The algorithm is summarized as:

1. Initially, a set $\Omega_A$ that includes all $L$ relays is generated and its SINR is calculated, denoted by $\mathrm{SINR_{pre}}$.
2. For the second stage, we calculate the SINR for $L$ combination sets with each dropping one of the relays from $\Omega_A$. After that, we pick the combination set with the highest SINR for this stage, recorded as $\mathrm{SINR_{cur}}$.
3. Compare $\mathrm{SINR_{cur}}$ with the $\mathrm{SINR_{pre}}$, if (22) is true, we save this corresponding relay combination as $\Omega_{\mathrm{cur}}$ at this stage and update the $\mathrm{SINR_{pre}}$ as in (23).
4. For the third stage, we drop relays in turn again from $\Omega_{\mathrm{cur}}$ obtained in stage two. $L-1$ new combination sets are generated, we then select the set with the highest SINR and repeat the above process in the following stages until either $\mathrm{SINR_{cur}} < \mathrm{SINR_{pre}}$ or there is only one relay left.

Similarly, the whole process is performed only once before each packet. Meanwhile, its complexity is less than $L(L+1)/2$, much lower than the exhaustive search.

## 5. SIMULATIONS

In this section, a simulation study of the proposed GL-SIC multiuser detector and the low cost greedy multi-relay selection method is carried out. The DS-CDMA network uses randomly generated spreading codes of length $N = 16$, it also employs $L_p = 3$ independent paths with the power profile $[0\mathrm{dB}, -3\mathrm{dB}, -6\mathrm{dB}]$ for each source-relay, source-destination and relay-destination link, their corresponding channel coefficients $h_{sr_l}^{l_p}$, $h_{sd}^{l_p}$ and $h_{r_l d}^{l_p}(l_p = 1, 2, ..., L_p)$ are taken as uniformly random variables and normalized to ensure the total power is unity. We assume perfectly known channels at the receiver. Equal power allocation with normalization is assumed to guarantee no extra power is introduced during the transmission. The grey area in the GL-SIC algorithm is determined by the threshold where $d_{th} = 0.25$. We consider packets with 1000 BPSK symbols and average the curves over 300 trials. For the purpose of simplicity, BPSK modulation technique is applied and $n = 2$ users are considered in the GL-SIC scheme at each stage.

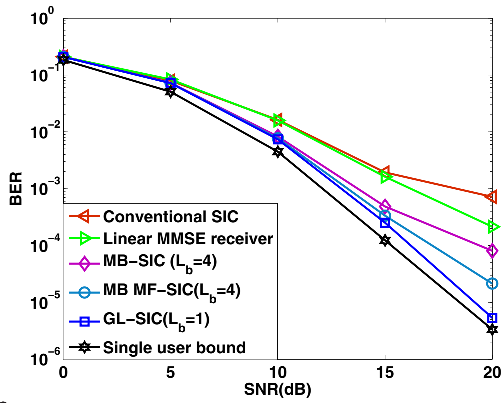


**Fig. 2.** BER versus SNR plot for uplink cooperative system with different filters employed in the relays and the destination

In order to verify the performance for the proposed cross-layer design, we compare the effect of different detectors with 10 users and 6 relays when the greedy multi-relay selection algorithm is applied in the system. The conventional SIC detector is the standard SIC with RAKE receivers employed at each stage and the multi-branch multi-feedback (MB-MF) SIC detection algorithm [21] is presented here for comparison purposes. We have also produced the simulation results for the multi-branch SIC (MB-SIC) where four parallel branches ($L_b = 4$) with different detection orders are applied. Simulation results depicted in Fig. 2 indicate that the single branch GL-SIC ($L_b = 1$) approach allows a more effective reduction of BER and achieves the best performance that is quite close to the single user scenario, followed by the MB MF-SIC, the MB-SIC, the linear MMSE receiver and the conventional SIC.

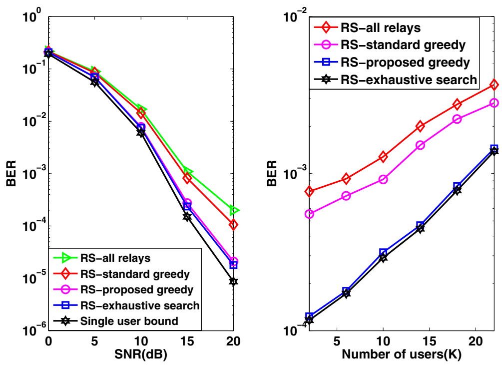


**Fig. 3**. a) BER versus SNR for uplink cooperative system b) BER versus number of users for uplink cooperative system

The second example shown in Fig. 3(a) reveals the BER versus SNR plot for the different multi-relay selection strategies, where we apply the GL-SIC $(L_b = 1)$ detection scheme at both the relays and the destination in an uplink cooperative scenario with 10 users and 6 relays. The performance bound for an exhaustive search is presented here for comparison purposes. From the results, it can be seen that with relay selection, the BER performance substantially improves. Furthermore, the BER performance curve of our proposed algorithm outperforms the standard greedy algorithm and approaches the same level of the exhaustive search, whilst keeping the complexity reasonably low for practical utilization. The algorithms are then assessed in terms of the BER versus number of users in Fig. 3(b) with a fixed SNR=15dB. Similarly, we apply the GL-SIC $(L_b = 1)$ detector at both the relays and the destination. The results indicate that the overall system performance degrades as the number of users increases. It also suggests that our proposed greedy relay selection method is more suitable than the standard greedy relay selection and non-relay selection scenario as a better BER performance is achieved when the number of users increases.

## 6. CONCLUSION

A cross-layer design strategy that incorporates the GL-SIC detector and a greedy multi-relay selection algorithm for the uplink of cooperative DS-CDMA systems has been presented in this paper. This approach effectively reduces the error propagation generated at the relays, avoiding the poorest relay-destination link while requiring a low complexity. Simulation results demonstrate that the performance of the proposed cross-layer design is superior to existing techniques and can approach the exhaustive search very closely.

## 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] L. Bai, L. Zhao, and Z. liao, "A novel cooperation scheme in wireless sensor networks," *IEEE Wireless Communications and Networking Conference*, pp. 1889–1893, Las Vegas, NV, Apr. 2008.

[6] M. Levorato, S. Tomasin, and M. Zorzi, "Cooperative spatial multiplexing for ad hoc networks with hybrid ARQ: System design and performance analysis," *IEEE Trans. Communication*, vol. 56, no. 9, pp. 1545–1555, Sep. 2008.

[7] S.Verdu, *Multiuser Detection*, Cambridge, 1998.

[8] R. Lupas and S. Verdu, "Linear multiuser detectors for synchronous code-division multiple-access channels," *IEEE Trans. Inform. Theory*, vol. 35, no. 1, pp. 123–136, Jan. 1989.

[9] P. Patel and J. Holtzman, "Analysis of a simple successive interference cancellation scheme in DS/CDMA systems," *IEEE J. Select. Areas Commun.*, vol. 12, no. 5, pp. 796–807, Jun. 1994.

[10] M. K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," *IEEE Trans. Communication*, vol. 38, no. 4, pp. 509–519, Apr. 1990.

[11] 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. Communication*, vol. 56, no. 5, pp. 778–789, May. 2008.

[12] 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.

[13] 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.

[14] 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.

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

[16] J. Tropp, "Greedy is good: Algorithmic results for sparse approximation," *IEEE Trans. Inf. Theory*, vol. 50, no. 10, pp. 2231?2242, Oct. 2004.

[17] R. Flury, S. V. Pemmaraju, and R. Wattenhofer, "Greedy routing with bounded stretch," *IEEE Infocom.*, Rio de Janeiro, Brazil, Apr. 2009.

[18] Y. Jia, E. Yang, D. He, and S. Chan, "A greedy re-normalization method for arithmetic coding," *IEEE Trans. Communication*, vol. 55, no. 8, pp. 1494–?503, Aug. 2007.

[19] R. C. de Lamare, "Joint iterative power allocation and linear interference suppression algorithms for cooperative DS-CDMA networks," *IET, Communications*, vol. 6, no. 13, pp. 1930–1942, Sep. 2012.

[20] W. Chen, L. Dai, K. B. Letaief, and Z. Cao, "A unified cross-layer framework for resource allocation in cooperative networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3000–3012, Aug. 2008.

[21] P. Li and R. C. de Lamare, "Multiple feedback successive interference cancellation detection for multiuser MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 10, no. 8, pp. 2434–2439, Aug. 2011.

[22] P. Li, R. C. de Lamare, and R. Fa, "Multi-feedback successive interference cancellation with multi-branch processing for MIMO systems," *Vehicular Technology Conference (VTC Spring)*, pp. 1–5, May. 2011.