ABSTRACT
In this work, we propose a cross-layer design strategy based on the parallel interference cancellation (PIC) 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 PIC (GL-PIC) 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 networks, cooperative communications, relay selection, greedy algorithms, PIC detection.

1. INTRODUCTION
Multipath fading is a major constraint that seriously limits the performance of wireless communications. Indeed, severe fading has a detrimental effect on the received signals and can lead to a degradation of the transmission of information and the reliability of the network. Cooperative diversity is a modern technique that has been widely considered in recent years [1] as an effective tool to deal with this problem. Several cooperative schemes have been proposed in the literature [2, 3, 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, 7]. Due to the multiple access interference (MAI) effect that arises from nonorthogonal received waveforms, the system is adversely affected. To deal with this issue, multiuser detection (MUD) techniques have been developed [8] as an effective approach to suppress MAI. The optimal detector, known as maximum likelihood (ML) detector, has been proposed in [9]. 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 [10, 11, 12, 13], the successive interference cancellation (SIC) [14], the parallel interference cancellation (PIC) [15, 16] and the minimum mean-square error (MMSE) decision feedback detector [17, 18].

In cooperative relaying systems, different strategies that utilize multiple relays have been recently introduced in [19, 20, 21, 22, 23, 24, 25]. 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 [26], internet routing [27] and arithmetic coding [28]. In relay assisted systems, greedy algorithms are used in [21, 22] to search for the best relay combination, however, with insufficient numbers of combinations considered, a significant performance loss is experienced as compared to an exhaustive search.

The aim of this work is to propose a cross-layer approach 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 [29, 30] to guarantee the quality of service and help increase the capacity, reliability and coverage of systems. However, involving MUD techniques with relay selection in cooperative relaying systems has not been discussed widely in the literature. In [31], an MMSE-MUD technique has been applied to cooperative systems, the results indicate that the transmissions are more resistant to MAI and obtain a significant performance gain when compared with a single direct transmission. However, extra complexity is introduced, as matrix inversions are required when an MMSE filter is deployed.

In this work, we devise a low-cost greedy list-based parallel interference cancellation (GL-PIC) strategy with RAKE receivers as the front-end that can approach the maximum likelihood detector performance. Unlike prior art, the proposed GL-PIC algorithm exploits the Euclidean distance between users of interest and the nearest constellation points, re-examines the reliability of the estimates so that all possible combination lists of tentative decisions can be checked. With this greedy-like approach, an improved detection performance can be obtained. We also present a low-complexity multi-relay selection algorithm based on greedy techniques that can approach the performance of an exhaustive search. In the proposed greedy algorithm, a selection rule is employed via several stages. At each stage, a limited number of relay combinations is examined and compared, resulting in a low-cost strategy to approach the performance of an exhaustive search. A cross-layer design strategy that brings together the proposed GL-PIC algorithm and the greedy relay selection is then considered and evaluated by computer simulations.

The rest of this paper is organized as follows. In Section 2, the system model is described. In Section 3, the GL-PIC multiuser detection method 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 $y_{sd}$, $y_{sr}$ and $y_{rd}$, 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 interference mitigation and relay selection are applied at the relays and at the destination. As shown in Fig.1, the received signal at the destination comprises the 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

$$y_{rd} = \left[ \sum_{k=1}^{K} a_{sd}^{k} s_{h_{sd,k}} b_{k} \right] + n_{rd},$$

$$y_{rd} = \left[ \sum_{k=1}^{K} a_{sd}^{k} s_{h_{sd,k}} b_{k} \right] + n_{rd},$$

where $M = N + L_p - 1$, $b_{k} \in \{+1, -1\}$ correspond to the transmitted symbols, $a_{sd}^{k}$ and $a_{rd}^{k}$ 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 $S_k$ contains the signature sequence of each user shifted down by one position at each column that forms

$$S_k = \begin{bmatrix} s_k(1) & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots \\ s_k(N) & \cdots & s_k(1) & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & s_k(N) \end{bmatrix},$$

where $s_k = [s_k(1), s_k(2), \ldots, s_k(N)]^T$ is the signature sequence for user $k$. The vectors $h_{sd,k}$, $h_{sr,d,k}$ 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 $n_{sd}$ and $n_{rd}$ contain samples of zero mean complex Gaussian noise with variance $\sigma^2$. $b_{r_{l,d,k}}$ is the decoded symbol at the output of relay $l$ after using the DF protocol. The received signal in (1) can then be described by

$$y_{d}(i) = \sum_{k=1}^{K} C_k H_k(i) A_k(i) B_k(i) + n(i),$$

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

$$C_k = \begin{bmatrix} S_k & 0 & \cdots & 0 \\ 0 & S_k & \cdots & 0 \end{bmatrix}.$$

$H_k(i)$ represents a $(L + 1)L_p \times (L + 1)$ channel matrix between the sources and the destination and the relays and the destination links. $A_k(i)$ is a $(L + 1) \times (L + 1)$ diagonal matrix of amplitudes for user $k$. The matrix $B_k(i) = [b_k, b_{1,r_{l,d,k}}, b_{2,r_{l,d,k}}, \ldots, b_{L_p,r_{l,d,k}}]^T$ is a $(L + 1) \times 1$ matrix for user $k$ that contains the transmitted symbol at the source and the detected symbols at the output of each relay, and $n(i)$ is a $2M \times 1$ noise vector.

### 3. THE PROPOSED GL-PIC MULTIUSER DETECTOR

In this section, we present a GL-PIC detector that can be applied at both the relays and destination in the uplink of a cooperative system. The GL-PIC detector uses the RAKE receiver as the front-end, which reduces computational complexity by avoiding the matrix inversion required when MMSE filters are applied. With the structure depicted in Fig.2, the proposed GL-PIC algorithm determines the reliability of the detected symbol by comparing the Euclidean distance between the symbol of users of interest and the potential nearest constellation point with a chosen threshold. After checking the reliability of the symbol estimates by listing all possible combinations of tentative decisions, the $n_a$ most unreliable users are re-examined via a number of selected constellation points in a greedy-like approach, which saves computational complexity by avoiding redundant processing with reliable users. Following the diagram in Fig.2, the soft estimates of the RAKE receiver for each user are obtained by

$$u_k(i) = \mathbf{w}_k^H y_{sr}(i),$$

where $y_{sr}(i)$ 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 $\mathbf{w}_k^H$ denotes the RAKE receiver that corresponds to a filter matched to the effective signature at the receiver. As shown by Fig.3, $\beta$ is the distance between two nearest constellation points, $d_{th}$ is the threshold. For the $k$-th user, the reliability of its soft estimates is determined by the Euclidean distance between $u_k(i)$ and its nearest constellation points $c_i$.

### Decision reliable:

If the soft estimation of $n_a$ users satisfy the following condition

$$u_{k(t)}(i) \notin C_{grey}, \quad \text{for } t \in [1,2,\ldots,n_a],$$

where $t_i$ is a $1 \times n_a$ vector that contains $n_a$ reliable estimates, $C_{grey}$ is the grey area in Fig.3 and the grey area would extend unlimitedly along both the vertical and horizontal directions. These soft estimates will be applied to a slicer $Q(\cdot)$ as described by

$$\hat{b}_{k(t)}(i) = Q(u_{k(t)}(i)), \quad \text{for } t \in [1,2,\ldots,n_a],$$

where $\hat{b}_{k(t)}(i)$ denotes the detected symbol for the $t_{i}$-th user.

### Decision unreliable:

In case that $n_0$ users are determined as unreliable, a $1 \times n_a$ vector $t_0$ with $n_a$ unreliable estimates included is produced, as given by

$$u_{k(t)}(i) \in C_{grey}, \quad \text{for } t \in [1,2,\ldots,n_a],$$

we then sort these unreliable estimates in terms of their Euclidean distance in a descending order. Consequently, the first $n_q$ users from
where
from the constellation point set
combination vector. Each entry of the vector is selected randomly
lations need to be considered and examined. The trade-off between
stellation values
unreliable users that are detected by the slicer
the ordered set are deemed as the most unreliable ones as they ex-
Following that,
subsequently to choose the best candidate list as described by
only a local optimum can be achieved. Unlike the traditional ways,
the proposed greedy multi-relay selection method can go through a
sufficient 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
expressed by
\[\text{SINR}_q = \frac{E[|w_q^H r_q|^2]}{E[|\eta|^2] + n} \tag{14}\]
where
\(w_q \) denotes the RAKE receiver for user \(q\),
\( E[|\eta|^2] = E[\sum_{k=1}^{K} H_q b_k^H |^2] \) is the interference brought by all other users,
\( n \) is the noise vector. For the RAKE receiver, the SINR is given by
\[\text{SINR}_q = \frac{H_q^H H_q}{H_q H_q + \sigma_n^2 H_q H_q}, \tag{15}\]
where
\(H_q\) is the channel matrix for user \(q\),
\(H\) is the channel matrix for all users,
\(\Omega\) represents the channel matrix of all other users except user \(q\).
It should be mentioned that in various relay combinations, the
channel matrix \(H_q\) for user \(q\) \((q = 1, 2, ..., K)\) is different as
different relay-destination links are involved, \(\sigma_n^2\) is the noise variance.
This problem thus can be cast as the following optimization:
\[\text{SINR}_{\text{best}} = \max \left\{ \min (\text{SINR}_{\Omega_l(q)}, q = 1, ..., K) \right\}, \tag{16}\]
where \(\Omega_l\) denotes all possible combination sets \((r \leq L(L+1)/2)\)
of any number of selected relays, \(\text{SINR}_{\Omega_l(q)}\) represents the SINR
for user \(q\) in set \(\Omega_r\), \(\min (\text{SINR}_{\Omega_l(q)}) = \text{SINR}_{\Omega_l}\) stands for the
SINR for relay set \(\Omega_r\), and \(\text{SINR}_{\text{best}}\) is the best relay set that provides
the highest SINR.

4.1 Standard greedy relay selection algorithm
The standard greedy relay selection method works in stages by re-
moving the single relay according to the channel path power, as given by
\[P_{h_{rd}} = h_{rd}^H h_{rd}, \tag{17}\]
where
\(h_{rd}\) is the channel vector between the \(l\)-th relay and the desti-
nation. At the first stage, the initial SINR is determined when all \(L\)
relays are involved in the transmission. Consequently, we cancel the
worst relay-destination link and calculate the current SINR for the
remaining \(L-1\) relays, as compared with the previous SINR, if
\[\text{SINR}_{\text{cur}} > \text{SINR}_{\text{pre}}, \tag{18}\]
we update the previous SINR as
\[\text{SINR}_{\text{pre}} = \text{SINR}_{\text{cur}}, \tag{19}\]
and move to the third stage by removing the current poorest link and
repeating the above process. The algorithm stops either when
\(\text{SINR}_{\text{cur}} < \text{SINR}_{\text{pre}}\) or when there is only one relay left. The se-
lection can be performed once at the beginning of each packet trans-
mision.

4.2 Proposed greedy relay selection algorithm
In order to improve the performance of the standard algorithm, we
propose a new greedy relay selection algorithm that is able to achieve
a good balance between the performance and the complexity. The
proposed method differs from the standard technique as we drop
each of the relays in turns rather than drop them based on the channel
condition at each stage. The algorithm can be summarized as:
1. Initially, a set \(\Omega_A\) that includes all \(L\) relays is generated and its
   corresponding SINR is calculated, denoted by \(\text{SINR}_{\text{pre}}\).
2. For the second stage, we calculate the SINR for \(L\) combina-
tion 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 \(\text{SINR}_{\text{cur}}\).
3. Compare $\text{SINR}_{cur}$ with the previous stage $\text{SINR}_{pre}$. If it is true, we save this corresponding relay combination as $\Omega_{cur}$ at this stage. Meanwhile, we update the $\text{SINR}_{pre}$ as in (19).

4. After moving to the third stage, we drop relays in turn again from $\Omega_{cur}$ obtained in stage two. If there is one relay left, we end this stage. Meanwhile, we update the $\text{SINR}_{pre}$ as in (19).

This new greedy selection method considers the combination effect of the channel condition so that additional useful sets are examined. When compared with the standard greedy relay selection method, the previous stage decision is more accurate and the global optimum can be approached more closely. Furthermore, its complexity is less than $L(L + 1)/2$, which is much lower than the exhaustive search. Similarly, the whole process is performed only once before each packet.

### Table 1. The proposed greedy multi-relay selection algorithm

| $\Omega_A$ | $\Omega_A$ denotes the set when all relays are involved |
| $\text{SINR}_{\Omega A} = \min(\text{SINR}_{\Omega A(q)}), q = 1, 2, ... K$ |
| $\text{SINR}_{\text{pre}} = \text{SINR}_{\Omega A}$ |
| for stage $n = 1$ to $L$ |
| for $r = 1$ to $L + 1$ |
| $\Omega_r = \Omega_A \setminus \Omega_{(r)}$ |
| $\text{SINR}_{\Omega_A} = \min(\text{SINR}_{\Omega_A(q)}), q = 1, 2, ... K$ |
| $\text{SINR}_{\text{cur}} = \max(\text{SINR}_{\Omega_A})$ |
| $\Omega_{cur} = \Omega_{SINR_{\text{cur}}}$ |
| if $\text{SINR}_{\text{cur}} > \text{SINR}_{\text{pre}}$ and length($\Omega_{\text{cur}}$) > 1 |
| $\Omega_A = \Omega_{\text{cur}}$ |
| $\text{SINR}_{\text{pre}} = \text{SINR}_{\text{cur}}$ |
| else |
| break |
| end if |
| end for |
| end for |

### 5. SIMULATIONS

In this section, a simulation study of the proposed GL-PIC multiuser detection strategy with a RAKE receiver and the low cost greedy multi-relay selection method is carried out. The DS-CDMA network uses randomly generated spreading codes of length $N = 16$ and employs $L_p = 3$ independent paths with the power profile $[0 \text{dB}, -3 \text{dB}, -6 \text{dB}]$ for each source-relay, source-destination and relay-destination link. Their corresponding channel coefficients 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. We consider packets with 1000 BPSK symbols and average the curves over 300 trials. For the purpose of simplicity, in the GL-PIC algorithm, a three-iteration PIC process is adopted, $d_{th} = 0.25$ and BPSK modulation technique are applied in the following simulations.

The first example, shown in Fig.4 depicts the performance for the proposed cross-layer design, where we compare the effect of different detectors with 10 users and 6 relays when the new greedy multi-relay selection algorithm is applied in the system. Simulation results indicate that the GL-PIC approach allows a more effective reduction of BER, followed by the conventional SIC detector and the conventional PIC detector. Additionally, it is worth noting that some extra performance gains are attained as more $n_q$ unreliable users are selected and re-examined.

The second scenario illustrated in Fig.5a) shows the BER versus SNR plot for employing different multi-relay selection strategies, where we apply the GL-PIC detection scheme at both the relays and 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, where it examines all possible relay combinations and picks the one with the highest SINR. From the results, it can be seen that with relay selection, the BER performance substantially improves. Furthermore, the BER performance curve of our proposed multi-relay selection 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.5b) with a fixed SNR=15dB. Similarly, we apply the GL-PIC detector at both the relays and 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 has a big advantage for situations without a high load when compared with the standard greedy relay selection and non-relay selection scenario.

### 6. CONCLUSIONS

A novel cross-layer design strategy that incorporates the greedy list-based parallel interference cancellation (GL-PIC) detection technique and a low cost greedy multi-relay selection algorithm for the uplink of cooperative DS-CDMA systems has been presented in this paper. This approach effectively mitigates the phenomenon of error propagation and selects the optimum relay combination while requiring a low complexity. Simulation results demonstrate that
the proposed cross-layer optimization technique can offer considerable gains as compared to existing detectors and can approach the exhaustive search bound very closely.

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