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Joint design of cooperative protocols and distributed beamforming for multi-hop cognitive radio networks

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Abstract

The increasingly crowded wireless spectrum has led to the need of new paradigms in wireless communications and the cognitive radio techniques that can offer promising solutions to the spectrum scarcity. In cognitive radio networks licensed primary users and unlicensed secondary users are allowed to coexist in the same frequency spectrum. Beamforming and MIMO technology can be used to minimize the interference from the secondary users to the primary users while improving the quality of communications when each node is equipped with multiple antennas to form an antenna array. However, equipping multiple antennas at each radio node is not feasible in many applications. In this paper, we consider the radio network with single antenna at each node. We first propose a cooperative network architecture in the network layer. The architecture consists of cooperative clusters used for distributed beamforming, and a routing backbone of the clusters that can avoid the interference to the primary users in the relay route. Distributed algorithms are designed for self-formation of the cooperative clusters and routing backbone. Then we propose a computationally efficient secondary users selection scheme in the link layer for the communications between two cooperative clusters while minimizing the interference to the primary users. The simulation results show that the proposed protocols and algorithms are effective and efficient in terms of time and energy.

Keywords: Cognitive radio, cooperative MIMO radios, distributed beamforming

1 Introduction

Cognitive radio is a promising paradigm in wireless communications that enables efficient use of frequency resources by allowing the coexistence of licensed primary users (PUs) and unlicensed secondary users (SUs) in the same frequency band. The solution is achieved by endowing the radio nodes with "cognitive capabilities," e.g., the ability to sense the electromagnetic environment, make short term predictions, and react consequently by adapting transmission parameters (e.g., operating spectrum, modulation, and transmission power) in order to optimize the usage of the available resources [1]. In [1, 2, 3], beamforming is used to reduce the interference at PUs. These beamforming approaches utilize antenna arrays in Multiple Input Multiple Output (MIMO) radio systems. MIMO radio systems employ multiple transmission and reception antennas to provide extremely high spectral efficiencies by simultaneously transmitting multiple data streams in the same channel. The gains induced by MIMO technology can be used in wireless network to improve system performance, e.g. raising data rate, reducing error rate or energy consumption, or extending communication range. However, it is not feasible in many applications to have the terminal devices equipped with multiple antennas due to the size and cost of the devices. Cooperative/Virtual MIMO technique is a proven solution to this problem [4, 5]. In cooperative MIMO technique, multiple single-antenna nodes cooperate on data transmission and reception to achieve the same spectral efficiencies that the MIMO nodes provide. Theoretically, a k-antenna transmit beamformer can form h $(0 < h < k+1)$ constructive beams and null out $k-h$ directions simultaneously. When PUs and SUs coexist, a preliminary paradigm is proposed in [6] for the communication link between two cooperative groups, where beamforming is used to minimize the interference at the primary users while still achieving high diversity gain for the system performance at secondary users. In order to full use the proposed distributed beamforming to benefit the whole network, two issues need to be investigated. One is the impact brought to the distributed beamforming by the constraints of individual radio node. The other one is how to design the network protocols to support distributed beamforming and leverage the benefit from the link layer to the whole network.

In this research, we explored antenna diversity which enables beamforming for electronmagnetic spectrum sharing in a congested spectrum environment. The diversity gain achieved through the collaboration of a set of small devices equipped with a single antenna radio is investigated. The research consists of two folds: the first is to optimize the distributed beamforming between two adjacent cooperative radio groups; the second is to design the network protocols that can best support the distributed beamforming at link layer, minimize the latency of data relay, and maximize the network lifetime. In this paper, we first propose a cooperative network architecture in network layer. The architecture consists of cooperative clusters which are used to enable distributed beamforming, and a unique routing backbone of the clusters which is built for minimizing the interference to the

[0]This is an abstract footnote

primary users in the route of data relay. Distributed algorithms are designed for self-formation of the cooperative clusters and routing backbone. Then we propose a computationally efficient SUs selection scheme in the link layer for the communication between two cooperative clusters. Due to some practical constraints such as synchronization and timely information sharing, the number of available SUs in a cluster is usually larger than the maximum number of the SUs that can participate in beamforming. Our SUs selection scheme achieves a near-optimal beamforming performance with very low computational complexity. Computer simulations are conducted to evaluate the performance of the proposed architecture and beamforming design and verified the efficiency and effectiveness of the algorithms. The preliminary result in this research was presented in [7]. In this paper, we added an energy model and used it for the analysis of the proposed cooperative network architecture. We also provided the full version of system model, algorithms, and performance evaluation.

The rest of this paper is organized as follows. Section 2 describes the network and system model. Sections 3 and 4 present the joint design of network protocols and distributed beamforming. In Section 3, a cooperative network architecture is proposed. It is used to construct the cooperative clusters among the SUs for distributed beamforming and form the routing backbone for multihop communications. In Section 4, the efficient cooperative distributed beamforming design with SUs selection is elaborated. Section 5 shows the performance of the proposed cooperative protocols and distributed beamforming through computer simulations. Finally, a conclusion is drawn in Section 6.

2 Network and System Model

We consider a cognitive radio network in which unlicensed SUs and licensed PUs coexist. All PUs and SUs are assumed to be stationary. We investigate the protocols and algorithms that enable the data communication and relay in the SUs network without interference to PUs. A MIMO radio is the radio equipped with an antenna array. In Figure 1, the top plot shows a cognitive radio system in which each SU is a MIMO radio equipped with an antenna array, and the bottom plot gives a graph representation of the secondary network formed by the SUs only. When SUs have MIMO radios, beamforming can be used at SUs by posing a null constraint to the PU receiver while transmitting the data to other SUs at the same time, as shown in Figure 2.

When SUs are equipped with only one single antenna, the SUs can form cooperative clusters, where each cluster plays the role of a MIMO radio by cooperating on data transmission and reception as shown in Figure 3. In this research, all nodes are assumed to agree that they will participate in the cooperation to form the distributed beamformer whenever needed. In a $mT \times mR$ MIMO link (for example, a 3×3 MIMO link as shown in Figure 4), mT nodes in A cooperate on the data transmission; on the other side, each of mR nodes in B receives mT data streams and the combined data stream can be up to mT times stronger. Detailed protocols and algorithms for the communication of two clusters are described in [5, 6].

Among the cooperative strategies, the amplify-and-forward and decode-and-forward are most widely used. In the amplify-and-forward strategy, the relay nodes simply boost the energy of the signal received from the sender and re-transmit to the receiver. In the decode-and-forward strategy, the relay nodes will perform physical layer decoding (signal detection and demodulation) and then forward the decoded results. Although the amplify-and-forward relay has lower relay power consumption, it also amplifies the noise in the received signal and is not suitable for long-haul transmission. Moreover, decoding may be necessary when data aggregation and/or fusions are required at some local points such as cluster heads. Furthermore, considering that the decode-and-forward relay can be extended to combine with coding techniques and is easier to incorporate into network protocols [8], it will be considered in this paper.

In Section III, we will construct a routing backbone for cooperative clusters in such a way that at each link AB all nodes in B can receive the data stream (with different signal strength) when the nodes in A cooperatively transmit the data to B and pose a null constraint to the primary receiver at the same time. In the following discussion, we focus on the data transmission from the selected n nodes in A to the head node in B. Due to the nature of wireless communications, the other nodes in B shall receive the same data stream (with different signal strength). We leave the optimal selection

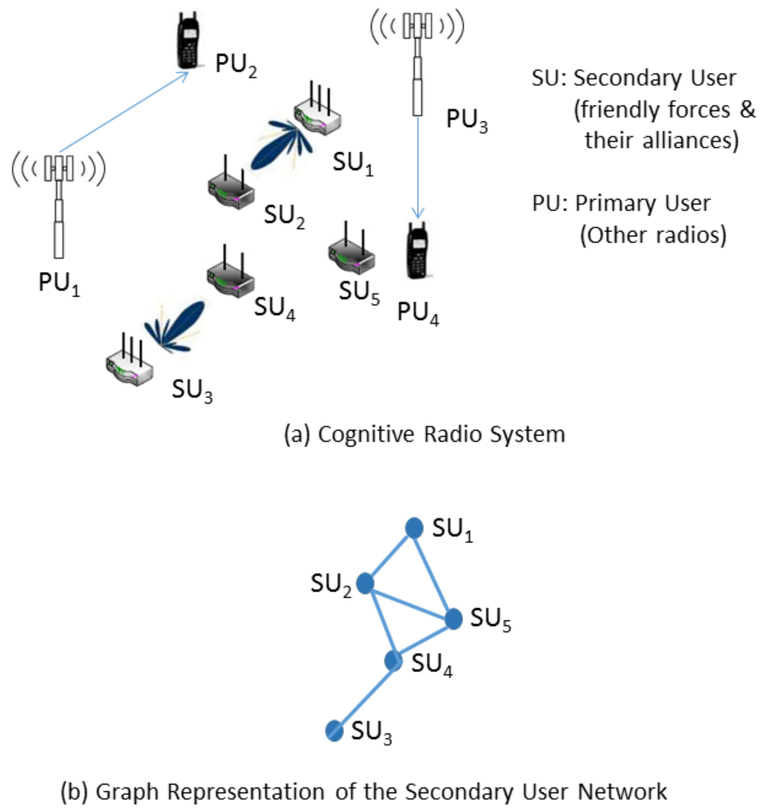

Figure 1: Cognitive radio system and the graph representation of the secondary user network

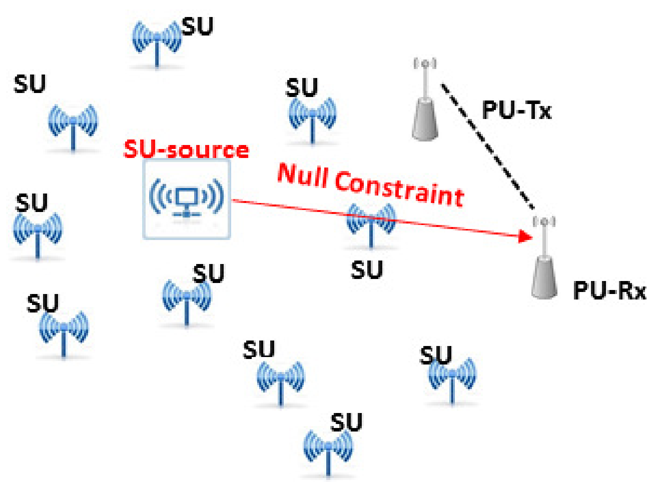

Figure 2: Beamforming for cognitive radio system

of the nodes in B to the future work.

We assume that the mT cooperative secondary user transmitters (SU-Txs) in the same cluster are located in a circle of radius R as shown in Figure 5. A polar coordinate system is used to define the node positions where the origin is taken at the center of circle. The position of the n^{th} SU-Tx is represented as (d_n, φ_n), where $n = 1, 2, \cdots, mT$, d_n and φ_n are the distance and angle of the node

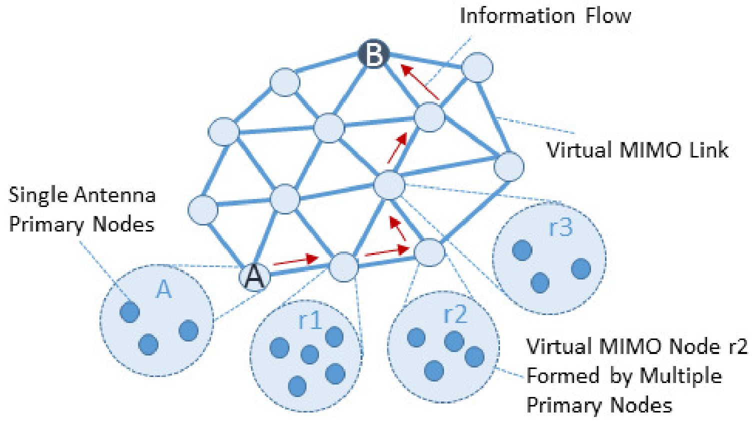

Figure 3: A cooperative radio network

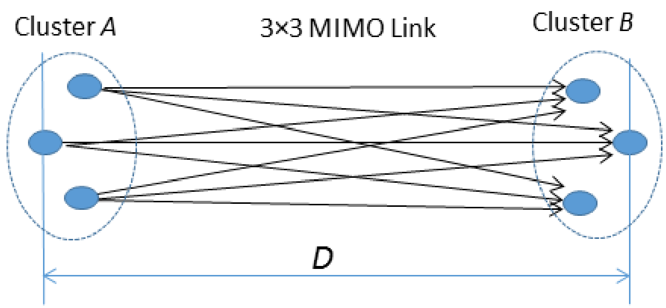

Figure 4: A cooperative MIMO link

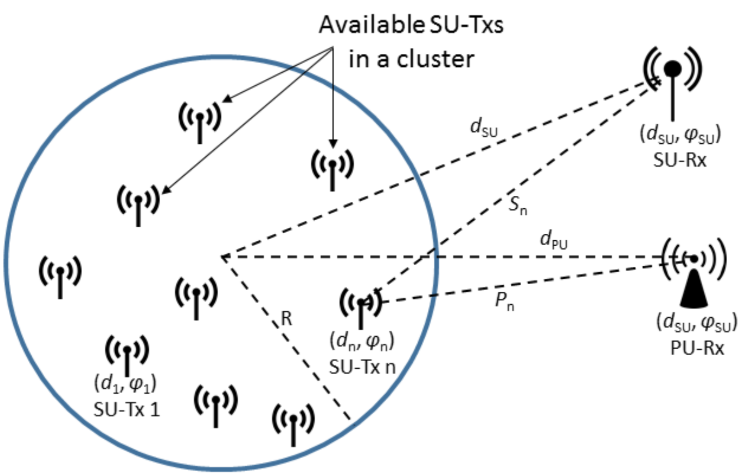

Figure 5: Cooperative cognitive radio system

from the center of the circle. The positions of primary user receiver (PU-Rx) and secondary user receiver (SU-Rx) are represented as (d_{PU}, φ_{PU}) and (d_{SU}, φ_{SU}) respectively. The distances of the n^{th} node from the primary and secondary receivers are denoted by P_n and S_n respectively.

As shown in Figure 6, a SU-Tx communicates with a SU-Rx by cooperating with other nodes to steer the signal towards the SU-Rx, while creating a null at the PU-Rx. We assume that only N

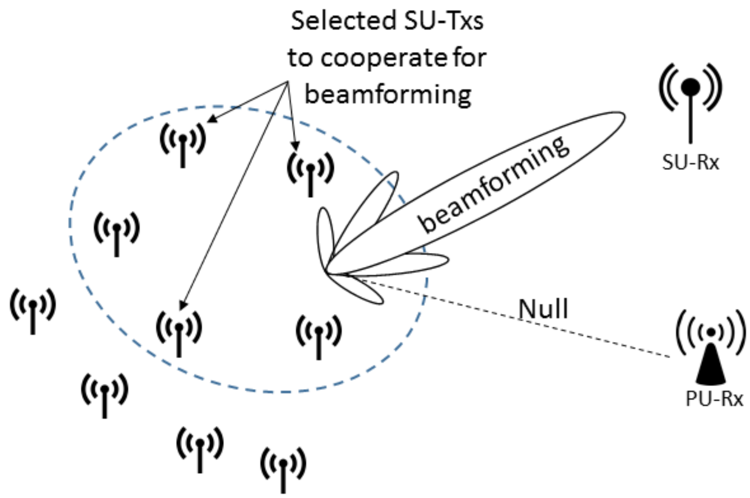

Figure 6: Desired beamforming with SU-Txs selection

nodes can collaborate at any given time due to system constraints such as synchronization and timely information-sharing. We also assume that the SU-Tx that participate in cooperative beamforming are controlled by a centralized node or through an ad-hoc network so that they can synchronize [9] and share their locations and other relevant information such as channel state information (CSI). Cooperative SU-Txs obtain direction estimates of PU-Rx and SU-Rx either through sensing, or by querying a geolocation database that provides the necessary information [10]. For realizing beamforming, a channel that provides necessary angular/spatial separation between the directions of SU-Rx and PU-Rx is chosen with the aid of a geolocation database.

3 Cooperative Network Architecture

In this section, we construct the cooperative network architecture. First, the radio nodes are self-formed into clusters, where each cluster is a star graph with at least two nodes. Then a spanning tree of the clusters is self-formed by the distributed beamformer in the way that no edge in the tree is towards the primary receiver if the primary receiver is in the communication range. This spanning tree enables the routing. For example, when clusters A and B are in the communication range but A, B and PU-Rx are collinear or near collinear, the edge AB is not in the tree, nonetheless, the data still can be relayed to B by using a different path between A and B. The spanning tree is used as a routing backbone in the secondary network. The distributed algorithms in this section are executed in rounds. One round allows one transmission, one reception, and one local processing. We assume that in one transmission a data package can be sent, and in one reception the data packages from its neighbors can be received. We also assume that the MAC protocol CSMA/CA is used to avoid the collision in the communications.

3.1 Cooperative clusters

Distributed MIMO technology and beamforming require at least two antennas. Given n single-antenna radios with distinct ids, Algorithm 1 is for self-formation of disjoint clusters [5]. Algorithm 2 is used for merging the singletons (the clusters consist of only a single node) to their neighboring clusters. After Algorithm 1 and 2, each cluster is a star graph with at least two nodes and each node knows its status as a head or member, its member list if it is a head or its head's id if it is a member. Algorithm 2 can be generalized to form the clusters with k ($k \geq 2$) nodes.

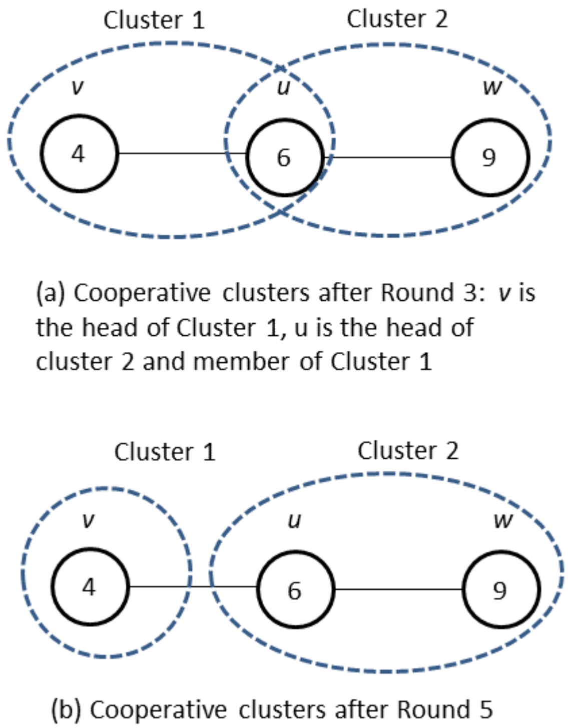

Figure 7: Self-formation of cooperative clusters

Algorithm 1 Self-formation of cooperative clusters
Each node u executes the follow rounds in the secondary radio network:
Round 1: u broadcasts its id to its neighbors (and receives the ids from its neighbors).
Round 2: u selects a node v which has the smallest id including itself after received the ids from its neighbors, and u sends a head request (u, v, "you are the head") to v to request v to be u's head.
Round 3: if u receives the head request (v, u, "you are the head") from any neighbor v, u sets itself to be a head and adds v to its member list, then u sends a head confirmation (u, v, "I am the head") to v.
Round 4: when u received a head confirmation (v, u, "I am a head") from v, if u is not a head, u sets its status to be a member and its head to be v, else if u is a head u sends v a message (u, v, "not your member").
Round 5: when u received the message (v, u, "not your member"), v removes u from v's member list.

Remarks: In Algorithm 1, Round 4 and Round 5 are partially used to remove the conflict that a node can be a member and a head at the same time. Consider three nodes v, u and w, where v's id is smaller than u and u's id is smaller than w, v and w are u's neighbors but v and w are not neighbors (as shown in Figure 7). It is easy to see that after Round 3 u is w's head and v's member at the same time; however, in Round 4 u sends a message (u, v, "Not your member") and in Round 5 v removes u from its member list. The running time of Algorithm 1 is $O(1)$ rounds.

In the clusters formed by Algorithm 1, some clusters may contain only one node (we call this single node as singleton). In Algorithm 2, for each singleton u, if u is picked by one neighbor v (u chooses one neighbor if it is picked by multiple neighbors) from its communication range (v is the node of other cluster), u merges itself to other cluster according to the following three cases (as shown in Figure 8): (i) if v is the head of another cluster, u becomes v's member; (ii) if v is a member (of other cluster) and v's cluster contains at most two nodes, say v and w, u merges to that cluster in which v is the head; (iii) if v is a member (of other cluster) and v has more than two nodes, v moves to u's cluster. For two neighboring singleton u and u', in order to avoid

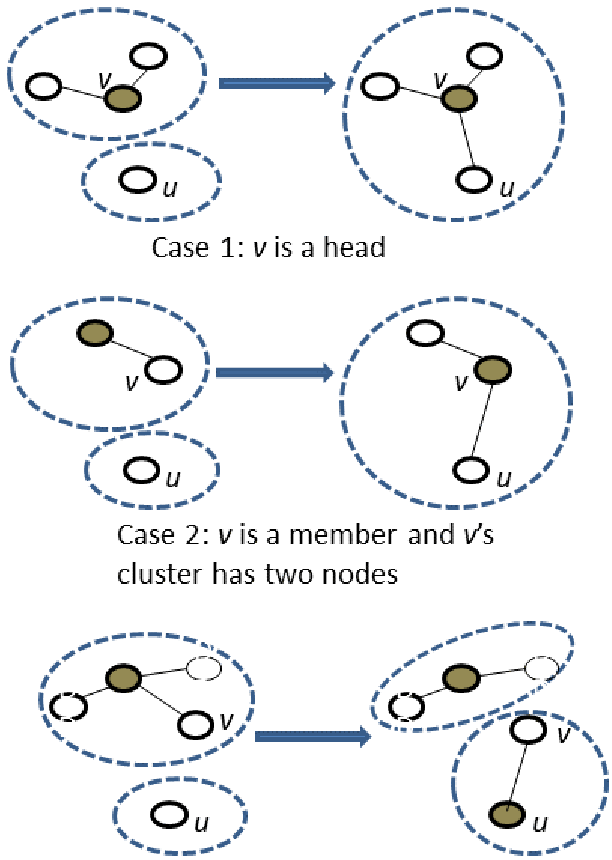

Figure 8: Merge singletons

both request to merge to another, in the algorithm, the one with a smaller id will merge to the other.

Algorithm 2 Merge Singletons
For each singleton u, while u is still a singleton, u executes the following rounds:
Round 1: u broadcasts a joining message (u, "join") to its neighbors.
// Round 2 - 4: in each cluster, the head selects at most one neighboring singleton for merge
Round 2: For each node v, if it receives joining message (u, "join") (it can receive multiple joining messages) and v is a member, v forwards u's information to v's head by sending a message (v, v'head, u, "forward") to v's head.
Round 3: For each head node v, (i) if v received only one joining message, either (u, v, "join") from u where v is neighboring to u or (w, v, u, "forward") where w is v's member and neighboring to u from a singleton u, v sends a message (v, u, "picked") to u with v'status and the size of v's cluster to u or v sends a forward message (v, w, u, "picked") to w where w is v's member and neighboring to u (in Round 4, w will forward the picked message to u); (ii) if v received multiple joining messages, v selects singleton u with smallest id, v sends (v, u, "picked") to u or sends (v, w, u, "picked") to w.
Round 4: For each node v, if v is member and received (v's head, v, u, "picked"), v sends (v, u, "picked") to u with v's status and the size of v's cluster.
// Round 5: u selects at most one neighboring cluster to merge
Round 5: if u received the id, status and cluster size from its neighbor(s), u picks a neighbor v

which has the smallest id, and then u sends a message (u, v, "merge") to v if (i) v is not a singleton or (ii) v is a singleton but v's id is smaller than u's id.
// Round 6-7: u either becomes the member of the selected cluster, or takes a node from that cluster to form a new cluster with two nodes
Round 6: For each node v, if it received (u, v, "merge"), v does the following: If v is a head, v adds u to its member list, and sends (v, u, "I am the head") to u. Otherwise, v is a member and v's cluster has at least two nodes. In this case, (1) if v's cluster has two nodes v and w, then u, v, w form a cluster: v sets its status to be head and adds u and w to its member list, and then v sends (v, u, "I am the head") to u and (v, w, "I am the head") to w; (2) if v's cluster has more than two nodes, v leaves its cluster and form a new cluster with u in which v is u's member, v sends (v, v'head, "I leave") to v's head and (u, v, "I am the member") to u.
Round 7: For each node v, when v is a member, if v received (w, v, "I am the head"), v sets w to be its head; when v is a head if v received (w, v, "I leave"), v removes w from its member list and if v received (u, v, "I am the member"), v adds u to v's member list.

Let n_s denote the number of the singletons in the clusters that are formed in Algorithm 1. In Algorithm 2, Round 1 - Round 7 can be executed multiple times. However, at each time at least one singleton will be merged to one of its neighboring clusters. In order to explain this, let's look at the singleton u which has the smallest id in all singletons. In Round 2 - 4, u will be selected by its neighboring clusters because it has the smallest id among all singletons. In Round 5, u will merge to one cluster but no singleton will merge to singleton u because u's id is the smallest. Therefore, u will be merged to the picked cluster successfully. Therefore, the running time of Algorithm 2 is $O(n_s)$ rounds. In general, the number of singletons is small unless the secondary radio network is sparse. Algorithm 2 can be used to form the clusters of with at least k nodes in each cluster by repeating the algorithm $log(n)$ times, where the diameter of the clusters is at most $k-1$.

3.2 Formation of routing backbone

Spanning tree has been well used as the routing backbone in a multi-hop wireless network [5]. However, in a secondary radio network, no edge is allowed towards the primary user receiver when the primary user receiver is in the communication range. In the following Algorithm 3 a spanning tree of clusters is self-formed by the beamformer in a way that no edge of the tree is towards to the direction of the primary receiver. For the simplicity, in the algorithm, "cluster(s)" are simply called as "node(s)".

Beamforming and MIMO technology: In any information transmission in Algorithm 3, the radios in the clusters cooperate on data transmission and reception using MIMO technology while poses a null constraint to the primary receiver to avoid the interference to the primary users at the same time. Therefore, the links/edges of the tree will not be towards the primary user.

Algorithm 3 Self-formation of Routing Backbone
Select one node as the root r.
Root r initializes the formation:
r broadcasts a find-message (r, "find children") to its neighboring clusters, then changes its status to "reception" to receive the response(s).
Each node executes the following rounds:
Round 1: If u received the find-messages (v, "find children") and u's status is not "reception", (i) u selects a message (w, "find children") from the received finding-messages which has the the weakest signal but larger than the threshold (for minimizing the diameter of the tree), and sets w to be u's parent; (ii) u sends declare-messages (u, w, "child") to w to declare w to be its parent and broadcasts message (u, "find children") to find u's children, and (iv) u changes its status to "reception".
Round 2: If u's status is "reception" and u received declare-messages (v, u, "child"), u adds v to u's children list and changes u's status to "inactive".

In Algorithm 3, each level of the tree is formed in two rounds. The running time of the algorithm is $O(L)$ rounds, where L is the diameter of the routing backbone tree. The routing algorithms on the routing backbone tree for broadcast (data dissemination) and unicast (relay data from one node to another node) in the network by the backbone tree can be found in [5].

From the analysis of Algorithms 1, 2 and 3, we can see that the cost for clustering and establishing the backbone tree depends on the number of singletons and diameter of the backbone tree. The number of singletons and the diameter of the backbone tree are small when compared with the number of nodes if the distribution of the nodes is relatively even and not sparse. In the backbone tree, the head can synchronize the data transmission from one cluster to the next cluster. In order to extend the network lifetime, the head can also be rotated to the one which has the largest energy level in the same cluster; furthermore, the cooperative data transmission can be used to extend the communication range to maintain the connection of the network. The details can be found in [5, 11].

4 Efficient Cooperative Distributed Beamforming Design with SU-Txs Selection

In Section 3, the network architecture that consists of clusters and routing backbone is proposed to support distributed beamforming and multihop communications in the network with the least interference to the primary receivers. In this Section, optimization of distributed beamforming in communications/link layer is considered. An efficient cooperative distributed beamforming design algorithm with SU-Txs selection is proposed.

4.1 Distributed beamforming design

To design the distributed beamforming, the received signal-to-noise ratios (SNRs) at the SU-Rx and PU-Rx are used as metrics to evaluate the performance of the proposed scheme. The objective is to maximize the SNR at SU-Rx while ensuring that the interference caused by the distributed beamformer towards the PU-Rx does not exceed a predefined threshold to satisfied the requirements of the cognitive radio system.

Based on the system model in Figure 5 and following the standard antenna theory [12], for a given set of cooperating SU-Txs, the steering vector towards a point (d, φ) is given as,

$$\boldsymbol{\alpha}(d, \varphi) = [exp\left(-j\omega a_1/c\right), \ldots, exp\left(-j\omega a_N/c\right)] \tag{1}$$

where $\omega = 2\pi f_c$, f_c is the carrier frequency in Hz, and a_n is the distance of the n^{th} $(n = 1, 2, \cdots, N_T)$ participating cooperative SU-Tx from the point (d, φ). a_n can be represented as

$$a_n = \sqrt{d^2 + {d_n}^2 - 2dd_n \cos\left(\varphi - \varphi_n\right)}. \tag{2}$$

Let the channel coefficient from an i^{th} cooperating SU-Tx, $i = 1, 2, \cdots, N$, towards SU-Rx and PU-Rx be h_{s_i} and h_{p_i} respectively. Let $\boldsymbol{h_s} = [h_{s_1}, h_{s_2}, \cdots, h_{s_N}]$, and $\boldsymbol{h_p} = [h_{p_1}, h_{p_2}, \cdots, h_{p_N}]$. If the beamforming weight for an i^{th} node is w_i, and let $\boldsymbol{w} = [w_1, w_2, \cdots, w_N]$, then the received signal at SU-Rx is given by [13],

$$y_s = \boldsymbol{H_s w} x + \psi_s \tag{3}$$

where $\boldsymbol{H_s} = diag(\boldsymbol{h_s})\boldsymbol{\alpha_s}$, $diag(\boldsymbol{h_s})$ is a diagonal matrix of size $N \times N$ with elements of $\boldsymbol{h_s}$ as the diagonal elements, $\boldsymbol{\alpha_s} = \boldsymbol{\alpha}(d_{SU}, \varphi_{SU})$ is the steering vector towards SU-Rx, and ψ_s represents additive white Gaussian noise with zero mean and variance σ_s^2.

Similarly, the interference signal received by PU-Rx from the cooperative SU-Tx cluster is

$$y_p = \boldsymbol{H_p w} x + \psi_p \tag{4}$$

with similar notation as the equation (3).

Let the interference tolerance threshold of the PU-Rx be I_P. To maximize the SNR at SU-Rx while ensuring that the interference caused by the distributed beamformer towards the PU-Rx does not exceed a predefined threshold, the distributed beamforming design problem can be formulated as the following optimization problem to find the optimum beamforming weights, $\boldsymbol{w}$.

$$\begin{aligned} \text{Maximize} \quad & \left|\boldsymbol{H_s w}\right|, \\ \text{subject to} \quad & \left|\boldsymbol{H_p w}\right| \leq I_P, \\ & \left|\left|\boldsymbol{w_i}\right|\right|^2 = 1. \end{aligned} \tag{5}$$

The first constraint ensures the protection of PU from SU induced interference. The second constraint on the weight vector implies that the total transmission power of each cooperating SU-Tx is a constant.

The above optimization problem is a non-convex problem. In order to simplify the computations, the following equivalent problem can be obtained through some mathematical manipulations [14]

$$\begin{aligned} \text{Maximize} \quad & \Re\left\{\boldsymbol{H_s w}\right\}, \\ \text{subject to} \quad & \left|\boldsymbol{H_p w}\right| \leq I_P, \\ & \left|\left|\boldsymbol{w_i}\right|\right|^2 = 1, \\ & \Im\left\{\boldsymbol{H_s w}\right\} = 0, \end{aligned} \tag{6}$$

where $\Re\{X\}$ and $\Im\{X\}$ are the real and imaginary parts of X respectively. For a given set of cooperating SU-Txs, this optimization problem can be solved using any second order cone programming (SOCP) solver.

4.2 Computational efficient SU-Txs selection

Often in cognitive radio systems, several practical constraints, such as synchronization and timely information sharing, limit the number of nodes that can participate in cooperative beamforming. When the number of available SU-Txs is larger than the maximum number of SU-Txs that can participate in beamforming, the selection of nodes is critical to the performance of cooperative beamforming. In this section, we propose an efficient SU-Txs selection scheme that achieves a near-optimal performance with very low computational complexity.

In distributed beamforming design, the gain achieved at the SU-Rx primarily depends on the choice of participating SU-Txs. We have found that a particular SU-Tx may perform poorly with an arbitrary set of $N-1$ SU-Txs, but the same SU-Tx may perform extremely well with some another set of $N-1$ SU-Txs that are selected from the remaining $mT-N$ SU-Txs. Thus, even if a given SU-Tx performs poorly with an arbitrary set of SU-Txs, it cannot be concluded that the SU-Tx is not one of the optimal SU-Txs. This insight forms the basis of our proposed algorithm. The proposed SU-Tx selection scheme selects a near-optimal set of SU-Txs, i.e., the set of SU-Txs that performs very close to the optimal set of SU-Txs. The major advantage of the proposed scheme is the reduction in computational complexity which makes it attractive to large cognitive radio systems.

The proposed SU-Tx selection algorithm works in the following way: first, a set of randomly chosen N SU-Txs, along with their channel state towards SU-Rx and PU-Rx, is used in beamformer design presented in previous section. For this set of SU-Txs, the optimal beamforming weights, as well the corresponding beamforming gain, is computed. Next, the SU-Tx that contributes the minimum towards cooperative beamforming among the N SU-Txs is identified. The minimum contributing SU-Tx is the one that has smallest value of $|H_{s_i} w_i| = |h_{s_i} \alpha_{s_i} w_i|$. Then the algorithm replaces the lowest contributing SU-Tx with another SU-Tx that is picked randomly from the remaining $mT-N$ SU-Txs. These two steps are repeated I_{th} number of times, and the algorithm picks the set of SU-Txs that performs the best among all I_{th} sets. Note that a node that was discarded in the earlier iteration may be repicked in the next iteration as it could perform well with the new set. Here, I_{th} is a threshold parameter that determines the complexity of the algorithm, as well as the performance of the beamformer. Small I_{th} corresponds to less computations, but it may result in poor beamforming performance. Thus, there is a trade-off between computational cost and beamforming gain. Comparing with [15], the proposed system can be designed to achieve a balanced trade-off between these two parameters.

5 Simulation Results

In this section, we provide detailed simulation results to demonstrate the performance of the proposed network architecture and the beamformer design algorithm with SU-Tx selection.

5.1 Efficiency of cooperative network architecture

In this subsection we show the quality of the proposed routing backbone tree and performance of multi-hop data relay in the backbone tree. We assume that each cluster consists of two single-antenna radio nodes and the link between any two clusters is a 2×2 MIMO link. We use Tree Y and Tree N to indicate the routing backbone trees that are formed with and without cooperative MIMO technology and beamforming, respectively.

5.1.1 Energy model and optimization

We consider the energy model for data transmission. For simplicity, we omit the reception energy since it is smaller and dominated by the transmission energy. We use $e^{MIMO(mT,mR)}$ to denote the energy cost for transmitting one bit for a MIMO link between two clusters with mT cooperative nodes in the transmission cluster and mR cooperative nodes in the receiving cluster which can be calculated with the following formula:

$$e^{MIMO}(mT, mR) = (1+\alpha)\hat{e}(P_b, b, mT, mR)\frac{(4\pi D)^2}{G_t G_r \lambda^2} M_l N_f + P_c(mT, mR), \quad (7)$$

where $P_c(t,r) = (tP_{ct} + rP_{cr} + 2P_{syn})/(bB)$, $G_tG_r = 5dBi$, $M_l = 40dB$, $N_f = 10dB$, $T_{tr} = 5\mu s$, $P_{ct} = 48.24$, $p_{cr} = 62.5$, $P_{syn} = 50mw$, $\alpha = \frac{3(\sqrt{2^b}-1)}{0.35(\sqrt{2^b}-1)}$. P_b, B, D, b are the bit error rate (BER), bandwidth, communication range of virtual MIMO link, and constellation size, respectively, and P_{ct}, P_{cr}, P_{syn} are the circuit energy needed for transmission, receiving, and synchronization. $\hat{e}(P_b, b, mT, mR)$ is defined by the target BER, constellation size b, and number of cooperative nodes at transmission side and receiving side. It can be calculated by numerical analysis according to the formulas in [16]:

$$P_b = \begin{cases} \mathcal{E}_H\left\{\frac{4}{b}\left(1 - \frac{1}{2^{b/2}}\right)Q\left(\sqrt{\frac{3b}{M-1}\gamma_b}\right)\right\}, & \text{for } b > 1 \\ \mathcal{E}_H\{Q(\sqrt{2\gamma_b})\}, & \text{for } b = 1, \end{cases} \quad (8)$$

where $\gamma_b = \frac{||H||^2 \hat{e}(P_b,b,mT,mR)}{N_0 \cdot mT}$, $N_0 = -171dBm/Hz$, and $M = 2^b$.

In the formation of the routing backbone and simulation, the constellation size b is selected by numerical analysis to minimize the energy cost.

5.1.2 Routing backbone tree

In the formation of Tree N, the communication range D is fixed. In order to compare Tree Y and Tree N, we first calculate the energy cost for transmitting one bit in a fixed communication range D without using cooperative MIMO and beamforming. In the formation of Tree Y, we use this energy cost to get the communication range D' for finding the children from a parent. Notice that posing a null constraint in beamforming requires an extra energy, therefore, D' is usually smaller than D. The extra energy cost mainly depends on the positions of the transmission cluster, reception cluster, and primary receiver. Consider a cluster SU_t transmits data to another cluster SU_r with beamforming. Without loss of generality, we assume that two antennas A and B in the cluster SU_t are collinear with the antenna of the primary receiver PU, and the distance r of A and B is equal to the wavelength or multiple of the wavelength. The phase delay in transmission between A and B

is π that poses a null constraint to PU. The energy in this case for transmitting one bit from SU_t to SU_r is given by

$$e_{bf}^{MIMO} = \frac{1}{2}\sqrt{2 + 2cos\Delta} \cdot e^{MIMO}, \tag{9}$$

where $\Delta = \pi[d(A, SU_r) - d(B, SU_r)]/r$ and e^{MIMO} is given in Equation (7).

Figure 9 shows Tree N (left) and Tree Y (right), where each node is a cooperative MIMO node consisting of two primary single-antenna radio nodes, and the root is in the center of the test area. As shown in the simulation results, we can see that in the lefthand side of Figure 9, the backbone contains the links directed to the primary receiver PU-Rx, which means that the paths contain these links cannot be used for data relay because the null constraint poses to PU-Rx may also pose to the node(s) in the path. In the righthand side of Figure 9, no link in the backbone is towards the direction of PU-Rx. Table I shows the diameter of the routing backbone tree in the network with 32, 64, 128, and 256 cooperative clusters, and D is only applied to Tree N without using MIMO and beamforming. It is easily understood that the smaller diameter indicates a faster data relay on the routing backbone. There are two-fold factors in Tree Y: on one side cooperative MIMO radios can extend the communication range under the same energy cost, and on the other side the beamforming with a null constraint requires extra energy which means when with the same energy cost the communication range can be smaller (i.e., the diameter of Tree Y can be larger than Tree N). From Table I we see that the proposed routing backbone tree not only enables the routing in a secondary radio network, but is also efficient because the diameter of Tree Y is not much larger (in some cases, it is even less) than that of Tree N.

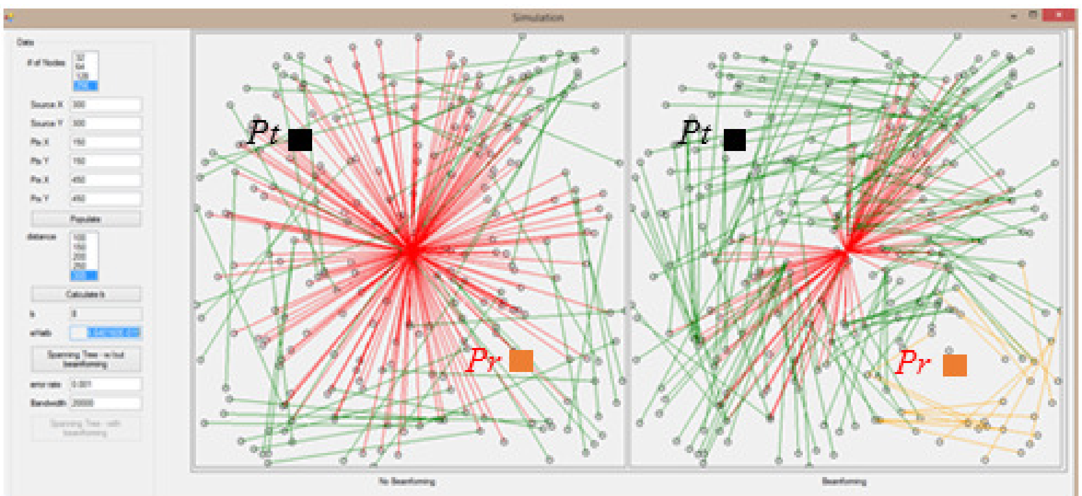

Figure 9: Routing backbone trees: the left is the one without using beamforming; the right is the one using beamforming; the red and black square blocks are primary transmitter PU-Tx and receiver PU-Rx

5.1.3 Multi-hop data relay

In order to show the performance of multi-hop data relay of the proposed routing backbone, we compare the energy cost for the following two tasks on Tree Y and Tree N: (1) broadcast (disseminate the data form one source node to all other nodes) one bit in the secondary network; and (2) unicasting (deliver the data from one node to another node along the path between two node) one bit in the secondary network. Table II and Table III show the total energy for broadcast and unicast. We can see the energy costs in Tree Y are not much larger (in some cases, they are even less) than that in Tree N.

As we showed in above, the proposed cooperative network architecture is effective and efficient.

Table 1: Diameter of the backbone tree

		D				
		100m	150m	200m	250m	300m
32 Nodes	N	5.0	5.0	3.0	2.6	2.0
	Y	2.8	4.8	4.6	4.6	4.2
64 Nodes	N	6.8	3.8	3.0	2.0	2.0
	Y	4.0	7.6	5.4	4.0	4.0
128 Nodes	N	7.0	4.0	3.0	2.0	2.0
	Y	12.0	7.2	5.2	4.0	3.4
256 Nodes	N	5.4	3.4	3.0	2.0	2.0
	Y	10.4	6.4	4.6	4.2	3.4

Table 2: Energy used for broadcast in the whole network

		D				
		100m	150m	200m	250m	300m
32 Nodes	N	4.69	8.03	7.47	6.55	3.55
	Y	1.53	5.09	7.09	8.18	8.53
64 Nodes	N	15.1	15.6	13.8	12.1	7.96
	Y	3.26	16.1	17.4	16.5	16.1
128 Nodes	N	31.1	29.5	23.3	26.7	17.2
	Y	27.1	31.9	30.4	29.5	31.8
256 Nodes	N	59.4	57.6	47.8	51.1	28.8
	Y	61.1	56.6	54.9	55.2	57.0

Table 3: Energy used for unicast on the longest path

		D				
		100m	150m	200m	250m	300m
32 Nodes	N	2.55	2.83	1.87	1.77	1.42
	Y	1.43	2.72	2.86	3.14	2.98
64 Nodes	N	3.47	2.15	1.87	1.36	1.42
	Y	2.04	4.30	3.36	2.73	2.84
128 Nodes	N	3.57	2.26	1.87	1.36	1.42
	Y	6.12	4.07	3.24	2.73	2.42
256 Nodes	N	2.75	1.92	1.87	1.36	1.42
	Y	5.30	3.62	2.86	2.86	2.42

5.2 Efficiency of distributed beamforming with SU-Tx selection

In simulations, we assume that $mT = 15$ cooperative SU-Txs, each equipped with a single omni-directional antenna, are distributed uniformly in a circular area of radius, $R = 75$ meters. Only $N = 5$ among mT SU-Txs can collaborate to form a cooperative beamformer. The intended SU-Rx is located in a direction of 30^o from the reference direction and at a distance, $d_{SU} = 1$ km. The PU-Rx is located in a direction of 80^o from the reference direction at a distance, $d_{PU} = 1$ km. The carrier frequency is $f_c = 900$ MHz, the interference tolerance threshold for PU-Rx is $I_p = -80$ dBm. The noise level is set to $\sigma_s^2 = \sigma_p^2 = -105$ dBm. Each node experiences an uncorrelated Rayleigh fading channel in all 360^o directions.

Figure 10 shows the performance of the proposed cooperative distributed beamfomer in terms of the average beamforming gain, $|\boldsymbol{H_s w}|$, over 500 simulation runs. It is clear that the beamforming gain towards the SU-Rx is maximized, and a null is generated in the direction of the PU-Rx. The sharp peak and the null towards SU-Rx and PU-Rx respectively verify that the cooperative beamforming considered in this study achieves the dual objectives of a cognitive radio system-(i) maximize the signal at the intended receiver, and (ii) minimize interference at the PU-Rx.

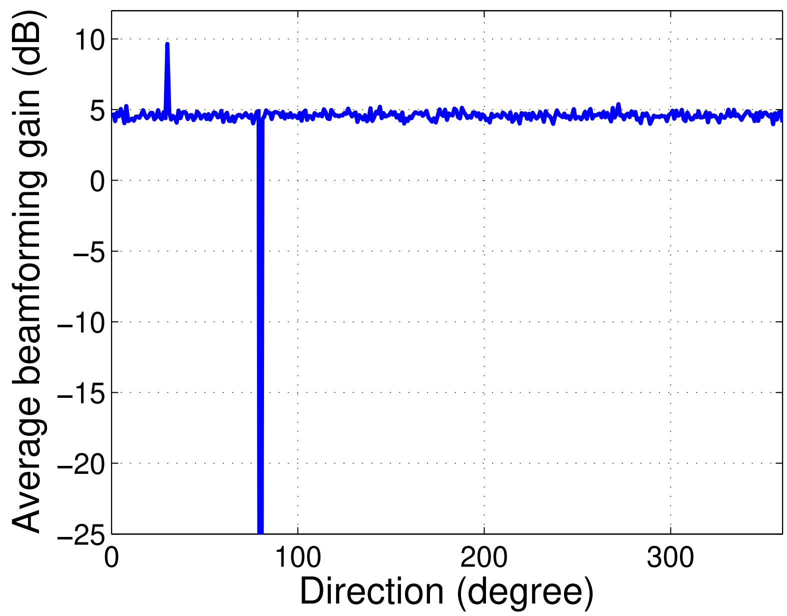

Figure 10: Beam pattern for the proposed cooperative distributed beamforming

Figure 11 shows the asymptotic performance of the proposed SU-Tx selection scheme in terms of the average SNR towards the SU-Rx. It is clear that when the number of iterations increases, the performance of the beamformer with proposed SU-Tx scheme closely resembles that of exhaustive search, the SU-Tx selection scheme that guarantee the best performance of the beamformer. However, the exhaustive search requires $\binom{mT}{N}$ SU-Tx searches, where $\binom{a}{b} = \frac{a!}{(a-b)!b!}$ with $a!$ represents the factorial of a. Therefore, $\binom{mT}{N}$ solution of the optimization problem presented in last section must be found. For example, with $mT = 15$ and $N = 5$, $\binom{15}{5}$ is 3003. The performance of the proposed scheme is approximately 98.5% of the optimal system performance (9dB vs 9.15dB average SNR) with only 1.67% computations ($\frac{50}{3003}$). Therefore, the asymptotic performance of the proposed scheme can quickly approaches the limit (the performance of the exhaustive search).

6 Conclusion

In this paper, joint cooperative protocols and a distributed beamforming design algorithm with efficient node selection have been proposed for multi-hop cognitive radio networks. The network layer cooperative architecture consists of cooperative clusters used for distributed beamforming, and a routing backbone used for avoiding the interference to the primary users in the relay route that optimizes the QoS and energy consumption. The cooperative distributed beamforming design maximizes the SNR at SU-Rx while ensuring that the interference caused by this distributed beamformer towards the PU-Rx does not exceed a predefined threshold. When the number of available SU-Txs is larger than the maximum number of SU-Txs that can participate in beamforming, an efficient SU-Txs selection scheme is proposed to achieve a near-optimal performance with much lower computational complexity than the exhaustive search approach used for optimum SU-Tx selection. Simulation results show that the proposed backbone not only enable the beamforming for data relay in the backbone, the energy for broadcast and unicast and the diameter of the spanning tree are not much larger (in most cases, they are less) than those in the protocol without beamforming. Simulation results also show that the proposed beamforming design scheme provides a near-optimal beamforming solution with significantly reduced computational burden. These verify that the proposed protocols and algorithms are effective and efficient.

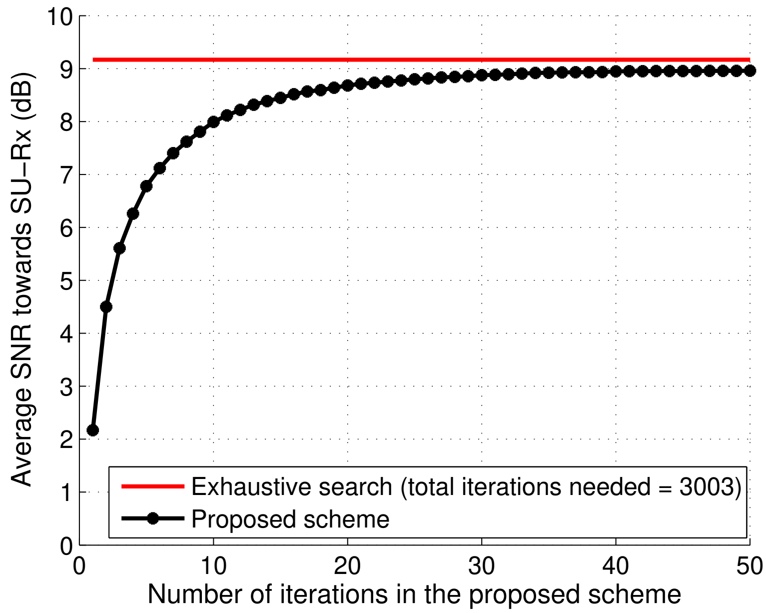

Figure 11: Asymptotic performance of the proposed SU-Tx selection scheme

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