SJTU

Cooperative Relay with MIMO Nodes

IEEE

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Abstract—**Cognitive radio has been proposed to promote the spectrum utilization by exploiting the existence of spectrum holes. The heterogeneity of both spectrum avail-ability and traffic demand in secondary users has brought significant challenge for efficient spectrum allocation in cognitive ad-hoc network. With the help of relay node that has rich spectrum resource, the traffic demand of secondary users can be better matched. To increase the network capacity as well as satisfy the performance requirements, we introduce MIMO techniques for improving the transmission capacity and reliability. In this project, we exploit a new cooperative strategy for cognitive ad-hoc networks by deploying MIMO nodes. The core aim of this work is the maximization of the data rate of the secondary user pairs while ensuring the QoS of primary users.**

Key words —**cognitive, cooperative, MIMO relay**

I. INTRODUCTION

Over the past a few years, uncoordinated multi-hop wireless networks such as Ad-hoc networks have gone through rapid development and are widely used in both military and civilian applications. However, the electromagnetic radio spectrum is so limited and valuable that significantly unbalanced usage of spectrum is a big challenge need solving effectively.

Resource allocation is a fundamental problem in cognitive radio networks and has been discussed a lot in the existing works[1,2]. However, the mismatching between the traffic demand and spectrum resource availability has been a Gordian knot until the paper[3] brought out a cooperative strategy to handle the unbalanced spectrum usage.

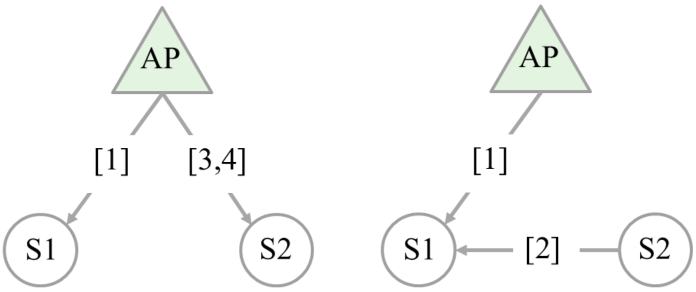

Fig 1 Cooperative relay transmission (left in time slot 1, right in time slot 2)

Multiple-input multiple-output (MIMO) technique has been proven to be able to provide high spectral efficiency and increase channel capacity substantially through multiple spatial channels without need of the additional spectrum. With multiple antennas at the transmitter and/or receiver, a MIMO system takes advantages of multiplexing to simultaneously transmit multiple data streams to increase the wireless data rate and diversity. There have been some studies on placing MIMO relay nodes. The paper[4] provides a MIMO relay deployment solution to enforce high-performance operation of wireless networks.

In our project, we combine the cooperative relay and MIMO techniques. More specifically, we propose a Cognitive Cooperative MIMO Relay System that fully utilizes the channel resources. Our observation is that desired secondary user pairs cannot communicate with each other because of their different channels. This circumstance results in not only communication inconvenient but also channel resources waste.

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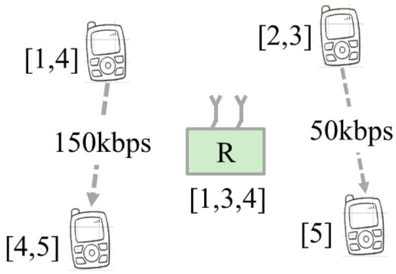
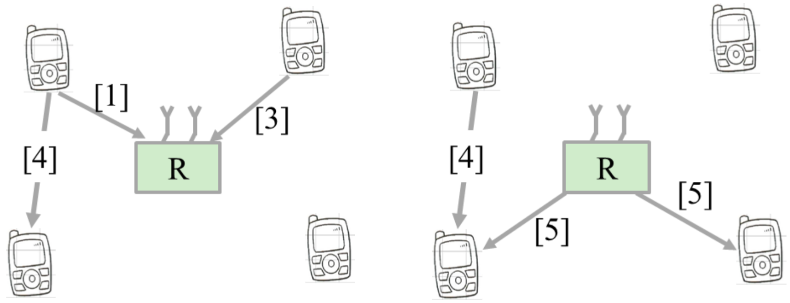


a) Channel and demand



b) Cooperative MIMO relay transmission (left in time slot 1, right in time slot 2)

Fig 2 An Example showing how cooperative MIMO relay works for cognitive ad-hoc network

Consider a network with two pairs of secondary users as shown in Figure 2. Figure 2(a) shows a simple topology of an infrastructure mode secondary network. The number on the dashed lines indicate the average traffic demand of the receivers. The numbers beside nodes indicate the available channels for the secondary usage of the nodes. For simplicity, we assume each common available channel between any pair of nodes can provide 100kbps data rate. As we can see, without relay nodes, left secondary user pair (SU pair) can only provide 100kbps date rate while right SU pair can even not communicate.

Improvement is possible if we introduce cooperative MIMO relay. The scheme is shown in Figure 2(b), which includes two time slots with equal interval. In time slot 1, sender 1 transmits data to receiver 1 on channel 4 and data to relay on channel 1, while sender 2 transmits data to relay on channel 3. In time slot 2, sender 1 keep transmitting data to receiver 1 while MIMO nodes transmits different streams to different receivers respectively on channel 5, which utilizes spatial multiplexing to increase channel capacity. In this case, the average rates in the two slots for SU pair 1 and pair 2 are 150kbps and 50kbps, respectively. Both of the demands are fulfilled.

From such simple observation, we can easily conclude that MIMO relay tremendously improves the achievable data rate as well as stability and reliability. We use this scheme to more effectively utilize spectrum resource so that system performance can be greatly improved. However, the algorithm turns complex for MIMO techniques complexity and the realization has challenges.

II. SYSTEM MODEL

In this section, we present the overview of the system architecture of cognitive ad-hoc network.

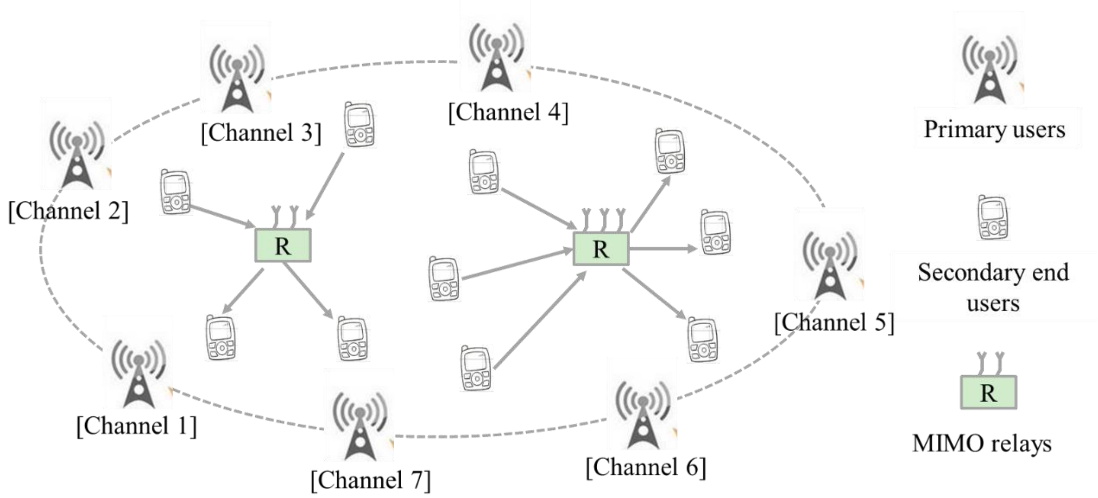


Fig 3 System architecture of secondary cognitive ad-hoc network with cooperative MIMO relays

We design the secondary system in an infrastructure mode as shown in Figure 3. Secondary end users equipped with a single antenna can communicate with anyone sharing the common channels. There are some primary users in the same region, who are willing to provide their abundant spectrum for secondary use. Each active primary user has a certain protection range such that its used spectrum bands cannot be used by secondary users within its protection range. Secondary users can access these spectrum of the primary users only when it is not currently used by primary users. More significantly, MIMO relay nodes each equipped with an array of antennas act as a bridge between some desired SU pairs, establishing or increasing traffic rate.

III. PROBLEM FORMULATION

In this section, we introduce the notations to mathematically describe the problem. And finally propose a heuristic algorithm to solve the problem.

The resource allocation problem can be formulated as follows.

- We denote the cognitive ad-hoc network as a set of nodes divided into N SU pairs (sources and destinations), $P = \{[s_1, d_1], [s_2, d_2], \cdots, [s_N, d_N]\}$ within a geographical area. Here we ignore the secondary end users who does not communicate because it will not occupy channel resources.
- In addition, MIMO relay nodes are denoted as a set of M nodes $M = \{u_1, \ldots, u_M\}$, and a set of M numbers is used to denote the number of MIMO nodes' antennas $N = \{n_1, \ldots, n_M\}$.
- Let f_{low} and f_{up} denote the lower and upper end of the spectrum band of our interest. In this work, we assume the spectrum $[f_{low}, f_{up}]$ is channelized into K channels with equal bandwidth, and there are guard bands with appropriate bandwidth between adjacent channels. For a particular location in the area, some channels may be occupied by primary users, thus cannot be used for secondary sharing.
- We use a 0-1 variable $a_i^{s,dk}$ to denote the channel availability: $a_i^{sk} = 1$ indicates the channel k at node s_i is available, and 0 otherwise. Similarly, $a_i^{dk} = 1$ indicates the channel k at node d_i is available. Each node is equipped with a single cognitive radio that is capable to dynamically access any combination of available channels. However, the radio cannot transmit and receive simultaneously.
- Correspondingly, we use a 0-1 variable α_i^k to denote the channel availability: $\alpha_i^k = 1$ indicates the channel k at node u_i is available, and 0 otherwise.
- We use $E = \{e_{ij}^{s,d}\}$ to denote the set of direct links, where $e_{ij}^{s} = 1$ means there exists a direct link between node s_i and u_j while $e_{ij}^{d} = 1$ means there exists a direct link between node d_i and u_j, and 0 otherwise.

The key is that we need to know how the channel resources allocated and the MIMO relay nodes support which pair of SU transmission nodes. So we also need denotations as follows.

- We define the traffic demand of each transmission pair as δ_i
- We define a 0-1 matrix $R = \{r_{ij}\}_{N\times M}$ to express the relay relationship:

  $r_{ij} = 1$ means that u_j performs as relay node for $p_i: [s_i, d_i]$
- Meanwhile, we use $X = \{x_{ij}^{s,dk}\}$ to denote the channel assignment:

  $x_{ij}^{sk} = 1$ if channel k is assigned to link e_{ij}^{s} for data transmission, and

  $x_{ij}^{dk} = 1$ similarly.
- Assume the transmission rate of each link in every channel is identical, which is denoted by c. In a certain frame, if node is equipped with a single antenna, its average throughput is c. When we use MIMO nodes acting as a relay, it can use only half of the time in one frame to receive data from sources, and the other half to transmit to destination. Therefore, the average throughput of the link from source to relay in one frame is $\frac{1}{2}c$, and the same for the link from relay to destination.

Considering the real situation, there have some constraints as follows.

- In this work, we assume relay relationship should follow the following constraints: transmission pair can have only one relay; MIMO relay can serve transmission pair no more than the number of antennas. Correspondingly, we have the following constraints:

$$\sum_{j=1}^{M} r_{ij} \leq 1, \quad 1 \leq i \leq N$$

$$\sum_{i=1}^{N} r_{ij} \leq n_j, \quad 1 \leq j \leq M$$

- Assuming all the nodes are in interference range of each other, to avoid interference, a channel can be used by only one active transmission link in one frame (except MIMO relay nodes, which can take fully use of channels by spatial multiplexing). The channel allocation should also satisfy the channel availability constraint at each node:

$$x_{ij}^{sk} \leq a_i^{sk}\alpha_j^{k}, \quad \forall i, j, k.$$

Now, we calculate the throughput of transmission pair under a certain strategy of relay selection R and channel allocation X. The total throughput can be divided into two kinds: data received from direct link and relay link. So the throughput can be expressed as:

$$\theta_{ij} = \min(cx_i^k + \min\left(\sum_{k=1}^{K}\frac{1}{2}cx_{ij}^{sk}, \sum_{k=1}^{K}\frac{1}{2}cx_{ij}^{dk}\right), \delta_i)$$

Then our problem is : given demands $\{\delta_i\}_N$, to compute a feasible relay selection and channel allocation scheme (R, X) so that total system throughput is maximized. The problem can be formulated as:

$$\max_{R,X} \sum_{i=1}^{N} \theta_i$$

IV. SOLUTION

The problem is a nonlinear integer programming problem with high complexity. Considering the practicability of the algorithm, we need to balance the complexity and optimization.

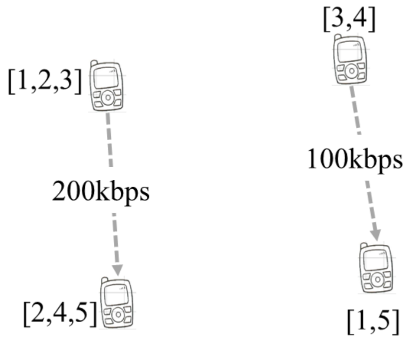
To simplify the algorithm, we first consider the single cognitive ad-hoc network without MIMO relay nodes. There have been a plenty of works to solve the problem and we can easily get the solution.

Then, with remaining channel resources, we can reuse the channel so that we can see MIMO nodes as third users to utilize spectrum. In this case, we just have to consider the transmission pairs that has not met traffic demands.

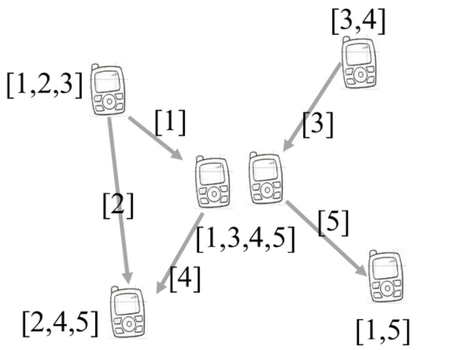
At first, we use a greedy method to choose a pair who need most help. Then for current matching M, we find an augmenting path P, which is an path alternating added into the current matching using remaining channel resources together with MIMO nodes.

V. Evaluation

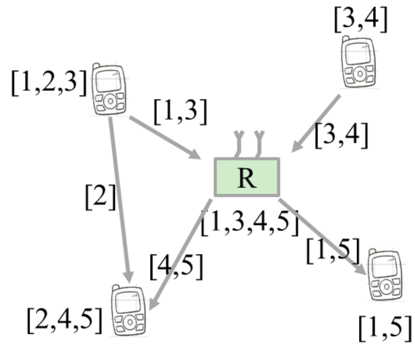
In this section, we evaluate relay scheme in a simple topology with 2 end user pairs as shown in Figure 4(a). Here, the numbers on the dashed lines indicate the traffic demands of each transmission pair and the number beside the secondary users indicate the available channel of each user. Assuming that each single available channel can provide 100kbps data rate.



c) Topology with channels



c) Transmission with regular relay nodes



c) Transmission with MIMO relay nodes

Fig 4 Experiment for 2 end user pairs

We compare two kinds of relay nodes so that we can find the benefit of MIMO relay nodes.

- In the regular relay nodes system, channel can only be used once, so the two relay nodes have to choose from their common channels. As the Figure 4(b) shows, in a time frame, SU pair 1 can get 150kpbs data rate while SU pair 2 can get 50kbps data rate, both cannot meet the traffic demand.
- In the MIMO relay nodes system, channel 3 and channel 5 are both utilized twice. Now we calculate the average data rate that SU pair 1 get 200kbps and SU pair 2 get 100kbps. Both of them meet the traffic demands.

VI. CONCLUSION

Our work introduce MIMO technique to cognitive network, it fully utilizes the spectrum and follow the trend that MIMO devices will be used widely. However, to simplify the problem, we consider the case that only MIMO nodes act as relay nodes while regular nodes act as senders or receivers. It decrease the channel efficiency in some degrees.

On the other hand, this algorithm need implementing in a Universal Software Radio Peripheral (USRP)-based testbed to evaluate the feasibility and practicability.

Finally, we need to gratitude our supervisors, elder schoolmates, and team members. Without the support and guidance, we cannot complete the project.