

Cooperative Relay for Cognitive Radio Networks

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Abstract—Cognitive radio has been proposed in recent years to promote the spectrum utilization by exploiting the existence of spectrum holes. The heterogeneity of both spectrum availability and traffic demand in secondary users has brought significant challenge for efficient spectrum allocation in cognitive radio networks. Observing that spectrum resource can be better matched to traffic demand of secondary users with the help of relay node that has rich spectrum resource, in this paper we exploit a new research direction for cognitive radio networks by utilizing cooperative relay to assist the transmission and improve spectrum efficiency. An infrastructure-based secondary network architecture has been proposed to leverage relay-assisted discontinuous OFDM (D-OFDM) for data transmission. In this architecture, relay node will be selected which can bridge the source and the destination using its common channels between those two nodes. With the introduction of cooperative relay, many unique problems should be considered, especially the issue for relay selection and spectrum allocation. We propose a centralized heuristic solution to address the new resource allocation problem. To demonstrate the feasibility and performance of cooperative relay for cognitive radio, a new MAC protocol has been proposed and implemented in a Universal Software Radio Peripheral (USRP)-based testbed. Experimental results show that the throughput of the whole system is greatly increased by exploiting the benefit of cooperative relay.

I. INTRODUCTION

The electromagnetic radio spectrum is limited and valuable resource, which is tightly managed by governments. Recent reports shown significantly unbalanced usage of spectrum: some frequency bands are largely unoccupied most of the time; some other frequency bands are only partially occupied; the remaining frequency bands are heavily used [1]. Spectrum utilization can be improved significantly by allowing secondary users to access spectrum holes unoccupied by primary users. Cognitive radio [2] has been proposed as the means for secondary users to promote the efficient utilization of the spectrum by exploiting the existence of spectrum holes.

In a cognitive radio network, the resource unbalance is much more severe than traditional wireless networks. The spectrum availability of secondary user is heterogeneous due to the location difference among different users, dynamic traffic of primary users and opportunistic spectrum access nature of secondary users [3]. Moreover, the traffic demands of secondary users can also be quite different. Then a nature question will be: how to allocate the spectrum resource so as to fulfill the user demand and mean-while achieve high spectrum utilization.

Resource allocation is a fundamental problem in cognitive radio networks and has been discussed a lot in the exist-

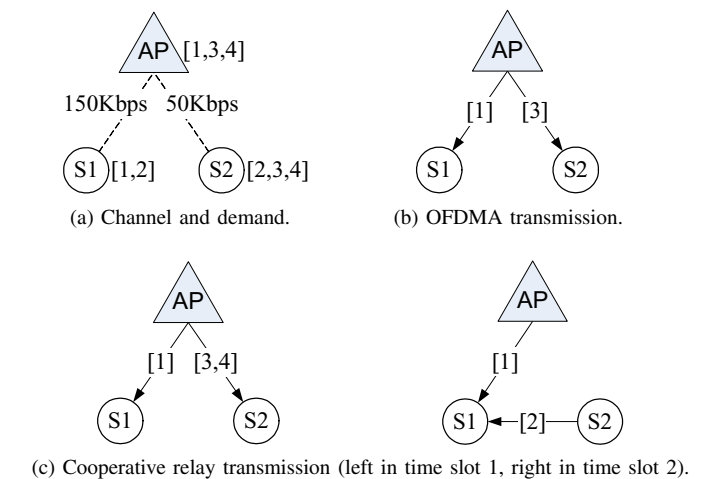


Fig. 1. An Example for the demand improvement using cooperative relay for cognitive radio network.

ing works [4]–[7]. However, when the traffic demand and spectrum resource availability are largely mismatched, these existing works cannot fully utilize spectrum resource and fulfill secondary users’ demands. Thus, an important issue is how to handle the unbalanced spectrum usage within the secondary network to fulfill the heterogeneous traffic demand from secondary users, which has not drawn much attention before. This paper is to fill this gap.

Our observation is that some secondary users do not need to use their entire available spectrum because of the low traffic demand. If we can utilize these “rich” nodes as helpers to relay the other secondary user’s traffic with their otherwise wasted spectrum, we can improve the system performance. Consider a network with two secondary end users associated with a single secondary access point (AP) as shown in Figure 1. Figure 1(a) shows a simple topology of an infrastructure mode secondary network. Two secondary end users $S1$ and $S2$ want to receive data from the AP. The numbers on the dashed lines indicate the average traffic demand of the users from AP. 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 100 Kbps data rate. Using the traditional Orthogonal Frequency Division Multiplexing Access (OFDMA) as shown in Figure 1(b), which allows concurrent transmission of multiple links from the AP, both end users can simultaneously receive data

from the AP on different channels: S_1 uses up the capacity of one channel and receives 100 Kbps; S_2 receives 50 Kbps because of its small traffic demand. The observation is that the heterogeneity of both spectrum and demand causes dissatisfaction (demand of S_1 is not met) and low spectrum utilization (spectrum resource of $AP-S_2$ and S_1-S_2 is not fully used).

Improvement is possible if we introduce cooperative relay. The scheme is shown in Figure 1(c), which includes two time slots with equal interval. In time slot 1, S_1 receives data from AP on channel 1, while S_2 receives its own data on channel 3 and data for S_1 on channel 4. In time slot 2, S_1 receives data from AP on channel 1 and data from S_2 on channel 2. Therefore, the average rates in the two slots for S_1 and S_2 are 150 Kbps and 50 Kbps, respectively. Both of the demands are fulfilled. Note that the example given here is for downlink transmission scenario; it is similar for uplink case.

Starting from such an interesting observation, in our work, we propose to use cooperative relay for cognitive radio network with single-radio end users. We use this scheme to more effectively utilize spectrum resource such that system performance can be greatly improved. However, the realization of this idea has several challenges.

- Traditionally, one radio can only transmit or receive at one channel at a specific time. The new relay-involved transmission raises a question from ground: how can such three-node multiple-channel (probably discontinuous) transmission be realized? To achieve this, the key challenges include how to make the sender transmit on multiple channels simultaneously with a single cognitive radio, and how to filter out the expected signal and decode it using only a fraction of sub-carriers under severe inter-channel interference. We propose a new relay-assisted discontinuous Orthogonal Frequency Division Multiplexing (D-OFDM) scheme and implement it in a software-defined radio testbed.
- The cooperative transmission scheme brings in new issues of resource allocation. For a network of secondary users, we need to address how to select the proper node as relay node, as well as how to allocate proper spectrum for secondary users. These problems are coupled together: relay selection determines the spectrum sharing among direct transmission nodes and relay nodes which definitely affects the overall spectrum allocation. Meanwhile, spectrum allocation impacts the potential throughput of destinations and relays, which clearly influences the relay selection decisions. In our paper, we formalize the joint relay selection and spectrum allocation problem, and propose a heuristic algorithm to partition and address it.

This work is the first one to explore the cooperative relay in the context of cognitive radio network to improve throughput, as well as present a practical design that is implemented in a testbed. Our contributions can be summarized as follows:

- We exploit a new research direction for cognitive radio networks in which intelligent secondary nodes use our

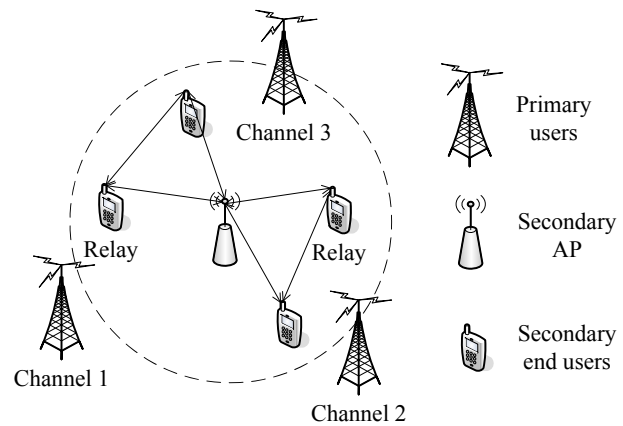


Fig. 2. System architecture of secondary cognitive radio network with cooperative relays.

proposed relay-assisted D-OFDM technology to exploit the under-utilized spectrum resource in relay node so as to achieve better spectrum utilization and improve system capacity. We also prove the feasibility of relay-assisted D-OFDM by implementation in software defined radio.

- We identify new resource allocation problems in cognitive relay networks, i.e., joint relay selection and spectrum allocation, and propose a heuristic algorithm to address them. Based on this, we develop a MAC protocol to carry out the resource allocation among secondary users.
- We implement a prototype system in a testbed of software defined radios. Experimental results show that our new system design can achieve convincing performance improvement.

The rest of the paper is organized as follows. Section II describes the overview of the system architecture. Section III is for the physical layer design of relay-assisted discontinuous OFDM scheme. Section IV is about the unique resource allocation problem in our system. Section V gives the MAC protocol design. Testbed implementation and experimental results are given in section VI. Related work is in section VII. Finally, section VIII concludes the paper.

II. SYSTEM ARCHITECTURE

In this section, we present the overview of the system architecture of cognitive radio network with cooperative relay.

We design the secondary system in an infrastructure mode as shown in Figure 2. Secondary end users equipped with a single cognitive radio connected to local secondary AP to enjoy last mile connections. 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 holes opportunistically, meaning use the spectrum of the primary users only when it is not currently used by primary users.

As shown in the previous motivated example, we can improve the throughput of secondary users by leveraging

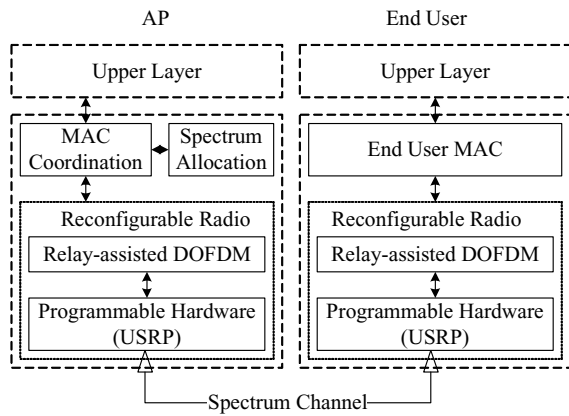


Fig. 3. Components in AP and end users.

cooperative relays. However, to put such an idea into practical work, we have several main challenges to address:

1) *Signal Processing*: The three-node cooperation first requires that signal for a single packet to be transmitted from a single radio on potentially discontinuous channels to avoid harmful interference for primary users. This can be realized by the existing approach of D-OFDM technology [8]. However, the signal partition, shifting and combination required by the introduction of relay node bring special challenges that cannot be handled by the traditional D-OFDM technology. Therefore, in this work we develop a novel signal processing scheme, named relay-assisted D-OFDM, to tackle those challenges.

2) *Resource Allocation*: Here the resource includes relay resource and channel resource. Adjacent secondary transmission pairs content for relays, and secondary nodes (pairs and relays) content for channels. Thus, the allocation of both relay resource and channel resource is coupled together and needs to be tackled jointly. Moreover, the resource allocation must take the transmission demand of each end user into consideration. Such a problem has not been observed by previous papers in cognitive radio networks.

3) *MAC Layer Coordination*: The unique operation of secondary nodes also brings challenges in MAC layer. We need the MAC protocol to coordinate the signal forwarding and packet transmission. Besides, the primary users' signal detection is of fundamental importance for correct operation of secondary networks. We design our system as a synchronized system to ease these operations. The synchronization is easy to implement since the AP can make the coordination.

The above functions are mapped to the components as shown in Figure 3. The hardware includes a reconfigurable radio which is implemented with programmable hardware (USRP [9]) as the radio frequency frontend to interact with wireless channel and workstations with general purpose processors to conduct signal processing (GNURadio [10]) in our testbed. Above the reconfigurable radio, AP has a spectrum allocation component to compute efficient spectrum allocation scheme for end users according to their spectrum availability and traffic demand information. Besides, the MAC coordination component coordinates the overall operations of both

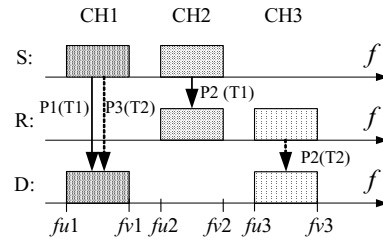


Fig. 4. Three-node relay-assisted D-OFDM.

AP and end users such as spectrum sensing, information collection, resource allocation notification, and etc. For each end user, the MAC is simply to execute the instructions given by AP.

In the following sections, we present the issues and the corresponding solutions in detail.

III. RELAY-ASSISTED DISCONTIGUOUS OFDM

In this section, we will first give an example to show the benefit of our relay-assisted D-OFDM, then address key challenges to realize this technique and present our solutions to overcome these challenges.

Assume that sender S has available channel 1 and channel 2, while receiver D has available channel 1 and channel 3 as shown in Figure 4. The other channels cannot be used due to the occupation of primary users. Under such circumstance, S can transmit data to D using only channel 1. We propose a relay-assisted transmission scheme using a third node which has common channels with both S and D . For example, node R with its available channel 2 and channel 3. With the help of R , the cooperative transmission can be operated as shown in Figure 4. During the first time slot, S transmits packet 1 and packet 2 from channel 1 and channel 2, respectively. D decodes packet 1 and R decodes packet 2. During the second time slot, S continues to transmit packet 3 on channel 1, while R modulates the received packet 2 onto channel 3 to transmit. D decodes packet 3 from channel 1 and packet 2 from channel 2. Thus, 3 packets can be transmitted within 2 slots. The throughput achieves 50% gain comparing with original 1 packet/slot.

According to such a transmission scheme, the sender should be able to transmit multiple packets on multiple channels at the same time using a single radio equipment. We can simply adopt D-OFDM as the physical layer technique [8]. By using OFDM, bits in different packets can be modulated into different orthogonal subcarriers. With some continuous subcarriers forming one channel and other continuous subcarriers forming another channel, multiple channels can be transmitted at the same time with the same radio frequency (RF) end. To prevent interference from neighboring channels, guard band is allocated between neighboring channels.

Besides, there are several key challenges to be addressed to achieve the functionalities described above. First, both relay and receiver should be able to alleviate the interference from other simultaneous transmitting channels to achieve a higher

SNR on the specific channel. Second, relay and receiver should be able to decode the packet correctly using only part of the whole subcarriers which are corresponding to their working channel. We will address all the above challenges in our proposed relay-assisted D-OFDM technology.

A. Radio Frequency Configuration

For the relay node or receiver node, it is important to correctly decode the transmitted signal from multiple concurrently transmitted signal on multiple channels. To achieve this, it should filter out the signal on the working channel while suppress the noise and interference on other channels successfully, which can be achieved by proper radio frequency configuration.

Assume that the frequency band of channel 1 is from f_{u1} to f_{v1} , and the radio frequency of the transmitter is set to be f_0 at the receiver end. If the RF is set to be the same frequency as the transmitter, then when we use a filter to keep the signal on $[f_{u1}, f_{v1}]$, signal in the symmetric frequency band $[2f_0 - f_{v1}, 2f_0 - f_{u1}]$ is also kept. However, there may be severe interference in this frequency band. Therefore, to avoid the interference in the symmetric channel, the receiver sets the receiving frequency to be f_1 , which is on the right side of the whole bandwidth. Then, a bandpass filter is used to filter the signal in band $[f_{u1}, f_{v1}]$. Finally, the resulting baseband signal is multiplied by a sine signal of frequency $f_1 - f_0$ to be moved back into subcarriers $[u_1, v_1]$.

B. Demodulation Using Part of Subcarriers

Another key challenge for cooperative relay is that both receiver and relay should be able to decode the packet from a fraction of the whole subcarriers which is corresponding to the working channel. After the signal has been filtered out, there are many other important functions need to be done, including time synchronization, frequency alignment and channel estimation. All these are done basing on the preambles added before the packet. Different from the traditional OFDM, we need to add preambles individually on each group of the subcarriers. So that the time synchronization, frequency alignment and channel estimation can be done basing on the signal filtered out which only include several subcarriers corresponding to the specific channel instead of the whole subcarriers.

Based on the preambles added before each channel, we use the delay and correlate algorithm to detect the beginning of packet and use cross-correlation based algorithm to do symbol synchronization [11]. Frequency error estimation is conducted after the fast Fourier transform (FFT) module using frequency domain algorithm to align the carrier frequency offset [12]. Frequency domain channel estimation is conducted to overcome the influence of the wireless channel [13]. Given the assumption that the channel is quasi-stationary, and the channel does not change during the time of transmitting a packet, we do channel estimation once for each packet. The implementation in the real testbed, which established with USRP board, shows that the relay-assisted D-OFDM we

proposed is feasible and can achieve significant throughput gain.

IV. JOINT RELAY SELECTION AND CHANNEL ALLOCATION

For a real network, there must be many secondary users associated with an AP. Therefore, in this section, we move on to a network perspective: how secondary nodes in a cognitive network with cooperative relays coordinate with each other to allocate the relay and spectrum resource?

The relay selection issue emerges when there are multiple resource-short nodes and resource-abundant nodes. We have to make a decision of how to match resource-short nodes to their helpers. Besides, the channel allocation issue inherited in multiple channel networks still exists here for both direct and relay links. What makes the whole problem further complicated is that these two issues are coupled. We in the following part address this joint problem.

A. Problem Statement

The resource allocation problem can be formulated as follows. We denote the cognitive radio network as a set of $N + 1$ nodes $V = \{v_0, v_1, \dots, v_N\}$ within a geographical area. Here v_0 is the secondary AP node. Let f_{low} and f_{up} denote the lower and upper end of the spectrum band of our interest. In this paper, 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^k to denote the channel availability: $a_i^k = 1$ indicates channel k at node v_i is available, and 0 otherwise. Each node v_i in V 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. We use $E = \{e_{ij}\}$ to denote the set of direct links, where $e_{ij} = 1$ means there exists a direct link between node v_i and v_j , and 0 otherwise. In this paper, we assume that links are symmetric, and that all nodes can communicate directly with AP (i.e., $e_{0i} = e_{i0} = 1$). We also assume that all nodes are in interference range of each other. For each secondary end user v_i , we use d_i (bit/s) to denote the demand of transmission that v_i would like to receive from v_0 (AP). Note that we only discuss the downlink in this part, as the uplink is similar.

Time is partitioned into time frames with length Δt . In any frame, there can be two types of transmissions going on in the network. One type is the direct transmission between AP and a node v_i . The other one is the advanced transmission among 3 nodes (AP, node v_i and its relay v_j).

We should make decision in each frame on how to arrange the active transmissions into these 2 types. Therefore, we define a 0-1 matrix $R = \{r_{ij}\}_{N \times N}$ to express the relay relationship, where element $r_{ij} = 1$ means that v_j performs as relay node for v_i , and 0 otherwise. In this paper, we assume relay relationship should follow the following constraints: one

node can have only one relay; one relay can serve only one node; when one node is served by a relay, this node cannot be the relay node of another node. Correspondingly, we have the following constraints:

$$\begin{aligned}
 \sum_{j=1}^N r_{ij} &\leq 1, \quad 1 \leq i \leq N \\
 \sum_{i=1}^N r_{ij} &\leq 1, \quad 1 \leq j \leq N \\
 r_{ij} \sum_{j'=1}^N r_{j'i} &= 0, \quad 1 \leq i \leq N, 1 \leq j \leq N \\
 r_{ij} &\leq e_{ij}, \quad 1 \leq i \leq N, 1 \leq j \leq N
 \end{aligned} \tag{1}$$

We use $X = \{x_{ij}^k\}$ to denote the channel assignment, where $x_{ij}^k = 1$ if channel k is assigned to link e_{ij} for data transmission, and 0 otherwise. 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. This constraint can be expressed as:

$$\sum_{e_{ij} \in E} x_{ij}^k \leq 1, \forall k. \tag{2}$$

The channel allocation should also satisfy the channel availability constraint at each node:

$$x_{ij}^k \leq a_i^k a_j^k, \forall i, j, k. \tag{3}$$

Assume the transmission rate of each link in every channel is identical, which is denoted by c . In a certain frame, if node v_i receives data directly from AP, its average throughput $c_i = c\Delta t/\Delta t = c$. If a node acts as a relay, it can use only half of the time in one frame to receive data from AP, and the other half to transmit to destination. Therefore, the average throughput of the link from AP to relay in one frame is $\frac{1}{2}c$, and the same for the link from relay to destination.

Now we calculate the throughput of node v_i under a certain strategy of relay selection R and channel allocation X . According to whether v_i is a relay or is helped by a relay, the calculation is divided into three categories:

- 1) If node v_i is a receiver without a relay's help, and is not acting as a relay itself, which satisfies $r_{ij} = 0$ and $r_{ji} = 0, \forall j$, its throughput can be expressed as:

$$\tilde{\theta}_i = \min\left(\sum_{k=1}^K cx_{0i}^k, d_i\right).$$

- 2) If node v_i acts as a relay for node v_j , which satisfies $r_{ji} = 1$, the throughput of its own data from AP is

$$\bar{\theta}_{ji} = \min\left(\sum_{k=1}^K \frac{1}{2}cx_{0i}^k, d_i\right).$$

Here the relay node v_i will satisfy its own demand first, and use the remaining bandwidth to serve v_j .

- 3) If node v_i receives data from the AP with the help of a relay v_j which satisfies $r_{ij} = 1$, its throughput is:

$$\hat{\theta}_{ij} = \min\left(\sum_{k=1}^K cx_{0i}^k + \min\left(\sum_{k=1}^K \frac{1}{2}cx_{ji}^k, \sum_{k=1}^K \frac{1}{2}cx_{0j}^k - \bar{\theta}_{ij}\right), d_i\right).$$

We can integrate the above throughput calculations into a single unified format for node v_i :

$$\theta_i = (1 - \sum_{j=1}^N r_{ij})(1 - \sum_{j=1}^N r_{ji})\tilde{\theta}_i + \sum_{j=1}^N r_{ji}\bar{\theta}_{ji} + \sum_{j=1}^N r_{ij}\hat{\theta}_{ij}.$$

Then our problem is: given demands $\{d_i\}_N$, 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:

$$\begin{aligned}
 \max_{R, X} \quad &\sum_{i=1}^N \theta_i \\
 \text{s.t.} \quad &(1)(2)(3)
 \end{aligned}$$

This problem is a nonlinear integer programming problem with high complexity. In the next section, we will propose a heuristic centralized solution for the whole problem.

B. Centralized Solution

Considering the complexity of the original problem, we propose a heuristic solution based on the observation as follows:

Proposition 1: If one user's demand is not fulfilled, it will not act as a relay to help others because this will definitely decrease the total throughput of the whole system.

Proof: Suppose one node's demand is not fulfilled by its common channels with AP (denoted as set C_1), but it still acts as a relay to help another node via channels from AP (denoted as set C_2). Then C_2 must be a subset of C_1 , otherwise, this node can improve its performance. Since only half of the time is available for relay link, the contribution to whole system using C_2 as relay link is thus half of its contribution as direct link for this node. ■

Based on this observation, we first partition nodes into two groups according to their traffic demand and spectrum availability. Then we increasingly select the pairs of destination and relay from the two groups to enlarge the system throughput.

1) *Nodes Partition:* Firstly, we do not involve relay transmission in the network, meaning each node receives data directly from the AP. The channels are assigned to the end users by the AP so that the overall throughput is maximized. Without relays, the problem can be simplified as follows:

$$\begin{aligned}
 \max_X \quad &\sum_{i=1}^N \min\left(\sum_{k=1}^K cx_{0i}^k, d_i\right) \\
 \text{s.t.} \quad &(2)(3)
 \end{aligned} \tag{4}$$

in which $\sum_{k=1}^K cx_{0i}^k$ (denoted by Cap_i) is the transmission capability of node v_i , $\min(Cap_i, d_i)$ is the real throughput of node v_i . Such a problem can be transformed to a max flow problem: each channel is represented by a channel node, and each end user is represented by a user node; there is an arc

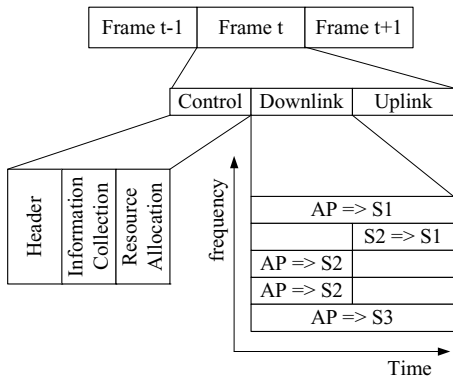


Fig. 5. MAC frame structure.

with capacity 1 from a source node to each channel node; there is an arc with capacity 1 from channel node k to user node i , if channel k is a common channel between AP and user i ; finally, there is an arc with capacity d_i from each user node to destination node. Therefore, it can be solved in polynomial time.

After it is solved, the throughput of each user is calculated by $\min(Cap_i, d_i)$. If $Cap_i < d_i$, the demand of the user v_i is not fully satisfied, in that case, v_i is called *potential destination* and still needs a relay node's help. If $Cap_i > d_i$, v_i 's demand is fully satisfied and it can further act as a relay to help other nodes, which is called *potential relay*.

2) *Relay Selection*: Next, we use a greedy method to choose at most one potential relay for each potential destination, as well as the corresponding channel allocation. This is a variation of maximum weighted bipartite matching problem, in which the potential relays and potential destinations form the two sides. The difference is that the weights of pairs are related to each other because of the channels.

At first, we calculate the most profitable pair of destination node and its relay node, along with their channels according to the channel availability and traffic demand. Then for current matching M , we find an augmenting path P , which is a path alternating between matched links and unmatched links with both ends unmatched. Denote the new matching as $M' = P \setminus M$. If M' is more profitable than M , we replace M with M' . Otherwise, we end up with M as the final relay selection along with the channel allocation.

So the problem is how to find such an augmenting path, which is coupled with allocating channel. To solve this, we greedily find the most profitable pair to increasingly construct a valid augmenting path, and update the channel availability. Note that the channels previously allocated to the current matching M can still be used, since M will be replaced if the new matching is more profitable. This process continues until no pair can be added.

V. MAC DESIGN FOR RELAY-ASSISTED COGNITIVE RADIO NETWORKS

The previous sections present the feasibility of leveraging a third node to improve the throughput of a single secondary

transmission pair as well as the system resource allocation algorithm. To make the cooperative relay scheme workable, MAC layer protocol is also needed to coordinate PHY layer operations among multiple nodes. We in this section describe the MAC protocol.

We design the MAC protocol based on the assumption of global synchronization, which is rather easy to implement considering the existence of the AP node. The time is divided into frames. At the start of each frame, secondary nodes with a single radio switch to the common control channel to exchange control messages and negotiate the resource allocation including both relays and channels. We assume the existence of an always available common control channel. Then in the remaining time of a frame, they switch to their assigned channels to conduct data transmission.

The MAC employs the frame structure depicted in Figure 5. Each frame includes three parts: control information exchange, downlink transmission and uplink transmission. The length of the frame is fixed, and is properly selected so that it can provide necessary protection for primary user by periodical spectrum sensing and prevent too high data transmission delay.

At the beginning of every frame, the AP sends a frame control header on the common control channel. Nodes receive this header and synchronize with the AP. After that, a short period is used to collect information of data demand and spectrum availability from each end user. With frame synchronization, primary user detection can be easily controlled and provided with high accuracy compared with cases without synchronization. The detection process is scheduled at the beginning of the information collection period. During the process, each secondary node keeps silent and senses the spectrum. Different sensing (energy detection, feature detection) methods can be applied. With such information, AP computes the resource allocation and notifies nodes. When the information is collected, centralized algorithm at AP is executed to calculate efficient resource allocation scheme for all the secondary end users. The allocation is broadcasted on the control channel.

After receiving the resource allocation message, each node adheres to the allocation decision made by the AP to do downlink and uplink transmission. During the downlink time of one frame, if one node is assigned to communicate directly with the AP, it switches to the assigned channel to receive AP's transmission, e.g. $S3$ in Figure 5 uses channel 1 to receive data from AP. For the relay node, it uses half of the downlink time to receive data from AP, and the other half time to forward data to the destination, e.g., $S2$ in Figure 5 receives data from AP on channel 2 and 3 in the first half time and transmits to $S1$ on channel 3 in the other half time. For the node assisted by a relay, it spends the whole downlink time to receive data from AP, and spends half of the time to receive data from relay on another channel, e.g., $S1$ in Figure 5. During each data transmission period, multiple packets are delivered.

Uplink is similar with the downlink. The duration of downlink and uplink can be determined by the demand and adaptively.

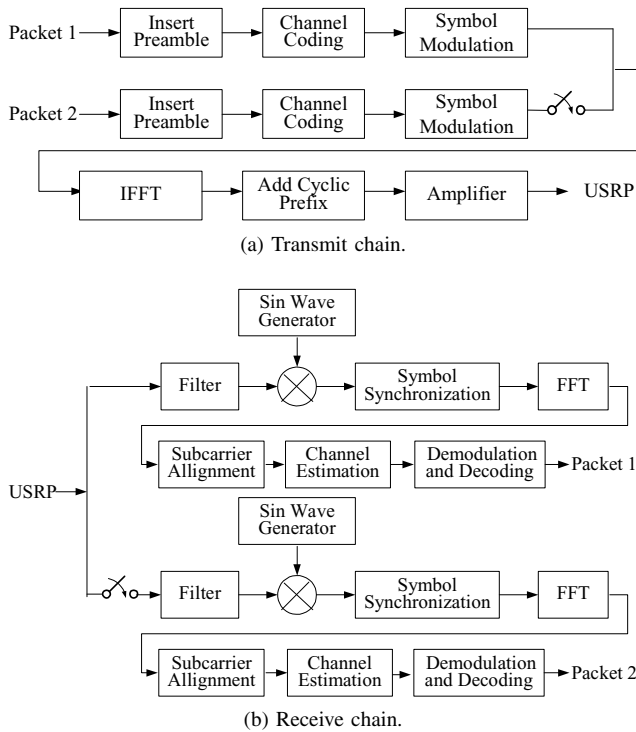


Fig. 6. Block diagrams of transmit and receive chains.

VI. EXPERIMENTAL EVALUATION

In this section, we setup a software-defined radio based testbed and implement our proposed relay-assisted D-OFDM and resource allocation algorithm. The purpose of this section is to demonstrate the following points:

- A software-defined radio based wireless testbed has been setup with infrastructure mode. The core technologies to support cooperative relay have been implemented within this testbed.
- Under different numbers of users and different traffic demands, our proposed cooperative relay scheme can consistently achieve good performance. The effectiveness of relay selection and channel allocation has been verified through the experiments.

A. Testbed Implementation

The whole system of the cognitive radio network consists of a secondary AP and several secondary end users. Each node is composed of an open-source reconfigurable RF front-end connected to a general purpose computer in which the relay-assisted D-OFDM, resource allocation algorithm and MAC functions are implemented in software.

In particular, the RF front-end is implemented with the USRP board with RFX2400 daughterboards, which operate in the 802.11 frequency range (i.e., 2.4 GHz) and have a transmit power of 50 mW. We use workstations with dual-core 3.2GHz CPU as general purpose computers.

The other modules are implemented within the GNURadio. We implement the relay-assisted D-OFDM based on the existing OFDM code in GNURadio. The transmitting and receiving

modules are shown in Figure 6. In the transmitter, multiple packets are added with preambles individually, coded and then modulated onto different subcarriers corresponding to different channels. By using inverse fast Fourier transform (IFFT), data in all subcarriers are combined together and finally sent out to USRP board after they are added with cyclic prefix and amplified. Whether the switch is on or off depends on whether there are multiple packets needed to be transmitted in multiple channels. In the receiver, signal from the USRP board is filtered by several different filters, with each one corresponding to each channel. Then signal in each channel is demodulated and decoded individually. Finally the packets can be received. The switch is on when the receiver needs to receive multiple packets on multiple channels simultaneously.

We use results from a software radio testbed described above to study the performance of our approaches. We demonstrate several aspects of performance with different setups. As comparison, for each experiment, the performance of transmission without cooperative relaying is also shown, which is called traditional approach (TA).

In our experiments, we set each radio such that DAC rate is 128 samples/ms and interpolation rate is 256, 2 samples/symbol, 1bit/symbol. Each channel is composed of 100 contiguous subcarriers, with 30 guard subcarriers between two neighboring channels, which can support about 60 Kbps data rate. The actual data rate varies depending on different channel conditions and system load of workstations.

Packet size is 200 bytes. Each run transfers 1000 packets in downlink, first with cooperative relays, and then with traditional approach without relaying. We repeat the experiments 20 times for each setup.

B. Three End Users

We evaluate relay scheme in a topology with 3 end user nodes as shown in Figure 7(a). Here, the numbers on the dashed lines indicate the number of common available channels between the two nodes connected and these channels are different. The traffic demands are 120 Kbps, 30 Kbps, 30 Kbps for node *D*, *R1* and *R2* respectively. Therefore, if we use traditional approach, node *D* receives about 60 Kbps, while node *R1* and *R2* both receive 30 Kbps, with large portion of available spectrum wasted. With relay scheme, both *R1* and *R2* can be the potential helper for *D*. Then according to our resource allocation algorithm, *R2* can contribute more since there are two common available channels between *R2* and *D* as well as another two common available channels between AP and *R2*. On the other hand, *R1* can only contribute one. The final transmissions are shown in Figure 7(b).

Figure 8 shows the CDF of throughput gains for 3 links topology. Our scheme provides a 37% (50% in theory) increase in throughput compared to the traditional approach for total system, while 87% (100% in theory) for node *D*.

The gap between the practical gain and the theoretical gain is due to the protocol overhead added to the relay scheme when it is switching between senders and receivers. Besides, with multiple channels working simultaneously, the

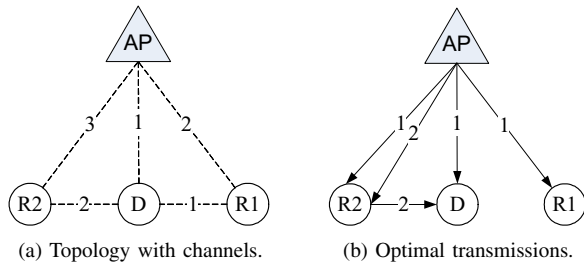
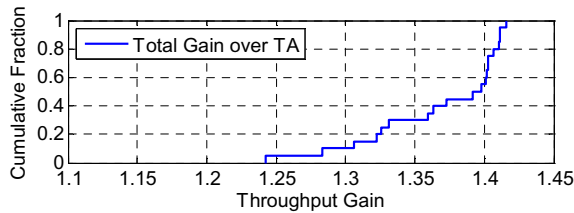
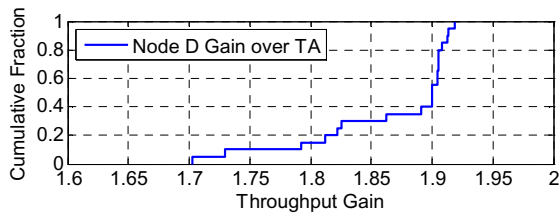


Fig. 7. Experiment for 3 end users.



(a) Total gain.



(b) Gain of node D .

Fig. 8. CDF of throughput for topology with 3 end users.

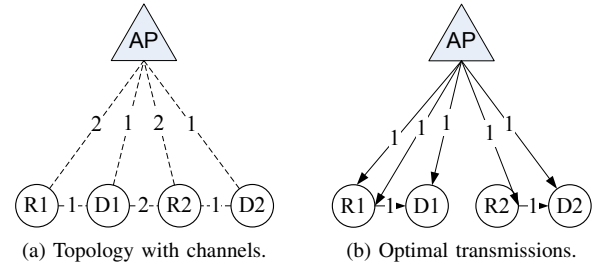
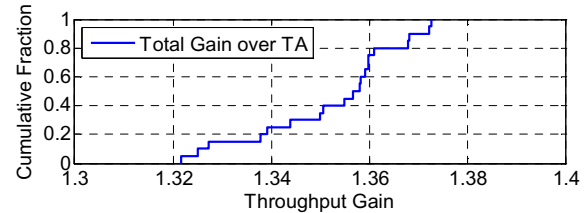
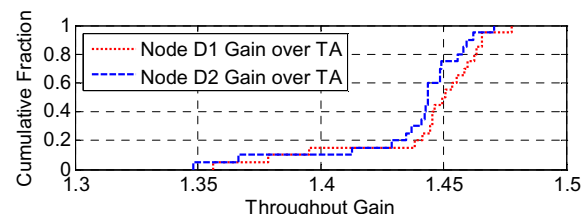


Fig. 9. Experiment for 4 end users.



(a) Total gain.



(b) Gains of node $D1$ and $D2$.

Fig. 10. CDF of throughput for topology with 4 end users.

interference from neighboring channels degrades the SNR level on each channel in the receiver, which increases the bit error rate and decreased the throughput. Another reason is that current hardware and software suit (USRP + GNURadio) has their inherited faultiness for OFDM implementation. The increased temper while running signal transmission makes the frequency alignment not accurate. This also contributes to the performance gap.

C. Four End Users

We next do experiment in a more complicated topology with 4 end user nodes as shown in Figure 9(a). The traffic demands are 100 Kbps, 100 Kbps, 30 Kbps and 0 Kbps, for node $D1$, $D2$, $R1$ and $R2$ respectively.

The link between AP and $D1$ via relay $R2$ can support data rate equal to one entire channel. However, if $R2$ is used by $D1$, it has too much bandwidth compared with $D1$'s demand, while $D2$ has no relay to fill its spectrum requirement. With our algorithm, an optimal transmission decision is made as shown in Figure 9(b): $D1$ uses $R1$ as relay, and $D2$ uses $R2$ as relay.

Figure 10 shows the CDF of throughput gains for this topology. Our scheme provides a 35% (40% in theory) increase in throughput, which comes from $D1$ and $D2$, with 44% and 43% respectively.

VII. RELATED WORK

D-OFDM is proposed and demonstrated in [8], [10], [14] to increase data rate while avoiding harmful interference with primary user transmission, by deactivating subcarriers within their vicinity. This feature is achieved by zeroing output power on primary occupied subcarriers while using remaining subcarriers for secondary transmission. Based on these existing works, we design a new physical layer technology, relay-assisted D-OFDM, to enable the efficient transmission among sender, relay, and receiver.

Flexible spectrum usage for transmission link is discussed in [4]–[7]. These works use adaptive bandwidth for individual transmission link, so that better spectrum efficiency can be achieved. DOSS [5] allows secondary links to use channels with variable bandwidth based on the spectrum availability. KNOWS [4] extends DOSS in that it provides a traffic-aware algorithm to allocate spectrum among secondary nodes. In [6], [7] authors consider more flexible spectrum access methods by using D-OFDM technology, with one focusing on admission control and another on optimal sensing strategy. Our work makes a difference. We observe the existence of spectrum unbalance within secondary networks, and allow spectrum-short nodes to use the channels of spectrum-abundant nodes, which are ignored in existing works.

There are several existing centralized cognitive radio sys-

tems. IEEE 802.22 [15] is the first standardization effort to define unlicensed operations in the TV spectrum. In 802.22, a base station serves multiple Consumer Premise Equipments (CPEs) and determines the availability of a TV channel by combining scanning results from the CPEs. The base stations are allowed to combine three contiguous TV channels to generate an 18 MHz-wide operating band. In DSAP [16], the centralized controller manages the spectrum access by offering long-term leases to secondary users. In contrast to the above systems, our system considers the spectrum and demand heterogeneity and is able to exploit more spectrum resource. The unique resource allocation problem does not exist in these works either.

In recent years, relay nodes have been widely used in various types of wireless networks for a variety of reasons. In multi-hop ad hoc networks, relay is used to increase the transmission rate of each link and maximize the spatial reusability. In cellular networks, relay is used to increase reliability as well as enlarge the coverage range [17], for example repeaters in cellular networks and relays in IEEE 802.16j WiMAX system. Recently, cooperative communication [18], [19] has also been a hot topic in wireless networks, where relay nodes are introduced to enable single antenna nodes share their antennas to form a virtual multiple-antenna transmitter, thus, transmit diversity is achieved and network capacity is increased. However, the relay nodes in our cooperative relay in cognitive radio networks play a different role compared with that in all the above scenarios. Instead of maximizing transmission rate in multi-hop ad hoc networks, we focus on the maximized spectrum utilization and use relay to bridge the channel availability from the source to the destination node. Besides, by allowing simultaneous transmission of different channels, the throughput of the whole network is increased.

Besides, this whole work can be regarded as a cross layer design, in which we jointly consider the physical layer and MAC layer issues. Cross layer approach has been used to improve network performance in existing work [20].

VIII. CONCLUSIONS

Facing the challenges brought by the heterogeneity in spectrum availability and also the traffic demand for secondary users, in this paper, we explore to use cooperative relay node to assist the transmission of cognitive radio networks and improve spectrum efficiency. We observe that spectrum resource can be better matched to traffic demand of secondary users with the help of relay node. As the first work of exploiting spectrum resource using relay nodes for cognitive networks, we focus on the design and implementation of an infrastructure mode secondary network. To achieve this, we address several issues. Firstly, we propose relay-assisted D-OFDM for data transmission as the fundamental component for the whole system. Secondly, we identify a new resource allocation problem of joint relay selection and channel allocation. A centralized heuristic is proposed to handle the problem. Finally, we design a practical MAC protocol to coordinate

the relayed transmission as long as resource allocation. To demonstrate the feasibility and performance of cooperative relay for cognitive radio, we implement it in a testbed consisting of USRP and GNURadio. Experimental results confirm significant gain compared with traditional transmission.

IX. ACKNOWLEDGEMENT

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