Cooperative Relay to Improve Diversity in Cognitive Radio Networks

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ABSTRACT

Recent studies demonstrated that dynamic spectrum access can improve spectrum utilization significantly by allowing secondary unlicensed users to dynamically share the spectrum that is not used by the primary licensed users. Cognitive radio was proposed to promote the spectrum utilization by opportunistically exploiting the existence of spectrum "holes." Meanwhile, cooperative relay technology is regarded widely as a key technology for increasing transmission diversity gain in various types of wireless networks, including cognitive radio networks. In this article, we first give a brief overview of the envisioned applications of: cooperative relay technology to CRNs, cooperative transmission of primary traffic by secondary users, cooperative transmission between secondary nodes to improve spatial diversity, and cooperative relay between secondary nodes to improve spectrum diversity. As the latter is a new direction, in this article we focus on this scenario and investigate a simple wireless network, where a spectrum-rich node is selected as the relay node to improve the performance between the source and the destination. With the introduction of cooperative relay, many unique problems should be considered, especially the issue for relay selection and spectrum allocation. To demonstrate the feasibility and performance of cooperative relay for cognitive radio, a new MAC protocol was proposed and implemented in a universal software radio peripheral-based testbed. Experimental results show that the throughput of the whole system is greatly increased by exploiting the benefit of cooperative relay.

INTRODUCTION

The radio spectrum is a limited and valuable resource that is tightly managed by governments. Recent reports showed a significantly unbalanced usage of spectrum; with a small portion of spectrum (e.g., cellular band, unlicensed band) increasingly crowded, most of the rest of the allocated spectrum is underutilized. Spectrum utilization can be improved significantly by introducing primary-licensed users and secondary-unlicensed users and allowing secondary users to access *spectrum holes* unoccupied by primary users. Cognitive radio [1] was proposed as the means for secondary users to promote the efficient utilization of the spectrum by exploiting the existence of spectrum holes.

The main challenges to the efficient development of cognitive radio networks (CRNs) include *primary user detection and transmission opportunity exploitation*. Here we focus only on the latter issue, which means that after a spectral hole is identified, secondary users must exploit the transmission opportunity so as to maximize their own performance while not interfering with the primary users. Secondary users might be competing for the resource or cooperating to improve efficiency and fairness of resource sharing [2].

The recent study illustrated that large benefits can be gained from cooperation among different terminals. In the following, we first provide a brief overview of the application of the cooperative technology to CRN and then focus on a specific example that shows the advantages of cooperation relay to improve spectrum diversity.

COOPERATIVE TRANSMISSION TO IMPROVE SPATIAL DIVERSITY

Cooperative transmission — where the original idea comes from the basic relay model that consists of three terminals: a source S, a relay R, and a destination D — is well known as a powerful technology that combats signal fading due to multipath propagation in a wireless medium. By enabling a set of cooperating relays to forward received information, this regime exploits spatial diversity through cooperation among distributed antennas belonging to multiple terminals in wireless networks [3].

In the context of CRN, cooperative transmission can give rise to the following two different but basic scenarios.

1 Cooperative transmission between secondary users: In this scenario, a secondary user acts as a relay from the transmission of another (source) secondary node. General considerations that are valid for cooperative transmission can be applied here; the only difference is that secondary nodes continuously must sense the spectrum for possible transmissions by the primary users.

2 Cooperative transmission between primary and secondary users: In this case, secondary

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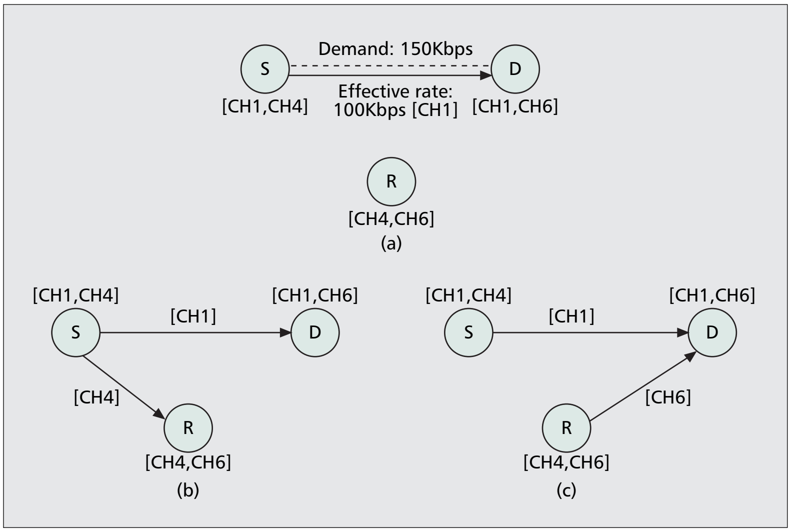


Figure 1. *Motivated example for cooperative relay to improve spectrum diversity: a) network setup and performance without cooperative relay; b) time slot 1 with cooperative relay scheme; c) time slot 2 with cooperative relay scheme.*

users can relay the traffic of a primary transmitter toward the intended destination. The rationale behind such a decision is that helping primary users finish their transmissions as quickly as possible will, in turn, lead to more transmission opportunities for secondary users [4].

We can see that cooperation transmission between secondary users aims to increase the secondary throughput for a given spectral hole, whereas cooperation transmission between primary users and secondary users aims to increase the probability of transmission opportunities. In summary, both of the above cooperation transmissions try to improve spatial diversity for the same spectrum frequency band.

Cooperative Relay to Improve Spectrum Diversity

The resource unbalance in CRNs is much more severe than in traditional wireless networks. The spectrum availability of secondary users is heterogeneous due to the location difference among different users, the dynamic traffic of primary users, and the opportunistic nature of the spectrum access of secondary users [5]. Moreover, the traffic demands of secondary users also can be quite different. Then, a natural yet important question is how to handle the unbalanced spectrum usage within the secondary network to fulfill the heterogeneous traffic demand from secondary users that has not drawn much attention before (Fig. 1).

Our observation is that some secondary users may not be required to use their entire available spectrum because of the low traffic demand. Utilizing these nodes as helpers, to relay the other secondary users' traffic with their otherwise wasted spectrum, can significantly improve system performance. In particular, suppose a transmission from *S* (with available channel *CH1*, *CH4*) to *D* (with available channel *CH1*, *CH6*) has 150 kb/s demand, but their common channel *CH1* can support only 100 kb/s. Meanwhile, a neighbor *R* of both *S* and *D* has abundant channels: channel *CH4* common with S and another channel *CH6* common with *D*. We can involve *R* as a helper in this transmission: while *S* and *D* still communicate on their original link over *CH1*, S sends additional data on *CH4*, and D receives on *CH3*, with R switching between *CH4* and *CH6* to relay data from *S* to *D*. In this way, the data rate between *S* and *D* is increased, and spectrum resources are efficiently utilized.

Starting from such a simple, yet interesting, observation, in this article we propose to use cooperative relay for CRNs with single-radio end users to more effectively utilize spectrum resources. However, the realization of this idea has several challenges:

- Traditionally, one radio can transmit or receive only at one channel at a specific time. The new relay-involved transmission raises a question from the start: how can such three-node, multiple-channel (probably discontinuous) transmission be possible? We propose and implement a new relay-assisted discontiguous orthogonal frequency division multiplexing (D-OFDM) scheme with which the receiver can receive one flow of data from the source directly; at the same time, the relay node can decode another flow of data transmitted on another channel and shift it to a third channel to forward it to the receiver.
- The cooperative transmission scheme brings in new issues of resource allocation. For a network of secondary users, we must address how to select the proper node as relay node and also how to allocate the proper spectrum for secondary users. These problems are coupled together. In the following section, we formalize the joint-relay-selection and spectrum-allocation problem and propose a heuristic algorithm to address it.

This work is the first one to explore the cooperative relay in the context of CRNs to improve spectrum diversity smartly by allowing spectrum-abundant nodes to help the spectrum-short ones.

System Architecture

In this section, we present an overview of the system architecture of a CRN with cooperative relay. In this article, we design the secondary system in an infrastructure mode as shown in Fig. 2: secondary end users, equipped with a single cognitive radio, connected to a local secondary access point (AP) to enjoy last mile connections. Primary users with different spectrums (channel 1 to 3, in this example) previously are deployed in the same region but are observed with quite low spectrum utilization. Secondary users can access these spectrum holes opportunistically, meaning they use the spectrum of the primary users only when it is not currently used by primary users. The secondary AP uses an OFDMA modulation scheme similar to the IEEE 802.22 standard [5]. Note that the spectrum availability of secondary users can be heterogeneous due to the location difference among different spectrum users, the dynamic traffic of primary users, and the opportunistic access nature of secondary spectrum users.

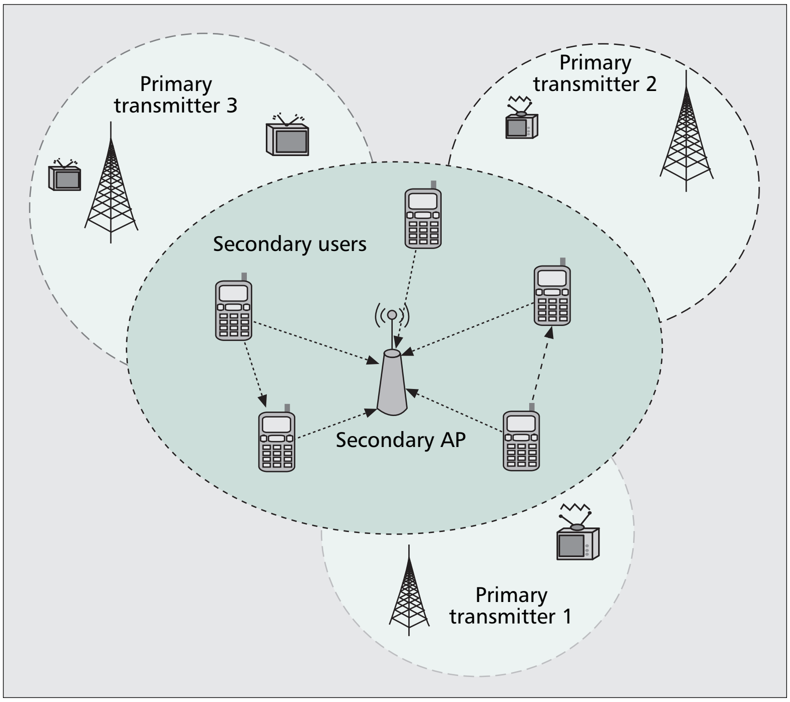
As shown in the previous motivated example, we can improve the throughput of secondary users by leveraging cooperative relays. However, to make such an idea practical, we must address several challenges to:

- *Signal processing*: The three-node cooperation requires a signal for a single packet to be transmitted from a single radio on potentially discontinuous channels to avoid harmful interference to primary users. This can be realized by the existing approach of D-OFDM technology [6]. However, the signal partition, shifting, and combination required by the introduction of a relay node bring special challenges. Therefore, in the next section, we develop a novel signal processing scheme, named relay-assisted, discontiguous OFDM, to address those challenges.
- *Resource allocation*: Here the resource includes relay and channel resources — adjacent secondary transmission (pairs) content for relays and secondary node (pairs and relays) content for channels. Thus, the allocation of both relay and channel resource is coupled together and must be addressed jointly. Moreover, the resource allocation must take the transmission demand of each end user into consideration. This problem has not been observed in previous papers about CRNs yet.
- *MAC-layer coordination*: The unique operation of secondary nodes also brings challenges in the medium access (MAC) layer. The MAC protocol must coordinate the signal forwarding and packet transmission. In addition, 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 because the AP can make the coordination.

Relay-Assisted, Discontiguous OFDM

In this section, we address key challenges during the realization of the three-node cooperation technique and present our solutions to overcome these challenges.

First, the sender must be able to transmit multiple packets on multiple channels at the same time using single-radio equipment. For this, we can simply adopt D-OFDM as the physical-layer technique, where signals on multiple channels can be transmitted simultaneously on single-radio equipment. Second, both relay and receiver should be able to alleviate the interference from other simultaneous transmitting channels to achieve a higher signal-to-noise ratio (SNR) on the specific channel. Third, relay and receiver should be able to decode the packet correctly using only some of all subcarriers that correspond to their working channel. We address these two challenges in the following two subsections, respectively.



■ **Figure 2.** *System architecture of secondary CRNs with cooperative relays.*

Radio-Frequency Configuration

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

Assume that the frequency band of channel 1 is from $fu1$ to $fv1$, and the RF of the transmitter is set to be $f0$ at the receiver end. If RF is set to be the same frequency as the transmitter, when we use a filter to keep the signals on [$fu1$, $fv1$], signals in the symmetric frequency band [$2f0$-$fv1$, $2f0$-$fu1$] also are kept. However, there can be severe interference in this frequency band. Therefore, to avoid the interference in the symmetric channel, the receiver set the receiving frequency to be $f1$, which is on the right side of the whole bandwidth. Then, a bandpass filter is used to filter the signals in band [$fu1$, $fv1$]. Finally, the resulting baseband signal is multiplied by a sine signal of frequency $f1$-$f0$ to be moved back into subcarriers [$u1$, $v1$].

Demodulation Using Part of the Subcarriers

Another key challenge for cooperative relay is that both the receiver and the relay should be able to decode the packet from a fraction of all subcarriers that correspond to the working channel. After the signals are filtered out, there are many other important functions that must be performed, including time synchronization, frequency alignment, and channel estimation. All these are performed based on the preambles added before the packet. Different from traditional OFDM, we must add preambles individually on each group of the subcarriers.

Each MAC 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 the required protection for a primary user by periodical spectrum sensing and can prevent high transmission delay.

Based on the preambles added before each channel, we use the delay-and-correlate algorithm to detect the beginning of the packet and use the cross-correlation-based algorithm to conduct symbol synchronization. Frequency error estimation is performed after the fast Fourier transform (FFT) module using the frequency domain algorithm to align the carrier frequency offset. Frequency domain channel estimation is conducted to overcome the influence of the wireless channel. Given the assumption that the channel is quasi-stationary and does not change during the time of transmitting a packet, we do channel estimation once for each packet. The implementation in the real testbed, introduced later, demonstrates that the proposed relay-assisted D-OFDM is feasible and can achieve significant throughput gain.

JOINT RELAY SELECTION AND CHANNEL ALLOCATION

In this section, we focus on a network perspective: how secondary nodes in a CRN 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 must make a decision of how to match resource-short nodes to their helpers. In addition, the channel allocation issue inherited in multi-channel networks still exists for both direct and relay links. What further complicates the problem is that these two issues are coupled. This is because relay selection has an impact on the channel allocation and vice-versa.

Suppose 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 is the traditional transmission between the AP and a node *vi*. The other one is the advanced transmission among three nodes (AP, *vi*, and its relay *vj*). We should make a decision in each frame on how to arrange the active transmissions into these two types. The detailed formulation for such a resource allocation problem can be found in a technical report [7], which is an NP-complete problem.

To tackle that problem, we propose a heuristic solution based on the observation that *if one user's demand is not fulfilled, it will not act as a relay to help others because this definitely decreases the total throughput of the whole system* (formal proof can be found in [7]). Based on this observation, we first partition nodes into two parts according to their traffic and spectrum availability. Then, we greedily select the best pair of destination and relay from the two parts to increase the system throughput.

MAC DESIGN FOR RELAY-ASSISTED CRNS

The previous sections present the feasibility of leveraging a helper to improve the throughput of a CRN. Then, we design a MAC protocol to coordinate physical (PHY)-layer operations among multiple nodes. Considering the existence of APs, global synchronization is rather easy to implement. The time is divided into time frames. At the start of each frame, secondary nodes with a single radio switch their radios to the common control channel to exchange control messages and negotiate the resource allocation, including both relays and channels. Then, in the remaining time of a frame, they switch to their assigned channels to conduct data transmission.

FRAME STRUCTURE

Each MAC 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 the required protection for a primary user by periodical spectrum sensing and can prevent high transmission delay.

PRIMARY USER DETECTION

With frame synchronization, primary-user detection can be controlled easily and provided with high accuracy compared to cases without synchronization. The detection process is put at the beginning of the information collection period. During the process, each secondary node is silent and senses the spectrum. Different sensing methods (energy detection, feature detection) can be applied.

COORDINATION

At the beginning of every frame, the AP sends a frame-control header on a common control channel. Nodes receive this header and synchronize with the AP. After that, a short period is used to collect information about the data demand and spectrum availability from each end user. Random access is used here. When the information is collected, a centralized algorithm at the AP is executed to allocate resources for all the secondary end users. Then, the allocation decision is broadcast on the control channel.

DATA TRANSMISSION

After receiving the resource allocation message, each node adheres to the allocation decision made by the AP for 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 the transmission of the AP. For the relay node, it uses half of the downlink time to receive data from the AP and the other half of the time to forward data to the destination. For the node assisted by a relay, it spends the whole downlink time to receive data from the AP and uses half of the time to receive data from a relay on another channel.

The uplink case is similar to the downlink one. The duration of downlink and uplink can be determined by the demand adaptively.

EXPERIMENTAL EVALUATION

In this section, we set up a CRN testbed and implement our proposed relay-assisted D-OFDM, resource allocation algorithm, and MAC protocol. The purpose of this section is to demonstrate:

- An infrastructure-based CRN testbed set up. The core technologies to support cooperative relay were implemented through this testbed.
- Under various numbers of users and various traffic demands, our proposed cooperative relay scheme can consistently achieve good performance. The effectiveness of relay selection and channel allocation was verified through the experiments.

Architecture for the CRN Testbed

We design a cognitive radio system with the architecture shown in Fig. 3. 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. Each node serves upper-layer requests and interacts with the radio spectrum, with the input of spectrum usage rules from the external radio-spectrum management entity.

Reconfigurable Physical Layer — The whole system is based on a reconfigurable hardware platform, and the physical layer is based on the platform of the universal software radio peripheral (USRP) and GNU radio. The USRP [4] recently became a popular experimental platform for wireless communication research projects. It implements front-end functionality and A/D and D/A conversion. RFX2400 daughter boards are used in our work, which operate in the 802.11 frequency range (i.e., 2.4 GHz) and have a transmit power of 50 mW (17 dBm). GNU radio [8] is an open-source toolkit for building software radios. It is designed to run on a PC; combined with minimal hardware, it enables the construction of simple software radios. GNU radio with version 7246 is adopted in our work, in which relay-assisted D-ODFM is implemented. With such a physical layer, we freely can adapt multiple dimensions of data transmission (power, frequency, and modulation).

Spectrum Information — This part is responsible for collecting and managing the spectrum information from the internal physical layer and for external radio spectrum management. The GNU radio of the internal physical layer can provide interfaces to deliver spectrum status, including both spectrum availability and channel condition, measured by the USRP.

MAC Layer and Network Layer — The MAC layer component is a self-developed part of the architecture. Depending on the detailed system configuration, the MAC protocol can be implemented in a standalone module, as a part of the GNU radio, or as a part of a routing layer. We leverage the work of the Click project as the routing part, which is built from fine-grained components, called elements, which perform packet processing.

Cross-Layer Management — Our cross-layer management component interfaces with other layers to collect network information and also to receive spectrum policy information from the radio-spectrum-management component. With such information, the cross-layer management component adjusts operation parameters to optimize network performance according to certain communication objectives.

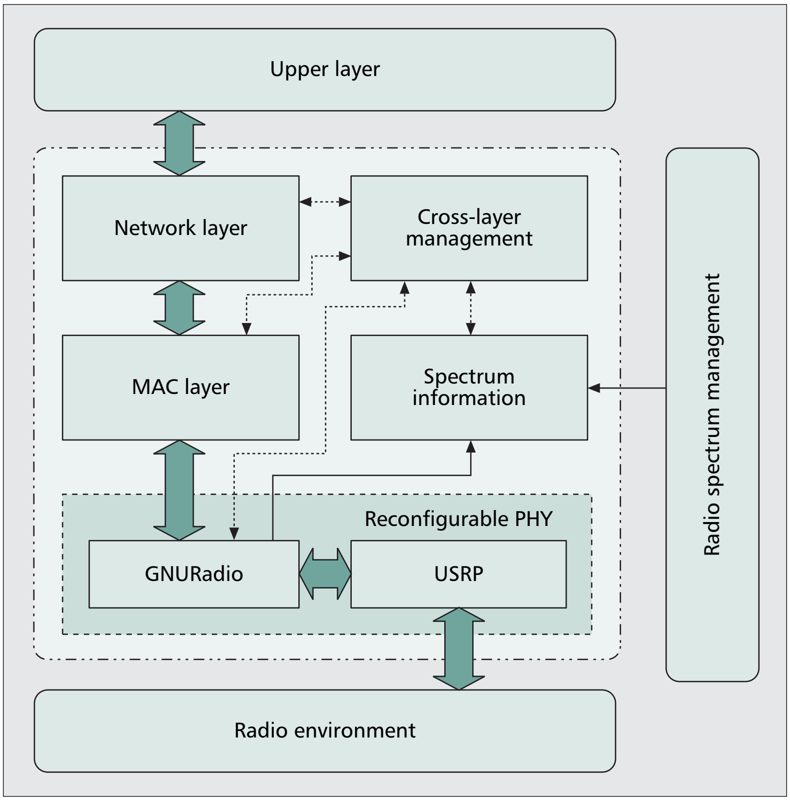


Figure 3. *CRN testbed architecture.*

Performance Evaluation

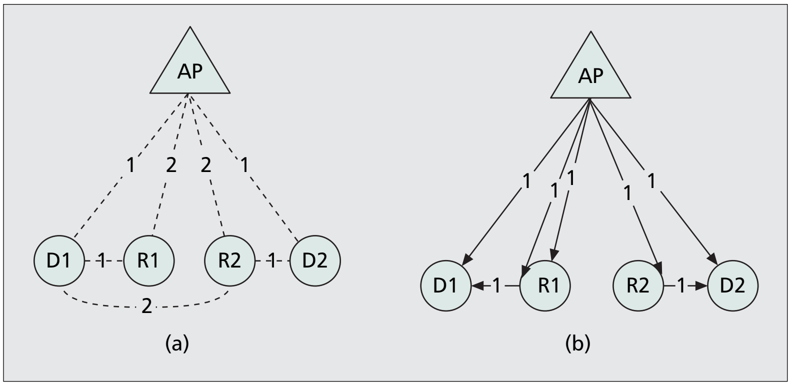
The CRN consists of a secondary AP and several secondary users (Fig. 4). We evaluate a relay scheme in different network configurations. Due to space limitations, only the topology with four nodes as shown in Fig. 5a is presented. Here, the numbers on the dashed lines indicate the number of commonly available channels between two connected nodes. The traffic demands are 100 kb/s, 100 kb/s, 30 kb/s, and 0 kb/s, for node *D1*, *D2*, *R1*, and *R2*, respectively. The link between AP and *D1* via relay *R2* can support a data rate equal to one entire channel. However, if R2 is used by *D1*, it has too much bandwidth compared to the demand of *D1*, whereas *D2* has no relay to fill its spectrum requirement. With our algorithm, an optimal transmission decision is made as shown in Fig. 5b: *D1* uses *R1* as relay, and *D2* uses *R2* as relay.

Figure 6 shows the cumulative distribution function (CDF) of throughput gains for this topology. Our scheme provides a 35 percent (in theory, 40 percent) increase in throughput, which comes from *D1* and *D2*, with 44 percent and 43 percent, respectively.

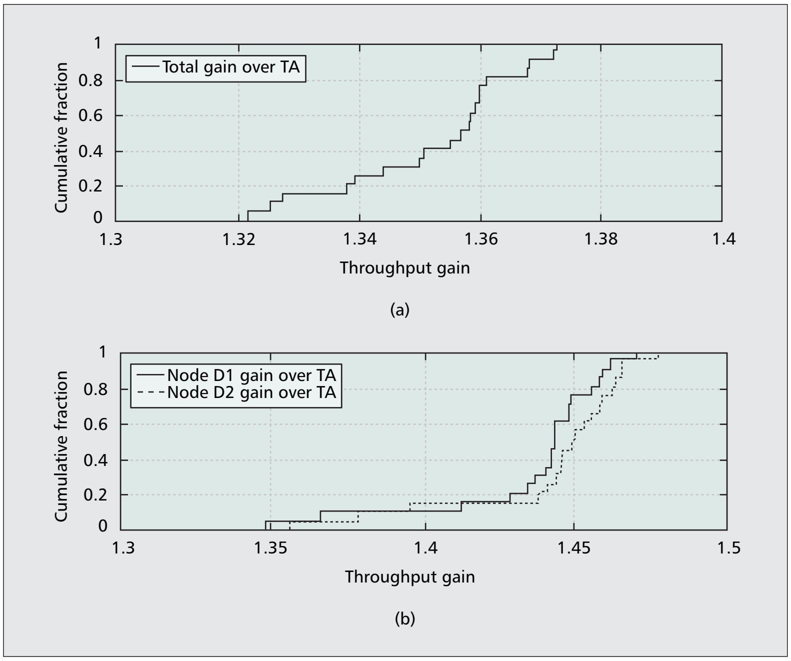
Further Discussion

This article demonstrates the key concept of using cooperative relay for CRN. As this is a new research direction, additional research topics can be explored from this starting point.

■ **Figure 4.** *A photo of our real testbed.*



■ **Figure 5.** *Experiment for four end-users: a) topology with channels; b) optimal transmission.*



■ **Figure 6.** *CDF of throughputs for topology with 4 end-users: a) total throughput gain; b) throughput gain of nodes* D1 *and* D2.

TRANSMISSION CONSTRAINTS

This work imposes several assumptions on the secondary users' transmission that can be relaxed in future research. For example, we limit the secondary users' transmission to be exclusive for each channel, meaning that within each time slot, a channel can be used by only one active transmission pair. System performance can be further improved if we allow simultaneous non-interfering transmissions among several distant destinations and relay pairs.

COMMON CHANNEL

So far, we assume that there is always a common channel for the control message exchange between the AP and the end users, for example, industrial, scientific, and medical (ISM) bands. When this is not the case, we must change the control channel dynamically according to spectrum availability. Another way is to use an OFDMA scheme such that each node uses its own channel common with the AP for control message exchange.

MULTIPLE RADIOS

In our article, we assume all nodes are equipped with a single cognitive radio. This is reasonable considering the cost and size of end users. However, if this is not a concern, better spectrum utilization can be achieved. For example, if each node has two cognitive radios, a relay node can act as a pipeline between the AP and its relayed destination, with one of its radios communicating with the AP and the other one communicating with the destination on different channels simultaneously. Therefore, channels in the relay node are fully used, in contrast to half the effective time of the current design.

AD HOC COGNITIVE RADIO NETWORK

Only infrastructure mode is discussed in this article. The cooperative relay concept also can be extended easily to ad hoc networks. In that case, multiple-source-destination pairs can exploit more spectrum channels with the help of relay nodes. However, coordinating ad hoc nodes is much more difficult than using the infrastructure mode. Synchronization, the multichannel hidden terminal problem, and distributed-spectrum sensing are several important issues that must be discussed.

CONCLUSIONS

Cooperative transmission appears to be a promising approach for improving the throughput of secondary nodes by increasing the spatial diversity and spectrum diversity.

In this article, we gave a brief overview about some of the aspects of the interplay of cooperation and cognitive radio technologies. Facing the challenges brought by the heterogeneity in spectrum availability and also the traffic demand for secondary users, we explored the use of a cooperative relay node to assist the transmission of CRNs and improve spectrum efficiency. We observe that spectrum resources can be better matched to traffic demand with the help of a relay node. As the first work about exploiting spectrum resources using relay nodes for CRNs, we focus on the design and implementation in the infrastructure mode. To achieve this, we address several issues. First, we propose relay-assisted D-OFDM for data transmission as the fundamental component for the whole system. Second, we identify a new resource-allocation problem of joint-relay selection and channel allocation that is NP-hard. Finally, we design a practical MAC protocol to coordinate the relay and spectrum allocation. To demonstrate the feasibility and performance of cooperative relay for CRNs, we implement a testbed consisting of the USRP and GNU radio. Experimental results confirm a significant gain compared to traditional transmission.

Leveraging a cooperative relay to improve spectrum diversity is a totally new research direction for CRNS; some interesting future research topics also are discussed.

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BIOGRAPHIES

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