Research Article

Cooperative Transmission in Cognitive Radio Ad Hoc Networks

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Cognitive radio technology is the key to realize dynamic spectrum access system and promote the spectrum utilization through exploiting the spectrum holes left by primary users. However, the spatial heterogeneity of spectrum availability imposes special challenges for efficient utilization of the spectrum resources for cognitive radio ad hoc networks (CRAHNs). The cross-layer cooperative transmission scheme is a promising approach to improve the efficiency of spectrum utilization and improve the performance of cognitive radio networks. Such an approach leverages relay-assisted discontinuous OFDM (DOFDM) for data transmission at physical and MAC layers in a basic three-node configuration. With this scheme, a relay node will be selected that can bridge the source and the destination using its common channels between those two nodes. In this paper, we investigate the application of such a cooperative transmission scheme to address the spectrum heterogeneity issue in CRAHNs. In particular, we describe several types of cooperative transmission and formulate a new resource allocation problem with joint relay selection and channel allocation. We propose a heuristic algorithm to solve the resource allocation problem, which is based on the metric of utility-spectrum ratio of transmission groups. Simulations demonstrate the performance improvement of the cooperative transmission over the direct transmission.

1. Introduction

There have been a lot of innovations of wireless devices and wireless services in recent years. However, due to the current fixed spectrum assignment and allocation rules, there is virtually no available spectrum band to experiment and deploy these new wireless products. Meanwhile, recent spectrum measurement reports have shown significantly unbalanced usage of spectrum, with some frequency bands largely unoccupied most of the time and some other frequency bands heavily used [1]. Observing such inefficient utilization of the scarce and valuable spectrum resource, new spectrum access rules are undergoing rapid development, whose core idea is to allow secondary users (or unlicensed users) to access spectrum holes left by primary users (or licensed 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.

Cognitive radio ad hoc network (CRAHN) is one of the major application fields, where there exist special research challenges and opportunities [3]. One important issue is the spectrum heterogeneity faced by CRAHNs, which is due to the location difference among different secondary users, dynamic traffic of primary users, and opportunistic spectrum access nature of secondary users. Several spectrum measurement reports have already demonstrated such spectrum heterogeneity. For example, in the UHF spectrum band, television stations represent the largest incumbent users. Spectrum heterogeneity exists on both large and small scales. For a wide area, spectrum availability depends on the location of TV transmitters and the number of operating stations. For an area with a smaller scale, spectrum availability depends on obstructions, construction material, and the existence of active wireless microphones with typical transmission ranges of a few hundred meters. As reported in [4], for the UHF spectrum in the tested area, the median number of channels available at one point but unavailable at another is close to 7.

Such a spectrum heterogeneity imposes a lot of challenges for resource allocation in CRAHNs. In [5, 6], a cooperative transmission scheme is proposed to address the spectrum heterogeneity issue in the infrastructure mode.
network with end user nodes served by a single access point node. With such a scheme, some end user nodes will relay the data traffic of other nodes based on the joint physical layer and MAC layer design. A centralized solution is proposed to address the new resource allocation problem with both relay selection and channel allocation. To demonstrate the feasibility and performance of cooperative relay for the cognitive radio infrastructure mode network, a new MAC protocol has been proposed and implemented in a testbed based on Universal Software Radio Peripheral (USRP) [7] and GNU Radio [8]. Experimental results show that the throughput of the whole system is greatly increased by exploiting the benefit of cooperative relay.

The exiting work mentioned above targets at relatively simple network structures, that is, a network with a single base station and its served end user nodes. There is little existing work on the general CRAHNs leveraging the above cooperative transmission scheme, which is the focus in this paper. In this paper, we study a general network model with multiple single-hop secondary transmission pairs where each node could act as a relay node for its neighbouring transmission pairs. Such a system model represents a typical application scenario. However, it complicates the problem due to the coupling of relay selection and channel allocation. To make the problem tractable, we impose some cooperation constraints and define two types of transmission groups with either one direct transmission pair or two cooperative transmission pairs. We propose to use utility-spectrum ratio as the metric to evaluate the transmission group. Based on this metric, an iterative algorithm is proposed to conduct relay selection and channel allocation.

The rest of the paper is structured as follows. Section 2 provides background knowledge of cooperative transmission scheme used in this paper and related works. Section 3 describes the system model and provides the problem statement. In Section 4 we propose our algorithm to solve the resource allocation problem. Section 5 presents the simulation results. Finally, Section 6 concludes the paper.

2. Background and Related Works

In this section, we provide a brief introduction to the cooperative transmission scheme in cognitive radio networks and summarize the related works.

2.1. Improve Spectrum Utilization with Cooperative Relay. 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. Meanwhile, the traffic demands of secondary users also demonstrate variation. One important problem in cognitive radio networks is to handle the unbalanced spectrum usage within the secondary network to fulfill the heterogeneous traffic demand from secondary users. The observation is that some secondary users can be utilized as helpers to relay the other secondary users traffic, which can significantly improve system performance.

We will use an example to illustrate the idea. Suppose there is a data transmission request from node $u$ to node $v$ as shown in Figure 1. Here the numbers besides the node represent the available channels for that node. Without loss of generality, we assume each common available channel between any pair of nodes can provide data rate of 1 unit. Note that each node has only one half-duplex radio for data transmission. In Figure 1(a), we use direct transmission between $u$ and $v$ on channel 1, which will result in data rate of 1 unit. Alternatively, we can use relay node $r$ to conduct two-hop transmission, with $r$ switching its single data radio between channel 2 (with $u$) and channel 3 (with $v$). However, the data rate is only 0.5 unit. Improvement is possible if we introduce cooperative relay. The scheme is shown in Figure 1(c). In time slot 1, $u$ sends data on channel 1 to $v$, while $u$ also sends data on channel 2 to $r$. In time slot 2, $u$ sends data on channel 1 to $v$, while $r$ sends data on channel 3 to $v$. Therefore, the total data rate increases to 1.5 unit.

2.2. Relay-Assisted Discontiguous OFDM. There exist challenges for the realization of the three-node cooperation technique. 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 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 challenges with the following two methods in [5, 6].

We design a new transmission scheme based on discontiguous OFDM to realize the above three-node transmission, which is called relay-assisted D-OFDM. Such scheme can allow a node with a single radio to transmit or receive from multiple nodes on different channels. It addresses several issues such as 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 and should be able to decode the packet correctly using only part of the whole subcarriers that are corresponding to their working channel. To demonstrate its feasibility and performance, we implement it in a testbed consisting of USRP and GNU Radio. Experimental results confirm significant gain compared with traditional transmission.

2.3. Existing Works on Cooperative Communication and Cognitive Radio. In recent years, relay nodes have been widely used in various types of wireless networks. In multihop ad hoc networks, relay nodes are used to connect distant nodes that are otherwise disconnected. Meanwhile, relay nodes can increase the transmission rate of each link and maximize the spatial reusability. In cellular networks, relay nodes are used to increase reliability as well as enlarge the coverage range [9].
Recently, cooperative communication [10, 11] has also been extensively studied, 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 this paper play a different role compared with that in all the above scenarios. Instead of maximizing transmission rate in multihop 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.

Several existing works investigate the spectrum heterogeneity issue in cognitive radio networks. Based on the design of cooperation relay in infrastructure-mode cognitive radio networks in [5, 6], the work in [12] proposes the routing protocols to improve end-to-end performance with a new link cost, which considers several aspects including channel availability, channel condition, channel utilization, and potential relays. A different system model is considered in [13], where there are a cognitive wireless relay network consisting of a source node that intends to communicate with a destination node aided by a number of secondary relay nodes. To exploit the maximum spectrum opportunities, a cognitive space-time-frequency coding technique is proposed that can opportunistically adjust its coding structure by adapting itself to the dynamic spectrum environment.

There are existing works on cooperative communication in cognitive radio networks. While cooperative communication can be applied within secondary users networks, some works propose schemes for the cooperation between primary users and secondary users. In [14], the authors propose a cooperation protocol in which multiple secondary users can use the spectrum from a primary user in exchange for cooperative transmission with the primary link. The cooperation has three phases: in the first phase, the primary transmitter transmits first, while secondary users receive; in the second phase, the secondary users use the space-time coded cooperative transmission to reply the received data to the primary receiver. At last, the secondary users conduct their own transmission. Following such a framework, the payment is also considered in [15] so that the cooperation opportunity is further enlarged. In [16], a two-phase cooperative relaying protocol is proposed for a primary transmission pair and a secondary transmission pair. In the first phase, the primary transmitter transmits its signal to the primary receiver, which is also received by the secondary transmitter and the secondary receiver and decoded. At the secondary receiver, the primary signal is regenerated and linearly combined with the secondary signal with appropriate power allocation. This combined signal is then broadcasted by the secondary transmitter in the second transmission phase. Different from these works, our cooperation scheme is within the secondary user ad hoc network and leverages the spectrum diversity.

3. System Model and Problem Statement

We consider a CRAHN. Primary users are located within the same region and have low spectrum utilization of their own spectrum. Based on spectrum usage policy such as
spectrum leasing, the unused primary spectrum channels can be temporarily used by the secondary network. In this paper, we assume each secondary node has one radio for data transmission and one radio for control messages, both of which are half-duplex. We assume there is a common control channel available for all secondary nodes. Some existing works of cognitive radio networks have the similar system model as ours [17–19].

There are $M$ adjacent channels from primary users $\{1, \ldots, M\}$ with equal bandwidth $W$. There are $N$ secondary transmission pairs $\mathcal{N} = \{1, \ldots, N\}$, which correspond to the set of senders $\mathcal{S}$ and targeted receiver set $\mathcal{T}$. We define the node set $\mathcal{V} = \mathcal{S} \cup \mathcal{T}$, with $|\mathcal{V}| = 2N$.

For a particular location in the area, some channels may be occupied by primary users and thus cannot be used by secondary users. We use $\mathcal{A} = \{a^m_v \mid a^m_v \in \{0, 1\}\}_{2N \times M}$ to denote the channel availability: $a^m_v = 1$ indicates that channel $m$ at node $v \in \mathcal{V}$ is available, and 0 otherwise. It is assumed that the data radio of each node in $\mathcal{V}$ is capable of dynamically accessing any combination of available channels. However, the data radio cannot transmit and receive simultaneously.

Two nodes can form a communication link if and only if both nodes have common available channels and they are within each other communication range. The communication ranges of all nodes in all channels are the same, denoted by $R_C$. Similarly, the interference range is denoted by $R_I$, with $R_I \geq R_C$. Let $\mathcal{E} = \{e_{vu} \mid e_{vu} \in \{0, 1\}\}_{2N \times 2N}$ denote the set of potential communication links, that is, $e_{vu} = 1$ if and only if $\delta(v, u) < R_C$, where $\delta(v, u)$ is the distance between the two nodes. Similarly, let $\mathcal{I} = \{f_{vu} \mid f_{vu} \in \{0, 1\}\}_{2N \times 2N}$ denote the set of interference/conflict relations between any two nodes in the network: $f_{vu} = 1$ if and only if $\delta(v, u) < R_I$. The interference set of node $v$ is denoted by $\mathcal{N}_v = \{u \mid f_{vu} = 1, u \in \mathcal{V}\}$.

If a link uses a channel for transmission, it can achieve a certain data rate determined by the transmission power and channel condition. Since interference-free channel allocation is considered, there is no interference from the other active links. We use $c^m_{vu}$ to denote the achievable data rate from node $v$ to $u$ using channel $k$, which is a constant.

### 3.1. Relay Selection

We use $\mathcal{R}^i = \{r^i_{ij} \mid r^i_{ij} \in \{0, 1\}\}_{N \times N}$ to express the relay selection for the source nodes, where $r^i_{ij} = 1$ means that source node $s_i$ of pair $i$ performs as a relay node for pair $i$. Similarly, we use $\mathcal{R}^j = \{r^j_{ij} \mid r^j_{ij} \in \{0, 1\}\}_{N \times N}$ to express the relay selection for the destination nodes. In this paper, during one cooperative operation we impose the following constraints.

(i) Each transmission pair can use at most one relay node for help:

$$
\sum_{j \in \mathcal{N}, j \neq i} (r^i_{ij} + r^j_{ij}) \leq 1, \quad \forall i \in \mathcal{N}. \quad (1)
$$

(ii) One relay pair can help at most one transmission pair:

$$
\sum_{i \in \mathcal{N}, i \neq j} (r^i_{ij} + r^j_{ij}) \leq 1, \quad \forall j \in \mathcal{N}. \quad (2)
$$

(iii) When one pair is served by another pair, this node cannot be the relay node of another node:

$$
\begin{align*}
&r^i_{ij} + \sum_{k \neq i} (r^i_{ki} + r^i_{kij}) \leq 1, \quad \forall i \in \mathcal{N}, \; j \in \mathcal{N}, \\
&r^j_{ij} + \sum_{k \neq j} (r^j_{kji} + r^j_{kij}) \leq 1, \quad \forall i \in \mathcal{N}, \; j \in \mathcal{N}.
\end{align*} \quad (3)
$$

(iv) When one node is serving another pair, the pair of this node cannot be helped by other nodes:

$$
\begin{align*}
&r^i_{ij} + \sum_{k \neq i} (r^i_{kji} + r^i_{kij}) \leq 1, \quad \forall i \in \mathcal{N}, \; j \in \mathcal{N}, \\
&r^j_{ij} + \sum_{k \neq j} (r^j_{kji} + r^j_{kij}) \leq 1, \quad \forall i \in \mathcal{N}, \; j \in \mathcal{N}.
\end{align*} \quad (4)
$$

According to the above relay constraints (1)–(4), we define a transmission group to be a basic component with a single direction transmission pair or two cooperating pairs. We have the following categories of transmission groups as shown in Figure 2:

(i) Category 1 has a single transmission pair,

(ii) Category 2 has two transmission pairs with one pair relaying for another pair.

### 3.2. Channel Allocation

Besides the relay selection, we need to decide the channel allocation for each transmission link. We use variable $\mathcal{X} = \{x^m_{vu} \mid x^m_{vu} \in \{0, 1\}\}_{2N \times 2N \times M}$ to denote the channel allocation: $x^m_{vu} = 1$ if and only if channel $m$ is allocated to the link between node $v$ and node $u$. Note that we have $x^m_{vu} = x^m_{uv}$. According to the above link definition, we have

$$
\begin{align*}
x^m_{vu} \leq c^m_{vu}, & \quad \forall v \in \mathcal{V}, \; u \in \mathcal{V}. \quad (5)
\end{align*}
$$

The channel allocation should satisfy the channel availability constraint, that is,

$$
x^m_{vu} \leq a^m_v \cdot a^m_u, \quad \forall v \in \mathcal{V}, \; u \in \mathcal{V}, \; m \in \mathcal{M}. \quad (6)
$$

We use conflict-free channel allocation, which requires that all the interference constraints are satisfied, that is,

$$
\begin{align*}
x^m_{vu} + \sum_{w \neq v, w \neq u, w \in \mathcal{N}_v} x^m_{wv} + \sum_{w \neq v, w \neq u, w \in \mathcal{N}_u} x^m_{uw} \leq 1, & \quad \forall v \in \mathcal{V}, \; u \in \mathcal{V}, \; m \in \mathcal{M}.
\end{align*} \quad (7)
$$

### 3.3. Data Rate for Each Transmission Pair

We calculate the throughput of pair $i$ under a certain strategy of relay selection $\mathcal{R}$ and channel allocation $\mathcal{X}$. According to whether $i$ helps other pairs or is helped by others, the calculation is divided into the following cases.

**Case 1.** If pair $i$ communicates without the other nodes help and is not acting as relay itself, which satisfies

$$
\begin{align*}
r^i_{ij} = 0, \quad r^i_{ji} = 0, \quad r^j_{ij} = 0, \quad r^j_{ji} = 0, & \quad \forall j \in \mathcal{N}, \quad (8)
\end{align*}
$$

...
its data rate can be expressed as
\[
\theta^1_i = \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m.
\]

Case 2. If pair \(i\) is helped by the source node of pair \(j\), that is,
\[
r^i_{ij} = 1,
\]
then the data rate of pair \(i\) is
\[
\theta^2_i = \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m + \min \left( \frac{1}{2} \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m, \frac{1}{2} \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m \right).
\]

Case 3. If pair \(i\) is helped with the help of the destination node of pair \(j\), that is,
\[
r^i_{ij} = 1,
\]
and then the data rate of pair \(i\) is
\[
\theta^3_i = \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m + \min \left( \frac{1}{2} \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m, \frac{1}{2} \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m \right).
\]

Case 4. If the source node \(s_j\) of pair \(i\) acts as a relay for pair \(j\), but the destination node \(s_i\) does not help, that is
\[
r^i_{ji} = 1, \quad r^i_{ij} = 0,
\]
the data rate of pair \(i\) is then
\[
\theta^4_i = \frac{1}{2} \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m.
\]

Case 5. Similar to Case 4, here the destination node \(s_i\) acts as relay, but the source node \(s_j\) does not, that is,
\[
r^i_{ji} = 0, \quad r^i_{ij} = 1,
\]
the data rate of pair \(i\) is then
\[
\theta^5_i = \frac{1}{2} \sum_{m \in M} c_{x_{t_i}t_j}^m x_{s_i}^m x_{t_i}^m.
\]

We can use a single equation to denote each pair’s data rate based on (9)–(17):
\[
\Theta_i = \left(1 - \sum_{j \in N} r^i_{ij}\right) \left(1 - \sum_{j \in N} r^j_{ij}\right) \left(1 - \sum_{j \in N} r^j_{ij}\right) \frac{\theta_i}{\rho_i} + \sum_{j \in N} r^i_{ij} \theta_i^j + \sum_{j \in N} r^j_{ij} \theta_i^j + \sum_{j \in N} (1 - r^i_{ij}) r^j_{ij} \theta_i^j.
\]

3.4. Optimization Problem. We consider that the channel availability is fixed for a relatively long term. The network utility is defined as \(U(\Theta)\), where \(\Theta = \{\Theta_i\}_{i \in N}\). Under such a quasistatic model, we want to maximize the network utility by optimizing over relay selection, channel allocation, and time partition, subject to the above constraints:
\[
\max_{R, X} U(\Theta).
\]

In this paper, we consider two typical formats of utility functions:

(i) Max-Sum: it maximizes the total utility of the network with
\[
U_{\text{sum}}(\Theta) = \sum_{i \in N} \Theta_i.
\]

(ii) Max-Fair: it maximizes the proportional fairness of the network with
\[
U_{\text{fair}}(\Theta) = \sum_{i \in N} \log(\Theta_i).
\]

**Theorem 1.** The optimization problem in (19) is NP-hard.

**Proof.** To prove this, we can check special cases where there is one single channel and there exist, only interference among pairs, but no communication links among pairs. Then, the problem is a weighted independent set problem, which is an NP-hard problem.

4. Resource Allocation Algorithms

In this section, we propose a heuristic algorithm to solve the problem suboptimally. The algorithm iterates with multiple times. During each iteration, a transmission group is chosen for resource allocation. We first describe the overall algorithm. Then, we present the proposed metric for transmission group selection.
4.1. The Overall Algorithm. For the overall algorithm, we maintain a list of all possible transmission groups belonging to different categories, denoted as $G$. During a single iteration, we select the transmission group $g$ with certain metric and allocate the channels accordingly. Such a selection metric will be presented in detail in the following part. After that, the group list $G$ is updated: transmission groups whose nodes overlap with the selected group $g$ will be deleted from the list. The channel availability matrix and group matrix are also updated.

4.2. Selection Metric of Transmission Group. To effectively utilize the spectrum resource, when we choose which transmission group to allocate in one iteration, we should consider both the achievable utility of a transmission group and the consumed spectrum resource.

We denote the selection metric of transmission group as $\mu_g$, which is the utility-spectrum ratio of a transmission group for a particular channel allocation for this transmission group $X_g$. $X_g$ is a maximal channel allocation without violating the constraints, which will be described later. Specifically, given $X_g$, we denote the utility of a transmission group by $U_g(X_g)$, which can be calculated with (20) or (21). We denote the spectrum consumption of a transmission group by $h_g(X_g)$, which is the number of occupied/interfered channels of the transmission group. Then, we have

$$\mu_g = \frac{U_g(X_g)}{h_g(X_g)}. \quad (22)$$

This is similar to the labelling rules suggested in [20, 21]. The difference is that we assess and allocate multiple channels for a node at once.

Depending on the category of a transmission group $g$, we determine the value of $X_g$ and calculate $\mu_g$ as follows (Algorithm 1).

4.2.1. Category 1. Suppose the single pair is $i$ for the transmission group $g$. For each channel, we check whether it is available at both source node $s_i$ and destination node $t_i$ in group $g$ and allocate it if it is the case, that is,

$$x_{m,t}^m = a_{m,t}^m, \quad \forall m \in M. \quad (23)$$

The contributed utility of this group can be easily calculated with (20) or (21):

$$U_g = \theta_1^1, \quad (24)$$

or

$$U_g = \log \theta_1^1. \quad (25)$$

The spectrum consumption is

$$h_g = \sum_{m \in M} \left( x_{m,t}^m \sum_{v \in N_i \cup N_i} 1 \right). \quad (26)$$

Algorithm 1: Transmission group selection metric calculation algorithm.

4.2.2. Category 2. It depends on whether the source node or destination node of pair $j$ is used for cooperation. In each case, one channel can be used for at most one active link among nodes $s_j$, $t_j$, $s_j$, and $t_j$ due to the constraint. Although there are only four links for the transmission group, the number of all possible channel allocations is with the order of $4^M$.

To reduce the computational complexity, we propose a heuristic approach to calculate the utility of the transmission group. The idea is that there is positive contribution via relay links for the transmission group if and only if both of the relay links (e.g., $s_i$-$v_j$ and $v_j$-$t_j$) are allocated with channels. Therefore, we assign pairs of channels to relay links first when calculating the utility. Totally, there are at most $M \times (M - 1)$ pairs of channels.

Specifically, we define the contributed data rate of a channel pair $(m, n)$ with $m \neq n$ as $\Delta_{(m,n)}$, which is the data
rate increase with channel \( m \) and \( n \) allocated for the two relay links, that is,
\[
\Delta'_{(m,n)} = \min\left(r_1 + \frac{1}{2} c^m_{\phi} r_2 + \frac{1}{2} c^m_{\psi}, r_1, r_2\right),
\]
where \( r_1 \) and \( r_2 \) are the data rate of link \( s_r-v_j \) and \( v_j-t_i \), respectively. For each time, we find the channel pair with the maximum \( \Delta'_{(m,n)} \) for the transmission group.

We also examine the contributed data rate when channel \( m \) and \( n \) are allocated to the two direct links. We have 4 combinations: channel \( m \) and \( n \) assigned to a direct link; channel \( m \) and \( n \) assigned to different links. We denote the maximum contributed data rate of these four possible allocations as \( \Delta^d_{(m,n)} \).

If \( \Delta'_{(m,n)} \) is larger than \( \Delta^d_{(m,n)} \), we allocate two channels to the two relay links. Otherwise, channel-pair-based allocation terminates. If there are any remaining channels unallocated, we continue to allocate them just as Category 1.

For each channel allocation, if the source node is the relay node, we have
\[
U_g = \theta^1 + \theta^4,
\]
or
\[
U_g = \log \theta^1 + \log \theta^4.
\]
If the destination node is the relay node, we have
\[
U_g = \theta^1 + \theta^5,
\]
or
\[
U_g = \log \theta^1 + \log \theta^5.
\]

Denote the nodes for the active link for channel \( m \) as \( v_m \) and \( u_m \). The spectrum consumption is
\[
h_g = \sum_{m \in M} \left( c^m_{\nu} u_m \sum_{\nu \in N_{v_m} \cap N_{u_m}} 1 \right).
\]

For the complexity of the metric calculation algorithm (Algorithm 1), obviously the calculation of Category 1 is dominated by the calculation of Category 2. For Category 2, the complexity is with the order of \( O(M^2(M^2+N)) \), which is the complexity for the whole metric calculation algorithm.

5. Simulation

In this section, we use simulations to evaluate the performance of the proposed algorithm. We conduct the simulations in a static CRAHN. The simulation area is \( 1 \times 1 \) with uniformly separated primary users in fixed locations. Each primary user occupies a single channel randomly picked from the channel set. Secondary users pairs are randomly placed in the same area. We compare our proposed cooperative transmission and resource allocation scheme with two other schemes. One scheme uses the same cooperative transmission with relaying, while the metric for transmission group selection during resource allocation depends solely on the achieved utilities of transmission groups. The other scheme uses the direct transmission without relaying and applies similar resource allocation as our scheme. We investigate the performance of the CRAHN in terms of the number of primary users, the number of secondary users, the number of channels, and the communication range of secondary users.

5.1. The Number of Primary Users. We first show the performance with different numbers of primary users. When we increase the number of primary users, the protected area expands, which reduces the number of available channels experienced by secondary users. In Figure 3, the utilities for both Max-Sum and Max-Fair decrease with increasing the number of primary users. The cooperative scheme with the metric of utility-spectrum ratio outperforms the other two schemes since our scheme allows secondary pairs to utilize more transmission links via potential relay nodes from neighbouring nodes on more channels while our resource allocation algorithm selects transmission groups and their channel allocation more efficiently. Moreover, the gaps between the two cooperative schemes and the direct scheme increase as the number of primary users increases. This is because with more active primary users the degree of spectrum heterogeneity seen from secondary users increases.

5.2. The Number of Secondary Users. We check the performance with different numbers of secondary users next. Increasing the number of secondary users leads to the increased total system utility, as shown in Figure 4. Besides, the performance gaps between the two cooperative schemes and the direct scheme increase as the number of secondary users increases, which demonstrates the advantage of our scheme. Note that the curves are sublinear since more secondary users means more interference created among them.

5.3. The Number of Channels. Here we examine the effect of the number of channels used in the system. Figure 5 shows that both types of utilities increase while increasing the number of channels. The cooperative scheme with the metric of utility-spectrum ratio outperforms the other two schemes, while the direct scheme performs the worst.

5.4. The Communication Range of Secondary Users. We also study the impact of the communication range of secondary users. On one hand, given a fixed topology, enlarging the communication range of secondary users increases the number of potential communication links among them, which creates more cooperation opportunities. On the other hand, the increased range also creates more interference among the secondary users, which will decrease the spatial reuse of the spectrum resource. According to the result in Figure 6, the system utilities degrade with the increased communication range. Therefore, the latter effect dominates the first one.
6. Conclusions

In CRAHNs, spectrum heterogeneity is quite a special issue that makes the resource allocation more challenging compared with the traditional wireless ad hoc networks. It is possible to use cooperative relay node utilizing spectrum holes to assist individual secondary transmission and improve link throughput. Based on this idea, we study a new resource allocation problem with relay selection and channel allocation in CRAHNs when applying the cooperative relay scheme. We propose algorithms to effectively solve the problem based on a metric of utility-spectrum ratio. We conduct simulations to evaluate the performance and conduct comparison with direct transmission scheme. The simulation results demonstrate the reasonable performance improvements of our scheme. In the future, we will further investigate the distributed algorithms for the relay selection and channel allocation in CRAHNs with cooperative relaying.
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