CHANNEL ALLOCATION FOR COOPERATIVE RELAYS IN COGNITIVE RADIO NETWORKS

Guodong Zhao[†], *Chenyang Yang*[†], *Geoffrey Ye Li*[‡], *Dongdong Li*[♭], *and Anthony Soong*[♭]

[†]School of EIE, Beihang University, Beijing, China
[‡]School of ECE, Georgia Institute of Technology, Atlanta, GA, USA
[♭]Wireless Advanced Research, Huawei Technologies, Plano, TX, USA

ABSTRACT

In this paper, we investigate channel allocation for cooperative relays in cognitive radio networks. Different from conventional cooperative relay channels, cognitive radio relay channels are actually a combination of three kinds of channels: direct, dual-hop, and relay channels, which belong to different spectrum bands and provide parallel end-to-end transmission. In order to maximize the achievable end-to-end throughput, we propose two channel allocation approaches with different complexities to assign all the channels cooperatively. Numerical results illustrate the performance improvement in different number of available channels. In particular, it has about 40% improvement in throughput when the average SNR is 15 dB and eight available channels are used.

Index Terms— Cognitive radio, cooperative relays, channel allocation, spectrum sharing.

1. INTRODUCTION

Cognitive radio (CR) is a smart wireless communication system that is capable of sensing and adapting to environment. It can adjust its transmission parameters, such as spectrum bands, transmission power, coding and modulation strategies, to opportunistically access available spectrum bands efficiently without interfering with *primary users* (PU's) [1]. Recent studies on CR [1] have shown that the available spectrum bands may vary with different CR users. Obviously, CR communication can only be established through common available bands between a pair of CR users. If there are no available bands in common, outage will happen. To achieve reliable secondary communications, CR users have to sense multiple spectrum bands simultaneously. However, two CR users may have no common available bands even when both have many available ones.

In order to solve the problem, cooperative relays have been considered [2]. With the assistance of relay nodes with rich available spectrum bands, some of non-common spectrum bands between two CR users can be bridged to exploit more spectrum opportunities. Recently, cooperative relays have been introduced into CR networks from various perspectives. In [3], a cognitive space-time-frequency coding technique is proposed to maximize spectrum opportunities. In [4], relays are used for balancing the traffic requests and available spectrum resources. In [5][6], *signal-to-interference-plus-noise ratio* (SINR) is enhanced by relays through spatial diversity. In [7], directional transmission of relays is used for exploiting spatial spectrum holes.

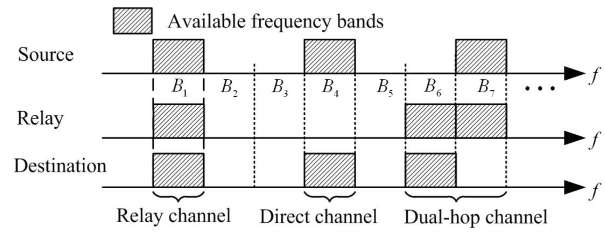

Fig. 1. CRRC in CR networks.

In this paper, we investigate cooperative relays with multiple channels[1] in a three-terminal CR network, which consists of a source, a relay, and a destination. In the context, the *CR relay channel* (CRRC) is a combination of three kinds of channels: direct, dual-hop, and relay channels as shown in Fig.1. If a channel is available at all three CR nodes, it is called a *relay channel* since it can provide end-to-end communication using a cooperative relay protocol [8]. If a channel is available at both the source and the destination but not at the relay, it is called a *direct channel* since it can provide end-to-end communication directly. If one channel is available at the source and the relay, and another channel is available at the relay and the destination, it is called a *dual-hop channel* since it can provide end-to-end communication via the relay node without the direct transmission. Furthermore, a channel could belong to any kind of the above channels depending on how it is used. So far, the combination channel in CR, i.e., CRRC, has not been discussed and it will bring new degrees of freedom and new challenges for designing cooperative relays in CR networks. In the rest of this paper, we will propose two channel allocation algorithms with different complexities to exploit the three kinds of channels cooperatively. Specifically, since the relay channel enables the communications among all three CR nodes, it can be used for direct, dual-hop, or relay transmission. Thus the achievable end-to-end throughput can be improved by adjusting the usage of relay channels in CRRC. They are different from existing works in [3]-[6], where only direct and dual-hop channels are considered. They are also different from conventional cooperative relays in [8]-[10], where neither direct nor dual-hop channels are considered.

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[†]Corresponding author email: zhaoguodong@ee.buaa.edu.cn.

[1]Here, we assume that each channel occupies a frequency band and has no interference with each other.

2. WIRELESS CHANNELS IN CR COOPERATIVE RELAYS

In this section, we investigate the CRRC and then analyze the achievable throughput without channel allocation as a baseline for comparison with the proposed approaches in the next section.

2.1. CR Relay Channel

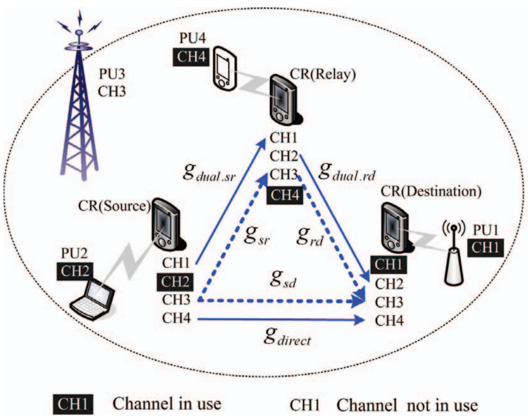

Fig. 2. System setup of cooperative relays in CR networks.

Figure 2 shows an example of cooperative relays in a three-terminal CR network. In the figure, the source intends to send data to the destination, and a relay node is to assist the transmission from the source to the destination. Assume that a common control channel is able to organize all CR nodes to perform cooperative transmission in CRRC. We further assume that all three CR nodes are equipped with omni-directional antennas and can simultaneously sense four typical licensed channels[2], CHi for $i = 1, \ldots, 4$. Each of them belongs to a PU exclusively. In particular, PU3 may be a base station or a TV tower with large coverage and uses CH3. All three CR nodes are assumed to obtain the same sensing result on CH3. If PU3 does not work, CH3 is a relay channel since it can provide cooperative relay communication, that is, the source broadcasts its data to both the relay and the destination in a time slot while the relay forwards the data to the destination in another one, and the source is silent when the relay transmits signals. Three links are involved in CH3, called SR, RD, and SD links, with channel gains g_{sr}, g_{rd}, and g_{sd}, respectively, as shown in Fig.2. By contrast, the rest of the channels, CH1, CH2, and CH4, are occupied by short range primary users, PU1, PU2, and PU4, respectively. Nevertheless, they can still be used by the CR system since those PU's only determine the sensing results of their nearby CR nodes. Here, CH1 and CH2 are dual-hop channels. Specifically, CH1 in Fig.2 is available at the source and the relay while CH2 is available at the relay and the destination. Then the data can be sent to the relay through the SR link in CH1 with channel gain $g_{dual.sr}$ and be forwarded to the destination through the RD link in CH2 with channel gain $g_{daul.rd}$. CH4 is a direct channel since it is available at both the source and the destination but not at the relay, then it can provide direct transmission through the SD link in CH4 with channel gain g_{direct}. Therefore, the CRRC is a combination of CHi for $i = 1, \ldots, 4$ with the three kinds of channels.

[2]Ideal spectrum sensing is considered here; therefore, no false alarm and missed detection events happen. The impact of the sensing errors is out of the scope of this paper.

When there are N available channels[3], where $N > 4$, any of them can be regarded as one of the above four typical channels, CHi for $i = 1, \ldots, 4$. This is a general CRRC and consists of N_{srd} relay channels, N_{sd} direct channels, N_{sr} and N_{rd} dual-hop channels from the source to the relay and from the relay to the destination, respectively, where $0 \leq N_k \leq N$ for $k \in \{srd, sd, sr, rd\}$ and $N = N_{sd} + N_{sr} + N_{rd} + N_{srd}$.

2.2. Achievable Throughput without Channel Allocation

In multi-channel CR communications, both power and channel allocation improve the achievable throughput. Since we only focus on channel allocation in CRRC, we omit power allocation and consider the transmit power of the source and the relay, denoted as P_s, is the same for each channel and satisfies the interference constraint on PU's. Moreover, we assume that the three CR nodes are with equal distance and the average *signal-to-noise-ratios* (SNR's) are identical[4], which is denoted as $\gamma = \frac{P_s}{P_n}$, where P_n is the noise power at the relay and the destination.

As indicated before, the achievable end-to-end throughput in CRRC is contributed by direct, dual-hop, and relay channels, which depends on the quality and quantity of each kind of channels. The achievable throughput of the direct channels can be expressed as

$$\mathbb{C}_{direct} = \sum_{l=0}^{N_{sd}} C(g_{direct}^{(l)}), \tag{1}$$

where $C(g) = B \log(1 + g\gamma)$ is the Shannon capacity and B is the bandwidth of each channel[5].

For the dual-hop channels, the data from the source is sent to the relay through N_{sr} channels. At the same time, the relay uses other N_{rd} channels to forward the data to the destination. Their throughputs can be expressed as

$$\mathbb{C}_{sr} = \sum_{l=0}^{N_{sr}} C(g_{dual.sr}^{(l)}) \quad \text{and} \quad \mathbb{C}_{rd} = \sum_{l=0}^{N_{rd}} C(g_{dual.rd}^{(l)}), \tag{2}$$

respectively. Then the achievable throughput of the dual-hop channels can be obtained by

$$\mathbb{C}_{\text{dual}} = \min\left\{\mathbb{C}_{sr}, \mathbb{C}_{rd}\right\}. \tag{3}$$

The *decode-and-forward* (DF) protocol [8] with half duplex will be used for relay channels in our discussion. The relay node decodes the data from the source, and then encodes and sends them to the destination. From [10], if the relay node decodes the data over all N_{srd} relay channels and encodes them together to forward, a high throughput can be achieved, which can be expressed as

$$\mathbb{C}_{relay} = \frac{1}{2} \min\left\{ \sum_{l=0}^{N_{srd}} C(g_{sr}^{(l)}), \sum_{l=0}^{N_{srd}} C(g_{sd}^{(l)}) + \sum_{l=0}^{N_{srd}} C(g_{rd}^{(l)}) \right\}. \tag{4}$$

Finally, the overall achievable end-to-end throughput will be

$$\mathbb{C} = \mathbb{C}_{direct} + \mathbb{C}_{dual} + \mathbb{C}_{relay}. \tag{5}$$

[3]They are the channels that are idle at least two CR nodes.

[4]The extension to the scenario with different distances among CR nodes is straightforward. Here, we omit it for simplicity.

[5]Even though we assume the bandwidth of each channel is the same, the developed methods can be directly applied in multiple channels with different bandwidths.

3. CHANNEL ALLOCATION IN CR NETWORKS

In this section, we will first introduce the principle of channel allocation in CRRC and then develop two methods with different complexities.

3.1. Principle

As shown in (5), the achievable end-to-end throughput can be improved by using a relay node for dual-hop and relay transmission. The dual-hop transmission exploits non-common channels while the relay transmission enhances the existing source-to-destination transmission by spatial diversity. However, the dual-hop transmission usually has a bottleneck in throughput since the two hops are connected serially at a relay node while the relay transmission can only be implemented in a half-duplex manner since the relay can not receive and transmit signals simultaneously at the same channel. In order to maximize the overall end-to-end throughput of CRRC, different kinds of channels should be used cooperatively. In particular, the relay channels in CRRC may be used for direct, dual-hop, or relay transmission, i.e., for the lth relay channel, where $l = 1, \ldots, N_{srd}$, it can be used in one of the following four modes:

1) Enhance direct transmission from the source to the destination by only using the SD link.
2) Enhance dual-hop transmission from the source to the relay by only using the SR link.
3) Enhance dual-hop transmission from the relay to the destination by only using the RD link.
4) Provide cooperative relay transmission by using all three links.

Since the transmission mode of each relay channel will affect the overall end-to-end throughput in CRRC, we will design channel allocation methods to maximize the throughput by assigning each relay channel for a proper transmission mode.

3.2. Optimal Method

When some relay channels are used for direct transmission, the achievable throughput of the direct channels can be enhanced, i.e.,

$$\mathbb{C}_{direct(SD)} = \mathbb{C}_{direct} + \sum_{l\in\Gamma_{sd}} C(g_{sd}^{(l)}), \tag{6}$$

where Γ_{sd} is a set including the relay channels assigned for direct transmission, and the second term indicates the extra throughput provided by the selected relay channels.

Similarly, when some relay channels are used for assisting dual-hop transmission, the extra throughputs from the source to the relay and from the relay to the destination can be expressed as

$$\mathbb{C}'_{sr} = \sum_{l\in\Gamma_{sr}} C(g_{sr}^{(l)}) \quad \text{and} \quad \mathbb{C}'_{rd} = \sum_{l\in\Gamma_{rd}} C(g_{rd}^{(l)}), \tag{7}$$

where Γ_{sr} and Γ_{rd} are the sets including the relay channels assigned for enhancing the first and the second hops in dual-hop transmission, respectively. Then the overall achievable throughput of dual-hop transmission can be obtained by

$$\mathbb{C}_{dual(\Gamma_{sr},\Gamma_{rd})} = \min\left\{\mathbb{C}_{sr} + \mathbb{C}'_{sr}, \mathbb{C}_{rd} + \mathbb{C}'_{rd}\right\}. \tag{8}$$

It shows that the smaller throughput of the dual-hop channels, i.e., $\min\{\mathbb{C}_{sr}, \mathbb{C}_{rd}\}$, which originally is a bottleneck, can be compensated by $\mathbb{C}'_{sr}$ or $\mathbb{C}'_{rd}$.

For the rest of the relay channels, which are used for relay transmission and belong to a set Γ_{srd}, the achievable throughput will be

$$\mathbb{C}_{relay(\Gamma_{srd})} = \frac{1}{2}\min\{\sum_{l\in\Gamma_{srd}} C(g_{sr}^{(l)}), \sum_{l\in\Gamma_{srd}} C(g_{sd}^{(l)}) + \sum_{l\in\Gamma_{srd}} C(g_{rd}^{(l)})\}. \tag{9}$$

Then the overall end-to-end throughput can be expressed as

$$\mathbb{C}_{(\Gamma_{sd},\Gamma_{sr},\Gamma_{rd},\Gamma_{srd})} = \mathbb{C}_{direct(\Gamma_{sd})} + \mathbb{C}_{dual(\Gamma_{sr},\Gamma_{rd})} + \mathbb{C}_{relay(\Gamma_{srd})}. \tag{10}$$

Our goal is to maximize the end-to-end throughput by adjusting the allocation of relay channels in CRRC. Since each of them can be used in one of the four possible transmission modes, there will be $4^{N_{srd}}$ different combinations of channel allocations for N_{srd} relay channels. Then the optimal channel allocation of maximizing the achievable end-to-end throughput can be obtained by comparing all combinations with exhaustive computer search. As the number of relay channels in CRRC increases, the complexity of the optimal channel allocation grows exponentially, i.e., $O(4^{N_{srd}})$. In the following subsection, we will propose a suboptimal approach with low complexity .

3.3. Suboptimal Method

Based on our simulation results in the next section, we find that the relay transmission mode in relay channels can be omitted with only minor performance loss. Then the channel allocation is to assign N_{srd} relay channels in CRRC for either direct or dual-hop transmission. Consequently, the searching complexity can be reduced from $4^{N_{srd}}$ to $3^{N_{srd}}$.

In particular, if the SD link in a relay channel is the best one among all three links, such a relay channel should be assigned for direct transmission. Therefore, channel allocation for direct transmission can be obtained by picking the relay channels with the best SD links. The rest of the relay channels will be used for dual-hop transmission, i.e., some of them are used for source-to-relay transmission and others for relay-to-destination transmission. In order to maximize the overall achievable end-to-end throughput, we need to maximize the minimum throughput in dual-hop transmission, i.e.,

$$\max\{\mathbb{C}_{dual(\Gamma_{sr},\Gamma_{rd})}\} = \max\{\min\{\mathbb{C}_{sr} + \mathbb{C}'_{sr}, \mathbb{C}_{rd} + \mathbb{C}'_{rd}\}\}. \tag{11}$$

It can be implemented by selecting relay channels with the strongest available link to compensate for the bottleneck link of dual-hop transmission and the complexity increases linearly as N_{srd} grows, i.e., $O(N_{srd})$. In brief, the suboptimal method can be realized as follows,

1) For the lth relay channel, if $g_{sd}^{(l)} > g_{sr}^{(l)}$ and $g_{sd}^{(l)} > g_{rd}^{(l)}$, it belongs to Set Γ_{sd}.
2) Repeat 1) for N_{srd} relay channels and obtain Set Γ_{sd} for direct transmission.
3) Calculate $C_\Delta = (\mathbb{C}_{sr} + \mathbb{C}'_{sr}) - (\mathbb{C}_{rd} + \mathbb{C}'_{rd})$ in the rest of relay channels.
4) If $C_\Delta \geq 0$, assign the relay channel with the best RD link to Set Γ_{rd}, otherwise, assign the relay channel with the best SR link to Set Γ_{sr}.
5) Repeat 3) and 4) to obtain Sets Γ_{sr} and Γ_{rd}.

4. NUMERICAL RESULTS

In this section, we will present numerical results to show the performance of the proposed methods. Assume that three CR nodes are with equal distance, which leads to the same path-loss among them. Rayleigh fading is also considered in our simulation. We further assume that channel usage states at different CR nodes are independent and with equal probability of busy and idle. Then each kind of channels in Fig.1 may appear with equal probability. The bandwidth of each available channel is regarded as 1 MHz and all curves are averaged on 3000 monte carlo trails.

4.1. Optimal Channel Allocation

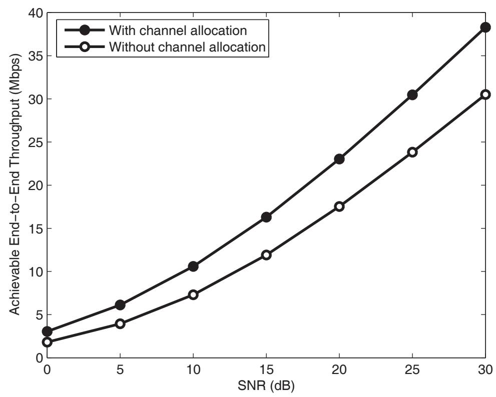

Fig. 3. Performance of the optimal channel allocation.

Figure 3 compares the achievable end-to-end throughput versus SNR for the optimal channel allocation method and that of the method without channel allocation in Section 2.2. Here, eight available channels are considered, i.e., $N = 8$. From the figure, the achievable throughput of our optimal method has about $3{\sim}5$ Mbps improvement over the method without channel allocation. In particular, when SNR$=15$ dB, the proposed method increases the throughput from 12 Mbps to 17 Mbps, i.e., about 40% improvement.

4.2. Suboptimal Channel Allocation

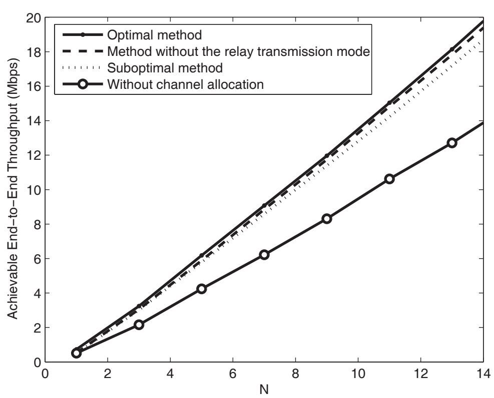

Fig. 4. Performance of the suboptimal channel allocation.

Figure 4 shows the performance of the suboptimal method with different number of available channels and compares with the methods with optimal channel allocation and without channel allocation. From the figure, when SNR $= 10$ dB, the throughput increases as the number of available channels goes up. The performance of the channel allocation without the relay transmission mode is almost the same as that of the optimal method, this indicates that the relay transmission mode can be omitted with only minor performance loss. The proposed suboptimal method obtains most of performance gains with low complexity. In particular, it only decreases the throughput from 10.5 MHz to 10 Mbps when 8 available channels are used.

5. CONCLUSIONS

In this paper, we have studied channel allocation methods for cooperative relays in a three-terminal CR network, where the CR relay channel consists of three kinds of channels, direct, dual-hop, and relay channels. We propose an optimal channel allocation method to improve the achievable end-to-end throughput. Based on the simulation, most of the benefits from channel allocation can be achieved by using relay channels to enhance direct and dual-hop transmission. We then propose a suboptimal method by omitting the relay transmission mode with only minor loss in performance, which reduces the complexity from exponential to linear increasing with the number of relay channels.

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