Distributed Robust Channel Assignment for Multi-Radio Cognitive Radio Networks

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***Abstract*—Cognitive radio users are allowed to utilize unused portions of the licensed spectrum, which leads to performance enhancement. However, they need to carefully inspect the environment and make intelligent decisions. Secondary Users (SUs) are required to vacate the channel when a Primary User (PU) appears on the same licensed channel. This may cause interruptions in the secondary network transmissions. In this paper we propose a distributed channel assignment scheme for cognitive radio networks. We consider a multi-radio node architecture in order to better utilize multiple available channels. Our RIMCA (Robust Interference Minimizing Channel Assignment) scheme includes a collaborative sensing mechanism as well as the channel assignment algorithm. We also consider channel reclaim by a primary user. When making decisions, secondary users consider the interference imposed on primary users as well as the total interference in the secondary network. Simulation results show that our RIMCA outperforms the most related channel assignment scheme. Moreover, our channel assignment scheme is robust to PU activities.**

***Index Terms*—Cognitive radio, channel assignment, multi-radio, multi-channel, cooperative sensing, channel reclaim**

I. Introduction

Based on the study in [5], a large portion of the wireless spectrum is underutilized, while other parts are heavily used. As an example, the GSM band for cellular systems and the ISM band for WiFi, Bluetooth and microwaves are heavily used, whereas some licensed bands (e.g., amateur radios) are underutilized at certain times and locations. Unlicensed or Secondary Users (SUs) were not allowed to use the licensed spectrum until 2008, when FCC permitted them to utilize the white spaces in the licensed television spectrum [6]. Since then, unlicensed users have been able to utilize the unused parts of the licensed spectrum, as long as they do not impose harmful interference on licensed or Primary Users (PUs).

Although SUs are allowed to use the spectrum not occupied by PUs, they are required to vacate the channel as soon as a PU appears. Upon a PU arrival, the corresponding SUs have to choose another channel to resume the ongoing communication. Choosing a new channel involves environment sensing, finding available channels, decision making and switching to a new channel. This process takes a significant amount of time, during which the secondary communication is disconnected.

In this paper, in order to minimize the disconnection time, we propose a distributed channel assignment scheme which is robust to PU activities. Since the frequency spectrum consists of multiple channels, we assume nodes are equipped with multiple cognitive radios to efficiently use the available channels. Adopting the node architecture proposed in [3] makes the channel assignment task simpler and more efficient. The idea is to have both fixed and switchable radios. Radios tuned to fixed channels are used for reception, while radios with switchable channels are for transmission. In our RIMCA (Robust Interference Minimizing Channel Assignment) scheme, we assume each node is equipped with a single receiving radio, two sending radios and one control radio. Each SU is then simply responsible for assigning a channel to its only one receiving radio. On the other hand, the transmitter's sending radio is tuned to the receiving channel of the destination node. At all times, each node maintains a list of channels sorted by the channel quality. As soon as a licensed channel is reclaimed, the node chooses the next highest quality channel from the list, so the transmission will continue on the new channel without the need of repeating channel sensing and assignment. Simulation results show that our proposed channel assignment scheme achieves lower network interference and less disconnection time when compared with the existing work.

The rest of the paper is organized as follows. In Section II we discuss the related work. The robust channel assignment problem is defined in Section III. In Section IV we propose the node architecture and a distributed channel assignment algorithm. Performance evaluation is given in Section V. The paper is concluded in Section VI.

II. Related Work

Since our work tackles both environment sensing and channel assignment, we briefly review the existing work in these two domains. Sensing can be done cooperatively or non-cooperatively. Each user can sense the environment individually (single-user detection) [12] or the users can cooperate in sensing (cooperative sensing) [11], [13]. Cooperative sensing is more efficient since it reduces the probability of misdetection and false alarms. Cooperative sensing can be done via a central unit [15], or in a distributed manner [14].

Channel assignment can either be centralized or distributed. For traditional wireless mesh networks without cognitive ability, [7], [8], and [10] proposed centralized channel assignment methods, while [9] discussed a distributed one. In cognitive radio networks, similar to traditional networks, channel assignment is either centralized [16], [17], or distributed [18], [19]. In this work, we present a cooperative and distributed sensing mechanism as well as a distributed channel assignment for cognitive radio networks. Moreover, our proposed scheme is robust to channel reclaim by primary users. Therefore if a licensed channel is reclaimed, secondary users can continue their data transfer on a new channel without excessive delay.

III. Problem Statement

In this section, we introduce our node architecture by adopting the idea from [3]. We also discuss the channel assignment problem in a secondary network.

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A. Node Architecture

We have adopted the multi-radio multi-channel architecture for network nodes, which has been widely used for the wireless mesh networks in recent years. For cognitive radio networks, because of the hardware limitations and cost, usually the single-radio multi-channel architecture has been assumed. However, [21] implemented a multi-radio cognitive radio network at UCLA which validates the assumption of nodes equipped with multiple cognitive radios. In our multi-radio architecture, each radio is capable of sensing the environment, collecting information about different channel status, analyzing the information and deciding the channel to be used for the following transmissions [1].

We assume each node is equipped with four radios: one for receiving, one for control purposes, and the remaining two for transmitting. There exists related work assuming that all radios are used for sending, receiving and sensing.

With a radio assigned to receiving, each node simply has to assign a channel to its only one receiving radio. Nodes transferring data to this node need to switch to the destination's receiving channel to establish a connection. Having only one radio per node for receiving can limit the maximum achievable capacity if a large number of sending radios are available at neighboring nodes. However, with two radios for transmitting, having only one radio for receiving is a reasonable assumption.

In this work we assume the control channel either exists globally for all nodes within the network, using an unlicensed channel, or is locally available by using a licensed channel. In the latter case, PUs may reclaim the control channel. There exist some schemes to ensure that the control channel is always at least locally available [2].

B. Channel Assignment Problem

As stated in the previous section, each node has a control radio for exchanging control messages with other nodes, which is assumed to exist in the network. The only radio that needs to be assigned a channel is the receiving radio of each node. To be more practical, we propose a distributed channel assignment strategy. Nodes make decisions based on the local information they obtain from either sensing the environment or their neighboring nodes. The only extra information nodes require is the location of PUs and SUs. Having this information allows SUs to calculate the interference value at PUs and other SUs.

Each SU has to periodically update its information in order to learn about the recent channels status. In terms of interference, each node has to first, ensure that the interference on all primary channels at primary node locations is below a tolerable threshold; second, the total interference in the secondary network is minimum. As a result, our method is an interference-minimizing channel assignment scheme. We give the detailed information on our channel assignment scheme in Section IV.

The interference model we use in this paper is not binary (i.e., two links either interfere or do not), but we consider interference as a value which depends on the distance between two nodes as well as the transmission power. Also, interference from different sources is accumulated at the receiver. The signal attenuates with distance, so if the source and the point where the interference is measured are spatially close, the interference would be large.

The total interference at a PU from different SUs on the same channel can be defined as:

$$P_I(j) = K \sum_{i=1}^{N_{SU}} P_{tx}^{SU} (\frac{d_0}{d_{ij}})^{\delta} \qquad \forall j \tag{1}$$

where K is an antenna related constant, P_{tx}^{SU} is the transmission power of SU, d_0 is the reference distance, d_{ij} is the distance between PU_j and SU_i, and δ is the path loss exponent.

Since PUs have the exclusive right for using the licensed channels, in case a channel currently used by SUs is reclaimed by a PU, the corresponding SUs have to vacate the spectrum to provide an interference-free channel to the primary node. Moreover, in order to be able to continue their transmission, the SUs need to pick another channel to replace the channel just being occupied by PUs. To solve this problem, in the following section, we propose a channel assignment scheme for multi-radio cognitive radio networks, which is robust to PU activities, i.e., our scheme is robust even when a channel is reclaimed by a primary node.

IV. Environment Sensing and Channel Assignment

In this section, we present the channel assignment algorithm. After the network is initialized, each node performs the channel assignment task.

Based on the interference measurements, nodes store information about the quality of channels they have sensed, and they also keep a *channel list* sorted by the channel quality. The channel at the beginning of the list is the one with the best quality, which is a candidate for the node's receiving channel. Channel quality is determined by the interference level of the channel.

In the following subsections, we discuss different stages of the scheme in detail. These stages include channel sensing, channel selection, channel list update and lastly, the strategy for dealing with a channel reclaim.

A. Channel Sensing

We propose a simple sensing scheme with which the SUs collaboratively help each other to obtain recent information on channels status. At the very beginning, each node performs a thorough sensing and builds the channel list based on the obtained sensing information. Sensing information for each channel includes channel quality and time stamp showing the most recent time the channel status was updated. The list is then sorted by the channel quality.

SUs perform channel assignment task in a distributed way. When an SU chooses a channel for its receiving radio, it broadcasts a message informing neighboring nodes about the selected channel. Upon receiving this message, the neighboring nodes learn about the channels currently occupied by other SUs, and update their channel lists accordingly. At the beginning of each time slot, the SUs examine their channel lists and find the least updated channel for re-sensing. This new sensing information is also forwarded to the neighboring nodes in order to help them keep their lists updated. Based on this sensing approach nodes do not need to sense all the channels by themselves, as channel sensing can be very time-consuming. Instead, they collaborate with each other to keep their channel lists updated.

It is worth noting that different SUs may have different realization of a specific channel depending on their locations and also the locations of PUs. As an example, an SU spatially close to the source PU will sense that the channel is busy, while another SU located spatially far from the PU will find the channel clear. Thus, sensing information obtained by a specific SU may not be valid for all other SUs in the network specially when the network size is large. We assume that the sensing information is locally valid within a 2-hop neighborhood.

B. Channel Selection

When selecting a channel for its receiving radio, an SU chooses the highest quality channel at the beginning of the list. This channel is also the one that makes the total network interference in the secondary network minimized. If the total interference on that channel at PU locations is below a specified threshold, the node is allowed to choose that channel. Because of the limited number of channels, SUs may have to share the available channels among themselves. However, in case they are spatially close, their simultaneous transmissions will cause collisions. Media access control protocols are adopted to reduce the collision probability. Note that the first priority is to guarantee that the SUs would not cause harmful interference to the primary nodes. Interference on secondary nodes is less of a concern.

C. Channel List Update

Each node updates the channel list periodically in order to maintain an up-to-date information on channels status. Updates should be done only when necessary. Frequent updates impose huge sensing overhead, while rare updates may cause the SUs to miss the network changes that can affect their channel assignment decision. At the beginning of each time slot, an SU performs the sensing task for the least updated channel in the list. The other situation where an update takes place is when a secondary node chooses a channel for its receiving radio, after which it broadcasts a message containing information about itself and the selected channel. This message is called *channel selection message*. Upon receiving this message, neighbors will update their channel lists accordingly. Moreover, a node may want to sense the channels again if enough time has passed since the last time it updated the list. To do so, for each channel in the channel list, a node records the last time it was updated.

Updating the channel list is a crucial task for all nodes as the channel quality can vary over time. Two kinds of updates may happen in the channel list: 1) once a channel becomes worse in terms of quality, it will be moved toward the end of the list based on its rank, 2) a channel will be moved toward the beginning of the list once its quality improves.

Channel assignment task is redone if the currently assigned channel is reclaimed by a PU, or if the interference level on the assigned channel increases dramatically.

D. Channel Reclaim by a Primary Node

Secondary nodes do not have any assumptions about when and which channel a PU becomes active on. That is the reason why the SUs need to keep their channel lists updated in order to make appropriate decisions in their channel assignment process. Since the channel availability may change over time, SUs need to be prepared to switch to a different channel when necessary. Assume secondary node S_1 has assigned channel C_1 to its receiving radio, and secondary user S_2 is sending data to S_1 on channel C_1. Meanwhile, a primary user, P_1, spatially close enough to S_1, appears on channel C_1. Either S_1 or S_2 that learns about the presence of P_1 first will notify the other peer. As a result, S_1 will switch to the next high quality channel in its channel list. S_1 will then inform S_2 about the newly selected channel. All these messages are transmitted via the control channel. Based on our algorithm, the connection is lost only for the time of channel switching, since the receiver already knows which channel it should switch to.

Our proposed channel assignment scheme is robust to PU activities, i.e., when a primary channel is reclaimed by a PU, the SUs using that channel will immediately switch to another channel. The transmission between two secondary nodes is interrupted only as long as the duration of the channel switching time.

V. PERFORMANCE EVALUATION

A. Simulation Setup

The simulation is performed in Matlab. We have chosen the simulation parameters such that our scenarios emulate a realistic application. Assume a $500 \times 500\ m^2$ area, almost the size of the downtown of a small city, and the cognitive users are the vehicles equipped with this technology. We consider a snapshot of the network where some of the vehicles are cognitive capable. Moreover, we assume that cognitive users are distributed in the area uniformly at random.

There are two kinds of nodes located in this area: secondary and primary nodes, both stationary at each snapshot. the SUs are assumed to be multi-radio capable, each with one radio for control purposes, one for receiving and two for transmitting. The transmission range of PUs is 200 m, and that of SUs is equal to 100 m. [4] gives the calculation of obtaining the required transmission power when the transmission range is known. Using the desired transmission ranges for PUs and SUs, and assuming the same data rate for both types of nodes, the required transmission power is $0.12\ W$ and $1.98\ W$ for SUs and PUs, respectively.

In order to measure the network throughput, we define a number of single-hop flows between random pairs of SUs. A node is randomly chosen as the source, and the destination is then chosen within the transmission range of the source. Each channel has a capacity equal to 2 $Mbps$. The flow data rate can be at most 2 $Mbps$ to fully utilize the channel capacity.

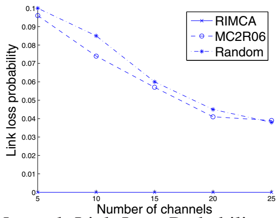

Fig. 1. Secondary Network Link Loss Probability vs. Number of Channels: 1 PU per channel

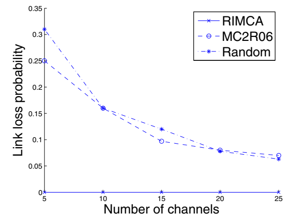

Fig. 2. Secondary Network Link Loss Probability vs. Number of Channels: 2 PUs per channel

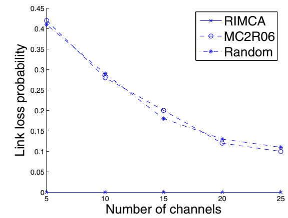

Fig. 3. Secondary Network Link Loss Probability vs. Number of Channels: 3 PUs per channel

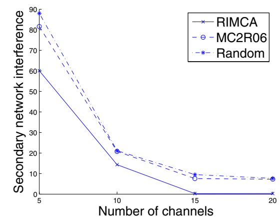

Fig. 4. Total Network Interference vs. Number of Channels: Sparse Topology

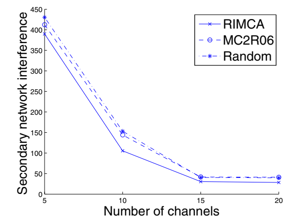

Fig. 5. Total Network Interference vs. Number of Channels: Dense Topology

The number of PUs and SUs vary from 10 to 20, and from 30 to 60, respectively. The number of licensed channels varies between 5 and 25.

We compare the results of our RIMCA scheme with two other schemes: (1) the channel assignment proposed in [3], and (2) the random channel assignment. [3] proposed a channel assignment scheme for wireless ad-hoc networks. In order to have a fair comparison, we have added cognitive ability to the nodes, so they can perform all channel assignment related tasks.

B. Probability of Secondary Link Loss due to PU Arrivals

PUs appear, disappear, and reappear over time without notifying SUs beforehand. When a channel, e.g., C_1 is reclaimed, it means one or multiple primary users have become active transmitting over it. In our simulations we consider the case where multiple primary users at different locations become active on the same channel, but we assume only one channel can be reclaimed at a time. With the proposed channel assignment algorithm, in case that a primary channel is reclaimed, the ongoing transmission between two secondary nodes over the reclaimed channel is interrupted only as long as the channel switching time, as each node maintains a list of available channels. Thus our channel assignment algorithm will provide the network with a robust topology. To the best of our knowledge, this work is the first to provide a robust channel assignment scheme for cognitive radio networks in case of a channel reclaim.

The probability of network partition is defined as the probability of losing existing secondary connections because of the channel reclaim by PUs. Figure 1 demonstrates the link loss probability in the secondary network when a channel is reclaimed by a single PU, assuming that 10 PUs and 30 SUs are located in the area. Figure 2 and Fig. 3 show the link loss probability when a primary channel is reclaimed by two, and three PUs respectively. The probability of link loss for RIMCA is zero since each node has a backup channel for its receiving radio. The link loss probabilities are much higher for the scheme modified from [3] (denoted as MC2R06) and the random channel assignment. However the link loss probability decreases when the number of channels is increased. The reason is that the channel reclaim by a PU affects a smaller number of links when a large number of channels are available in the secondary network. Comparing these three figures, we observe that the link loss probability increases as the number of PUs per channel is increased.

C. Network Performance

In this section, performance metrics such as the total network interference and network throughput are measured and compared with the existing work.

1) Total Network Interference: Network interference within the secondary network is defined as the number of interfering pairs of secondary receiving radios, i.e., the number of receiving radio pairs of secondary nodes which are within the interference range of each other and are on the same channel.

We measure the total network interference within the secondary network after channel assignment. This measurement is done for both sparse and dense topologies. In sparse scenarios, 10 PUs and 30 SUs are distributed within the 500×500 m^2 area uniformly at random. In the dense topology, there are 20 PUs and 60 SUs in the same area.

Results are shown in Fig. 4 and Fig. 5 for sparse and dense topologies, respectively. As the number of channels increases, for both scenarios, the total network interference decreases, since nodes have more channel choices. Figure 4 shows that our proposed RIMCA scheme outperforms the other schemes since it is interference-aware. The proposed scheme in [3] performs slightly better than the random assignment. Figure 5 demonstrates the results for dense topologies. Similar to the sparse scenarios, the total network interference decreases as the number of channels is increased. Compared with Fig. 4, for all studied cases, interference in the dense network is much higher than that in the sparse network assuming the same number of primary channels.

2) Network Throughput: We measure the network throughput in two scenarios: 1) a fixed number of flows, PUs and SUs, but a variable number of channels; 2) a fixed number of PUs, SUs and channels, but a variable number of flows. For each scenario we measure the best and the average network throughput and show the difference between these

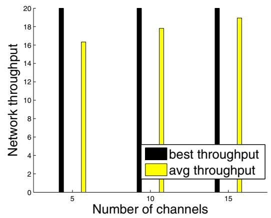

Fig. 6. Network Throughput vs. Number of Channels

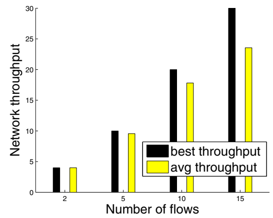

Fig. 7. Network Throughput vs. Number of Flows

two measured values. The best throughput is the maximum achieved throughput in simulation for each scenario, and the average throughput is the average of the results from 100 simulation runs.

In the first experiment we investigate the effect of the number of primary channels on the network throughput. The number of channels varies from 5 to 15. There are 10 PUs and 30 SUs in the area, and 10 flows are considered. As expected, and as the simulation results in Fig. 6 show, when the number of available channels increases, the average network throughput also increases. The reason is that having more channels brings more flexibility to the SUs in terms of channel assignment. As a result, more channels can be used in the secondary network, which in turn increases the average network throughput. In all three cases, the best throughput is around 20 $Mbps$, which is the maximum achievable throughput in our scenario based on the channel capacity and the number of flows. As the number of channels increases, the average throughput becomes closer to the best throughput, indicating that the average network throughput is improved with the increased number of channels.

Next, we investigate the effect of the number of flows on the network throughput, keeping other parameters fixed. The number of flows varies between 2 to 15. There are 30 SUs, 10 PUs, and 10 channels. Results are shown in Fig. 7. As the number of flows increases, the probability of interference in the network increases, which causes the average network throughput to decrease more significantly. This is demonstrated by the difference between the best and average network throughput. As an example, in the case of 2 flows, both the best throughput and the average throughput are equal to 2 $Mbps$ (the highest achievable network throughput). However, as the number of flows increases, the gap between the best and the average throughput grows bigger, e.g., in the case of 15 flows, the best throughput is almost 30 $Mbps$ while the average throughput is around 24 $Mbps$.

VI. Conclusions

In this paper we proposed a Robust Interference Minimizing Channel Assignment (RIMCA) scheme for a secondary cognitive radio network. Each node is equipped with a semi-fixed radio for receiving and two dynamic radios for sending. Nodes assign channels to their receiving radios. A collaborative sensing mechanism is adopted where SUs exchange information about the channels status. Based on the collected information, each node will be able to determine the best channel for its receiving radio. Our proposed method also handles the channel reclaim by PUs. The work can be extended to consider different channel bandwidth, where the channel assignment needs to be done based on the flow requirements. Moreover, the case where multiple PUs reclaim different channels simultaneously can be taken into account.

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