Channel Selection Scheme for Cooperative Routing Protocols in Cognitive Radio Networks

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Abstract—In this work, we propose CSCR, a channel selection scheme for cooperation-based routing protocols in cognitive radio networks. The proposed scheme increases the spectrum utilization through integrating the channels selection in the route discovery phase of the cooperation-based routing protocols. The best channels, that are less congested with primary users and that lead to minimum switching overhead, are chosen while constructing the cooperative group. Evaluating CSCR via NS2 simulations shows that it outperforms its counterparts in terms of goodput, end-to-end delay, and packet delivery ratio. The proposed scheme can enhance the network goodput, in some cases, by more than 150%, as compared to other related protocols.

I. INTRODUCTION

Cognitive Radio Networks (CRNs) appeared as a promising solution for the spectrum under-utilization problem. In these networks, the primary users (PUs) are the only licensed users to use the spectrum. However, secondary users (SUs) are able to use it too, but under the condition of not interfering with the PUs. Several routing protocols were designed to construct routes between SUs in CRNs [1], each has its own criteria. In this paper, we are extending Undercover [2] which utilizes the cooperative communication techniques in the routing process. Using these cross-layer techniques, the signal quality can be enhanced in the direction of the receiver SU (cooperative diversity), while nulling the transmissions in the directions of the PUs (cooperative beamforming). Although this idea allows the full coexistence between SUs and PUs, the existing work ignores choosing the proper channel to transmit signals on, and this leads to an inefficient use of the spectrum.

In this paper1, we propose CSCR: a Channel Selection scheme for Cooperative Routing protocols in CRNs. This scheme aims at choosing dynamically the best channel to use at each relay along the route. It avoids choosing the channels with high PUs activities while having the least possible channel switching delay. This strategy enhances the network metrics in terms of achievable capacity, packet delivery ratio, and end-to-end delay. Although the core idea has been used previously in the CRNs literature, the task of selecting the best channel for a cooperative group (during routing) was not discussed before. Thus, this is the first work that investigates this problem and integrates the channel selection with a cooperative routing protocol.

Our scheme is motivated by the example in Figure 1 in which the advantage of choosing the appropriate channel, to send the data over, is shown. Consider having a cooperative group of three SUs that are required to select a channel (channel 1 is the default) to send some data through. Sending on the default channel (channel 1) is not a good choice due to the high number and activity of the surrounding PUs.

1More elaboration and results can be found in our technical report [3].

Fig. 1: Example on the effect of choosing the optimal channel to send the data over. Note that \( p_{\text{active}} \) represents the activity probability of a primary user on a particular channel.

(Figure 1a). Also, sending on channel 10 (Figure 1c) is not the best choice too, since switching from the default channel to channel 10 will take a long time, as the latter channel is the farthest one from the default channel [4]. Thus, the best channel is channel 3 (Figure 1b) because, it achieves the compromise between avoiding highly active PUs and minimizing the channel switching overhead.

The proposed scheme has been evaluated using NS2 [5], and its performance is compared to two other CRN protocols. Results show that CSCR can enhance the network goodput, in some cases, by more than 150%. In addition, it is shown that CSCR always experiences a higher data delivery ratio, with the least end-to-end delay, compared to its counterparts.

The rest of the paper is organized as follows: Section II presents the related work. Then, our system model is described in Section III. The proposed channel selection scheme is given in Section IV. Section V evaluates CSCR and Section VI concludes the paper and gives directions for future work.

II. RELATED WORK

Routing protocols in multi-channel wireless networks take two main decisions: (1) choosing a route to the destination and (2) choosing channels used for transmission at each hop on this route. Thus, channel selection is considered an integral part of the routing process in such networks [6, 7]. The main goals of the channel selection, in this case, are to achieve the maximum utilization of the spectrum and to decrease the interference between active flows as much as possible. Specifically, in the context of CRNs, Tragos et al. [8] and Saleem et al. [9] presented surveys that give some approaches of utilizing the available channels to achieve different goals. In some publications [10, 11], the channel assignment problem has been formulated as an optimization problem with different objectives. Joshi et al., in [10], aimed at using the minimum power that can be used to transmit data successfully without being considered noise. However, Salameh et al., in [11], sought to maximize the achievable capacity. A brute force search for the best channel, according to different metrics, has been proposed in other publications [12, 13]. Lee et al., in [12],
aimed at choosing the ones that minimize the end-to-end delay for all connections. Kim et al., in [13], chose the channel that is not congested with highly-active PUs. Along the same line, Li et al., in [14], proposed a heuristic algorithm that seeks to have reliable and robust paths, in terms of avoiding PUs, for the secondary network. However, some important parameters were not taken into consideration in the formulations proposed in these publications. For example, Salameh et al., in [11], did not account for the PUs activities in their proposed solution. Also, Kim et al., in [13], ignored the switching delay and the SUs flows interference on each other. Finally, Li et al., in [14], did not consider maximizing the achievable capacity.

### III. System Model

In this paper, we consider solving the channel selection problem for a cooperation-based routing protocol. The main additional requirement in the cooperative case, than the default case of sending using only one node, is that: all group members should operate on the same channel. This allows the transmitted signals to null each other at PUs directions. The channel selection algorithm aims at choosing the channel that achieves (1) the best achievable capacity for SUs flows, (2) the least interference between SUs flows and each other, (3) the least impact on surrounding PUs, and (4) the minimum channel switching delay. We combine all these requirements in a routing metric which is used to determine the best group to relay the data, along with the best operating channel.

Our protocol is designed to work in a CRN which consists of two types of users: PUs and SUs. PUs have the license to use the spectrum according to their data delivery requirements. Moreover, we assume that SUs can detect and sense the activity of the surrounding PUs. Primary network is supposed to adopt an overlay transmission policy which means that SUs can transmit data in two cases only: (1) surrounding PUs are not currently active, or (2) SUs are able to use cooperative beamforming, so that their transmissions cannot interfere with the PUs. For the wireless channels at all nodes, the slow fading multipath model is assumed, in which the channel coefficients are constant over some specified time period. Reliable estimates for the channel coefficients, between SUs and each other and between SUs and PUs, can be done through the channel estimation techniques on the preambles of transmitted packets between different nodes [15]. Through utilizing these channel coefficients, an accurate beamforming can be implemented. SUs are assumed to transmit control packets over a Common Control Channel (CCC) such as the 2.45GHz ISM band.

While Undercover [2] assumed that all nodes have only one channel to send the data over, we released this assumption in CSCR. All nodes in the CRN (SUs and PUs) can operate on multiple channels. The sending channel may differ from the receiving channel, and each node is able to switch to any of these channels at any time. Channel switching delay is assumed to depend on the difference between frequencies of the current and the target channels [4, 16]. Channels are assumed to be non-overlapping which means that sending data on one channel does not interfere with the transmitted data on other channels.

### IV. Proposed Channel Selection Scheme for Cooperative Routing

In this section, we give an overview for the proposed channel selection scheme for cooperative routing in CRNs. First, we present the goals which we considered while designing CSCR and then we show how we achieve these goals through the model we propose. Then, we give details of the implementation and the flow of the proposed channel selection scheme.

#### A. Design Goals

We have designed CSCR to achieve some goals which ensure feasibility, usability, and efficiency of the proposed protocol. First, CSCR is designed in a decentralized approach, where each group can independently choose the channel it will send the data over. Second, as a protocol planned to operate in CRNs, the PUs activities are considered while choosing the operating channel. Taking this into consideration gives more reliable routes that interfere less with the surrounding PUs. Also, we take care of the changing environment of CRNs which includes the periodic changes in the number of active flows between all nodes (including SUs and PUs), the PUs activities, and the channels’ conditions.

Since we assume a multi-channel environment, the channel switching delay is taken into consideration. We aim at minimizing this overhead as much as possible, given that all participating nodes in the group should operate on the same channel while sending data. Although switching of all group members to one channel, to send data, is costly, one may not have another choice if all channels are occupied by active PUs. Another important parameter we take into consideration is the operating channels of the other active flows passing by the nodes participating in the chosen group. Switching the sending channel of one of the group members while one of its flows is active may cause preemption of this flow and loss of data. Thus, we aim at choosing the channels that avoid causing this preemption. Finally, we take care of the same goals of Undercover [2] which are: increasing the achievable capacity and minimizing the interference with other SUs flows.

#### B. Routing Metric

In this section, we present how the mentioned goals are achieved through the proposed routing metric. First of all, the group construction method is inherited from Undercover protocol [2]. The channel selection algorithm is added to the group construction phase, so that a group can choose the best channel to work on. This removes the overhead of choosing a channel while sending the data and also, decreases the possibility of losing data due to the potential interruption/contention caused by other active flows. Based on this, each group in the network (even on the same flow path) chooses independently and periodically the optimal channel for data transmission. This periodic decision is done so that the algorithm can adapt to the changing network environment.

We define the routing metric\(^2\) that node \(i\) (which has some data to send) or a relay can achieve, with the help of a chosen cooperative group, while sending data to node \(j\) by:

\[
LC_{ij} = \frac{\hat{C}_{ij}}{(N_{n} + \beta(N_{f} - N_{n})) \times P_{pu} \times T_{\text{switch}}}. \tag{1}
\]

Where:

- \(\hat{C}_{ij}\) is the maximum achievable capacity between nodes \(i\) and \(j\) among all checked groups. This term depends on the available bandwidth, maximum power can be achieved by the node, and the channel coefficients between group members and the receiver node.

\(^2\)We have inherited the first three terms from Undercover metric [2].
$N_n$ and $N_f$ represent the interference caused from the outgoing flows to the group members and due to the group construction on other flows, respectively. Specifically, $N_n$ is the number of direct neighbors, of all group members, which carry active flows, and $N_f$ is the number of flows that are in the interference range of the cooperative group.

$\beta$ is a user-defined design parameter to alter the possible possible egoistic/altruistic behavior of the cooperative group.

$p_{pu}$ defines the probability of at least one of the surrounding PUs to be active, on the checked channel, within some specified time period $\tau$. According to our two-state ON-OFF birth-death PUs model, this is given by [16]:

$$p_{pu} = 1 - e^{-\tau \sum_{i=1}^{n_{pu}} \mu_i}. \quad (2)$$

where $n_{pu}$ is the number of surrounding PUs that are active on the considered channel and $\mu_i$ is the parameter of the exponential distribution of the OFF period of $PU_i$. Thus, this term traces the surrounding PUs effect.

$T_{switch}$ represents the delay cost that results from switching of all group members to the selected channel. This is given by:

$$T_{switch} = \max_{m \in g} d_{chan_{m}} \times c. \quad (3)$$

where, $g$ is the set of cooperative group members, $d_{chan_{m}}$ represents the distance between the current channel of node $m$ and the target channel, and $c$ is a constant that reflects the cost of switching between two consecutive channels. Since all group members switch their channels simultaneously, the total switching cost is the delay that results from the node that has the farthest channel from the target one.

Finally, it is important to note that this metric is calculated for each available valid channel while constructing a group. A channel is considered to be valid in two cases only: (1) there is no other active flows on this node or (2) all flows passing through this node are transmitted using this channel. These conditions ensure that there will be no channel switching while a node is transmitting data. This gives the protocol more reliability in delivering the data from the source to the destination. If no channel with the specified criteria is found, the algorithm chooses to use the channel that costs the minimum switching delay.

C. Information Exchange

In order to implement the channel selection task, each node should know a set of information which may change from time to time. This set of information includes:

1) The node direct neighbors, their available channels, and all channels coefficients between them and the node.
2) All flows passing by the node neighbors and the channels they are working on.
3) All PUs that are sensed by the direct neighbors along with their activity probabilities, activity channels, and the channels coefficients between them and the node neighbors.

These pieces of information are communicated between the nodes through periodic “Hello” packets. In addition, each node takes some parameters into account while choosing a channel to work on including (1) IDs of the available channels, (2) the currently occupied channels by other flows, and (3) the current sending channel.

D. Channel Selection Algorithm Flow

Figure 2 gives the flowchart of the entire algorithm. The main part of the protocol (which searches for the best channel to use) works in the group construction phase. In this phase, all channels are checked for their feasibility. If the channel is infeasible, it is added to the invalid channels set and the next channel is checked. However if the channel is valid, different cooperative groups are considered by the routing protocol1. For each group, the routing metric is computed according to Equation (1) and is kept with the node, if it is better than the best metric the node has got. At the end, the best value of routing metric is considered. However, if one cannot find any valid channel, the invalid channels are checked along with the groups considered by the routing protocol. In this case, the

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1 According to [2], the possibility of using one node in sending data, instead of using a cooperative group, is also checked. This ensures that the protocol will not use beamforming unless it is really useful.
channel that achieves the minimum switching delay is chosen. Finally, this node can send to the source node the best routing metric which represents a chosen group for sending data, along with a channel that is recommended to work on.

V. PERFORMANCE EVALUATION

In this section, the performance of CSCR is evaluated in different network configurations. First, the simulation setup and the used parameters and metrics are presented. Then, we present the results of our experiments.

A. Simulation Setup

We used a cognitive extension of NS2 [5], [17] for simulation. Table I introduces the simulation parameters used in the evaluation. We model the PUs’ activities as an ON-OFF process. The means of the exponentially-distributed active and inactive periods are randomly chosen with the activity percentage shown in Table I. We follow the same assumptions stated in Section III. The used MAC layer protocol is IEEE 802.11 protocol. The source and the destination of each connection are selected randomly. We compare CSCR against two other protocols which are LAUNCH [16] and Undercover [2]. LAUNCH is a location-aided channel-aware routing protocol that is designed to work in CRNs. However, it does not use beamforming in the routing process. On the other hand, Undercover uses beamforming in routing, but it never knows about the existence of channels nor how to benefit from them. We have chosen these two protocols to show the advantage of the main properties of our integrated channel selection scheme with the cooperative routing protocol. Throughout the evaluation, we use goodput, end-to-end delay, average group size, and routing overhead as our main metrics.

B. Experimental Results

1) Changing Number of SUs: Figure 3 compares the performance of the three protocols while changing the number of SUs. We can derive some key conclusions from Figure 3a. First, we can see that the goodput is enhanced as the number of SUs increases, due to the availability of new opportunities and routes in this case. In addition, the goodput increase for CSCR is even higher than that of other protocols since, CSCR is able to construct cooperative groups (as shown in Figure 3c) and uses beamforming on the best available channels. In some experiments, groups of six nodes are attained and the average number of constructed groups exceeds 225 groups per flow. Although Undercover uses cooperative groups too, it achieves lower goodput than CSCR since, Undercover chooses a random channel to send the data on, which may not be the best channel. However, the advantage of using these groups can be observed at high SUs’ density where there are many opportunities to construct groups. On the other hand, LAUNCH chooses the best channel to send on, but it lacks the advantage of using cooperative groups. To summarize, Undercover and LAUNCH performance are near to each other, and both achieve goodput lower than that of CSCR in almost all configurations.

Taking the discussion to Figure 3b, we can notice some interesting points. Although new and better routes can be attained when the number of SUs increases (as discussed in Figure 3a), the average end-to-end delay of all packets increases too, for Undercover and LAUNCH. This is attributed to the congestion at the MAC layer which results in increasing the number of transmissions between network nodes and increasing the queuing lengths and delays, increasing the total end-to-end delay. However, for CSCR, the average end-to-end delay decreases with the increase of SUs’ density since, CSCR can choose the best channel to send on. This channel is the one that has the lowest PUs activities and the least interference with the existing flows. This choice leads to introducing new flows for data without interfering with either PUs or SUs flows.

Finally, in Figure 3d, the number of control packets of CSCR and Undercover are higher than that of LAUNCH; this is attributed to the extra packets sent by both former protocols to employ the beamforming. Comparing overhead of CSCR and Undercover, we can observe that they are almost the same in all cases since, both of them transmit the same types of control packets. On the other hand, the difference between the control packets of CSCR and LAUNCH is almost constant. Thus, this extra overhead of CSCR can be outweighed by its
better throughput and end-to-end delay performance, especially at higher number of SUs.

2) **Changing Number of PUs:** Figure 4 shows the effect of changing the number of PUs on the performance of the three routing protocols. In Figure 4a, CSCR outperforms Undercover and LAUNCH since, CSCR is always able to choose the best channel to operate on; this gives the protocol the ability to avoid PUs' active channels. Likewise, CSCR uses cooperative groups to even beat the areas where PUs are there and active. The final note we can draw from this figure is that Undercover performs better than LAUNCH at low number of PUs since, the former can construct cooperative groups to overcome the PUs effect. However, in the case of dense PUs area, the effect of the improper choice of channels appears and Undercover performance becomes worse than LAUNCH.

The average end-to-end delays, in Figure 4b, decrease for both CSCR and Undercover with the increase in the number of PUs due to the decrease in the number of transmissions and congestion as discussed in Figure 3. In contrast, LAUNCH delay increases with the increase of the PUs density since, it adopts the interweave model in which SUs are not allowed to send any data if the surrounding PUs are active [16]. This forces SUs on the route to wait for a long time before sending the data, keeping in mind the high activity of all PUs.

3) **Changing Number of Available Channels:** Figure 5 shows that the effect of changing the number of channels have different effects on the performance metrics of the compared protocols. Thus, we discuss the behavior of each protocol separately. First, CSCR performance is enhanced with the increase of the number of channels in terms of goodput (Figure 5a) since, new opportunities and better routes are discovered in this case. As discussed before, the average end-to-end delay increases with the increase of goodput. But, towards the end of the graph, the number of channels becomes higher than the number of PUs (at nine channels in Figure 5b). At this point, CSCR becomes able to send on - at least - one channel that is free of the existence of PUs, decreasing the end-to-end delay.

Second, Undercover performance degradation is, surprisingly, attributed to the cooperative groups construction, since it does not know how to choose the best channel to send on, so it may fall in using a bad channel. That is why the goodput and consequently the end-to-end delay, both decrease with the increase in the number of available channels.

Finally, LAUNCH shows an obscure performance with the increase in the number of channels. Although LAUNCH is considered a channel-aware protocol, it cannot make the perfect use of the newly introduced channels. This highlights an important fact in the design of LAUNCH as it is designed to minimize the switching delay as much as possible. This is achieved through choosing the channel which gives the least switching delay. In addition, a channel locking mechanism is used to hinder nodes from switching their sending channels freely. Thus, source nodes always choose the same channels (which give the least delay) regardless of the available channels number, achieving the same performance in all cases.

**VI. CONCLUSION AND FUTURE WORK**

In this paper, we propose CSCR which is a channel selection scheme for cooperative routing protocols in Cognitive Radio Networks. The cooperative protocol, we base our work on, utilizes cooperative communication techniques (cooperative diversity and cooperative beamforming) to enhance the quality of the signal at the receiver secondary user and null-out the transmissions at primary users. At each hop along the route, a group of nodes is chosen to send the data on some selected channel. The cooperative group and the operating channel are selected in a way that increases the achievable capacity, decreases the interference between secondary users flows, avoids the primary users activity areas, and decreases the channel switching delay. Simulations on NS2 are carried to evaluate the efficiency of CSCR compared to two related protocols. Results show that CSCR always outperforms both protocols in terms of network goodput, end-to-end delay, and the packet delivery rate.

Future extensions of this work include investigating the effect of mobility on the cooperative routing and the channel selection. In addition, the scheme can be extended to support sending data to a multicast group instead of having one secondary receiver only. Finally, we can experiment the proposed scheme with other link layer contention management protocols.

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