Analysis of a Distributed Cluster-Based Spectrum Mobility Protocol for Cognitive Radio Ad-Hoc Networks

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Abstract—This work presents ongoing research on a distributed cluster-based spectrum mobility protocol with the aim to reduce the impact of Primary User activity on Secondary User communication and enable higher throughput and better QoS in CRNs.

I. INTRODUCTION

The increasing bandwidth demand for new emerging applications and services has led to a spectrum scarcity problem [1]. Studies have shown that large portions of the licensed spectrum remain unused most of the time [2], [3]. Regulations state, that unlicensed users or Secondary Users are not allowed to use licensed bands for communications causing a spectrum availability problem.

Cognitive Radio Networks (CRNs) are described in the literature [4] as a possible solution to the spectrum scarcity problem without changing the well-established regulation of spectrum allocation [5]. Cognitive Radios are devices that can modify their behavior based on perception and programming, like changing their transceiver parameters by interacting with the environment in which they operate [4]. In the CRN networking paradigm Secondary Users use Cognitive Radios to access licensed spectrum bands in an opportunistic manner using Dynamic Spectrum Access without interfering with the communication of licensed users or Primary Users [6].

Due to the nature of Dynamic Spectrum Access networks, Secondary User communication is often interrupted to not interfere with Primary User transmissions or other channel interferences. Therefore spectrum mobility is a key feature to enable a continuous data flow while switching communication channels. The problem of vacating the channel claimed by the Primary User is that the Secondary User needs to restart the whole connection state again. This means sensing the spectrum for available channels, performing rendezvous with other Secondary Users to communicate over a common channel and finally reestablishing the last data transmission. These processes impose a delay in the Secondary User communication, therefore reducing the throughput of the Secondary Users and thus Quality of Service (QoS) aware communication like voice-chat will not run smoothly as expected.

One possible strategy to coordinate a graceful channel migration for a set of nodes are cluster-based approaches. A cluster is a hierarchical structure in which Cognitive Radio nodes are divided into different virtual geographically adjacent groups according to a rule set. The nodes are linked with each other sharing at least a common channel. Clustering in ad-hoc networks has been studied intensively by researchers, primarily in the context of wireless sensor and mesh networks. A good overview is given by Yu et al. in [7].

This paper presents ongoing research that aims to reduce the impact of Primary User activity and the channel switching delay. For this purpose, a new cluster-based distributed mobility protocol called Spectrum Mobility Coordination Protocol (SMCP) is proposed, that coordinates the negotiation of a common Backup Channel among a cluster of nodes that are within communication range of each other but may not share the same view on the available spectrum. SMCP assumes that the cluster has a single-hop structure.

The rest of the paper is organized as follows: in section II the system model and assumptions are described. Section III focuses on the proposed mobility protocol and its function. Section IV describes the procedure to evaluate and measure the protocol. The paper concludes with a description of future work in section V.

II. SYSTEM MODEL AND ASSUMPTIONS

In this section the system model and assumptions which are needed for the understanding of the protocol are introduced. The used notation is introduced in table I.

The Secondary User and Primary User are defined as an entity with one or more transceiver units, a network protocol stack and a user application which sends and receives data. In addition, the Secondary Users have a Cognitive Radio protocol stack with spectrum sensing modules, a Cognitive Radio engine, a Cognitive Radio capable MAC and network layer and an unlimited energy source. The Primary User is mostly a stationary user like a TV broadcaster, a mobile user using the IEEE 802.11 standard or a GSM station.

For the purpose of this work, the Cognitive Radio nodes are equipped with a half-duplex transceiver module, meaning that the Cognitive Radios cannot transmit and receive simultaneously. Each Cognitive Radio node is identified by a natural number $i \in \mathbb{N}$.

It is assumed that the Secondary Users access the spectrum using the overlay technique. As described by Doyle [4], using
this method, Secondary Users are only allowed to transmit using the white spaces. White spaces are chunks of unused spectrum. This spaces may fluctuate over time and location. In contrast using the underlay technique the Secondary Users are allowed to transmit at the same time in the same licensed frequency as the Primary User but with lower power with the aim to not disrupt its transmission.

The Cognitive Radio nodes implement the Flexible Link-Layer (FLL) Cognitive Radio Protocol stack as proposed by Puschmann et al. [3]. This layer controls the transfer of data between neighbor Cognitive Radio nodes.

A data channel is defined as a common channel between two or more communicating entities, establishing a data link. This channel must be free of any Primary User activity before the Secondary User starts to send. The available channels for each node are in $\mathcal{O}_i$.

A Backup Channel is in addition to a common (data) channel, an alternate available channel used as a fallback channel to hop on, when Primary User activity is detected or the signal quality decreases in the first channel. The aim of a Backup Channel is to be able to continue with the data transmission without long delays. The selected Backup Channels for the cluster are in $\tilde{\mathcal{O}}$.

This work does not consider the use of a Common Control Channel for coordination. Instead the control packets are sent in-band, thus avoiding overhead from the use of a second channel.

A. Spectrum mobility

As explained by Christian et al. [5], spectrum mobility is a cognitive radio capability in which the Cognitive Radio node suspends its data transmission if a Primary User transmission is detected in the current channel, then it leaves the licensed channel and resumes the ongoing communication using a Backup Channel. Additionally to vacate the current channel Cognitive Radio nodes may execute one of the following spectrum mobility strategies: stay in the original channel and wait until the Primary User is done (non-handoff strategy), proactively search for a Backup Channel and then switch the channel, reactively search for a Backup Channel and then switch or a combination of the proactive and reactive strategy (hybrid strategy).

B. Clustering

For this work a clustering scheme is used as a hierarchical one-hop network topology. Inside the network the Secondary Users share at least two or more common channels. The network is assumed as slotted in the temporal domain, i.e. the time is divided in discrete slots. The clustering scheme offers some key benefits, on the downside it produces overhead costs while executing cluster formation, cluster head selection and assignment.

The ordinary Cognitive Radio nodes inside a cluster are called Cluster Members. Additionally a Cluster Head is elected among the Cluster Members. The Cluster Head is the leader and local coordinator of a cluster.

In [9] Gardellin et al. describe algorithms for coordination, cluster head selection and cluster formation. Based on when the Cluster Head is elected the cluster formation is classified in leader-first or cluster-first approaches. The Cluster Members of a cluster elect the Cluster Head based on a distributed consensus algorithm, using metrics such as degree of connectivity, spatial mobility, residual energy or node ID. For the purpose of this work the lowestID heuristic is used.

III. MOBILITY PROTOCOL

This section describes the proposed distributed cluster-based mobility protocol.

After successful rendezvous, each Member starts SMCP and runs a distributed consensus algorithm in a state machine to coordinate the Cluster Members to select a common Backup Channel set. It also assumes that all the Cluster Members can identify the presence of a Primary User in the current communication channel, this constrain eliminates the need to send control messages to notify other nodes, that a Primary User is in the channel.

SMCP is conceived to work in parallel to a MAC protocol or as an application above the MAC layer. For the purpose of this work SMCP runs in the spectrum mobility module located in the FLL of a Cognitive Radio device. This module receives and shares information with the sensing and link-layer modules. SMCP messages can be sent as Information Elements in IEEE 802.22 frames, as normal wireless frames IEEE 802.11 for the current ad-hoc network or as piggy-back information in the headers of data packages, or a combination of other methods. The decision to change the current communication channel remains on the cognitive engine running a particular spectrum handoff strategy, e.g. non-handoff-strategy.

A. SMCP

The Secondary User start by sensing the spectrum in order to determine the set of available channels $C_i$. After successful rendezvous in a common channel building a virtual cluster, each Cluster Member starts the mobility protocol. Each Member then broadcasts a mobility packet containing its set of open channels $\mathcal{O}_i$ and its own nodeID. This messages are used to identify the members and also contain their corresponding available channels to be used as possible Backup Channels. Then the Cluster Members wait for a certain amount of
time to receive possible mobility packets from other nodes. Based on all received mobility packets, each member selects implicitly the \textit{Cluster Head} using the lowestID heuristic and then computes the common \textit{Backup Channel} set \( \mathcal{O} = \bigcap_i \mathcal{O}_i \). This set contains the common available channels to be used as \textit{Backup Channels} and may be also the empty set (\( \emptyset \)) or as large as the maximal number of free channels available \( \mathcal{O} = \mathcal{O}_m \). After computing \( \mathcal{O} \), the \textit{Cluster Head} broadcast to the cluster its final decision. The \textit{Cluster Head} is important to coordinate the final decision of the consensus algorithm and confirm the results of each \textit{Member}. Again, all \textit{Cluster Members} wait for a period to receive the common \textit{Backup Channel} set confirmation from the \textit{Cluster Head}. This period is the maximal time needed for a broadcast packet to be send from one border of the cluster and reach the opposite border. Finally, all \textit{Members} update their \textit{Backup Channel} set, \( \mathcal{B}_i = \mathcal{O} \), and get into the idle state waiting for new mobility packets and restart the procedure.

Figure 1 illustrates the SMCP message exchange between three \textit{Cluster Members} in a cluster with at least a common \textit{Backup Channel}. This initial algorithm does not consider if any given \textit{Cluster Member} do not share at least a common channel with the other \textit{Members}: \( |\mathcal{O}_i \cap \mathcal{O}_j| > 0 \).

Listing 1 shows the algorithm in pseudocode notation. Due to the simplicity of the algorithm SMCP is conceived to run in small devices with low computing power. The protocol does not need a global time synchronization because the state machine is triggered by events sent from other FLL components, such as \textit{newChannelAvailable}, \textit{rendezvousCompleted} or \textit{newMobilityPacket}.

As a drawback SMCP needs to exchange at least \( n + 1 \) messages among the nodes to compute a common \textit{Backup Channel} set, where \( n \) is the number nodes in the cluster. To reduce the total amount of exchanged messages, instead of restarting the whole procedure when a new \textit{Member} joins the cluster, the following procedure is used: after electing the \textit{Cluster Head} and broadcasting the common \textit{Backup Channel} set, all \textit{Cluster Members} stay idle. When a new mobility packet arrives, this may be a new \textit{Member} joining the cluster or an older \textit{Member} just updating \( \mathcal{O} \), all \textit{Cluster Members} elect the \textit{Cluster Head}. The \textit{Cluster Head} broadcasts its final decision \( \mathcal{O} \). Each time the \textit{Cluster Head} is elected to keep up with changes in the network due to spatial mobility or the addition or subtraction of \textit{Cluster Members} to the cluster. If one \textit{Cluster Member} disagrees with the result, because it does not share any common channel with the other \textit{Members} \( (\mathcal{O}_i \cap \mathcal{O}_j = \emptyset) \) it broadcasts a negative response. This would make the algorithm run in a loop until at least one common \textit{Backup Channel} is found. If the \textit{Cluster Members} do not receive a \textit{Backup Channel} set broadcast in a defined amount of time, e.g., because the \textit{Cluster Head} has moved away from the cluster, they restart the whole procedure.

The performance of SMCP depends on the availability of common channels between the nodes. If there is at least one common \textit{Backup Channel} among all \( \mathcal{O}_i \), i.e., \( |\mathcal{O}| \geq 1 \), SMCP will reach and remain in the stable state \textit{Idle}, therefore reaching a final solution of the proposed coordination problem.

### IV. Evaluation

To evaluate if the proposed algorithm is able to reduce the impact of \textit{Primary User} activity in \textit{Secondary User} communication, the protocol has been implemented as a Cognitive Radio-MAC layer component in a clustered environment using Omnet++ 4.3 [10]. Omnet++ simulates a CRN environment with the help of CnSimulator [11].

A series of experiments with varying parameters will be run with the aim to test different scenarios and collect the needed metrics to analyze the feasibility of the proposed protocol. To be able to compare the results with other studies and strategies in the literature, the experiments will collect the following metrics: throughput vs. \textit{Primary User} activity under a specific scenario and the number of spectrum handoffs.

Each scenario is composed by the following varying parameters:

- Number of available common channels in the cluster, from 1 to 3.
- Probability of \textit{Primary User} activity based on the exponential or generalized Pareto distribution.
- \textit{Primary User} channel hopping scheme: stable, round-robin, random.
- Spectrum mobility strategy.

Having a different scope of interest, mainly focusing on a smaller, user-controllable environment and practical challenges, the main setup is built by eight \textit{Secondary Users}.

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**Listing 1. Pseudocode of SMCP**

```python
O_i = sense_channels()
send_cluster_member_broadcast(nodeID, O_i)
while true:
    determine_cluster_head()
    if (i_am_cluster_head):
        BCS = determine_backup_channel_set(received_broadcasts[])
        wait_for_broadcast()
        if (BCS is not None):
            BCS = BCS | BCS
            update_backup_channel_list()
        else:
            update_backup_channel_list()

send_cluster_head_broadcast(BCS)
wait_for_broadcast()
if (i_am_cluster_head):
    if (BCS is not None):
        BCS = BCS | BCS
        update_backup_channel_list()
    else:
        update_backup_channel_list()
```

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**Figure 1. SMCP message exchange**
forming a one-hop cluster. It is assumed that they already achieved rendezvous and can exchange data between them. For the purpose of this work, the Secondary Users do not need to communicate with other clusters or the Internet. This network layout is similar to a cluster-sensor network. Two Primary Users, e.g., DVB-T broadcast stations, are placed so that their transmissions are able to reach each Cognitive Radio node and therefore prevent them to transmit. The Primary Users are able to change their transmitting channel. The Primary User-activity (duty-cycle) is modeled based on the General Pareto Distribution activity model proposed by López-Benítez et al. [12] and by the exponential distribution due to its ability to describe inter-arrival times of Primary Users to the system that occur at a constant rate [13].

After a scenario is chosen it will be measured how much data is exchanged between the Secondary Users in a fixed amount of time. Then, while the Secondary Users are transmitting data, the Primary Users will wake up, based on a statistical distribution, and start being active, therefore forcing the Secondary Users either to backoff from the current channel and come back after the Primary User transmission ended or to change to an available Backup Channel and continue there with the ongoing communication. The time required to transmit the amount of user data is used to determine the handoff delay. It will also be analyzed if the handoff delay decreases using the proposed spectrum mobility technique compared to the case when no strategy is used.

V. CONCLUSION

This abstract presented an ongoing research towards a distributed cluster-based mobility protocol. The objective of this work is to examine if spectrum mobility in CRNs is able to reduce the impact of Primary User activity on Secondary User communication. A spectrum mobility protocol to try to solve the problem has been introduced and explained.

The collected throughput results, taking account of protocol overhead, will show if the Secondary Users benefit from the proactive coordination of a common Backup Channel set to enable a fast channel switching, enable higher throughput and better QoS for selected applications in CRNs. If so, the Secondary Users should have transferred more data in the same amount of time under the same Primary User-activity probability in a one-hop clustered environment.

To the best of my knowledge, this paper is the first step towards a practical realization of a self-organized distributed cluster-based spectrum mobility solution for Cognitive Radio ad-hoc networks.

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