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On the optimal, fair and channel-aware cognitive radio network reconfiguration ☆

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ABSTRACT

In this work, we focus on the Joint Channel Assignment and Routing (JCAR) problem in Cognitive Radio Networks (CRNs) and especially on the optimal reconfiguration of secondary networks under the presence of primary users. Secondary CRN users need to adapt their transmission channels promptly, while effectively limit additional or escalating system modifications triggered by the intertweaved primary user activity. Our approach takes into consideration the underlying spectrum switching dynamics and concurrently aims at a fair resource allocation among the active network flows. We take an optimization perspective and formulate the JCAR and network reconfiguration problems as mixed integer linear programs, addressing fairness concerns as well. We propose a heuristic approach which is based on a sequential reduced search space methodology, in order to obtain efficiently solutions of otherwise tough and demanding reconfiguration problems. The operation, effectiveness and performance of the proposed mechanisms are evaluated through analysis and simulations under various working conditions. The obtained numerical results indicate the benefits of the proposed schemes in terms of overhead performance and their scaling properties with respect to more realistic and thus demanding topologies.

1. Introduction

Recent advances in the technology of Software Defined Radios (SDRs) have propelled the proliferation of opportunistic devices that are able to exploit the under-utilized spectrum and form multi-hop networks without disturbing the entrenched users. Such flexible devices form networks that are referred to as Cognitive Radio Networks (CRNs), but face more challenges than the traditional multi-hop ones. Contrary to the latter decentralized networks where changes are mainly due to failures and environmental factors, in CRNs variations are mainly dictated by the time-varying channel activity of Primary Users (PUs). To avoid interfering with the rightful spectrum owners, Secondary Users (SUs) are frequently forced to switch their radios to other unoccupied bands, which is not the case in traditional wireless networks. To make matters worse, the available spectrum bands in CRNs are not necessarily continuous. Instead they are usually rather distantly apart, and combined with the reconfiguration capabilities of modern CR-enabled devices, they result in increased channel switching costs. Consequently, previous approaches and techniques assuming such costs fixed or negligible seem rather unsuitable for current and near-future practical CRNs.

Frequency hopping [1] is suitable for SUs, in order to ensure transparent operation, while avoiding interference to the primary network. However, apart from the required physical layer adaptations, switching between available channels introduces various types of higher-layer overhead, such as delay, which impacts various mechanisms

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of these higher layers of the protocol stack. In this work, we address optimal secondary network reconfiguration through Joint Channel Assignment and Routing (JCAR), while taking into account the dynamics of frequency hopping in CRNs. PU activity triggers several cascaded secondary network modifications, which are required to ensure seamless primary network operation. In order to avoid such escalated and time-intensive adaptations by sequential channel switchings, this work is involved in introducing in CRNs appropriate reconfiguration mechanisms that alleviate the induced overhead and restore network optimality as quickly as possible, while keeping the associated cost low.

The JCAR problem jointly considers link layer (channel assignment) and network layer traffic (flow routing) decisions, by taking into account the interdependence of channel assignment to radio interfaces and the amount of traffic that is expected to flow over each link. Few approaches have recently addressed this problem from the perspective of multi-hop networks. They typically formulate it as a centralized optimization problem, while heuristic algorithms are applied for obtaining approximate solutions in practical purposes. The majority of these approaches are based on the principle of "vertical decomposition" [2] of the protocol stack, which is also partially based on scheduling techniques. Although efficient, such works assume negligible channel switching costs and tight synchronization among nodes, which is not always achievable. However, a limited number of works avoid scheduling, while notably taking into account the fundamental principles of CRNs. Most of the latter are usually based on the application of the general-purpose heuristic "Diving" [3] for obtaining integer solutions. Nevertheless, none of the previous works study the problem of channel reconfiguration under channel availability variations. It should be also noted that existing reconfiguration approaches consider only rerouting cost elements, ignoring inherent channel switching costs. Most of them are based on assumptions that do not seamlessly carry over to CRNs, thus requiring further consideration and analysis.

In this work, we study the problem of JCAR from the perspective of CRNs. In addition, by taking into account early recommendations of regulatory bodies, we apply fair spectrum sharing among competing nodes [4]. Our main contribution is to provide a mechanism that alleviates the problem of costly reconfigurations on a CRN due to the time-varying PU activity. We focus on frequency switching dynamics, in order to optimally reconfigure the already allocated resources in a convenient and efficient manner. We aim at minimizing the cumulative delay due to PU-triggered and cascading channel switchings with the objective of limiting the complete service interruption incurred in a reconfiguring network.

Initially, we define the "Cumulative Switching Delay" according to recent advances in SDRs. In the sequel, we formulate JCAR as a multi-commodity flow problem augmented with channel interference constraints and thus, we obtain a Mixed Integer Linear Program (MILP). We should highlight that our approach does not simply aim to provide yet another JCAR heuristic or extend the existing formulations to include reconfiguration cost constraints. However, we propose a novel mechanism extending JCAR to minimizing network reconfiguration overheads considering the current resource allocation, the new state of the underlying topology and a system target indicator related to throughput and fairness. This is essentially a form of cross-layer decomposition of the JCAR and reconfiguration overhead minimization problems, rather than a joint consideration of them. Our approach allows for any heuristic to be applied for solving the JCAR problem. In this work we use the common "Diving" [3] heuristic in the context of CRNs, a modified version of the latter where a backtrack step gives more opportunities to the algorithm to overcome infeasibility and poor performance, as well as the general-purpose technique "Truncated MIP" [3]. The secondary network reconfiguration problem is also formulated as a MILP, while a problem-specific heuristic is proposed to provide good approximate solutions in reasonable time. Exploiting the structure of our problem, the main idea is to benefit from the improved capabilities of modern optimization software and solve sequences of extremely reduced size MILPs, compared to the original problems. On a more practical consideration, we demonstrate the effectiveness of such approaches, by considering multi-hop secondary networks operating in the so-called TV White Spaces (TVWSs), i.e. spectrum portions in the UHF/VHF TV bands which are left unoccupied at specific locations and times after the digital switch-over [4]. Finally, we provide numerical results that quantify the underlying reconfiguration overhead and the corresponding benefits achieved.

The rest of the paper is organized as follows. In Section 2, we review related works on the JCAR problem (Section 2.1) and JCAR reconfiguration approaches (Section 2.2), while in Section 3 we present our system model and the employed interference model. Section 4 presents the MILP formulation of JCAR with fairness constraints (Section 4.1) and introduces approximation techniques for obtaining efficiently solutions (Section 4.2). Section 5 presents the MILP reconfiguration problem formulation (Section 5.1) and reconfiguration heuristic design (Section 5.2), while Section 6, describes the performed simulation studies and presents the corresponding results. Finally, Section 7 concludes the paper.

2. Related work

2.1. Joint Channel Assignment and Routing problem

In the literature, the JCAR problem is frequently formulated as an optimization problem and, due to its inherent complexity, heuristic methodologies have been proposed to obtain good approximate solutions. Aiming at fair resource allocation, the JCAR problem in [5] was modeled as an Integer Linear Program (ILP) and its Linear Programming (LP) relaxation was used to schedule the allocation of resources. LP relaxation frequently led to infeasible solutions, which stimulated a new channel assignment algorithm with flow rates readjustments. Avallone et al. [6], on the other hand, proposed a greedy heuristic considering jointly the channel and rate assignments to schedule a set