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Implementation of Cognitive Radio Networks to evaluate spectrum management strategies in real-time

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This paper illustrates a Universal Software Radio Peripheral (USRP)-based real-time testbed that is able to evaluate different spectrum management solutions that exploit the Cognitive Radio (CR) paradigm. The main objective of this testbed is to provide an accurate and realistic platform by which the performance of innovative spectrum management solutions for a wide set of scenarios and use cases in the context of Opportunistic Networks (ONs) and Cognitive Radio Networks (CRNs) can be entirely validated and assessed before their implementation in real systems. Real-time platforms are essential to carry out significant studies and to accurately assess the performance of innovative solutions before their implementation in the real world. This work provides a comprehensive description of the testbed, highlighting many interesting implementation details and illustrating its applicability for different studies that rely on the CR paradigm. Then, a particular application in a realistic Digital Home (DH) scenario is also illustrated, which allows demonstrating the effectiveness of the real-time testbed and assessing its practicality in terms of user-perceived end-to-end Quality of Experience (QoE) in a realistic environment.

1. Introduction

The Cognitive Radio (CR) paradigm has been considered as an innovative solution to mitigate the spectrum scarcity problem by enabling Dynamic Spectrum Access (DSA), designed to conciliate the existing conflicts between the ever-increasing spectrum demand growth and the currently inefficient spectrum utilization [1,2]. The basic idea of DSA is to provide proper solutions that allow sharing the radio spectrum among several radio communication systems for the sake of optimizing the overall spectrum utilization.

With the advent of CR as a key enabler of DSA, several papers proclaimed the need for Cognitive Radio Networks (CRNs), which allow a wireless communication system based on the so-called cognitive cycle that enables observing the environment, acting and learning to optimize its performance. For instance, in [3,4], a CRN is defined as a wireless network with the capabilities of radio environment awareness, autonomous decision-making, adaptive reconfiguration of its infrastructure and intelligent learning from experience of a continuously changing environment to solve the challenges of efficient spectrum management and high-quality end-to-end performance.

Furthermore, several papers have illustrated the expected benefits of developing cognitive management functionalities, which support CRNs in exploiting the mentioned CR capabilities in many specific scenarios [3–5]. For instance, in [5], a cognitive management framework is illustrated to carry out an autonomous optimization of resource usage in next-generation home networks. The proposed framework is able to autonomously improve the performance of network nodes in a dynamic environment according to the aims, restrictions and policy regulations formulated by network stakeholders. In [6], cognitive management functionalities are proposed to improve the efficiency of medical applications, and a novel cognitive architecture defined as Co-health is designed to exploit available knowledge and previous experience to support electronic healthcare, especially in emergency situations. In [7], the authors propose considering cognitive management systems for provisioning efficient applications in the Future Internet (FI). The main objective of the FI is to provide new and emerging applications through a wide range of Internet-enabled devices. Specifically, the solution proposed in [7] is based on the Opportunistic Networks (ONs) defined as extended infrastructures, temporarily created to serve specific regions providing application needs, which follow the policies dictated by the operator. Because of the temporary nature of the ONs and the highly dynamic nature of the environment, including traffic and application issues, as well as the need to identify radio resource opportunities, solutions incorporating the autonomous decision-making and reconfigurability

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mechanisms provided by a cognitive management system are deemed essential.

On the other hand, several research works have promoted the usage of specific analytical tools to assist in cognitive management functionalities for spectrum management by exploiting different forms of cognition of the radio environment. Some examples of the most popular criteria of cognition considered in the literature are reinforcement learning [8,9], Partially Observable Markov Decision Processes (POMDPs) [10–12], fuzzy logic tools [13] and game theory solutions [14,15].

These proposals have been demonstrated to efficiently support spectrum management in different scenarios and use cases. However, the introduction of advanced cognitive management functionalities relying on some form of cognitive support to assist the spectrum management decision-making process has also arisen in the literature. This is the case for instance of the Functional Architecture (FA) proposed in [16] by the European Telecommunications Standardization Institute (ETSI) for Reconfigurable Radio Systems (RRSs) and its later extension for ONs [17]. In this context, in [18], a generic cognitive management FA for assisting the spectrum management decision-making process has been proposed based on the fittingness factor concept defined in [19]. In detail, this architecture integrates the fittingness factor to track the suitability of spectral resources to support a set of heterogeneous services subject to unknown changes in interference conditions.

Spectrum management policies supported by cognitive management functionalities proposed in the literature frequently rely on analytical models and off-line system-level simulators. The employ of such tools is typical within the research and industrial communities and can be convenient for achieving preliminary performance results. However, to carry out appropriate and relevant studies and to properly evaluate the performance of innovative solutions before progressing to a prototype or full-scale deployment, assessment on realistic platforms is crucial as a step towards implementation in real systems. In this context, real-time platforms enable the emulation of realistic scenarios to test algorithms, applications, protocols and policies under realistic conditions and represent a powerful tool for assessing the Quality of Experience (QoE) of end-users that could not be obtained through off-line simulations, as well as the Quality of Service (QoS).

Guided by this motivation, this paper provides a comprehensive description of a real-time testbed based on reconfigurable Universal Software Radio Peripheral (USRP) devices that can transmit/receive in different dynamically configured frequencies. This testbed has been envisaged, implemented and validated for the evaluation of a cognitive management functional architecture inspired from [16–18] in a real environment. In detail, this solution provides a framework to assess innovative spectrum management strategies exploiting the CR paradigm that have applicability in a wide set of scenarios and use cases. The functionalities of this architecture have already allowed achieving satisfactory results as published in referenced papers [20–23]; notwithstanding, these publications either provide a general overview or address particular testbed issues and capabilities, and they do not provide an overall or exhaustive vision of the presented platform. Then, the aim of this work is twofold: (i) to provide a very detailed description of the whole developed platform, its entire potential and its applicability, with a holistic vision and discussion of the testbed, and demonstrate how it can be useful in a wide range of studies and scenarios; and (ii) to illustrate a particular application in a realistic Digital Home (DH) scenario to assess the practicability of the platform in terms of user-perceived end-to-end QoE, also in a realistic environment.

The rest of the paper is organized as follows. Section 2 provides a review of previous related works. On the one hand, the analysis of the state of the art in terms of spectrum management solutions in CRNs is presented; on the other hand, this section illustrates several CR platforms found in the literature and describes the motivation for carrying out the new testbed presented in this paper. Section 3 discusses the applicability of the testbed, providing a general description of the previous works from authors whose results have been achieved through the platform in a broad set of scenarios and use cases. Then, Section 4 provides a holistic overview of the testbed architecture, including details about the implementation, the designed functionalities and their applicability. In Section 5, a detailed DH entertainment application carried out through the testbed is illustrated to assess the capabilities of the emulation platform also in a realistic scenario. Finally, Section 6 provides concluding remarks.

2. Related works and motivations

Spectrum management solutions in CRNs are responsible for proper utilization of the radio resources, and they are decisive to allow spectrum sharing among different radio systems, guaranteeing QoS requirements for different service classes without causing any interference. Hence, spectrum management functionalities are an interesting topic of research for different studies in the context of CRNs. For instance, in [24], the authors analyse different wideband spectrum sensing policies for CRNs, discussing the advantages and disadvantages of each solution. The research work developed in [25] proposes a game theoretic framework for joint spectrum sensing and spectrum access by considering the mutual influence between sensing and access for unlicensed users or Secondary Users (SUs) in two different scenarios: a synchronous scenario where the primary network is slotted, and an asynchronous scenario characterized by a non-slotted network. In [26], a cooperative channel state learning method based on a Bayesian learning rule for multi-channel sensing in different scenarios of the SUs is proposed. In [27], the authors focus their attention on a hierarchical DSA model to open the licensed spectrum to SUs while limiting the interference perceived by licensed ones or Primary Users (PUs). In particular, the basic components of this work include spectrum opportunity identification, spectrum opportunity exploitation, and a regulatory policy. The studies carried out in [28] and [29] propose strategies where SUs listen to feedback parameters that allow achieving information on the licensed spectrum channels. In detail, [28] focuses on an opportunistic spectrum sharing scheme where SUs can co-exist with the PUs; precisely, they can achieve feedback of licensed channel quality information that allows defining transmission parameters, such as the optimal transmit power and the transmission rate. Then, SUs can consider such information to enable the maximization of their own throughput. James et al. [29] propose a transmission scheme for SUs co-existing with a primary system based on the Automatic Repeat reQuest (ARQ) policy. Based on the ACK (positive acknowledge) or the NACK (negative acknowledge) message from the PU, this scheme exploits several probing time slots to achieve a general overview on the primary channel condition and operate accordingly with suitable transmission modes. In [30], the authors introduce a DSA algorithm for the SUs that do not know the interference behaviour of the PUs. Then, this paper analyses the SUs' behaviour in the licensed channel, demonstrating that it represents a renewal process. Finally, through the Renewal Theory [31], the authors perform an in-depth study of the interference provoked by the SUs.

Several research works rely on POMDPs that combine partial observations of the radio environment at specific periods of time with a statistical characterization of the system dynamics. In this direction, [10] proposes opportunistic spectrum access approaches to channels that can be either busy or idle, assuming a single SU. In [11,12], the use of a POMDP for spectrum selection in CRNs is proposed; moreover, these studies do not rely only on binary (i.e., idle/busy) measurements but instead consider a generalization in which the temporal variation of each available channel is able to capture different degrees of interference. Furthermore, different decision-making