Int. J. Electron. Commun. (AEÜ) 69 (2015) 1833–1846

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Dynamic resource allocation using load estimation in distributed cognitive radio systems☆

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ARTICLE INFO

Article history:
Received 13 April 2015
Accepted 10 September 2015

Keywords:
Cognitive radio network
Spectrum occupancy
Distributed algorithm
Load estimation
Analytical model

ABSTRACT

Cognitive radio is an emerging wireless technology that is envisaged as a solution to the spectrum scarcity issue. To improve spectrum utilization, cognitive (unlicensed) wireless users are assigned an opportunistic access to vacant channels on the condition they avoid interference with primary (licensed) users. In this paper we present an impressive design of a low complexity and high efficiency dynamic spectrum access technique for cognitive radio networks. This spectrum assignment algorithm does not require central controllers nor the pre-establishment and maintenance of common control channels. Yet, it can provide throughput and fairness levels that approach the performance of centralized systems. In addition, the proposed technique reacts extremely well to disturbances in the cognitive radio network configuration, including when primary users are activated, or when newcomer cognitive users join the network. Furthermore, we present in this work an analytical model that can be used to provide quick predictions of the performance of our proposed algorithm.

1. Introduction

Cognitive radio systems received significant attention in recent years because of their potential to considerably increase spectrum utilization. A cognitive radio network consists of two classes of users: The first class belongs to *primary users* (PUs) that are licensed to use the frequency spectrum, but often leave the spectrum underutilized at a specific location or time. A popular example is the VHF/UHF TV broadcasters in rural and suburban areas. The underutilized spectrum bands are known as *spectrum holes* or *white spaces* [1–3]. The other class of users in cognitive radio networks is *secondary users* (SUs), who are cognitive users that are given an opportunistic and temporary access to the spectrum holes, after of course performing sensing measurements on such bands and deciding that they are not occupied by PUs.

A substantial standardization effort went into allowing cognitive radio devices to utilize TV whitespaces when broadcasters are not using them. These include the IEEE 802.22 Wireless Regional Area Network (WRAN) standard [4], IEEE 802.16-2012 WiMAX standard [5], IEEE 802.11af standard for Wi-Fi [6], ECMA-392 standard [7], and ETSI TS 102 946 and TS 103 154 standards for Reconfigurable Radio Systems (RRS) [8,9].

When multiple uncoordinated cognitive users attempt access to the unutilized spectrum, conflicts can arise. Several researchers [10–13] proposed using a *common control channel* (CCC) as a means for cognitive users to contact a centralized controller that makes decisions about spectrum assignment by considering the needs of cognitive users and the spectrum-sensing information they acquired. The controller then transfers those decisions back to the cognitive users through the CCC.

Establishing, and then maintaining, a reliable CCC between a central controller and the various cognitive users in a cognitive radio network is quite challenging. For starters, due to the dynamic nature of the wireless environment (device location, shadowing by obstacles, fading, etc), the spectrum bands available for different cognitive users might vary widely, which means finding a common channel that connects all cognitive devices to one central controller might not be possible. This problem is exacerbated by the time-varying nature of the spectrum holes due to PUs activating unexpectedly.

Reserving an out-of-band licensed channel for the CCC is often suggested as a pre-cursor for building cognitive radio systems to overcome the aforementioned problems. However, this also suffers from several drawbacks: One includes that the CCC band (or bands) is reserved for sending control information and not actual

☆ This work was supported in part by the Deanship of Academic Research at The University of Jordan.

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http://dx.doi.org/10.1016/j.aeue.2015.09.008
1434-8411/

data. This means that bandwidth is wasted when the cognitive radio network is stable, as the amount of signaling information is minimal in that case. On the other hand, when the cognitive radio network goes through a period of variability or when the number of cognitive nodes increases, the CCC can suffer from *saturation* because of excessive signaling information [10], thus severely affecting system performance and limiting the scalability of the network.

It is also worth mentioning that the CCC is an easy target to jamming and denial of service (DoS) attacks, allowing malicious users to disrupt the whole system with minimal effort. A similar thing can be said about the centralized controller, which is prone to malicious attacks and represents a single point-of-failure for the cognitive radio network.

Decentralized cognitive radio systems attempt to overcome these problems by avoiding the use of a CCC or a centralized server. Rather, they adopt channel assignment strategies that are executed in a completely distributed manner [14–17]. However, once a decentralized ad hoc architecture is adopted, the problem of contention arises, and the need for contention-resolution algorithms becomes obvious.

Such contention-prone systems typically suffer from bad throughput at high load scenarios due to excessive collisions [18,19]. Hence, the challenge is to come up with a distributed channel assignment algorithm for cognitive radio networks that has all the benefits of a distributed system, but does not suffer from excessive collisions at high loads, a challenge we embark on in this work, as we introduce a novel technique for resource allocation in cognitive radio networks that intelligently minimizes collisions by estimating the load on the network, and reacting accordingly. We call this algorithm *Spectrum Occupancy Using Load Estimation* (SOULE). In this technique, each cognitive user adjusts its behavior based on the behavior it observes from other cognitive users in the network, without the need to contact them or contact a centralized controller, which avoids the need for a CCC. We prove, via simulation, that the proposed technique reacts quickly to changes in the structure of the cognitive radio network. It also provides a high level of fairness, scalability and robustness.

The rest of this paper is organized as follows: In Section 2 we survey related literature. In Section 3 we describe our proposed distributed algorithm for sharing spectrum in cognitive radio networks. The metrics and experiment setups used to assess the performance of our SOULE technique are described in Section 4. Section 5 offers a theoretical analysis of our proposed technique that can be used for quick performance evaluation. The simulation results are thoroughly discussed in Section 6. Finally, we provide conclusions in Section 7.

2. Related work

Optimal and robust channel assignment represents a major challenge for cognitive radio networks, which explains the rich body of research regarding this issue.

Existing mechanisms for channel assignment can be generally classified into cooperative and non-cooperative techniques. Non-cooperative methods include transmit power control [20], in which cognitive base stations reduce their interference to other cognitive base stations by adjusting their transmit power. Power control is also used by cognitive base stations to avoid exceeding an interference temperature limit at the PUs [21]. Another non-cooperative method for channel assignment is listen-before-talk [22], where a transmitter assesses the channel busy state before using the channel. Non-cooperative mechanisms can be sufficient for short distance and low data rate communications. However, such mechanisms do not work well in networks with large spectrum demand and wider coverage areas.

On the other side of the coin, cooperative mechanisms include running optimization techniques amongst the cognitive base stations to reach the desired channel assignment. Different approaches have been suggested to solve this optimization problem. Examples include genetic algorithms [23,24], quantum genetic algorithms [25], particle swarm optimization [26,27], mutated ant colony optimization [28], neural networks [24] and fuzzy logic [29].

The above centralized decision making policies can outperform the conventional random selection policies that are executed independently by the secondary users in a decentralized cognitive radio network, because random selection can suffer from excessive collisions between the secondary users, thus lowering utilization of spectrum bands [30,31]. However, optimization techniques suffer from extra implementation complexity, reduced robustness to link or node failures, and the extra communication overhead and delay compared to the decentralized solutions.

Game-theoretic models [32–35] have been suggested in literature to address the distributed channel selection problem, where each cognitive base station is seen as a player, and hence has to decide independently on channel selection by formulating various games based on its local observations of spectrum usage. The goal of the game is usually to reach the Nash equilibrium. Utility functions are typically used to improve certain performance metrics, such as throughput and delay. Strategic form games, repeated games, and mixed strategy games can all be used to address the channel assignment issue [34].

Irrespective of the game model adopted for a decentralized channel assignment technique, the fact that collisions can occur, combined with the fact that the number of collisions will increase as the cognitive base stations demand more spectrum, means that distributed channel assignment techniques will suffer from lower utilization and unchecked fairness issues. Overcoming these problems using intuitive channel assignment is the objective of our proposed SOULE algorithm, which is based on novel heuristics that can improve throughput, fairness and require lower implementation complexity and overhead.

3. SOULE spectrum assignment

3.1. System model

We consider a distributed cognitive radio network as depicted in Fig. 1, in which multiple cognitive *secondary base stations* are located within a particular geographical area. For the secondary

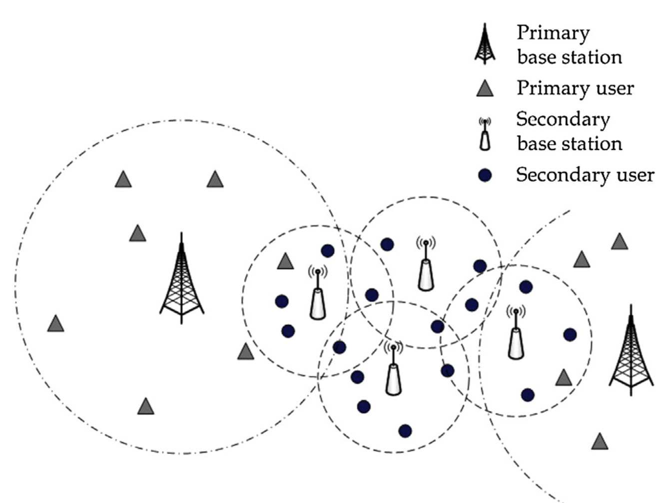

Fig. 1. A decentralized cognitive radio network consisting of secondary and primary users.