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CRAHNs: Cognitive radio ad hoc networks

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ABSTRACT

Cognitive radio (CR) technology is envisaged to solve the problems in wireless networks resulting from the limited available spectrum and the inefficiency in the spectrum usage by exploiting the existing wireless spectrum opportunistically. CR networks, equipped with the intrinsic capabilities of the cognitive radio, will provide an ultimate *spectrum-aware* communication paradigm in wireless communications. CR networks, however, impose unique challenges due to the high fluctuation in the available spectrum as well as diverse quality-of-service (QoS) requirements. Specifically, in cognitive radio ad hoc networks (CRAHNs), the distributed multi-hop architecture, the dynamic network topology, and the time and location varying spectrum availability are some of the key distinguishing factors. In this paper, intrinsic properties and current research challenges of the CRAHNs are presented. First, novel spectrum management functionalities such as spectrum sensing, spectrum sharing, and spectrum decision, and spectrum mobility are introduced from the viewpoint of a network requiring distributed coordination. A particular emphasis is given to distributed coordination between CR users through the establishment of a common control channel. Moreover, the influence of these functions on the performance of the upper layer protocols, such as the network layer, and transport layer protocols are investigated and open research issues in these areas are also outlined. Finally, a new direction called the commons model is explained, where CRAHN users may independently regulate their own operation based on pre-decided spectrum etiquette.

1. Introduction

Recent technological advances have resulted in the development of wireless ad hoc networks composed of devices that are self-organizing and can be deployed without infrastructure support. These devices generally have small form factors, and have embedded storage, processing and communication ability. While ad hoc networks may support different wireless standards, the current state-of-the-art has been mostly limited to their operations in the 900 MHz and the 2.4 GHz industrial, scientific and medical (ISM) bands. With the growing proliferation of wireless devices, these bands are increasingly getting congested. At the same time, there are several frequency bands licensed to operators, such as in the 400–700 MHz range, that are used sporadically or under-utilized for transmission [23].

The licensing of the wireless spectrum is currently undertaken on a long-term basis over vast geographical regions. In order to address the critical problem of spectrum scarcity, the FCC has recently approved the use of unlicensed devices in licensed bands. Consequently, dynamic spectrum access (DSA) techniques are proposed to solve these current spectrum inefficiency problems. This new area of research foresees the development of cognitive radio (CR) networks to further improve spectrum efficiency. The basic idea of CR networks is that the unlicensed devices (also called cognitive radio users or secondary users) need to vacate the band once the licensed device (also known as a primary user) is detected. CR networks, however, impose unique challenges due to the high fluctuation in the available spectrum as well as diverse quality-of-service (QoS) requirements [3]. Specifically, in CR ad

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hoc networks (CRAHNs), the distributed multi-hop architecture, the dynamic network topology, and the time and location varying spectrum availability are some of the key distinguishing factors. These challenges necessitate novel design techniques that simultaneously address a wide range of communication problems spanning several layers of the protocol stack.

Cognitive radio technology is the key technology that enables a CRAHN to use spectrum in a dynamic manner. The term, cognitive radio, can formally be defined as follows [22]:

> A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.

From this definition, two main characteristics of the cognitive radio can be defined as follows [32,82]:

- *Cognitive capability:* Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency bands of interest but more sophisticated techniques, such as autonomous learning and action decision are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.
- *Reconfigurability:* The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [41].

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurability as described before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Fig. 1. The cognitive radio enables the usage of temporarily unused spectrum, which is referred to as *spectrum hole* or *white space* [32]. If this band is further utilized by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference as shown in Fig. 1.

According to the network architecture, cognitive radio (CR) networks can be classified as the infrastructure-based CR network and the CRAHNs [3]. The infrastructure-based CR network has a central network entity such as a base-station in cellular networks or an access point in wireless local area networks (LANs). On the other hand, the CRAHN does not have any infrastructure backbone. Thus, a CR user can communicate with other CR users through ad hoc connection on both licensed and unlicensed spectrum bands.

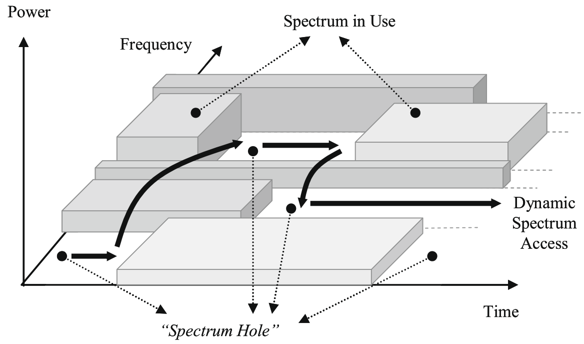

Fig. 1. Spectrum hole concept.

In the infrastructure-based CR networks, the observations and analysis performed by each CR user feeds the central CR base-station, so that it can make decisions on how to avoid interfering with primary networks. According to this decision, each CR user reconfigures its communication parameters, as shown in Fig. 2a. On the contrary, in CRAHNs, each user needs to have all CR capabilities and is responsible for determining its actions based on the local observation, as shown in Fig. 2b. Since the CR user cannot predict the influence of its actions on the entire network with its local observation, cooperation schemes are essential, where the observed information can be exchanged among devices to broaden the knowledge on the network.

This paper presents functional descriptions and current research challenges of CRAHNs. We first give the differences between CRAHNs and classical ad hoc networks in Section 2. In Section 3, we provide a brief overview of the spectrum management framework for cognitive radio ad hoc networks. In Sections 4–7, we explain the existing work and challenges in spectrum sensing, spectrum decision, spectrum sharing, spectrum mobility, respectively. These functions need a reliable control channel for message exchanges, whose design approaches are described in Section 8. Next, we investigate how CR features influence the performance of the upper layer protocols, and explain the research challenges on routing and transport protocols in Sections 9 and 10, respectively. The efforts underway in realizing coexistence among the CR users in absence of the licensed users are presented in Section 11. Finally, we conclude the paper in Section 12.

2. Classical ad hoc networks vs. cognitive radio ad hoc networks

The changing spectrum environment and the importance of protecting the transmission of the licensed users of the spectrum mainly differentiate classical ad hoc networks from CRAHNs. We describe these unique features of CRAHNs compared to classical ad hoc networks as follows:

- *Choice of transmission spectrum:* In CRAHNs, the available spectrum bands are distributed over a wide frequency range, which vary over time and space. Thus, each user shows different spectrum availability according to the