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A MAC protocol with mobility support in cognitive radio ad hoc networks: Protocol design and analysis

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ABSTRACT

Cognitive radio ad hoc networks (CRAHNs) have recently been proposed as a way to bring cognitive radio (CR) technology to traditional ad hoc networks. An important problem is to design a medium access control (MAC) protocol that addresses the decentralized control and local observation for spectrum management. In this paper, we propose a cognitive MAC protocol with mobility support (CM-MAC) based on carrier sense multiple access/collision avoidance (CSMA/CA) technique, where our protocol can respond to the vicinity state of CR nodes to primary exclusive regions. This paper analyzes the throughput performance for the proposed MAC protocol with the consideration of multiple PU activities and CR nodes. Our analytical results show that the proposed MAC protocol outperforms the throughput performance of the classical CSMA/CA MAC and statistical channel allocation (SCA) MAC protocols.

1. Introduction

As a result of the development of cognitive radio technology, the concept of cognitive radio ad hoc networks (CRAHNs) has recently been proposed in the literature [1], which involve more challenges than those in classical cognitive radio networks (CRNs). These challenges are due to variable radio environments caused by spectrum-dependent communication links, hop-by-hop transmission, changing topology, and node mobility.

Different from traditional medium access control (MAC) protocol used in ad hoc networks, the MAC protocol for CRAHNs has to address the spectrum sharing function [2], as well as to improve the throughput and spectral efficiency. Furthermore, because the primary exclusive region (PER) [3] of primary users (PUs) is an important factor that can make a significant impact on CR and PU communications, a scheme addressing the PER should be considered in MAC protocols.

Furthermore, the classical carrier sense multiple access/collision avoidance (CSMA/CA) based MAC protocols have the advantage of solving hidden terminal problems and having distributed operations (e.g., distributed coordination function in IEEE 802.11 MAC); thus, state-of-the-art MAC protocols [4–9] for CRNs have been proposed. However, PER, PU/CR activity and PER have not been comprehensively addressed in the literature.

In this paper, we propose a CSMA/CA-based MAC protocol called CM-MAC for CRAHNs to improve the performance of the network. Although the throughput performance can be related to the poor network organization and routing as the cross-layer nature of CRAHNs, the proposed mobility support algorithm (MSA) solution to PER issues working mostly at the MAC layer is mainly twofold. One is the MAC layer is a right place to address the PER issues. If an upper-layer scheme like a routing scheme is employed, a MAC layer mechanism is still needed to address the issues caused by PER like spectrum sharing, mobility, and detection. The other is solving the PER issues in MAC layer is lightweight as either the path formation or scheduling in routing is

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costly. For the topology, it might be an issue but we assume the nodes have sufficient communication with each other in the network. In summary, the main contributions of the paper are as follows:

1. We focus on a CM-MAC protocol that addresses CR mobility and PER issues.
2. We analyze the throughput of CM-MAC protocol assuming that the PU traffic follows a Poisson process.
3. We show that the throughput and spectrum utilization are improved by CM-MAC compared to classical MAC protocols.

The remainder of the paper is organized as follows: Section 2 discusses the related work regarding MAC protocols for CRAHNs; Section 3 presents the system model and motivation; Section 4 describes the CM-MAC protocol; In Section 5, the throughput analysis of the CM-MAC protocol is given; Section 6 presents numerical results; and Section 7 concludes the paper and presents some future work.

2. Related work

The objectives of the CRAHN MAC protocol not only include the improvement of channel utilization and throughput without degrading PU communications, but also include the control of spectrum management modules such as spectrum access and spectrum sharing functions to determine the timing for data transmissions [1].

The use of multiple channels for throughput improvement has been addressed in several MAC protocols. A feasible solution for throughput improvement is to find a set of good quality channels. A dual-channel MAC protocol (DUCHA) was proposed in [10] which can improve the one-hop throughput up to 1.2 times and multi-hop throughput up to five times compared to the IEEE 802.11 MAC protocol. An opportunistic multi-radio MAC (OMMAC) was proposed in [11], where a multi-channel-based packet scheduling algorithm was employed and packets were sent on a channel having best spectral efficiency (i.e., the channel with the highest bit rate).

In a CRN, the spectrum utilization can be improved if we choose the appropriate set of channels that meet the transmission rate requirement. A MAC protocol based on statistical channel allocation (SCA) was proposed in [4] which uses a channel aggregation approach to improve the throughput and dynamic operating range to reduce the computational complexity. Results of [4] show that SCA-MAC can use spectrum holes effectively to improve spectrum efficiency while keeping the performance of coexisting PUs. However, the PER issue was not addressed explicitly in [4]. In order to meet data rate requirement for data transmissions, a MAC with a so-called multi-channel parallel transmission protocol was proposed in [7], where the minimum number of channels was selected to meet a certain data rate. The results of [7] show that the proposed MAC protocol improves spectrum utilization and system throughput than the results shown in [8], where the proposed scheme selects a channel by the best signal-to-interference-plus-noise ratio (SINR) value. In [9], an opportunistic auto-rate MAC protocol was used to maximize the utilization on individual channels.

Spectrum sharing and spectrum access functions are explicitly addressed in [6], where spectrum access and spectrum allocation schemes are introduced in the proposed cognitive radio MAC (COMAC) protocol. Specifically, the spectrum utilization is improved by providing enough channels instead of assigning all the possible channels to a CR node, so that the other available channels could be reserved for other CR transmissions. In [5], the authors employed a distance-dependent channel assignment scheme in a proposed distance-dependent MAC (DDMAC).

However, the aforementioned works did not comprehensively consider several important factors. Firstly, although the spectrum sensing can be simultaneously performed in one shot [12], the sensing time cannot be ignored, as it may be relatively long, which may lead to end-to-end throughput degradation [13]. Secondly, with the existence of PER where CR communications tend to interfere with PU communications, the CR should retain silent when moving into this region if maintaining PU communication is a priority.

Because CRAHN MAC protocols favor distributed solutions, the distributed function like distributed coordination function (DCF) is a good option for protocol design. In fact, most of the aforementioned MAC protocols [5–9,11] are DCF-based with request-to-send (RTS)/clear-to-send (CTS) handshaking procedures, which intrinsically solved the hidden terminal problem. Other non-CSMA/CA-based MAC protocols like multi-channel MAC (MMAC) [14] and cognitive MAC (C-MAC) [15] can also solve the hidden terminal problem; however, they require a periodic synchronization which can hardly be applied to large-scale CRAHNs.

3. System model and motivation

3.1. System model

Before further discussion, we describe the system model used in this paper. A CRAHN is deployed in a plane containing N_p PUs and N_{CR} CR nodes. In a certain time period, a set of channels, denoted by $\mathbf{K}_i(t)$, is available to a CR node i and thus the total number of channels available to CR node i is $|\mathbf{K}_i(t)|$. The set of channels on a transmission link between ith CR and $(i+1)$th CR is $\mathbf{K}_{i,i+1}$. There are K spectrum bands in total available to CRs and PUs, while the typically used $(K+1)$th out-of-band common control channel (CCC) [16] is employed to exchange control information. When the jth PU is active for a transmission, its traffic flow takes one channel C_k, i.e., $\mathbf{K}_j^P(t) = \{C_k\}$. For simplicity, we use the following notation: $\mathbf{K}_j^P(t) = \{k\}$. When the jth PU is active, $\mathbf{K}_j^P(t) = \{k|k > 1 \text{ and } k \le K\}$. In the paper, the PU traffic flow is assumed to follow a Poisson process with parameter λ [17]. Note that in this paper, a PU that occupies multiple channels is equivalent to multiple PUs that occupy different channels.

We consider a CRAHN with a PER as shown in Fig. 1, where it is located at the center of the network and the primary receivers are within the PER bounded by the circle of