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A distributed multichannel MAC protocol for rendezvous establishment in cognitive radio ad hoc networks

Md Akbar Hossain*, Nurul I Sarkar

Department of IT and Software Engineering, School of Engineering, Computer and Mathematical Sciences, Auckland University of Technology, Auckland 1010, New Zealand

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A B S T R A C T

Rendezvous in cognitive radio ad-hoc networks is an essential step for a pair of unknown cognitive radio (CR) users to initiate a communication. Most of the existing studies address rendezvous problems as a design of a search strategy to meet on the same channel at the same time. However, in a multi-user environment, a rendezvous cannot guarantee even if two users are on the same channel at the same time due to channel contention and the multi-channel hidden node problem. To overcome problems, we propose a novel cognitive radio rendezvous (CR-RDV) protocol by integrating the rendezvous and medium access control (MAC) issues. We modify the traditional backoff strategy based on remaining transmission time and packet length to avoid the concurrent transmission with the primary users (PUs). Moreover, an additional sensing period is introduced immediately after the RTS packet to solve the blocking problem in the multi-user environment. The proposed CR-RDV protocol is analysed based on the modified Bianchi model and an absorbing Markov chain model to capture the multi-user and rendezvous channel contention. Through extensive simulations, we show that the proposed CR-RDV protocol outperforms the existing methods with respect to throughput, delay, and packet dropping.

1. Introduction

IEEE 802.11-based multi-channel wireless local area networks are widely used in home, office and corporate networking environments due to their simplicity in operation, robustness, low cost, well-defined standards (e.g. 802.11a/b/g/n) and the user mobility offered by the technology. However these protocols cannot be directly applied to cognitive radio ad-hoc networks due to the following functional requirements.

- *Channel coordination*: In cognitive radio ad-hoc networks, channel coordination is required to update and exchange the surrounding radio information with neighbours. There are numerous channel coordination or rendezvous protocols have been proposed in cognitive radio literature. However, the success of channel coordination depends on underneath channel access method for channel probing. Moreover, the same coordination is required for data transmission upon successful channel negotiation.
- *Incumbent user protection*: One of the most essential requirements for a CR-MAC protocol is to protect the PU's transmissions under any circumstances. Hence, a CR node should always be aware of PU activity in its vicinity and react accordingly, either by handoff to another channel, changing the power level, or resuming the transmission after the PU is finished.
- *Spectrum efficiency*: Due to the dynamic radio environment and intermittent PU activities, the availability of the radio spectrum changes with time and space. Thus, a CR node should always have updated spectrum usage information to efficiently and opportunistically utilize the radio resources.

To accommodate the above mentioned requirements, a multi-channel MAC protocol can be used as an effective solution to provide the incumbent user protection by changing the channel based on incumbent user activities and enhance the spectrum usage efficiency. The MAC protocol in multi-channel cognitive radio networks can be classified in two broad categories: centralised and distributed. The centralised protocol is focused on mainly infrastructure based cognitive radio networks. To address the contention problem in an ad-hoc environment, distributed multi-channel protocols are used.

In [1], the authors have proposed a distributed multi-channel cognitive MAC (C-MAC) protocol for channel co-ordination and mitigate the effects of distributed quiet periods for PUs signal detection. In C-MAC, a CR node is equipped with a single half duplex radio transceiver which performs in-band and out-band spec-

* Corresponding author.
E-mail address: akbar.hossain@aut.ac.nz (M.A. Hossain).

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trum sensing during network-wide quiet periods. It is assumed that each channel is organised in a logically divided recurring superframe structure which has two parts: i) beacon period, and ii) data transmission period. For synchronization and coordination in different channels, a CR node periodically visits the common channel, called the rendezvous channel. However, the strong dependency on network-wide tight synchronization is a performance issue in CRAHNs. Su and Zhang [2] proposed a multi-channel MAC protocol for cognitive radio ad-hoc networks which utilizes different channel sensing policies and integrates sensing information for packet scheduling. It shows that if the number of SUs is higher than the number of available free channels, the random sensing policy outperforms negotiation based sensing and vice versa. This protocol requires the existence of dedicated common control channel (CCC). Another CCC based multi-channel MAC protocol for cognitive radio (MMAC-CR) is proposed in [3] which utilised two data structures to exchange channel usage by PUs and CRs. It is worth to mention that in a dense network, a CCC is prone to saturation and single point failure problem.

In [4], a synchronised MAC (SYN-MAC) protocol is proposed based on hybrid channel access mechanism. A control signal is exchanged in time slotted fashion and data transmission is based on random access. In SYN-MAC, time is divided into time slots equal to the total number of channels and the dedicated radio is turned on the channel in accordance with time slots to send/receive a beacon. However, interference with the PUs is not addressed in SYN-MAC protocol. To enhance spectrum utilisation while protecting the PUs transmission, a multi-channel cognitive radio MAC protocol (SMC-CR-MAC) is proposed in [5] which facilitate channel switching based on the PUs activity.

In [6], authors have proposed a distributed CSMA/CA based cognitive radio MAC (COMAC) protocol without any online interaction with primary radio networks. Each CR node maintains a list of locally available channels and exchanges this information with the intended receiver to select the set of data channels based on dynamically adjusted SINR. COMAC provides a soft guarantee on PU performance without considering a predefined interference power mask. However, a multi-channel hidden terminal problem is not addressed in this protocol. Hence, in [7], it is assumed that each CR is equipped with a single radio transceiver and multiple channel sensors to simultaneously observe multiple channel activity. Another CSMA/CA based cognitive radio MAC protocol (CR-CSMA/CA) is proposed in [8] for both single and multi-channel scenarios. It introduced a three-way handshake procedure PTS (prepare to send)/RTS/CTS. A PTS is used to notify the other nodes that the current time interval is reserved for spectrum sensing. A CR node that overhears the PTS can update the network allocation vector. CR nodes that overhear the PTS packet will update the network allocation vector (NAV) value accordingly. However, this extra NAV value may prolong the false blocking problem. To reduce the interference with neighbouring nodes, an optimum operating range is introduced whereby each node dynamically adjusts the spectrum sensing range to find spectrum opportunities [9].

In most of the above studies, rendezvous is considered as a separate problem to the channel access in multi-channel environment. Therefore, a dedicated global or local CCC is considered to address the rendezvous issue. However, considering a network wide CCC is unrealistic due to channel saturation, single point failure and jamming problem. Moreover, when the channel is small, the dedicated use of one channel for control message can be costly. Rendezvous is a significant process to be completed in multi-channel cognitive radio ad-hoc networks to initiate a communication. Therefore it is necessary to combine the rendezvous process with medium access control and contention.

In this paper, a CSMA/CA based cognitive radio rendezvous (CR-RDV) protocol is proposed for cognitive radio ad-hoc networks that can minimise the latency as a result of channel reestablishment when PU appearance on current serving channel. The proposed CR-RDV can solve the rendezvous collision due to multiple CRs achieve rendezvous on the same channel. Moreover, the blocking problem due to RTS/CTS collision is addressed in this protocol. The fundamental idea is to select the channel based on receiver preference and maintain a backup channel list to be used for service interruption. Thus, we modify the RTS/CTS packet to integrate the channel list. The CR-RDV is developed by redefining the traditional backoff procedure and incorporating a sensing period immediately after the RTS, so that the incumbent PU's transmission is protected and blocking problems are resolved. Moreover, an analytical model is developed to capture both transmission probability and rendezvous success by using a two-dimensional Bianchi model and an absorbing Markov model.

The remainder of this paper is organised as follows. Section 2 introduces three major performance issues such as rendezvous collision, handshake collision and blocking problem. Section 3 provides a detail description of the CR-RDV MAC protocol and it's different components. An analytical model is presented in Section 5 to evaluate the effectiveness of the proposed protocol. It consists of three major subsections to explain saturated throughput, packet drop probability, and mean packet delay. An absorbing Markov chain model is presented to analyse the probability of capturing channel access (i.e. rendezvous success) in the throughput analysis subsection. The performance of the CR-RDV protocol is evaluated and simulation results are presented in Section 6. A brief discussion in Section 7 ends the paper.

2. Performance issues

A medium access design in multi-channel environment is subject to successful rendezvous achievement. To achieve rendezvous, a CR node transmits an RTS packet and waits for a CTS packet. Upon receiving CTS, rendezvous is established. However in cognitive radio ad-hoc networks, CTS may not be received if RTS/CTS is lost in an error-prone wireless channel or there is a collision between different RTS/CTS packets. In this scenario rendezvous cannot be guaranteed, even if the sender and receiver are on the same channel at the same timeslot. Therefore, the current setting of the RTS/CTS mechanism has to be reviewed. In this section, different performance issues in current RTS/CTS implementation are investigated from a cognitive radio ad-hoc networks point of view (Table 1).

2.1. Rendezvous collision

In existing CH based rendezvous mechanisms, each user generates a CH sequence based on channel sensing and probe the channel to achieve rendezvous. However, rendezvous collision happens when transmission from a user on a channel in the CH sequence collides with another users' transmission. Let us consider a scenario where two users CR_A and CR_B generate CH sequences based on local spectrum sensing as {1, 2, 3, 4} and {1, 5, 6} respectively for their corresponding receiver. As depicted in Fig. 1, CR_B already achieved rendezvous on channel 1st on 7th time slots while CR_A performs channel probing in another channel. Thereby channel 1 becomes unavailable for CR_A. As CR_A does not perform sensing during or before hopping on a channel, it will transmit an RTS on channel 1 on 8th time slot and causes a collision.

2.2. Handshake collision

In a multi-user environment, a CR node has to contend for the channel. According to CSMA/CA, the channel contention is performed by using four-way (RTS/CTS/DATA/ACK) handshake mecha-