Journal of Network and Computer Applications 98 (2017) 114–124

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

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

Cross layer optimization for outage minimizing routing in cognitive radio ad hoc networks with primary users' outage protection

Surajit Basak, Tamaghna Acharya*

Department of Electronics & Telecommunication Engineering, Indian Institute of Engineering Science and Technology, Shibpur 711103, India

ARTICLE INFO

Keywords:
Cognitive radio ad hoc networks
Cross-layer approach
Distributed routing
End-to-end outage probability

ABSTRACT

Path selection to minimize end-to-end (e2e) outage experience of cognitive users (CUs) in a given communication session is one of the key challenges in multi-hop cognitive radio ad hoc networks, where each CU node experiences a unique spatio-temporal variation of spectrum access opportunity. We study the problem under the constraint of probabilistic interference to primary receivers, in contrast to the popular trend of considering detection probability of primary user (PU) transmissions. This is formulated as a joint transmit power control, spectrum assignment and routing problem and a constrained optimization framework are presented for it. Further, using a standard technique for solving the convex optimization problem, a closed form expression for the transmission power of source as well as relay nodes is derived. Based on this, a centralized solution is proposed for optimal spectrum assignment and route selection. In addition, due to the prohibitive complexity of the optimal solution, a low complexity spectrum aware-outage minimizing opportunistic routing (SA-OMOR) solution is presented, along with its possible distributed implementation. Simulation results are used to validate our analytical results as well as the performance comparison between the proposed SA-OMOR scheme and the optimal one.

1. Introduction

A cognitive radio ad-hoc network (CRAHN) (Akyildiz et al., 2009), where each user, also referred as cognitive user (CU), is equipped with a cognitive radio (CR) transceiver based network interface card, offers a self organized, fast deployable, multi-hop and scalable wireless network architecture without the help of any dedicated physical infrastructure. Possible deployments of CRAHNs include smart grids (Khan et al., 2016), IoT for smart cities (Afzal and Zaidi et al., 2015), disaster management (Onem et al., 2013), military operations (Younis and Kant et al., 2010), etc. For successful deployment of CRAHNs in many of the above applications, solving routing problem is imperative. However, routing in CRAHNs is a highly daunting task since the existing routing challenges of wireless ad hoc networks (WANETs), inherited by such networks, get coupled with the uncertainty in the underlying spectrum availability, constrained spectrum access privileges and imperfect spectrum sensing (SS). Hence designing a routing metric, exploiting novel interactions between the routing and the spectrum management functionalities, is of paramount importance in any efficient routing protocol. A comprehensive survey of the available routing metrics may be found in Singh and Moh (2016). As noted in Singh and Moh (2016), both single path and multi-path routing metrics are designed based on some traditional performance metrics like delay, hop count, power consumption, as well as some new performance criteria unique to CRAHNs like spectrum availability, route stability. Cluster based collaborative multi-hop routing has received great attention to improving network performance in CR network. In Jiang et al. (2015b), the authors proposed a collaborative multi-hop routing strategy to maximize the network throughput. Jiang et al. (2016b) proposed a joint power control, spectrum assignment, and cluster based collaborative multi-hop routing algorithm to improve spectrum efficiency in CR network.

For the above reasons, we are motivated to further investigate the routing problem in CRAHNs. Our goal is to support reliable communication of delay sensitive traffic over a multi-hop wireless fading link in a CRAHN which could operate without any dedicated spectrum for communication.

1.1. Related works

In Jayasinghe and Rajatheva (2010), transmit power control problem is addressed aiming to minimize the end-to-end (e2e) outage probability in a relay assisted CR network with underlay mode (Goldsmith et al., 2009), of operation. A similar problem is dealt in Yu et al. (2012), considering a joint SS and data transmission

* Corresponding author.
E-mail addresses: surajit.basak2007@gmail.com (S. Basak), t_acharya@telecom.iiests.ac.in (T. Acharya).

http://dx.doi.org/10.1016/j.jnca.2017.09.004
Received 18 November 2016; Received in revised form 1 September 2017; Accepted 14 September 2017
Available online 19 September 2017

framework. Both the studies consider interference temperature (IT) constraint (Haykin, 2005), for protection of primary user's (PU's) interest. However, (Kang et al., 2011) show, in fading environments, maximum PU transmission outage probability constraint could achieve a substantial improvement in CU performance compared to the case of IT based constraint for PU protection. The authors, in Kang et al. (2011), study the CU transmit power control problem for maximizing CU ergodic and outage capacity in a single hop underlay CR network. Lin et al. (2013) also use a similar probabilistic PU outage constraint for efficient opportunistic access of available *spectrum holes* (Haykin, 2005). The authors (Lin et al., 2013), show that instead of following the popular approach of minimizing the false alarm probability at any CU node, while meeting a target PU detection probability for improving opportunistic spectrum access of the CU, a probabilistic PU interference constraint could result in the efficient discovery of spectrum holes. In this paper, we follow their proposed metric for protection of PUs' communications. Optimal CU transmit power allocation for joint improvement ergodic capacity and outage probability under average transmit power and PU outage constraint is investigated in Xu and Li (2014). However, transmit power control problem is also studied to improve the energy efficiency of the ad-hoc network (Jiang et al., 2016a). Recently, a power control scheme based on a non-cooperative game is proposed in Zhu et al. (2017), to improve power efficiency in a distributed cognitive wireless sensor network.

Although the routing problem for improving outage experience of end-users in existing multi-hop wireless networks has already been investigated in (Babaee and Beaulieu, 2010; Lang et al., 2011; Gupta and Bose, 2013; Mahboobi and Ardebilipour, 2013), the same problem in CRAHNs is not well investigated. In Dall'Anese and Giannakis (2012), the authors propose a cross layer framework for designing a statistical routing scheme in CRAHNs. In Jia et al. (2015), the authors investigate the problem of network throughput maximization under signal-to-interference plus noise ratio (SINR) based model for multi-radio CR based wireless mesh networks. The optimization framework is decomposed into two sub-problems: one focuses on joint power control and channel allocation which is solved by genetic algorithm (GA) and the other is a routing sub-problem, solved by linear programming techniques. In Basak and Acharya (2015), we propose a joint routing and transmit power control solution for simultaneous improvement in route lifetime and PU interference experience considering underlay mode of operation for a CRAHN. In Basak and Acharya (2016), a path selection scheme is studied in a multi-hop CRAHN that causes minimum interference to PUs under an e2e average data rate constraint for CUs. Unlike (Basak and Acharya, 2015), the nodes in the CRAHN are assumed to use opportunistic spectrum access model for their communications.

In CRAHNs, besides route selection and power allocation, intelligent spectrum assignment is also important for improvement in network performance. With the assumption that no perfect global channel state information (CSI) is obtained by the relay nodes, the authors (Ning et al., 2014), investigate the problem of instantaneous channel gains estimation based on outage probability. An opportunistic scheduling scheme is also proposed to maximize the minimum link transmission rate. In Jiang et al. (2015a), a dynamic channel allocation strategy is proposed in multi-hop cognitive wireless networks to maximize spectrum utilization and reliable communication between PUs and CUs. Song et al. (2014) propose a joint power allocation and channel assignment scheme for network throughput maximization under IT constraint in CR networks. A cooperative game theoretic approach is adopted for the aforementioned problem. An evolutionary game theory is also used in Zhu et al. (2016), for channel assignment strategy to maximize network throughput in wireless multimedia sensor networks. Jianga et al. (2016) propose a dynamic spectrum access scheme, combining opportunistic spectrum access and dynamic spectrum assignment, among multiple channels in CR network. In Jiang et al. (2017), three channel allocation strategies are proposed to each node in a given route to maximize the network lifetime in a cognitive wireless network.

1.2. Contributions

In this paper, we aim to find the route that maximizes the reliability of CU communication in a multi-hop CRAHN in presence of the challenges of multipath fading channel between any CU node pair, uncertain spectrum availability, imperfect SS, PU outage constraint and the limited number of PU channels for spectrum access. In contrast to our simplified linear model for PU interference (Basak and Acharya, 2016), we consider a recent probabilistic interference model (Lin et al., 2013), for efficient protection of PUs' interests. In Basak and Acharya (2016), the transmit power adaptation strategy for a source as well as the relay node is much simple since it only aims to meet the target data rate. The PU channels are reused in the optimal route since the routing metric is designed only to minimize the interference to PU. In this paper, not only interference to PU but the possibility of interference between CU nodes is considered. To avoid interference between CU nodes, our problem definition for spectrum allocation for a given multi-hop link ensures that reuse of PU channel is not allowed. Moreover, SS model followed in Basak and Acharya (2016), is not also realistic as it does not consider fading nature of the SS channels. Our main contributions may be outlined as follows. (i) Considering outage probability as a popular design parameter to characterize the reliability of any (one-hop or multi-hop) fading wireless link, we present an analytical model for e2e outage probability in a decode-and-forward (DF) relay assisted multi-hop route in a CRAHN considering the opportunistic mode of spectrum access. (ii) We aim to find the route between a given source-destination pair with minimum e2e outage probability. For this, we formulate the e2e CU outage minimization problem in a CRAHN as a joint routing, SS, spectrum assignment and transmission power control problem and present a constrained optimization framework for the same. (iii) The constrained optimization problem is solved as a convex optimization problem and a closed form expression, for determining the optimal transmission power of CU source and relay nodes, is obtained. The expression clearly illustrates the complexity of the transmit power adaptation scheme compared to that of Basak and Acharya (2016), as it aims to manage outage experiences of CU and PU communications together. (iv) Based on the expression, a centralized solution is designed for optimal channel assignment and routing. Computation complexity of the proposed approach is analyzed. (v) In order to avoid the high computational complexity and the requirement for global network topology and SS statistics in the centralized solution, a suboptimal solution for transmitting power control, channel assignment and selection of appropriate route is proposed, which is also amenable to distributed implementation. We call this solution *spectrum aware-outage minimizing opportunistic routing* (SA-OMOR). It may also be noted that no new MAC protocol for CRAHNs is proposed here. (vi) The scheme is shown to have polynomial complexity. (vii) Finally, extensive simulation results are provided to validate our proposed solution. The results also illustrate that the proposed SA-OMOR scheme succeeds in delivering a highly competitive performance to that of the optimal solution.

The remainder of the paper is organized as follows. Section 2 describes the system model along with the problem formulation. In Section 3, we present a centralized solution for the outage minimization problem. We elaborate our proposed SA-OMOR algorithm in Section 4. Simulation results are presented in Section 5 and finally, the paper is concluded in Section 6.

2. System model and problem formulation

2.1. Network model

A multi-hop CRAHN with N number of CUs is considered. The network architecture is shown in Fig. 1. The primary network consists