A Graph-Intersection-Based Algorithm to Determine Maximum Lifetime Communication Topologies for Cognitive Radio Ad Hoc Networks

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INTRODUCTION

A cognitive radio is a software-defined radio that can dynamically adapt its transmission parameters to the channels (frequencies) available for use in the operating environment (Akyildiz et. al., 2006). A cognitive radio network (CRN) is thus a network of wireless devices embedded with cognitive radios that can sense the available channels in the neighborhood and switch the communication channel, if needed. Cognitive radios have been considered as a promising solution to alleviate the spectrum scarcity problem (Zhao & Sadler, 2007). Accordingly, CRNs typically comprise of two categories of users: primary users (PUs) who own licensed channels and secondary users (SUs) who do not own any licensed channel (Akyildiz et. al., 2006). The SUs use the licensed channels of the PUs when the latter do not use them. When the PUs of the currently used channels become active, an SU relinquishes the channel and switches to any other available PU channel.

In this chapter, we target a well-known category of CRNs called the cognitive radio ad hoc networks (CRAHNs) - a self-organized ad hoc network of the licensed PU nodes and the unlicensed SU nodes (Akyildiz et. al., 2009). Depending on the activity status of the PU nodes, the set of common PU channels in the neighborhood of the SU nodes changes dynamically with time. Thus, even in a static network of SU nodes and PU nodes, communication topologies (like paths and trees) that connect the SU nodes may have to be frequently reconfigured depending on the availability of the PU channels in the SU-SU neighborhoods. Not much work has been done on determining stable paths or trees that could exist for a longer time in a CRAHN. Specifically, to the best of our knowledge, there has been no work done to determine stable sequence of a communication topology that spans (i.e., connect all the SU nodes) the entire CRAHN network of SU nodes.

Our focus in this chapter is to develop a generic benchmarking algorithm that can be used to arrive at upper bounds for the lifetime of any communication topology that spans the entire network of SU nodes. Referred to as the Maximum Lifetime Communication Topology (MLCT) algorithm, the algorithm can be used to determine a stable sequence of instances of any communication topology that spans the entire network of SU nodes (say, shortest path tree, minimum spanning tree, connected dominating set, etc) for the lifetime of the network as long as there is a polynomial-time algorithm or heuristic to determine that topology.

BACKGROUND

Most of the work done so far in the CRAHN literature focused on developing routing solutions that are either full spectrum knowledge based or local spectrum knowledge based. The full spectrum knowledge based solutions assume each SU node to be completely aware of all the available PU channels in the network and choose optimal

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routes with respect to either minimum number of hops per SU-SU path (Xin et. al., 2005), maximum conflict-free assignment (Zhou et. al., 2009) of PU channels or minimum number of channel switches per SU-SU path (Xin et. al., 2008); there is bound to be switching of channels when none of the common available PU channels for the end nodes of an SU-SU link are the same as the preferred PU channels for one or both the end nodes to which they stay tuned by default for transmission and reception. Such full spectrum knowledge-based solutions take a centralized approach like we took in this chapter; however, the full spectrum knowledge for the current time instant alone cannot be used to arrive at benchmarks for the routing metric, if one intends to stay with a route as long as it exists.

The local spectrum knowledge based routing solutions are distributed in nature and rely only on the spectrum information gathered in the neighborhood through the common control channel (Lo, 2011). The local spectrum knowledge based routing solutions proposed so far could be classified into sub classes that target at optimizing a particular metric in a distributed fashion. The minimum power routing protocol (Pyo & Hasegawa, 2007) is designed to discover SU-SU paths that incur lower energy consumption by taking into consideration the energy loss incurred due to transmission, reception, broadcast route discovery as well as channel switching. The bandwidth footprint (BFP) minimization-based routing protocol (Shi & Hou, 2008) attempts at discovering an *s-d* (source-destination) path that will minimally impact the on-going *s-d* sessions with respect to the interference area of the SU nodes (called the bandwidth footprint). Xie et al (2010) evaluated the tradeoffs associated with farthest neighbor routing (FNR) and nearest neighbor routing (NNR) for CRAHNs; results indicate FNR to achieve better end-to-end channel utilization and reliability and NNR to be relatively more energy-efficient. Cheng et al (2007a), Cheng et al (2007b) and Ma et al (2008) attempted to develop delay-sensitive routing protocols for CRAHNs: while Cheng et al (2007a) and Cheng et al (2007b) focus on minimizing the sum of the channel switching and access delays at the intermediate nodes, Ma et al (2008) focus on minimizing the sum of the queuing delays at the intermediate nodes.

In earlier works, we had proposed separate benchmarking algorithms based on the idea of taking graph intersections (Meghanathan, 2008) to determine stable sequence of unicast paths, multicast Steiner trees and broadcast connected dominating sets for mobile ad hoc networks (MANETs) and to determine stable sequence of data gathering trees (Meghanathan & Mumford, 2013) for wireless mobile sensor networks (WMSNs). The characteristic of both MANETs and WMSNs is that the nodes are mobile and it is the mobility of the nodes that triggers the topology changes. On the other hand, nodes in the CRAHNs considered in this research are static and it is the availability of the PU channels that changes dynamically with time, triggering changes in the communication topology of interest.

NETWORK MODEL AND ASSUMPTIONS

We assume a centralized setup of the CRAHN comprising of the licensed primary users (PU nodes) and unlicensed secondary users (SU nodes) uniform-randomly distributed. Each PU node is assumed to own a licensed channel that has a unique frequency and is identified with the ID of the PU node itself. Both the PU nodes and SU nodes are assumed to be static. Let R be the fixed transmission range for both the categories of nodes. A PU node is said to be a neighbor of an SU node if the Euclidean distance between the two nodes is less than or equal to R. Accordingly, we say that a PU channel is available for use by an SU node at a particular time instant only if the corresponding PU node is in the neighborhood of the SU node (which is always the case, as the nodes are static) and that the PU node is idle (i.e., the PU node is turned OFF) and not using its licensed

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