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Metric-based taxonomy of routing protocols for cognitive radio ad hoc networks

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ABSTRACT

Cognitive radio (CR) technology is introduced to solve the problem of spectrum under-utilization in wireless networks by opportunistically exploiting portions of the spectrum temporarily vacated by licensed primary users. Devices with cognitive capabilities can be networked to create cognitive radio ad hoc networks (CRAHNs) that face many challenges in different layers due to the flexibility in the spectrum access process. In this paper, we present a survey of recent routing solutions in CRAHNs. We start by listing routing challenges associated with the CRAHNs. We then present different routing protocols that are designed for CRAHNs, they can be classified according to the routing metric into six main categories: delay based, link stability based, throughput based, location based, energy-aware, and combined or multi-metric protocols that either combine many metrics together or use different metrics according to some specific rules. Finally, possible future research directions are discussed.

1. Introduction

Recent spectrum measurements (McHenry, 2003) show that the fixed spectrum assignment policy is becoming unsuitable for today's wireless communication. According to the Federal Communications Commission (2004) (FCC) report, many spectrum bands allocated through static assignment policies are used only in bounded geographical areas or over limited periods of time, and that the average utilization of such bands varies between 15% and 85%. In order to make good use of the unutilized bands, devices with cognitive capabilities can be networked to create a Cognitive Radio Network. Cognitive radio ad hoc networks (CRAHNs) are an emerging multi-hop wireless networking technology where nodes are able to change their transmission or reception parameters based on interaction with the environment in which they operate. In CRAHNs, there are two types of users sharing a common spectrum portion but with different rules: Primary Users (PUs) have the priority in spectrum utilization within the band they have licensed, and Secondary Users (SUs) must opportunistically access the spectrum without interfering with PUs.

The research in cognitive radio networks is primarily on spectrum sensing techniques and spectrum sharing approaches, spectrum sensing techniques (Akyildiz et al., 2006, 2009; Ma et al., 2009; Yucek and Arslan, 2009; Akyildiz et al., 2011) are used to determine which portion of the spectrum is available and detect the presence of licensed users when a SU operates in a licensed band in order to avoid any harmful interference to PUs, spectrum sharing (Cao and Zheng, 2005; Huang et al., 2008; Ma et al., 2005; Sankaranarayanan et al., 2005; Zhao et al., 2005a,b) seeks to coordinate access to some channel with other users in order to provide a fair spectrum scheduling method among them. On the other hand, routing problem in cognitive radio networks faces the additional route failure challenges caused by the dynamic behavior of the PUs and their effects on changing spectrum opportunities (SOPs) availability of SUs. In the last few years, many new algorithms have been proposed for the problem of routing in CRAHNs. Based on the metric used to construct the route, they can be classified as: delay based, link stability based, throughput based, location aware, energy based, combined metrics and multi-metric protocols. This paper aims to survey different CRAHNs routing protocols with the main focus on describing the metrics used in the routing discovery and maintenance procedures of each protocol.

The paper is organized as follows. Section 2 summarizes the main challenges for routing information through multi-hop CRAHNs. Section 3 discusses the taxonomy of routing protocols in CRAHNs. Finally, Section 4 concludes the paper highlighting some open research issues for future investigations.

2. Routing challenges in cognitive radio networks

Routing in CRAHNs is very challenging due to the stochastic activity of PUs which distinguishes them from traditional multi-channel multi-hop ad hoc networks. In CRAHNs, nodes have to

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deal with the simultaneous transmissions of the PUs which dynamically change network topology and spectrum opportunities (SOPs) availability. Thus, some additional challenges are added to the CRAHNs which can be listed as follows:

- In CRAHNs, not only nodes' location but also their communication frequencies affect network connectivity, unlike multi-channel multi-hop networks where the distance between nodes is the only parameter that affects network connectivity.
- Channel availability in CRAHNs is different from traditional wireless multi-channel multi-hop networks, nodes have partially overlapping and non-overlapping set of available channels, and these channels vary with time according to PU activity and its effective area.

For the above challenges, classical ways of measuring the quality of routes (e.g. throughput, delay, energy efficiency, etc.) are not sufficient in CRAHNs. They should be coupled with new measures that consider the path stability/PU presence and spectrum availability, and capture the spectrum information and integrate them into the routing process in CRAHNs.

3. Metric-based taxonomy

In this section, we present a metric-based taxonomy of routing protocols that have been designed for CRAHNs. As shown in Fig. 1, we categorize the proposed protocols into six categories: (1) Delay based protocols in which the delay is used as the routing metric; (2) Link stability based protocols which focus on selecting the most stable routes; (3) Throughput based protocols seek to maximize the throughput; (4) Location based protocols that make use of location information to construct routes using nodes that are close to the destination; (5) Energy-based protocols that aim to minimize the consumed energy at each node; (6) Combined and multi-metric protocols that either combine many metrics together or use different metrics according to some specific rules to satisfy QoS requirements. The following sections describe the route discovery process of the surveyed protocols in each category in detail focusing on the used routing metrics.

3.1. Delay based routing protocols

This section overviews routing approaches that measure the quality of routing solutions in terms of delays. End-to-end delay along a route is a traditional metric for routing algorithms, while it faces several different cases in multi-hop CRN. Delay-aware routing metrics are proposed in Cheng et al. (2007a,b), Yang et al. (2008), and Song et al. (2009), which consider different delay components such as

1. *Switching delay*: occurs when a node in a path changes its frequency band.
2. *Backoff delay*: MAC protocols result in backoff delay when trying to solve hidden-terminal and exposed-terminal problems (while working on an identical frequency band).
3. *Queuing delay*: depends on the transmission capacity of a node on a given frequency band.

The following sections give brief description of each protocol that use the delay metric, and specify the delay components that are used for each of them.

3.1.1. Joint on-demand routing and spectrum assignment

A Delay motivated On-demand Routing Protocol (DORP) (Cheng et al., 2007b) is a delay-based approach that combines many delay metrics (switching delay, backoff delay and queuing delay) to efficiently select the minimum end-to-end delay route, the switching and backoff delay along the path or at the intersecting nodes are represented as PATH-delay (DP) and NODE-delay (DN), respectively. They are used to evaluate the cumulative delay of the path. At a relay node m, a metric representing the cumulative delay along a candidate route is computed as

$$D_{route,m} = DP_m + DN_m \tag{1}$$

The *PATH-delay* (DP) takes into account the switching delay and backoff delay caused by the path and depends on the frequency bands assigned to all nodes along the path. As a consequence, suppose there are H hops between node m and the destination, we have

$$DP_m = D_{switching,m} + D_{backoff,m} \tag{2}$$

And

$$D_{switching,m} = \sum_{j=m}^{H} k|Band_j - Band_{j+1}| \tag{3}$$

where k is a constant with the suggested value of 10 ms/10 MHz. The backoff delay depends on the bandwidth on the current frequency band, the number of consecutive nodes sharing the same frequency, and the packet size. The derivation of the expression $D_{backoff}$ is reported in Cheng et al. (2007b).

The *NODE-delay* (DN) is caused by existing flows at the relaying node; it depends on the number and frequency bands of traversing flows, and is defined as

$$D_{node} = D_{switching} + D_{backoff} + D_{queueing} \tag{4}$$

$D_{backoff}$ is defined as the time from the moment a packet is ready to be transmitted to the moment the packet starts its successful transmission. The backoff delay on $Band_i$ is obtained as

$$D_{backoff}(Num_i) = \frac{1}{(1-p_c).[1-(1-p_c)^{1/(Num_i-1)}]} \cdot W_0, \tag{5}$$

where Num_i is the number of contending nodes, p_c denotes the probability that a contending node experiences collision, and W_0 represents the minimum contention window size, while the

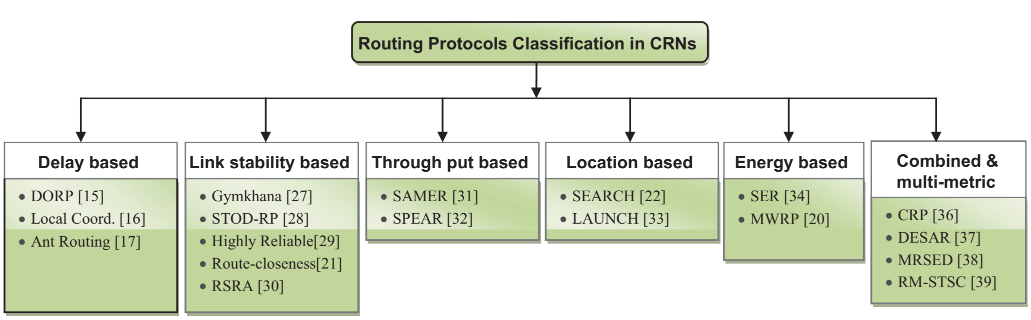

Fig. 1. Metric-based taxonomy of routing protocols in CRNs.