ENERGY EFFICIENT ROUTING IN COGNITIVE RADIO NETWORKS: CHALLENGES AND EXISTING SOLUTIONS

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Abstract
Dynamic Spectrum Allocation using Cognitive Radio (CR) is a promising solution to the spectrum availability problem in wireless networks. Cognitive Radio, however, opens up certain new issues, mainly at the physical, medium access control and routing layer levels. Several solutions have been proposed to tackle these issues and use dynamic spectrum allocation to improve the performance of wireless networks. The focus of most of these has been to improve the throughput and other Quality of Service (QoS) metrics. However, energy spent by a node is also an important matter of concern in most wireless networks e.g. wireless sensor networks. In this paper, we focus on the challenges posed by CR in routing data in an energy efficient manner. We then study some existing solutions to route data energy efficiently in CR networks and suggest some directions for future research.

Keywords:
Wireless Networks, Energy Efficiency, Cognitive Radio, Routing

1. INTRODUCTION

Wireless ad hoc networks offer tremendous promise in several forms – wireless sensor networks (WSNs), body sensor networks (BSNs), vehicular ad hoc networks (VTNs) etc. Due to the multitude of applications that use wireless networks, spectrum allocation is a major problem. Dynamic Spectrum Access (DSA) attempts to solve this problem to a large extent by allowing opportunistic spectrum access using Cognitive Radio (CR).

In a CR Network (CRN), the spectrum is divided among a set of Primary Users (PUs). Wireless nodes which are not PUs are called Secondary Users (SUs). When a SU wants to transmit data, it does so by using the spectrum allocated to some PU, but not currently in use. In case the PU to which that frequency was allocated wants to transmit, the SU typically stops using that frequency and scans for some other frequency which is currently not in use by a PU or SU.

Most wireless networks are battery-powered. When one node runs out of battery power, it can no longer be used as an intermediate node on the path from the source to the destination of data. Routing algorithms for wireless networks generally have a route maintenance component which reroutes data away from such dead nodes. This may mean that other nodes now spend more power to relay this data and will drain their batteries faster, resulting in a cascade of dead batteries and a disconnected network graph. For this reason, protocols for wireless networks should be designed to minimize power consumption wherever possible. Generally, the lifetime of a wireless network is considered as the time till the failure of the first node in the network.

Recently, energy harvesting is being explored as a attractive option for wireless nodes. If the battery of the node can be recharged (e.g. using RF harvesting, with solar power in sensor networks used out doors or movement of human limbs in body sensor networks), the lifetime of the network can be increased.

From the above discussion, it can be seen that networks that use CR techniques for routing data and are energy efficient combine the benefits of opportunistic spectrum access with long network lifetime. The problem however, is that designing such networks is not easy and requires careful consideration of several factors. In this paper, we discuss some of the challenges faced while designing energy efficient routing protocols for cognitive radio networks. We then discuss the work done till now in this direction. Finally, we conclude this paper with some suggestions for future research.

2. ROUTING IN CR NETWORKS - CHALLENGES

Traditionally, routing algorithms try to find the optimal path from the source of data to its destination. In a static network whose topology does not change with time, this can be done using algorithms like Bellman-Ford, Link State Routing etc. In a network with a set of PUs and SUs, finding a route from the source to destination involves other considerations, some of which are as below.

Dynamic Topology: Some wireless networks such as VANs have dynamically changing topology because of mobile nodes. CR results in dynamic topology even with fixed nodes, as the links from/to SUs depend on the activity of neighboring PUs. CR networks suffer from rapidly changing topology if the PUs send have bursts of data.

Deafness Problem: When a node has its radio tuned to a particular frequency band, it cannot receive transmissions on other frequency bands. This makes transmission of control messages (e.g. routing request/reply messages) difficult. One solution to the deafness problem is to have a common control channel for all nodes.
to transmit/receive control messages. This scheme wastes bandwidth by setting aside a channel for control messages, which are normally sporadic in nature. Other solutions to the deafness problem include channel synchronization and sending the same control message on all frequencies [1], [2]. However, these incur extra delay and spend extra power. A good routing algorithm should deal with the deafness problem with as little overhead as possible.

Interaction with the physical and MAC layers: Cognitive radio networks try to route data along a path with available frequency bands. This information about the available bands should be acquired from the physical and MAC layers. Hence, CR networks mandate cross-layer interactions between the physical, MAC and routing layers.

A more detailed discussion on routing in CRNs (without specific focus on energy efficiency) can be found in [3], [4] and [5]. [3] is a comprehensive survey of routing techniques for CR networks. [4] is study of the metrics used in routing protocols for CRNs. [5] classifies CRN routing protocols based on the metrics used for routing.

3. ENERGY EFFICIENT ROUTING IN CR NETWORKS – SOME EXISTING SOLUTIONS

In the following sub-sections, we discuss some important techniques to reduce energy consumption in CRNs and existing work using these techniques.

3.1 REDUCING ENERGY USED FOR SPECTRUM SENSING

In CRNs, each SU performs continuous spectrum sensing operation to detect the presence of PUs. This is an extra burden in terms of energy for the SUs. The power aware routing protocol [6] discusses five important metrics for energy saving at each node. These metrics are as follows:

1) Minimization of energy consumed per packet.
2) Maximize time to network partition: The minimum set of nodes (which have high battery drainage rate) whose removal leads that to network partition is found and the load is balanced over these set of nodes.
3) These routing goals balance the load and improve the life of the network.
4) Minimize variance in node power levels: this goal makes all the nodes in the path remain as active.
5) Minimize the total cost (which is the energy consumed by a node so far) / packet
6) Minimize maximum node cost

3.2 BALANCING ENERGY CONSUMPTION AMONG USERS

The SER [7] protocol has the objective of balancing energy consumption among users. SER can route and allocate time slots for users to meet this objective. The MAC model of SER divides the frame into three fixed length segments – the sensing window, the ATIM window and the communication window. The communication window is time slotted and each CR user can either send/receive packets or go to sleep for saving energy. The RREQ broadcast (based on DSR protocol) has a header field which specifies the minimum residual energy and communication channel availability at each relay node along a path. After receiving multiple RREQs along different paths, then the destination CR node selects a path p based least on the number of hops and the minimum residual energy of a relay node along that path [7] as below:

\[ P = \max \left\{ \frac{mE_{res,k}}{HC_k}, \forall K \right\} \]

Here, \( mE_{res,k} \) minimum residual energy at a relay node and \( HC_k \) is a hop count for path \( K \).

3.3 HETEROGENEOUS INTERFACES

When a CR node has heterogeneous interfaces for data transmission, the properties of the interface can be considered for minimizing energy. The minimum weight routing protocol (MWRP) [8] considers the required transmitted power to reach the destination over a certain interface. Different wireless interfaces such as cellular (e.g., CDMA, TDMA, FDMA) or WLAN (i.e., IEEE 802.11 b/g) are used to access wireless systems and these support different communication ranges. A dedicated common control channel (CCC) is used for communication among CR users. The route discovery process of MWRP is almost similar to that of the link state routing algorithm. The weight assignment of the link/ the wireless interface used by CR users to communicate with neighboring nodes is based on the transmission power (assuming a free space transmission model) required by the corresponding wireless interface. In addition, some links may be not possible while using some interfaces, based on the maximum transmission range supported by that interface. The feasible link which consumes minimum transmission power is selected as a part of the route.

3.4 MULTI-METRIC ROUTING

In most applications, certain QoS metrics are also important, besides the energy spent. Multi-metric routing protocols which consider several metrics for choosing an optimal route are used for such applications. The Delay and energy based spectrum aware routing protocol (DESAR) [9] one such multi-metric routing protocol, which aims to reduce both delay and energy. During route discovery process, the DESAR protocol checks both delay and energy-available at each intermediate node to select an efficient route between source and destination. The delay metric is a combination of switching delay, back-off delay and queuing delay. The energy metric gives the energy available at each intermediate node. It is calculated based on the number of packets transmitted and received at a time \( t \) as follows:

\[ C_{Es} = N_r * T_s + N_r * R_x \]
Here, $C_{Es}$ the consumed energy till time $t$, $N_s$, $N_r$ are the transmitted/received number of packets and $T_s$, $R_s$ are the constants that indicate energy consumed for transmitting and receiving a single packet.

### 3.5 EFFICIENT MODULATION TECHNIQUES

One of the early papers dealing with energy-efficient cognitive radio for WSNs is [10]. In this paper, the authors propose a joint design of cognitive radio and multi-carrier modulation (MCM). At the physical layer the entire spectrum partitioned into M sub carriers, each node detects all available sub carriers which are not busy with PU activity to initiate a new communication in a given time slot. An adaptive modulation strategy using the optimal constellation of QAM modulation is used to maximize the life time of a network.

### 3.6 MODIFIED REACTIVE ROUTING

More recently, the Energy and Cognitive-Radio-aware routing (ECR) protocol [11] has been proposed. It adds energy and cognitive-radio-aware features to the existing AODV routing protocol for WSNs. During route discovery process ECR checks residual energy and availability of common channel at each relay node. The relay node which does not satisfy the above metrics drops RREQ packet. The dropping of RREQ packet indicates that the relay node is not participating in route discovery process. The relay nodes which participate in routing process piggyback the node information on the RREQ packet, broadcast the RREQ packet to their nearby nodes and setup reverse path in their routing table (as in AODV protocol). The source node upon receiving RREP selects a route which has the least hop count to reach the destination.

In addition to residual energy checking while flooding the RREQ packets, preference is given to routes with more common channels between adjacent nodes. This reduces frequent channel switching and the energy spent doing that.

### 3.7 OPTIMIZATION AND HEURISTICS FOR MINIMIZATION OF ENERGY

The authors in [12] consider maximization of energy efficiency while scheduling resources among secondary users in CRN as an optimization problem. To make the solution to this computationally feasible, the authors suggest two ways. First, they propose EEHS (Energy-Efficient Heuristic Scheduler), a heuristic algorithm that takes polynomial time. The EEHS allocates idle frequencies to the CR that has maximum efficiency at these frequencies.

As an alternative, the original optimization problem is divided into two problems - one with throughput maximization with some constraints on energy consumption (TMER) and the second with energy consumption minimization to achieve throughput guarantees (EMTG). The TMER and EMTG work based on satisfaction parameter- the CR/SU which have lower satisfaction requirement are favored in frequency allocation. This leads to increase of their satisfaction ratio and in turn the CRs which are less satisfied are favored in the subsequent frames.

The authors propose a distributed optimization algorithm for a multi-hop CRN [13]. The goal of the optimization is to maximize the data rates for a set of user communication sessions. The proposed distributed algorithm deals the problems of cross-layered nature of CR networks with modules for routing, minimalist scheduling and power control/scheduling.

The routing module uses the bandwidth-footprint product (BFP) as the metric. This metric is a product of the bandwidth used by a CR node and the interference footprint of the node. The limited transmission range of a node is a hurdle to achieve high data transmission rates and due to this reason, the proposed algorithm employs multi-hop for data routing.

### 3.8 COOPERATIVE SPECTRUM SENSING

Since a significant amount of energy is spent in sensing the spectrum, cooperative spectrum sensing (CSS) has been proposed by some authors. Under CSS, each SU senses the spectrum and sends the findings to a fusion center. The fusion center then assigns transmission frequencies based on the gathered information. [14] proposes two Time-Saving and Energy Efficiency One Bit CSS (TSEEOB) schemes. TSEEOB has two stages - the first stage of coarse spectrum sensing is used when no PU exists or the SNR (signal to noise ratio) is high. This stage reduces sensing time and saves energy. The second stage is needed in case of low SNR for fine spectrum sensing. This stage increases the spectrum sensing accuracy, but consumes extra energy. Only one bit decision is sent to the cognitive base station (fusion center) to minimize overhead.

### 3.9 RF HARVESTING

RF harvesting, a technique in which the received RF signals are converted into electricity, is a new and novel solution for the energy scarcity problem in wireless networks. An excellent survey of RF-EHNs is in [15]. Cognitive radio routing protocols which incorporate RF-EHNs (Radio Frequency energy harvesting networks) can find efficient and effective routes. Unlike the traditional energy-aware routing protocols in CRN, the routing protocols with RE-EHNs can consider energy harvesting parameters (sensitivity of harvester and conversion rate, distance from PU, etc) as routing metric. During PU activity the nearby SUs can harvest energy.

In [16], the authors propose one such technique. The proposed method considers that the SUs in the CRN are equipped with RF energy harvesting devices. SUs perform channel access either to transmit a packet when the accessed channel is idle or to harvest RF energy when the selected channel is busy by PU activity. The authors present an optimization formulation to obtain the channel access probability for the SU and increase its throughput. They consider two cases, one where the SU knows about the current state of the channels and another where it knows the probability of channels being idle in future. Since this knowledge may not always be present, they also present an online learning algorithm using which the SU can adapt channel access by observing the environment.
4. CONCLUSION AND FUTURE DIRECTIONS

Routing based on cognitive radio has been explored widely in the past. However, energy efficient cognitive radio routing techniques are fewer. In this paper, we have presented some of the existing work on energy efficient CR routing. The following are some of the areas in which future work may be done.

1) **Support for routing with QoS:** Routing with assured QoS is necessary for some applications. For example, real-time applications require very less delay. It is a challenging task to perform routing in CR networks while minimizing energy and providing deterministic or probabilistic QoS.

2) **Fault tolerant routing:** Existing routing protocols for CRNs are based on traditional reactive or proactive routing protocols using RREQ messages used during the route discovery phase. As the network topology changes over time, maintenance of routes while conserving energy is an interesting problem which needs more attention.

3) **Secure routing:** The presence of malicious nodes in a CRN results in unreliable communication between nodes. Detecting such malicious nodes and routing data along secure paths while conserving energy needs to be addressed in more detail.

4) **Development of realistic protocols:** Most of the existing routing algorithms are simulated. To develop more realistic protocols and study the performance of in terms of energy, the designed protocols should be tested using actual deployments or test-beds.

REFERENCES


