A CRITICAL REVIEW OF THE ROUTING PROTOCOLS FOR COGNITIVE RADIO NETWORKS AND A PROPOSAL FOR LOAD BALANCING LOCAL SPECTRUM KNOWLEDGE-BASED ROUTING

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ABSTRACT

We present a critical review and analysis of different categories of routing protocols for cognitive radio networks. We first classify the available solutions to two broad categories: those based on full spectrum knowledge (typically used to establish performance benchmarks) and those based on local spectrum knowledge (used for real-time implementation). The full spectrum knowledge based routing solutions are analyzed from a graph-theoretic point of view, and we review the layered graph, edge coloring and conflict graph models. We classify the various local spectrum knowledge based routing protocols into the following five categories: Minimum power, Minimum delay, Maximum throughput, Geographic and Class-based routing. A total of 25 routing protocols proposed for cognitive radio networks have been reviewed. We discuss the working principle and analyze the pros and cons of the routing protocols. Finally, we propose an idea of a load balancing-based local spectrum knowledge-based routing protocol for cognitive radio ad hoc networks.

KEYWORDS

Routing Protocols, Cognitive Radio Networks, Load Balancing, Ad hoc Networks, Local Spectrum Knowledge, Full Spectrum Knowledge

1. INTRODUCTION

A cognitive radio (CR) is defined as a radio that can change its transmitter parameters based on the interaction with the environment in which it operates [1]. CRs have the ability (cognitive capability) to sense and gather information (such as the transmission frequency, bandwidth, power, modulation, etc) from the surrounding environment [2] as well as swiftly adapt (reconfigurability) the operational parameters, for optimal performance, according to the information sensed [3]. The cognitive radio technology is being perceived as the key enabling technology for the next generation dynamic spectrum access networks that can efficiently utilize the available underutilized spectrum allocated by the Federal Communications Commission (FCC) to licensed holders, known as *primary users* (PUs). Cognitive radios facilitate a more flexible and comprehensive use of the limited and underutilized spectrum [4] for the *secondary users* (SUs), who have no spectrum licenses.

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Cognitive radios enable the usage of temporally unused spectrum, referred to as *spectrum hole* or*white space* [3], and if a PU intends to use this band, then the SU should seamlessly move to another spectrum hole or stay in the same band, altering its transmission power level or modulation scheme to avoid interfering with the PU. Traditional spectrum allocation schemes [5] and spectrum access protocols may no longer be applicable when secondary unlicensed users coexist with primary licensed users. If SUs are allowed to transmit data along with PUs, the transmissions should not interfere with each other beyond a threshold. On the other hand, if SUs can transmit only in the absence of PUs, then a SU transmitting data in the absence of a PU should be able to detect the reappearance of the PU and vacate the band.

The problem of routing in multi-hop cognitive radio networks (CRNs) refers to the creation and maintenance of wireless multi-hop paths among the CR users (another name for Secondary Users, SUs) by deciding the relay nodes and the spectrum to be used on each of the links in the path. Even though the above problem definition exhibits similarities with routing in multi-channel, multi-hop ad hoc networks and mesh networks, the challenge in the form of dynamic changes in the available spectrum bands due to simultaneous transmissions involving PUs needs to be handled. Any routing solution for multi-hop CRNs needs to be tightly coupled with spectrum management functionalities [7] so that the routing modules can take more accurate decisions based on the dynamic changes in the surrounding physical environment. As the topology of multi-hop CRNs is highly influenced by the behavior of the PUs, the route metrics should be embedded with measures on path stability, spectrum availability, PU presence, etc. For instance, if the PU activity is low-to-moderate, then the topology of the SUs is almost static, and classical routing metrics adopted for wireless mesh networks could be employed; on the other hand, if PUs frequently become active, then the routing techniques employed for ad hoc networks could be more applicable [4]. Also, the routing protocols should be able to repair broken paths (for nodes or used channels) due to the sudden reappearance of a PU.

With respect to the issue of spectrum-awareness, the routing solutions for CRNs could be classified as those based on the full spectrum knowledge and local spectrum knowledge. In the former case, the spectrum availability between any two nodes in the network is known to all the nodes (or to a central control entity). This is often facilitated through a centrally-maintained spectrum database to indicate channel availabilities over time and space. The routing solutions built on the top of the availability of full spectrum knowledge are mostly based on a graph abstraction of the CRN and, though not often practically feasible for implementation, are used to derive benchmarks for routing performance. The routing module is not tightly coupled with the spectrum management functionalities for centralized full spectrum knowledge-based solutions. On the other hand, for local spectrum knowledge based solutions, information about spectrum availability is exchanged among the network nodes along with traditional network state information (such as the routing metrics, node mobility, traffic and etc). On these lines, the local spectrum knowledge-based routing protocols could be further classified as those that aim to minimize the end-to-end delay, maximize the throughput and path stability. In addition to the above, we have also come across probabilistic approaches for routing (e.g., [8, 9]) in which CR users opportunistically transmit over any spectrum band available during the short idle periods of the surrounding primary users.

The Common Control Channel (CCC) is used for neighbor discovery as well as for path discovery and establishment. Nodes share their neighbor information on different interfaces through broadcast messages sent on the CCC to all the potential neighbors, using a high transmission power, corresponding to the maximum transmission range of the CR nodes. The CCC could be either in-band or out-of-band with respect to the data channels. If in-band, the CCC may be one of the data channels to which all nodes can tune in; if a data channel common to all CR nodes is not possible to be found, then the network could employ more than one CCC, each of which having certain region of coverage. In the case of out-of-band CCC, a dedicated control channel, separate from the data channels, is used for control signaling, either network-wide or coverage-based. If the CCC and the data channels are accessible through a single radio, the routing solutions are prone to the channel deafening problem wherein the control message received on one channel is not received when the radio is tuned to a different data channel. If a dedicated radio is allotted for the CCC, one could avoid the channel deafening problem [6]; however it would be expensive to employ more than one radio per CR node, and also CR nodes employing more than one radio suffer from the cosite interference problem [6] when signals transmitted and/or received on one radio interfere with signals transmitted and/or received on the other radio.

2. ROUTING SOLUTIONS BASED ON FULL SPECTRUM KNOWLEDGE

The general strategy under this approach is to first abstract the physical network as a graph with nodes and edges with weights, all capturing the network dynamicity and spectrum availability, and then run a route calculation algorithm on the graph to find a path/tree or any appropriate communication topology connecting the nodes. In [10], the authors propose a generic framework for modeling CRNs comprising of nodes with a single half-duplex cognitive radio transceiver that can be tuned to the available spectrum bands or channels. The framework is based on creating a layered graph (one layer per available channel). Each CR device is represented in the layered graph with a node, A, and M additional sub nodes A_1, A_2, …, A_M, one for each available channel, and M is the total number of available channels. Three kinds of edges exist in this layered graph: The *access* edges connect a node with all its corresponding sub nodes; the *horizontal* edges connect the sub nodes of two different nodes on the same logical layer if the two nodes can be tuned to the corresponding channel; the *vertical* edges connect sub nodes of different layers of a single CR device to switch from one channel to another. Figure 1 illustrates a layered graph with four nodes and two channels. The weights of the horizontal edges typically capture the cost involved in propagating data from one CR node to another on the particular channel and the weights of the vertical edges typically capture the cost involved to switch from one channel to another at a particular CR device. Graph theoretic algorithms optimizing the overall cost of a path between every source-destination pair, or trees connecting a group of nodes (for multicasting) or all nodes (for broadcasting) could then be run on such a weighted layered graph. For example, in [11], the authors represent the horizontal edge weights to be proportional to the traffic load and interference, and propose a centralized heuristic algorithm to calculate shortest paths.

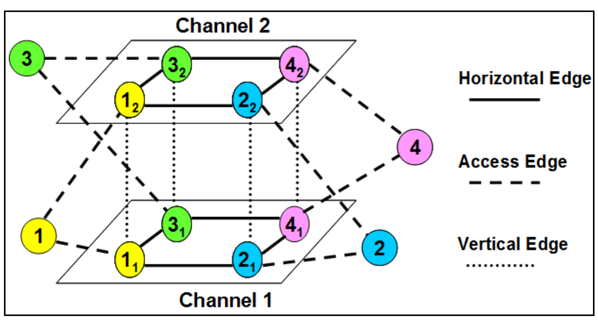

Figure 1: Example for Layered Graph Model

The main weaknesses of the layered graph model presented above are that it requires a network-wide signaling to generate such a global graph at each node and it may not scale well as the network dimensions increase. To circumvent the scalability problem, an edge coloring model was proposed in [12] that gets away with representing sub nodes of a node in multiple layers, and instead connects the nodes with edges of different colors, with each edge color indicating whether the nodes can communicate on a particular channel (i.e., one color per channel). The edge coloring model has also been extended to locally optimize the adjacent hop interference.

Another solution is to capture the network as a conflict graph [13] where each node in the conflict graph is actually an edge between two nodes in the network graph and there exists an edge in the conflict graph only if the edges corresponding to the two end nodes of the conflict graph cannot be active at the same time. One can then run a maximum independent set (or maximum clique) heuristic on the conflict graph to derive a conflict-free channel assignment for the original network graph. Nevertheless, all of the three graph theory models (layered, colored or conflict graphs) suffer from the weakness of being centralized in nature and requiring the full knowledge of the network topology and the available spectrum bands.

3. ROUTING SOLUTIONS BASED ON LOCAL SPECTRUM KNOWLEDGE

The routing solutions based on local spectrum knowledge (that varies both in time and space) are distributed in nature and differ depending on the specific metric used to assess the route quality. One class of routing distributed local spectrum knowledge-based routing protocols assume the availability of the CCC across all the CR nodes in the network. Route discovery is launched through a Route-Request-Reply (RREQ-RREP) cycle run on the CCC at all the nodes. An AODV (ad hoc on-demand distance vector) [15]-style routing protocol for CRNs has been proposed in [16]: the RREQs are broadcast on the CCC; the intermediate forwarding nodes keep track of the cost accumulated on the path traversed by the RREQs; the destination initiates the RREP packet, propagated back on the reverse route (with the minimum cost) setup during RREQ propagation. However, by using CCC for RREQ propagation, one cannot easily/accurately capture the availability of data channels at intermediate CR nodes.

An alternate strategy for route discovery (without using the CCC) is to broadcast the RREQ packets on all the available channels and let a flood of RREQ packets reach the destination, on multiple paths and on multiple channels. The destination processes these RREQ packets and selects the best path(s) that satisfies the route selection criteria. The RREP messages are forwarded on all the available channels. The CAODV-BR [17] protocol, a cognitive adaptation of the AODV routing protocol, chooses backup routes in conjunction with a primary route and reverts to one of these backup routes when one or more hops/channels in the primary route is occupied by a PU. In a similar vein, the authors in [18] propose to use a backup control channel, in addition to a principal control channel (both of which are locally selected) at a node to coordinate the route discovery and channel switching mechanisms. Nevertheless, broadcasting across all the spectrum bands for route discovery would be too much of an overhead compared to broadcasting the RREQ packets on one CCC and including information about all the available channels at each node in these RREQ packets.

3.1 Minimum Delay-based Routing

In [23], the authors propose routing protocols to optimize the various components of the delay incurred at a node, with the overall objective of minimizing the delay incurred on a path. The delay at a relay node is conceived as the sum of the delays incurred to switch from channel to another; access the channel corresponding to the chosen spectrum band; and the queuing delay suffered by the packet before it is transmitted on the particular channel. The switching delay includes two components: the delay to switch the packet from one frequency band to another frequency band – a measure of the separation of the two frequency bands, and also the delay incurred due to the scheduling (the round-robin scheduling is often chosen for fairness) of the packet transmissions at the node across the spectrum bands in use. The queuing delay suffered by a packet is also influenced by the channel scheduling component of the switching delay. While

[23, 24] focused on minimizing the sum of the switching and access delays incurred at the relay nodes; [25] focused on minimizing the sum of the queuing delays at the relay nodes. In [26], the authors proposed a routing protocol that lets an intersecting node (a node that lies on more than one path from the source to the destination) to locally coordinate among the neighboring nodes to decide whether to accommodate an incoming new flow or to redirect it to one of its neighbors to obtain a relief to the workload on the node. If such a route redirection materializes, this would actually lead to a scenario wherein the route discovery RREQ-RREP packets traverse through the intersecting node and the data packets traverse (a different path) through the neighbor node that took up the load from the intersecting node to provide relief to the latter's workload. In [27], the authors propose to shift traffic to the edge of the network away from the high-density regions to effectively use the available capacity throughout the CRN. This strategy has been observed to maximize the utilization of channel capacity in CRNs, compared to shortest path routing.

3.2 Minimum Power Routing

In the minimum power routing protocol proposed in [19], the weight of a link (for each interface) is modeled as the transmission power to be spent to reach the other end of the link within an appreciable received signal threshold. An energy loss is associated to switch from one frequency channel to another. An intermediate forwarding node includes in the RREQ the transmission power loss to be incurred for each of its outgoing channels. The destination receives the RREQ packets along all the paths and finds the path that minimizes the sum of the energy lost across all the links and their corresponding channels as well as the switching energy loss, if any, is incurred. The RREP packet containing information on the chosen route is sent through the CCC. The main weakness is the protocol is oblivious to the presence of PUs and their impact on neighbor discovery among the CR users. In [20], the authors propose an energy-efficient quality-of-service aware routing (EQR) protocol, built on top of the Dynamic Source Routing (DSR) protocol [21] for MANETs: the idea is that the source estimates and specifies, in the RREQ packets, the number of time slots needed for an ongoing session with a destination node; only those intermediate nodes that can commit the requested number of time slots forward the RREQ packets. EQR has been extended as Spectrum and energy-aware routing (SER) protocol [22] for multi-path routing. Both EQR and SER are not suitable for dynamic CRNs in which the availability of the PU channels changes quite unpredictably.

3.3 Maximum Throughput-based Routing

In [28-34], throughput-based solutions for routing in CRNs have been proposed. The Spectrum Aware Mesh Routing (SAMER) protocol [28] first establishes paths based on the periodically collected global states, and at the time of packet transmissions, the packets are delivered opportunistically along the path with the highest value for a throughput metric, referred to as the Path Spectrum Availability (PSA). The PSA captures the number of available spectrum blocks at each node as well as their aggregated bandwidth and loss rate. Though throughput is the primary routing objective, SAMER imposes an upper bound on the number of intermediate nodes to be used on the path and for which the PSA values are calculated. In [29, 30], the authors propose a cross-layer, spectrum utility based routing algorithm called ROSA (Routing and Spectrum Allocation) to maximize end-to-end throughput. The spectrum utility of a link (i, j) is the product of the achievable capacity of the link and the maximum differential backlog of packets between nodes i and j. ROSA maximizes the weighted sum of the differential backlogs and thereby gives preference to high-capacity links without generating harmful interference to other users (the bit error rate is guaranteed to be within a threshold) – all of these leading to increase in the throughput of the end-to-end communication [30].

In [31], a bandwidth footprint (BFP) minimization-based maximum throughput routing protocol has been proposed to find an appropriate channel and capacity for a session with minimal impact (with respect to interference and throughput) on the ongoing sessions of the PU and SU users. The BFP for a node refers to the interference area of the node for a given transmission power. With a node switching from one band to another and each band incurring a certain footprint corresponding to its transmission power, the objective of the protocol is to minimize the network-wide BFP, which is the sum of the BFPs of all the nodes. The routing protocol goes through an iterative procedure to fit in an incoming session request with the existing sessions. First, the session is assigned to an available capacity on a channel; if this is not sufficient, the transmission power of the band is increased to increase the session rate (referred to as Conservative Iterative Procedure, CIP). However, if the increase in transmission power violates the interference constraints and significantly increases the BFP, the alternative channels are considered to migrate the session to achieve the targeted session rate. To do this, the capacity allocated for the existing sessions in the alternate channel need to be reduced (referred to as Aggressive Iterative Procedure, AIP). If the reduction impacts the quality-of-service guaranteed for these sessions beyond a limit, then the new session is accommodated; otherwise, it is allocated a capacity in the alternate channel. In [32], the above work has been extended to develop a distributed cross-layer optimization algorithm (encompassed with routing, scheduling and power control modules) to iteratively increase the data rates for user communication sessions based on the notions of the CIP and AIP.

In [33], the authors propose a weighted cumulative expected transmission time (WCETT)-based routing protocol to determine high-throughput routing paths in multi-radio, multi-hop CRNs. The WCETT of a path is the weighted average of (1) the sum of the expected transmission times of the individual links on the path and (2) the maximum value of sum of the expected transmission times of the bottleneck channel used across one or more links/hops on the path. The idea is to avoid the use of the same channel over more than one hop on a multi-hop path to reduce co-channel interference along adjacent links. The hypothesis behind WCETT to maximize throughput is to choose a path that would incur channel switching along the links to minimize the delay incurred to wait for the same channel across several links. However, the protocol is only suitable for multi-radio environments, where channel switching is feasible. In [34], the authors propose a routing metric called Cognitive Transport Throughput (CTT) to capture the potential relay gain over the next hop. The locally calculated CTT values of the links (based on the local channel usage statistics) form the basis for selecting the best relay node with the highest forwarding gain in the Opportunistic Cognitive Routing (OCR) protocol for multi-hop CRNs.

3.4 Geographic Routing

In [35], the authors proposed a routing protocol whose objective is to choose the next hop that would minimize the interference to the PUs operating in the vicinity of the transmission and satisfy the QoS parameters for the SUs to the maximum. With respect to deciding on the next hop neighbor for a CR node employing geometric/geographic forwarding, the tradeoff observed is that the Farthest Neighbor Routing (FNR) scheme achieves a better end to end channel utilization and reliability; whereas, the Nearest Neighbor Routing (NNR) scheme has better energy efficiency.
The spectrum-aware beaconless (SABE) geographical routing protocol proposed in [38] selects the next hop forwarding node as follows: A source or intermediate CR node broadcasts a *request-to-forward* (RTF) packet in its neighborhood. The receiver CR nodes set their reply timer to be proportional to the distance to the destination node – i.e., the receiver node that lies closest to the destination responds the earliest with an *accept-to-forward* (ATF) packet. The RTF-ATF exchange happens on the CCC and the two nodes negotiate on the data channel to use for the actual packet transfer. The implicit assumption (a weakness) is that all the nodes know the exact location of the destination at any time (cannot hold true in the presence of node mobility). Besides, SABE suffers from the *dead end problem*, typical of geographic routing protocols. With the neighbor nodes not exchanging periodic beacon packets, they have to resort to a technique called Beaconless Forwarder Planarization (BFP) [37] to overcome the scenario wherein there are

no neighbor nodes that are closer to the destination node vis-à-vis the source or the intermediate node trying to forward the message to the destination. BFP identifies the neighbor node closest to the forwarder node to further relay the data towards the destination. However, this would result in significant waiting time for an ATF packet at the forwarder node. A forwarder node has to wait for a maximum timeout period expecting an ATF packet from its neighbor nodes and when only none of them respond within this period, the forwarder node can switch to BFP/nearest neighbor node forwarding.

3.5 Class-based Routing

The Farthest Neighbor Routing (FNR) strategy has been observed [38] to be more effective to offer better service differentiation for high-priority traffic in dynamic CRNs where the availability of the communication channel can be much shorter than the communication time. This observation formed the basis for the development of the Opportunistic Service Differentiation Routing Protocol (OSDRP) for dynamic CRNs. At each node, OSDRP basically sets up multiple forwarding nodes for a destination node, depending on the priority of the traffic flowing to the destination: The larger the priority of the traffic, the farther is the next forwarding node (i.e., more closer to the destination). In another related work [39] on class-based routing for CRNs, the authors propose two routing classes: Class I for routes that require lower end-to-end delay while guaranteeing minimum PU interference avoidance; Class II for routes that prioritize PU protection at the expense of permissible performance degradation for the CR users. The spectrum and next hop forwarding node are selected simultaneously at the time of route search: the RREQs of Class I routes are given priority (for spectrum and next hop node selection) over Class II routes.

4. Proposal for a Load Balancing Spectrum Knowledge-based Routing Protocol

We outline a brief idea for a load balancing local spectrum knowledge-based routing protocol for cognitive radio ad hoc networks that we are currently developing. We propose to balance the routing load at each intermediate forwarding node by letting each node to adopt one principal control channel and one backup control among all the available channels in the vicinity and broadcasting this information to the neighbor nodes on all the available channels. This way, a node gets to know the principal and backup control channel to use to communicate with each of its neighbors. By default, a node stays tuned at its principal control channel. When necessitated to do a channel switch, the node resorts to use the backup control channel as the principal control channel and anoints different available channel as the new backup control channel. The node updates this change in the control channel information to all its neighbor nodes by simply broadcasting this information to the neighbor nodes on all the available channels. The RREQ messages forwarded by a node contain the list of channels in use at the node, and the number of source-destination (*s-d*) sessions that are currently in progress through each of these channels. The RREQ messages are forwarded on all the available channels. The RREP message is propagated back on the principal control channel (or on the backup control channel if the principal control channel is not available) of the upstream nodes on the path from the source to the destination, as follows:

- When a destination receives the RREQ message, it chooses the neighbor node that is lightly loaded (the load at a neighbor node is the sum of all the number of *s-d* sessions going through the node), and selects a common channel (available to both the chosen neighbor node and the destination) that is the least used at the neighbor node. The RREP with the selected channel information is sent to the chosen neighbor node on the latter's principal control channel.

- The receiving neighbor node checks if any of the upstream neighbor nodes is the source node. If so, the neighbor node chooses a common channel that is lightly loaded at it and forwards the RREP with the chosen channel information on the source node's principal control channel. Otherwise, the node chooses the further upstream neighbor node that is the least loaded and also computes a weighted usage score of the common channels available/in use at both the chosen neighbor node and itself, and selects the common channel incurring the lowest weighted usage score. The RREP with the selected channel information is sent to the upstream neighbor node on the latter's principal control channel.

The LB-AODV protocol [40] (only available work on load balanced routing for CRNs) uses the number of packets buffered in the queue as the principal link metric and determine paths with minimum queue length (the sum of all the queue lengths at the individual nodes). A hop count limitation is imposed on these paths to constrain the end-to-end delay within certain bound. The primary weakness with LB-AODV is that it is agnostic to the spectrum availability and spectrum management is not tightly integrated with the routing protocol design. Secondly, the packet queue length is considered on a per-node basis and not on a per-channel basis for two neighbor nodes.

5. Conclusions and Future Research Directions

In this paper, we have presented an exhaustive review and analysis of the routing protocols that have been proposed in the literature for cognitive radio networks. From a design point of view, a common thread that should be prevalent in any proposed mechanism for CRNs is that the solution should not require the PU to be capable of adapting its transmission parameters due to the presence of the CR user. In fact, a licensed user need not be even aware of the presence of the unlicensed CR users, and there should be no appreciable degradation in the quality of service for the primary users. While the routing solutions proposed for centralized and/or infrastructure-based CRNs are typically construed to provide performance benchmarks, the solutions proposed for distributed/cooperative and/or infrastructure less ad hoc CRNs capture the practical difficulties and performance bottlenecks in real-time implementations.

Most of the active research conducted in the area of CRNs has been so far focused on spectrum sensing, allocation and sharing, and medium control access. As can be seen, more work needs to be yet done to develop routing protocols tightly integrated with spectrum sensing and management modules. Cross-layer protocol design (e.g. [30]) is a promising solution to accomplish effective interaction between the routing protocol network layer and the rest of the layers of the TCP/IP protocol stack so that the potential of cognitive radios can be fully realized from an application standpoint. Also, more work needs to be done towards design of routing protocols that minimize the number of channel switches (without overloading any node) by being able to model the PU activities and predict the availability of channels in the neighborhood. In addition, node mobility needs to be handled. In this context, we should target developing stability-based CRN routing protocols to minimize the number of route changes due to both channel switches/availability and node mobility.

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