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BioStaR: A Bio-inspired Stable Routing for Cognitive Radio Networks*

Mohammad A. Hoque, Xiaoyan Hong
Department of Computer Science
The University of Alabama
Tuscaloosa, AL, USA
{mhoque,hxy}@cs.ua.edu

Abstract—**Techniques derived from biological systems explore a new dimension of research in Cognitive Radio Networks (CRNs). In this paper, we address the stability issue of CRN routing, being motivated by the adaptive 'Attractor-Selector' model.Our work includes designing a routing protocolnamed Bio-inspired Stable Routing (BioStaR) that increases route stability by maximizing the Spectrum Opportunity (SOP)and also minimizes the channel switching delay and signaling overhead. To the best of our knowledge, this is by far the first bio-inspired CRN routing that takes into account the above mentioned factors. Our simulation results show that this protocol accounts for both higher stability of route and less signaling overhead in spectrum-agile CRN environments.***(Abstract)*

Keywords- Attractor-Selector, Spectrum Opportunity, channel switching delay, route stability, signaling overhead (key words)

I. INTRODUCTION

Cognitive Radio Networks (CRNs) have become an innovative paradigm of mobile computing. Based on opportunistic use of unoccupied licensed spectrum, cognitive radios dynamically switch from one band to another to acquire the available free channels from spectrum holes. Hence joint spectrum selection and routing has become a popular area of research in the CRN arena. The challenge it to deal with potential network isolation and unreachability due to sudden fluctuations of primary user (PU) activity or unpredictable spectrum usage resulting to unreliable end-to-end delivery. Many schemes have been proposed for CRN routing. Unfortunately, none of these protocols focus on the route stability and signaling overhead in a spectrum agile environment.

Interestingly, routing approaches that are modeled from biological systems rely on utilizing fluctuations for self-organization which allows them to find secondary route that is more persistent in case of critical events[1]. Clearly, this feature has made the bio-motivated routing approachescapable to survive atsingle point of failure, despite of the fact that they are likely to operate through sub-optimal routes with relatively degraded performance compared to the optimized greedy algorithms [1,2]. Considering the case of CRN environment, where the primary users' activity regulates the connectivity of the cognitive network, the bio-inspired approach may compromise with additional hop count by selecting a longer path that is less vulnerable to PU interference while avoiding the unpredictable optimal route but eventually gaining the recovery time for new route setup in the event of spectrum unavailability.

In this paper we introducea self adaptive stable routing scheme 'BioStaR' for cognitive radio environment motivated by the*'Attractor Selection'* model [3] originated from *E. Coli*bacteria. In the original biological model, *Attractors* belong to the equilibrium points in the solution space that stabilizes thedynamic conditions of the system [4, 5]. In our routing protocol, the subsequent hop is determined by the attractor selection model. The basic Attractor Selection mechanism consists of two different types of behaviors, i.e., deterministic and stochastic behaviors. When the current system conditions (route, channel availability) are suitable for the environment, that is, the system state is close to one of the possible attractors, deterministic behavior drives the system to the attractor (best forwarding neighbor). Where the current system conditions are poor (sudden interference caused by PU), stochastic behavior dominates over deterministic behavior (random forwarding neighbor). When the system conditions recover (spectrum becomes available), deterministic behavior again controls the system [4]. In this way, attractor selection model self-adapts to surrounding challenges by selecting attractors, using stochastic as well asdeterministic behavior.

Our current work includes the design of CRN routing protocol BioStaR that accounts for route *stability* by maximizing the *Spectrum Opportunity (SOP)* and also minimizes the channel switching delay and signaling overhead. We define a route to be *stable* when it is capable to maintain the same path in case of sudden PU activity that normally causes an interruption of the secondary node communication. In our work, this stability is achieved by selecting a better sub-optimal path that contains the intermediate nodes which have multiple common channels available (we refer this as *SOP*) between two successive nodes along the path. In case, a PU encounters the path, the effected intermediate nodes can switch to non-interfering channels without having to detour the route. Thus, we prefer long term less vulnerable sub-optimal paths to short term more vulnerable optimized paths by exploiting the biological model.

We tested our protocol with our self-developed graphical simulator for evaluation. Our simulation results show that this protocol accounts for both higher stability of route and less signaling overhead in spectrum-agile CRN environments compared to the optimized route or shortest path route. The rest of the sections are organized as follows: Section II discusses about the related works, sections III and IV describes the system model and routing protocol. Section V analyzes the performances and finally we conclude in section VI.

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II. RELATED WORKS

The original theoretical concept of 'Attractor Selector' modelwas introducedin [3], whichacted as the key motivation for most of the works done by the successors. Several routing applications by exploiting this model are described for different types of wireless networks [1, 2, 4, 5]. In [5], the authors proposed a self-adaptive routing protocol named ‘MARAS’ for ad hoc sensor networks where the attractor resembled the next forwarding node in the path. But these works are not dedicated to CRN routing. Our work considersthe complicated CRN scenario with unpredictable and fluctuating spectrum.

On the other hand, not many CRN routing algorithms account for the stability of route in such a dynamic spectrum environment. Wang et. al. [6] proposed a routing metric that accounts for the spectrum opportunity (available channels) and hop count.Some of the routing schemes [8, 11] consider the heterogeneous channel properties for different spectrum bands while others focus on switching delay [7, 9, 10] as well as unpredictable behavior of primary users [12]. Some of the previous works advocate for geographical routing which also proved to be productive as well [10, 12]. The novelty of our work relies on the fact that it not only considers the above features but also concentrates on route stability.

III. SYSTEM MODEL

A. PU Activity Pattern

We consider ON-OFF pattern for the primary users. This means, whenever the primary user occupies a specific channel, the secondary users within the interference range immediately give up the spectrum until the primary user finishes the communication.Once the *PU* releases the channel it again becomes available to the CR nodes.

B. Distributed Local Updating

Our routing protocol is based on local network information where the nodes are only aware of the spectrum availability of their one- hop neighbors. Any change in channel availability will trigger the corresponding node to update its directly connected neighbors. Hence, the route discovery and maintanence procedure works in distributed fashion.

C. Geographic location information

We assume that all the secondary nodes have the information of geographical locations of other secondary nodes from GPS. However, this information does not provide any idea about the topology because there is no centralized information available about the spectrum opportunities (SOP) for all the nodes.

IV. BIOSTAR ROUTING PROTOCOL

A. Attractor Selection Criteria

While designing our routing metric for the proposed *BioStaR* algorithm, we considered the following criteria that increased the stability but reduced the overhead of route maintenance costs. Here, we define attractor as the successive forwarding node. The unpredictable and fluctuating spectrum, neighbor locations and directions of the destinations are modeled to be part of the selection criteria.

1) Minimizing Channel Switching Delay

Channel switching delay is one of the major factors in controlling the overhead of cognitive radio networks. Typically the delay is around 40ms. We attempt to minimize the channel switching delay by introducing a factor within our routing metric that helps avoiding paths with frequent switching. More specifically it checks for every two consecutive hops for channel switching. By minimizing consecutive channel switching, our algorithm reduces the relaying overhead that contributes to the end-to-end delay.

2) Maximizing Spectrum Opportunity (SOP)

This is the criterion that helps the routing scheme to be more stable than most other protocols. The way it works is like choosing a sub-optimal route that provides maximum spectrum opportunity along the path and reduces the probability of future detour in case of PU interference. For example: Fig. 1 shows a topology where there are three different paths from node 1to node 2.The first route is a2-hop path [1−3−2] with both the hops involving single channel sharing neighbors. The second route is a 3-hop path [1−3−6−2] with 2 single channel links (1−3) and (3−6) and one 2-channel link (6−2). The third route [1−4−6−2] is also a 3-hop path but here all the links consist of multiple channel sharing intermediate nodes.The figure shows double lines for those links which have 2 channels in common. Our algorithm will prefer the latter path due to more spectrum opportunity. The basic idea is to make a trade-off between the optimal and sub-optimal route by giving up the shortest route for avoiding the chance of future detour.

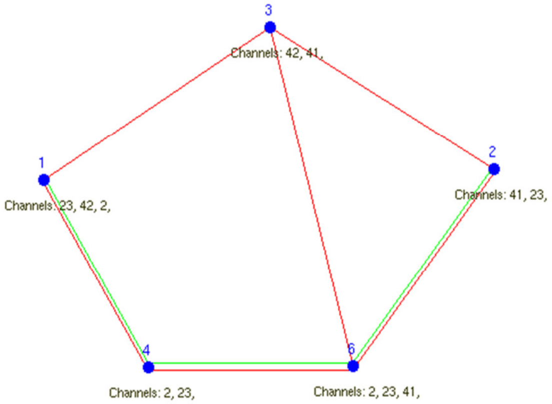

Figure 1. Example topology showing spectrum opportunity

3) Minimizing Hop count

The metric also has a maximum bound of path length for preferring sub-optimal route. We define a threshold as the maximum number of hops that can be considered in excess of the minimum hop reachability. Typically this value is set to 3 which means the preferred sub-optimal route can be at most 3 hops longer than the optimal route to increase the probability of stability in case a primary users suddenly appears within the interference range.

4) Directional Propagation

While selecting the attractor, our protocol gives preferences to those neighbors that are closer to the destination from the current node. But it does not completely exclude those neighbors who are located slightly off the direction towards destination as it may end up in a void area that could fail a greedy geographical routing despite of having a path.

TABLE I. NOTATIONS

$x = \begin{cases} 1 & if\ channel\ switching\ required \\ 0 & if\ no\ channel\ switching\ required \end{cases}$
$C_i =$ $Number\ of\ Common\ Channels\ with\ Neighbor\ i$
$C_{max} =$ $Maximum\ number\ of\ Available\ Channels$
$h = Current\ hop\ count$
$l_i =$ $Shortest\ Path\ Length\ from\ neighbor\ i$
$d =$ $Geographical\ Distance\ from\ Current\ Node$
$d_i =$ $Geographical\ Distance\ from\ Neighbor\ i$
$n =$ $Total\ number\ of\ neighbors\ for\ the\ current\ node$

B. *Routing Metric*

Based on the above four criteria, we define our routing metric as aggregated functions of these factors:

$$\rho = \max_{0\le i\le n} f(Channel\ Switching, SOP, Hop, d)$$

$$= \max_{0\le i\le n} \left(\frac{1}{2^x}\right)^{\alpha} \times \left(\frac{C_i}{C_{max}}\right)^{\alpha} \times \left(\frac{h}{l_i}\right)^{\beta} \times \left(\frac{d}{d_i}\right) \qquad (1)$$

The above table (TABLE I) defines the nomenclature for equation (1). Here,α, β are two weight factors which we vary during our simulation to see the performance difference. $\rho$is the ultimate routing metric that selects the best attractor from all the neighbors for the next hop.

C. *Description of the Protocol*

Our protocol, BioStaR,is a reactive protocol that works in a distributed manner as we consider no centralized topology information is available to the nodes. Each node is aware of only the one-hop neighbors or direct neighbors. It must be noted that, two nodes can be treated as neighbors only if there is at least one common channel available for transmission between the two nodes and the distance between the nodes has to be within the transmission range. Each wireless node possesses a routing table that keeps track of all available route information. The routing table is updated frequently based on the reply messages for route request (RREQ) (see below). The data structure of each entry in the routing table includes <destination ID, Forwarding Node, Current Path, No. of Hops>.Figure 2 shows the flowchart of the algorithm from high-level overview. In the following subsections, we describe the major functional steps involved in the routing protocol:

1) *Neighbor discovery*

All the nodes periodically broadcast *HELLO (Beacon)* messages in all the available channels. In order to receive the *Beacon* messages, the nodes periodically switch between the available channels and sense the media for any potential neighbor. The nodes that are located within the transmission range and share at least a common channel are supposed to receive the *Beacon* after every periodic interval. Through a *Beacon* message, every node informs its neighbors about all the available channels. Hence, in this way every node keeps track of the spectrum opportunities of its neighbors.

2) *Route Request Message(RREQ)*

The route establishment and maintenance part of our protocol is handled by sending route request (RREQ) messages. A major difference between our protocol and most other reactive protocols is that, our algorithm only sends route request to one of the neighboring nodes that appears as an attractor instead of broadcasting it to everybody. The RREQ packet will propagate from node to node in a uni-cast manner instead of traditional broadcast or flooding approach. The benefit of this approach is that on an average with a probability of more than 95%, the routing algorithm will successfully find a route, if there is any, by following the subsequent attractors all the way to the destination without having created the broadcast storm. In case the path along the attractor does not lead to the destination, the algorithm will forward RREQ to a randomly selected neighbor and this will continue until a route is found. The RREQ packet contains the information about previous node, destination node, current hop count and maximum allowable hop which is no more than 3 hops longer than the shortest path.

3) *Route Establishment*

Let us consider a source node *s* and a destination node *d* for a particular data traffic flow. Initially, the source node has no information about the path to destination unless the destination is a direct neighbor. So, it sends *RREQ* packet to the local attractor node calculated by the routing metric defined by equation (1). The attractor node checks if it is the destination updates the flag of RREQ message receipt for this source-destination pair. It again forwards the RREQ to the next attractor. If the destination node receives the RREQ it replies with the number of hop count. If the path following the attractors does not lead to the destination, the algorithm backtracks and goes for a random forwarding node. This continues until the destination is reached or there is no route to the destination.

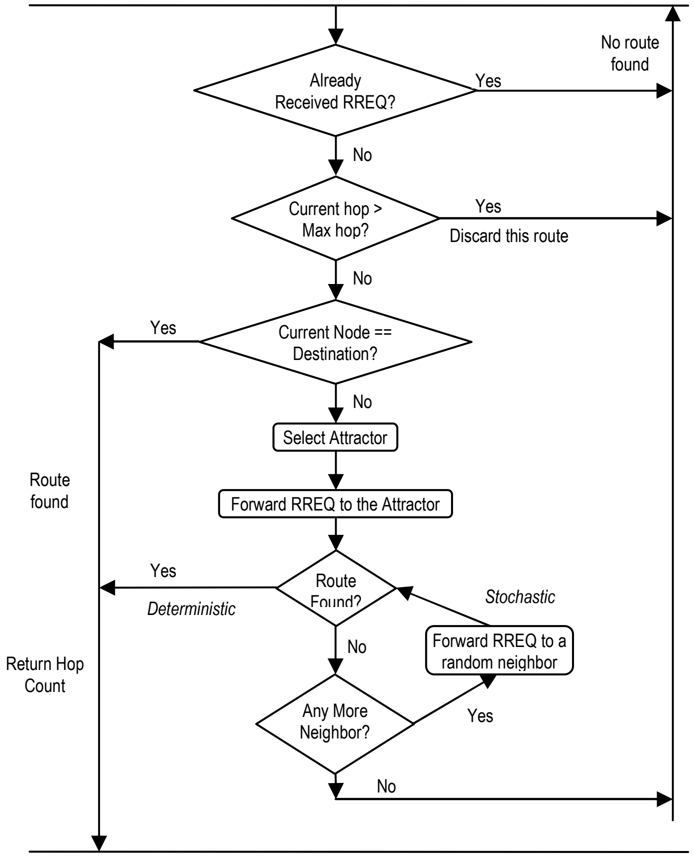

Figure 2. Flowchart for BioStaR routing algorithm

4) *Route Maintanence*

First the source node will look up the routing table for destination *d*. If it finds an existing path for *d* it will forward packets to the next node along that path. Every node along the path will check its own routing table for the subsequent forwarding node. If any intermediate node *m* discovers that the existing route is broken due to the interference from primary users, it will send a route request (RREQ) to the local attractor.

V. SIMULATION AND PERFORMANCE ANALYSIS

We have used an in-house developed CRN simulator for analyzing the performance of the BioStaR routing protocol in terms of stability and signaling overhead.Compared to the traditional protocols using broadcast signaling approach, our protocol incurs significantly less amount of overhead for both route discovery and maintenance. We also analyzed the effectiveness of the attractor selection metric in terms of the average probability of finding the route. We also performed robust analysis to measure the impact of PU activity on the connectivity of CR users for a large scale random network. In the following subsections we describe the results of simulation for each of the above mentioned analysis.

A. *Simulation Parameters*

We specified a simulation area of 1000 1000m. The transmission range for cognitive radio nodes were fixed at 200m. The GUI based simulator allows both random and interactive node placement for the wireless nodes. In our current experiment we only evaluated scenarios for static CR nodes in order to closely visualize the routing performance under variable PU density. However, the simulator is capable of handling CRN with random waypoint mobility model. We left the evaluation of mobile secondary users for our future work. The total number of CR node was kept fixed for a particular simulation run. The tuning parameters α and β were also varied. We examined the scenarios for four different densities of secondary users: 25, 30, 35 and 40. In all the four cases, we initialized the PU topology with 10 nodes randomly placed within the terrain boundary. Then in each successive step of the simulation, more primary users were introduced to create interference to the secondary network. We considered the shortest path routing algorithm as a benchmark for comparing with BioStaR.

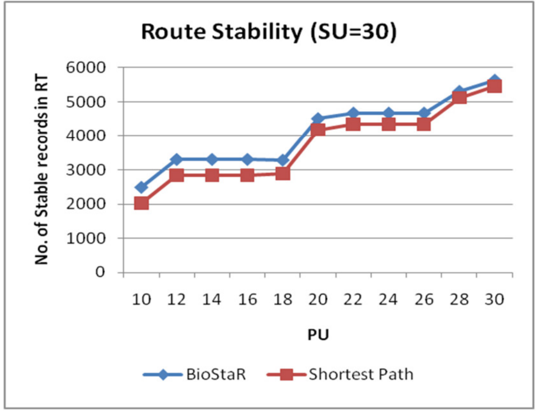

Figure 3. Comparative analysis of route stability

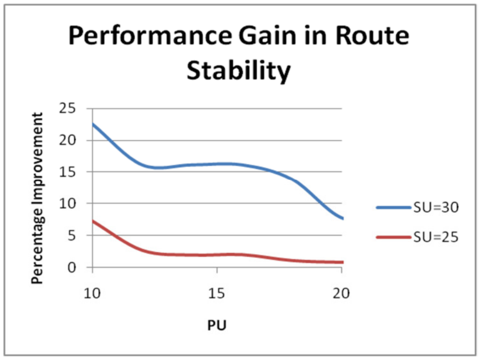

Figure 4. Performance gain in BioStaR

B. *Route Stability*

With the aid of the custom built CRN simulator, we were able to keep track of every single change in the routing tables of CR nodes caused by the sudden PU activity. Fig. 3 shows the total number of stable records in the routing tables of all the CR nodes for both BioStaR and Shortest Path routing after each random addition of new PUwithin the simulation area. We refer the term "stable record" as the routing table entry that remains same in terms of path after sudden appearance of PU.It may be noted that, the PU additionis likely to cause distortion of routes to some of the CR nodes, particularly to those nodes which were located within the interference range of that PU. The CR nodes that are affected by the PU activity needs to update their routing tables accordingly which may either result into unreachability or route change. In either case, we consider the corresponding routing entry to become unstable. Those pair of neighbors which have multiple spectrum opportunities (SOP) can possibly retain their original path by switching the channel even if one of the channels become unavailable. This helps them to avoid unnecessary detour or route maintenance at the cost of a channel switching interval (about 40us) which is considered as negligible compared to the alternative route establishment cost (in the order of several hundreds of milliseconds up to seconds). If the CR nodes manage to retain their previous paths, they are counted as stable route. In Fig. 3, we can see that for the same topological and network condition with a total of 30 secondary nodes, BioStaR has more stable routes than the shortest path routing (SPR) throughout the simulation period. In fig.4 we analyzed the percentage of performance gain in BioStaR compared to SPR for stable routes in two different simulation scenarios. In all cases, BioStaR has been proved to be more stable than SPR even though the performance difference becomes less noticeable after a certain period when the CR network begins to get disconnected and sparse.

C. *Signaling Overhead*

BioStaR showed a considerable amount of performance increase in terms of signaling or protocol overhead. The total number of control messages, transmitted from all the secondary nodes in order to perform route maintenance after each addition of new primary user, was used as a measurement for comparison of signaling overhead with the shortest path algorithm. We simulated three topologies with three different secondary user (SU) density. Fig. 5 shows the comparative analysis of control messages per path length for a given density of secondary users where total number of SU equals to 30. Here we can see that throughout the simulation, the normalized overhead for BioStaR is less than that of shortest path routing. Fig. 6 shows that, the maximum performance gain occurs for the secondary user topology with 30 nodes where an average improvement of 22-24%.

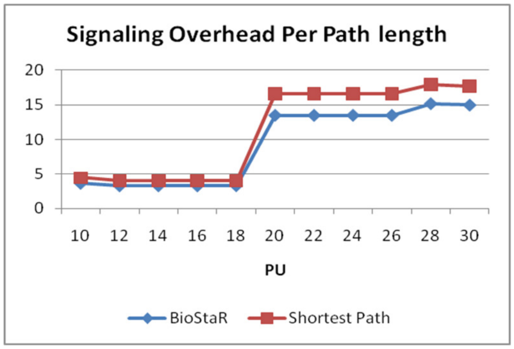

Figure 5. Comparative analysis of signaling overhead

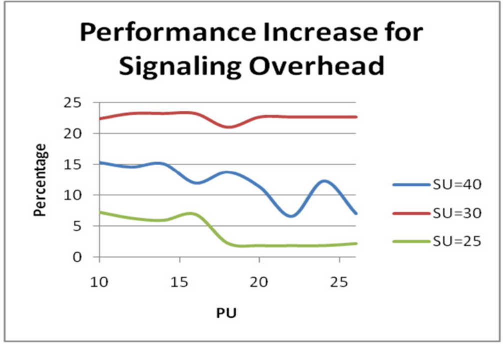

Figure 6. Percentage increase in signaling overhead for BioStaR

D. *Effectiveness of Attractor Selector Metric*

The effectiveness of the attractor selector metric is calculated by measuring the percentage of deterministic route and stochastic route out of total routes found. Our calculation shows that, given the routing metric in equation (1), the percentage of deterministic routing is always above 99% irrespective of the values of tuning parametersα, β. But from the Fig. 7 it is evident that the probability of deterministic routing decreases when the value of α is increased.

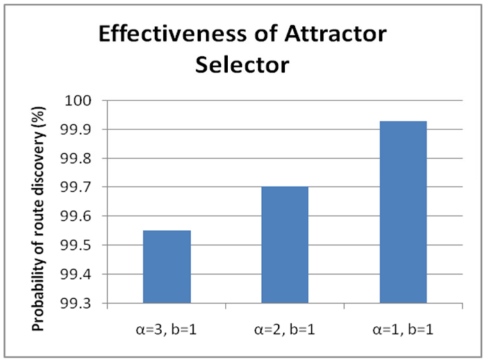

Figure 7. Effectiveness of the routing metric

E. *Channel Switching Overhead*

We also measured the probability channel switching by calculating the total number of times the subsequent links requires a channel switching along an end-to-end path divided by path length. It was revealed that, increasing the value of α reduced the probability of channel switch which is also evident theoretically from equation (1).

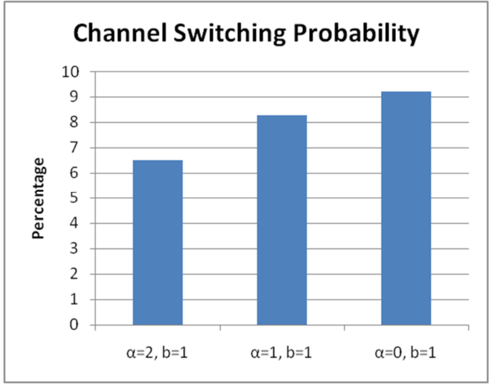

Figure 8. Channel switching probability

VI. CONCLUSION

This paper proposes a distributed stable routing protocol for cognitive radio environmentsmotivated by a novel idea of utilizing the highly adaptive bio-inspired 'Attractor Selector' model. The simulation results show that, on the average BioStaR protocol is 15-20% more stable than shortest path routing. Also the signaling overhead is reduced greatly in our protocol. Our futureextensions of this work will include considering the different mobility patterns along with the support for heterogeneous channel properties that controls the topology to a great extent.

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