A Cross-Layer Routing Protocol (CLRP) for Cognitive Radio Network

Ramzi Saifan   Ahmed E.Kamal   Yong Guan
Dept. of Electrical and Computer Engineering, Iowa State University, Ames, IA 50011
{ramzi, kamal, guan}@iastate.edu

***Abstract*—Routing in cognitive radio networks (CRNs) necessitates a cross-layering approach. However, according to [1], CRN routing protocols proposed in literature are partially cross-layer, because the information flow is only from physical layer to network layer, e.g., about channels availabilities. In this work, we introduce a cross-layer routing protocol (CLRP), which considers both the channels that are known to be available at each node, as well as other channels that may be available. The availabilities of the latter channels are considered using a stochastic approach. CLRP computes an end to end path, and feeds the physical layer with information about which channels to sense and which nodes should perform the sensing, such that the expected route quality is enhanced. Simulation results show that CLRP outperforms other cross-layer routing protocols in terms of throughput and stability of the path being setup, and increases the probability of finding an end-to-end path.**

I. Introduction

While the low frequency wireless spectrum bands have already been allocated, the Federal Communications Commission (FCC) measurements of spectrum utilization have shown that wireless spectrum utilization in some frequency bands can be very low, and the overall spectrum utilization is less than 15% [2]. Opportunistic spectrum sharing (OSS) was proposed to enhance spectrum utilization, where in OSS the unlicensed users, also called secondary users (SUs) can use the spectrum bands of the licensed users, also called primary users (PUs), provided that the SUs do not introduce harmful interference to PUs. The enabling technology for OSS is cognitive radio (CR) which enables the SU (or CR) to sense the channels and adapts its transmission characteristics accordingly.

A PU can usually tolerate interference for certain maximum intervals called tolerable interference delay (TID). For example, in TV channels, TID is 2 seconds [3]. Therefore, the CR that is using the PU's channel, should stop using that channel and sense (monitor) the PU every TID. In CRN, when the CR node announces to its neighbors that a set of K channels are available at the node, then it should monitor each of those K channels every cycle. Monitoring time is affected by many factors like how far is the CR from the PU, signal to noise ratio (SNR), fading, shadowing and PUs requirements. In some cases, the monitoring time of one channel consumes more than half of the TID cycle time.

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R. Saifan is now with The University of Jordan, Amman, Jordan; email: r.saifan@ju.edu.jo

In addition to the monitoring time of each channel, to switch from one channel to another channel in order to monitor it, a CR is expected to dynamically adjust its transceiver parameters to suit each communication opportunity. This switching time increases with the difference between the center frequencies of the initial and final channels. Therefore, it is not practical for the CR node to monitor the whole set of channels as this will practically result in reducing the transmission opportunities to a very small fraction of the time. Moreover, the number of available channels in CRNs is not fixed and the set of available bands may change over time and from one region to another.

Due to the aforementioned reasons, existing routing algorithms assume that each node observes and monitors a small set of available channels. Although increasing the size of this set enhances the routing decision and increases the probability of finding a path, this comes at the expense of increasing sensing overhead. Moreover, it is not possible to have all the nodes in the network sense all channels, each time there is a need to set up a path from a source to a destination. Therefore, each node starts with a small set of available channels, and a path that optimizes a certain quality metric based on these sets of available channels is found. However, some other channels may be available, but the nodes may not be aware of their availability. These channels may enhance the route quality and may increase the probability to find a path if the nodes knew their availablity, and this is the motivation behind proposing the cross layer routing protocol (CLRP) in this paper.

In this paper, we propose to take a broader view in which we consider all channels to be in the set of candidate channels for use in route setup. Under the CLRP protocol, each CR node monitors a small set of channels periodically. Channels that are monitored by a node are known for sure to be either available (probability of availability = 1), or unavailable (probability of availability = 0). Other channels which are not monitored by the node will be considered available with certain probabilities. Therefore, the routing approach calculates the quality of a path between a source and a destination using these probabilities (including the deterministic availability or unavailability of sensed channels). The quality metrics include the expected throughput and route stability. This proposed approach, as will be shown below, our proposed approach achieves better throughput and longer stability than traditional approaches which only consider the channels that are known to be available at the nodes. Moreover, we will show by simulation that our approach increases the probability of finding an end-to-end path.

The rest of this paper is organized as follows. The system model is introduced in Section II. In Sections III and IV we show how to use this approach to enhance the throughput and the stability of the routing algorithms respectively. Simulation results are introduced in Section V. Section VI surveys the related work and finally we conclude with some remarks in Section VII.

II. System Model and Problem Definition

The intuition behind our proposed approach is that when setting up a path, increasing the pool of available channels (either deterministically or probabilistically) may lead to enhancing the performance of routing protocols in terms of throughput and/or path stability, and may also increase the probability of finding a path. Therefore, the system model below takes into consideration these two types of channel availabilities, deterministic and probabilistic.

We assume that each channel is assigned to one PU which has an exclusive right to use the channel. If the PU can tolerate interference up to 1 second, then the CR should sense (monitor) the channel every second. If the CR node is monitoring a set of channels, the CR node should monitor each of these channels periodically. Also, the CR node spends time to switch from one channel to another, and this time depends on the frequency step, i.e., to switch from a channel on central frequency, f1 MHz, to a channel on central frequency, f2 MHz, the switching time will typically be $SW(f1, f2) = \alpha * |f1 - f2|$ [4], where α is the switching time per 1 MHz step, and is technology dependent. In some practical cases, the switching time may not be dependent on the frequency step, in this case the switching time becomes constant.

The monitoring time of each channel is affected by many factors like the signal to noise ratio, required detection probability, noise, impairments that may affect signal quality like shadowing and fading, and more. Monitoring time is assumed to be different from node to node and from channel to channel.

Sine channel availability is dependent on its location with respect to the PU location, and it is also dependent on whether the node is monitoring the channel periodically or not, different nodes see different available channels.

The inputs to CLRP are: 1) CRN topology, which consists of the CR nodes, their locations, the set of channels known to be available at each node, one source, and one destination, 2) The set of all the channels that the CRN can potentially use, and 3) Statistics about the PUs activity, i.e., the expected active times, the probability of the PU being busy or idle, their locations, the required periodic monitoring time at each CR node, TID which determines how often the CRs should sense the channel. These statistics can be measured by long term monitoring, and it is not within the scope of this paper. We assume that these statistics are available.

The output of CLRP will be a proposed path from the source to the destination that is composed of a set of nodes and the proposed channel to be used on each hop. Some of the selected channels at some relay nodes are available with certain probabilities because they are not monitored or sensed periodically. Therefore, the relay nodes should sense those selected channels after the path is determined. If the channel at the relay node was found to be available, it is used. Otherwise, the node will sense another channel to be used. However, the sensing step comes after setting up the path, where the nodes that are required to perform the sensing and the channels to be sensed have been determined.

We assume that all channels have the same bandwidth. We also assume that the activities of the PU on channel k can be represented by a birth/death process as shown in Figure 1, with birth rate (becoming busy), β, and death rate (becoming idle), λ, then the expected time for channel k to be idle within a cycle of activity is ($E(K) = \frac{1}{\beta}$). Moreover, probability for the PU's channel to be available, $Pr(\mathcal{H}0) = \frac{\lambda}{\lambda+\beta}$, and probability to be busy, $Pr(\mathcal{H}1) = \frac{\beta}{\lambda+\beta}$. λ and β for each PU is assumed to be known and it is out of the scope of this paper to calculate or update their values.

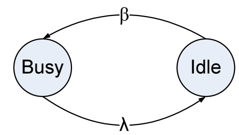


Fig. 1. PU activity model

For a channel that is within the set of available channels that the CR node senses periodically, $Pr(\mathcal{H}0)$ = 1. For a channel that the CR node knows for sure that it is not available, for example it has just sensed it and found to be unavailable, $Pr(\mathcal{H}0)$=0. For a channel that is available at one of x's neighbors, e.g., y, then $Pr_x(\mathcal{H}0)$ = 1 - Pr(it is not available on x given it is available at y) = 1-$P(\mathcal{H}1$ at $x|\mathcal{H}0$ at $y)$. These conditional probability can be found while taking into account the channel model [5] or using radio cartography maps [6].

The routing protocol is initiated by the source node, which floods a route request packet (RRQP) to all of its neighbors. When the RRQPs arrive to the destination, it finds which upstream node and which upstream channel maximize the quality and sends a route reply packet (RRPP) to that node which will be forwarded back to the source. The RRQP and RRPP are sent through a common control channel (CCC).

III. Enhancing Throughput

Since we are assuming that all the channels have the same bandwidth and same cycle length (T_c), and since each channel must be sensed every cycle, then the throughput can be represented by the transmission time per cycle, i.e.,

$$\text{transmission time} = \text{cycle length} - \text{overhead time per cycle}$$

The overhead time per cycle is the time that the CR node uses for sensing, switching between channels, access the channel, or anything else. In this subsection, we assume that initially each node is subject to a specific load per cycle. For example, node i carries load L_i, where this load is defined as follows. Asuming that node i is initially an intermediate node on v paths, where $v \geq 0$, and the node is initially monitoring K channels to receive/send on these paths, where $K \geq 0$. If the total sensing time needed to monitor the K channels is ST_K seconds per cycle, and if the time to receive/send on the v paths is TX_v per cycle, then the initial load at node i is:

$$L_i = ST_K + TX_v.$$

Consequently, node i is idle for time $T_c - L_i$ per cycle, where T_c is the cycle time length. Therefore, maximum throughput that can be achieved is $T_c - L_i$ when i is selected as an intermediate node on the path that is being set up.

Based on the above definitions, assuming that node i is going to use channel x (at central frequency f_x) for reception, and channel y (at f_y) for transmission, the load on i is:

$$L_i + ST_i(x) + ST_i(y) + \alpha * |f_x - f_y|.$$

where $ST_i(y)$ is the sensing time of channel y at node i. The throughput at i if it uses channels x and y for reception and transmission, respectively, for the route under study cannot exceed $T_c - (L_i + ST_i(x) + ST_i(y) + \alpha * |f_x - f_y|)$.

The process of route setup will be initiated by the source node by building a route request packet (RRQP) to be broadcast to each of its neighbors. The RRQP is composed of a table, with each record in the table representing a specific channel. Each record contains two values: the channel ID and the maximum throughput that the source achieves in case it uses that channel for transmission. The throughput at the source node, s, for each candidate downstream channel (c), is given by

$$q_s^d(c) = T_c - L_s - ST_s(c).$$

The throughput is calculated for all candidate channels whether they are known to be available at the source or not. After building the RRQP, the source broadcasts it to its neighbors.

Algorithm 1: : Finding the expected upstream quality, $q_w^u(c)$ for each channel, c at node w

algocf
1: **for** each candidate upstream channel, c **do**
2: $MaxQuality \leftarrow -1$
3: **for** each received RRQP from neighbor, x **do**
4: **if** (c is available at w) **then**
5: $Qua \leftarrow \min\{q_x^d(c), T_c - L_w - ST_w(c)\}$
6: **else**
7: $Qua \leftarrow \min\{q_x(c) * Pr_w^c(\mathcal{H}0), (T_C - L_w - ST_w(c)) * Pr_w^c(\mathcal{H}0)\}.$
8: **end if**
9: **if** ($Qua > MaxQuality$) **then**
10: $MaxQuality \leftarrow Qua$
11: $UpStramNode \leftarrow x$
12: **end if**
13: **end for**
14: $q_w^u(c) \leftarrow MaxQuality$
15: UpStream Node of channel $c \leftarrow UpStramNode$
16: **end for**

Each intermediate node may receive multiple RRQPs, and will use the throughput values in these RRQPs to calculate the best expected upstream quality on each candidate upstream channel. Algorithm 1 shows how node w performs the calculation when it receives multiple RRQPs from its neighbors. The outer *for loop*, inspects all candidate upstream channels, and decides for each of the candidate upstream channels what the best expected upstream quality of that channel is. The inner *for loop*, inspects all received RRQPs, and decides which neighbor maximizes the expected upstream quality of the channel.

Line 5 in Algorithm 1 means that if channel c is available at w, the expected quality of channel c when w receives from x over the channel c, is the minimum of: 1) the quality value sent from x on channel c, $q_x^d(c)$ and 2) the load on w if it uses channel c for reception. The load equals the cycle time (T_c), minus the initial load on w (L_w), and minus the sensing time of channel c at w, $ST_w(c)$.

If channel c is available at w with probability $Pr_w^c(\mathcal{H}0)$, line 7 shows the expected upstream quality on channel c. It is similar to line 5, but is multiplied by the probability of the channel being idle to find the expected quality value, since w is not sensing channel c, and the status of this channel is therefore unknown. This is because w is unsure whether channel c is available or not. Lines 9-12 keep track of the maximum quality (Line 10), and the node that maximizes the quality (Line 11). After the inner *for loop* finishes, w knows the maximum expected upstream quality that can be achieved if channel c is used for reception, $q_w^u(c)$ (Line 14), and the node that maximizes the upstream quality (Line 15).

Then, w decides for each candidate downstream channel c, that it can potentially send on, what is the best expected quality value, $q_w^d(c)$ achievable if w uses c for transmission, and on which upstream channel and from which upstream node it is better to receive, if the channel c is used for transmission downstream. Algorithm 2 describes how to calculate this.

Algorithm 2: : Finding the expected downstream quality, $q_w^d(c)$ for each channel, c at node w

algocf
1: **for** each candidate downstream channel, c **do**
2: $MaxQuality \leftarrow -1$
3: **for** each candidate upstream channel, c_u **do**
4: **if** ($c_u \neq c$) **then**
5: $Qua \leftarrow \min\{q_w^u(c_u), T_c - L_w - ST_w(c) - ST_w(c_u) - SW(c, c_u)\}$
6: **else**
7: $Qua \leftarrow \min\{q_w^u(c_u), T_c - L_w - ST_w(c)\}$
8: **end if**
9: **if** ($Qua > MaxQuality$) **then**
10: $MaxQuality \leftarrow Qua$
11: $UpStramCh \leftarrow c_u$
12: **end if**
13: **end for**
14: **if** ($MaxQuality > q_w^d(c)$) **then**
15: $q_w^d(c) \leftarrow MaxQuality$
16: Upstream Channel of $c \leftarrow UpStramCh$
17: $SendRRQP \leftarrow True$
18: **end if**
19: **end for**

In the outer for loop, w loops over all the candidate downstream channels, and for each candidate downstream channel c, it calculates the quality if w used c for transmission. The inner *for loop*, loops over all the candidate upstream channels, c_u, w finds the quality if c_u is used for reception and c for transmission on the route being setup.

Line 5 shows when the upstream channel, c_u is different from the downstream channel c. The quality equals the minimum of $q_w^u(c_u)$ which was calculated in Algorithm 1, and the maximum throughput that can be achieved at w, if channels c_u and c are used for reception and transmission, respectively. The maximum throughput that can be achieved is the cycle length, minus the initial load, minus the sensing times of the two channels, and minus the switching time incurred due to switching between the two channels to monitor them and to use them. If $c = c_u$ (Line 7), then w senses one channel and the switching overhead equals zero. Downstream quality is not multiplied by the probability of the channel being idle, because it was considered in the upstream quality. If the calculated $MaxQuality$ is greater than the old $q_w^d(c)$ of channel c (Lines 14 -18), then $q_w^d(c)$ is modified to $MaxQuality$ (Line 15), and w keeps track of the upstream channel that w will be receiving on, if w used channel c for transmission (Line 16). Also, node w modifies the flag $SendRRQP$ which indicates that w should forward the RRQP to its neighbors because it has enhanced quality on one or more channels.

Each node, after modifying and sending the RRQP, may receive new RRQPs, and some of them are from nodes that have already sent the RRQP to the node previously. These new RRQPs must have been received because they include enhanced quality values on certain channels. Therefore, the node recalculates the RRQP given all the received RRQPs. It overwrites each entry that resulted in better quality and it does not change other entries. If one or more entries have been changed, the node will re-broadcast the RRQP to its neighbors.

The process continues until the RRQPs arrive to the destination (dst). The destination applies Algorithm 1 to calculate the $q_{dst}^u(c)$ for each channel c, and it decides which upstream channel, say c_u, maximizes the throughput and from which node, say n_u. Then, the destination sends a Route Reply Packet (RRPP) to n_u that it is expecting to receive on channel c_u. Node n_u knows when it sends on channel c_u what the matched best upstream channel (from Algorithm 2) will be, and what is the matched best upstream node (from Algorithm 1) to receive from. Therefore, n_u forwards the RRPP to that upstream node to inform the upstream node that n_u is going to receive on that channel from the upstream node. The process will be repeated until the RRPP arrives at the source.

Now the path is setup and each node knows on which channel to receive and on which channel to send. The availability of some of these channels is probabilistic. Therefore, any channel that was proposed to be used for routing at a specific node, if it is not within the node's monitored set of available channels (periodically senses them), the node must sense the channel, and use it if it is found to be available. If it is found to be unavailable, the node senses the next channel that maximizes the throughput. One advantage is that multiple nodes can do sensing in parallel. Also, the nodes that are required to perform sensing are known, while not all CR nodes need to sense. In our previous work [7], we empirically showed that this additional time takes usually less than a second.

IV. Enhancing Stability

We define stability as the duration that the path is expected to stay available without interruption by the PUs. One of the differences in routing in CRNs from other types of networks is that routing in CRNs is highly dependent on the PUs' behavior, i.e., if a PU becomes active, then the nodes that are using the PU's channel should stop using this channel, which results in disconnected paths. Since some applications may need paths that are expected to stay connected as long as possible regardless of the throughput or the end-to-end delay, then path stability can be another quality metric.

The stability of a multi-hop path, is measured by the minimum stability on all the hops of the path. For example, if a path is composed of 5 hops and the channels that are used on the five hops are expected to be available for 9, 9, 6, 3, and 10 seconds, respectively, then, the path stability is 3 seconds. The expected available time of a channel can be calculated from the PUs' behavior as shown in Section II. Therefore, the expected available time of the channel is PU dependent, not CR node dependent. But, the probability of the channel being sensed idle by some nodes will be different among the CR nodes because it depends on the location of the node, and whether the channel is known to be available on one or more of the node's neighbors.

Route setup with enhancing stability quality objective has some similarities to the process of enhancing throughput. However, there are some differences.

1) Line 5 in Algorithm 1, becomes

$$Qua \leftarrow \min\{q_x^d(c), E(c)\} \tag{1}$$

where $E(c)$ is the expected available time of channel c.

2) Line 7 in Algorithm 1, becomes

$$Qua \leftarrow \min\{q_x^d(c) * Pr_w^c(\mathcal{H}0), E(c) * Pr_w^c(\mathcal{H}0)\} \tag{2}$$

3) Both Lines 5 and 7 in Algorithm 2, become equal to

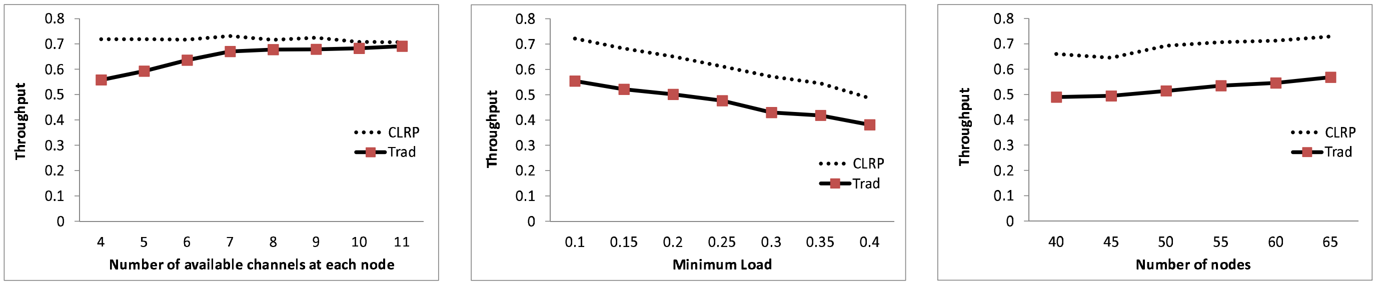
$$\min\{q_w^u(c), E(c_u)\} \tag{3}$$

4) To prevent cycles, each node should modify the downstream quality by subtracting a very small number (ϵ) from $q_w^d(c)$ for each channel c, such that always the downstream quality of a channel is less than the upstream quality even for the same channel.

V. Simulation results

We conducted our simulation on Java. We compare our routing approach (CLRP) with the traditional approach (referred to it in the figures by Trad). Traditional approach refers to the protocols that do not consider channels other than those sensed while making routing decision. For example, if a node monitors a set of 4 channels periodically, then during route setup, the route decision at that node is made based on these four channels without considering extra channels.

Throughout the simulation, we assume the following unless stated otherwise: total number of candidate channels = 40, PU TID = 1 second, channel bandwidth is 6 MHz, PUs are located randomly in a square area between (0,0) and (5000,5000), where the distances are in meters. The transmission range of the PU is 2500m, transmission range of the CR is 400 m, λ and β for each PU are selected randomly between 1ms and 100 ms, a CR source is at (0,0), a CR destination is at (1000,1000), 60 other CR nodes are distributed randomly in the square area (0,0) to (1000,1000), load at each CR node is randomly selected between 0.1 and 0.7, Switching α = 1 ms/1MHz, initial number of available channels at each CR node = 4 channels, sensing time of each channel was selected randomly between 1ms and 100ms, and PU status is found randomly based on the probability of being idle or busy.



(a) (b) (c)

Fig. 2. Throughput results: number of available channels in (b) and (c) is 4 channels at each node; CR node's transmission range is 400m

Figures 2.a-c compare the throughput of CLRP with the traditional approach. The throughput in the figures is the achieved throughput after path setup, sensing the channels at the nodes where channels' availabilities are with certain probabilities, and after finding available channels. Each point in these figures is the average of 100 runs. The effect of the initial number of available channels at each node on the throughput is shown in Figure 2.a. The channels available at a node are selected randomly out of the entire set of available channels. As the number of available channels increases, the throughput of traditional approaches enhances. This is because the network will be more connected and the nodes have more options for routing. However, CLRP is not affected by increasing the number of available channels because CLRP considers all the channels, whether they are sensed and were found to be available, or have not been sensed, but were considered based on probabilistic availability. Although the traditional approach will be close to CLRP as the number of available channels increases, but this requires too much overhead because the nodes have to perform periodic sensing for all of these channels.

Figure 2.b compares CLRP with the traditional approach for different values of the minimum load at each node. In this figure, the initial load at each node is selected randomly between the minimum load value and 0.7. It is obvious that as the minimum load increases, the throughput decreases. During this experiment, in 9% of the cases, the traditional approach did not find a path from the source to the destination. However, using CLRP, a path was always found in all simulation runs. Similarly, in Figure 2.c, in 13.3% of the times there was no path from the source to the destination using the traditional approach. Also, as the number of nodes increases, the throughput gets better because as the network dimensions are fixed, the network gets more connected.

Figure 3.a shows the effect of the PU behavior on the stability of the path. In this figure, the values of λ and β for each PU are selected randomly between the value in the figure and 100. Path stability under both CLRP and the traditional approach decreases with increasing minimum λ and β. But, CLRP is highly affected by increasing the minimum values because according to the equations in Section II, the expected available time of the channels will decrease. The decrease under the traditional approach is slight, because usually there are not many options for the traditional approach, where the path is selected only based on the channels known to be available at each node. Also, the stability equals the minimum stability on all channels along the path.

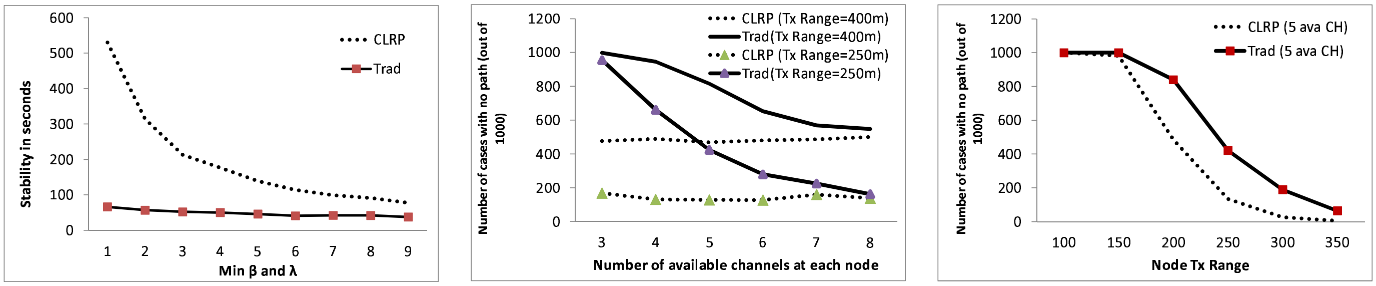
Another benefit of CLRP is increasing the probability of finding a path. For example Figures 3.b-c show the effects of changing the number of available channels at each node and the CR transmission range on the number of cases to find a path. Each point is the average of 1000 runs. In Figure 3.b, the results for the case of a CR transmission range of 400m were taken on a CR network that spans an area of 2000m x 2000m, while the results under CR transmission range 250m are for a CR network that spans an area of 1000m x 1000m. We can see that CLRP is not affected by how many channels are initially available at each node because the CR nodes consider all channels (either sensed and found to be available, or not sensed but are considered probabilistically). However, CLRP is affected by the CR transmission range because the number of neighbors decreases.

VI. RELATED WORK

Routing decision in cognitive radio network includes deciding jointly the relay nodes and the channels to be used at each node. Reference [8] showed that separating these two steps may result in not finding a path or the performance will suffer. Therefore, most routing protocols in literature consider joint selection of relay nodes and the channels at each hop [9], [8], [10], [4], [11].

Also, routing in CRNs requires spectrum awareness, where the nodes should have local knowledge about the available channels at the node. Therefore, routing in CRN requires cross layer design, where route decision that is done in the network layer should be based on the channels availability collected by the physical layer through sensing. Work in [9], [8], [10], [4], [11] present as cross layer routing according to this definition.

However, the authors of [1] argued that these routing protocols as not true cross layer protocols. They explained that in a true cross layer protocol, the information should flow in both directions. However, the information in such routing protocols flows only in one direction, from the physical layer to the network layer, where the physical layer informs the network layer which channels are available. Moreover, the network layer and the routing protocol do not instruct the physical layer about which channels to be sensed. Our proposed approach tries to close this gap by adopting the revised definition of CRN cross layer routing protocols where the information flows in both directions between the physical and network layers. The physical



(a) (b) (c)

Fig. 3. Stability results: (b) and (c) show the number of cases where a path was not found from the source to the destination out of 1000 runs

layer informs the network layer of the initial channels available, and the network layer informs the physical layer which channels to be sensed, while taking the sensing time overhead into consideration.

From another perspective, routing in cognitive radio network can be classified according to the quality objective that the routing protocol tries to optimize. Some protocols like the protocol in [9] tries to maximize the stability. Some others try to maximize the throughput [8], [10]. Also, end-to-end delay is considered in other protocols [4], [11]. However, none of these protocols considered monitoring time as overhead. Most of them assume that the set of available channels is generated by sensing, but without considering the overhead.

The authors in [12] takes into account channel sensing during route setup. The source first performs the sensing sequentially until finding an available channel, and then decides which of the candidate neighbors on geographic basis, and based on statistical measures, is the best relay node. It then sends a route request packet to the candidate nodes, where they will repeat the process and perform sensing for the channels sequentially. However, sensing time forms a non-negligible overhead because sensing is based on energy detection. The authors in [12] assume that when the source node or any relay node senses a channel, it will tell all of the neighbors to stop using that channel until sensing is done. However, since the node senses the channels sequentially, this takes large overhead where each node will repeat the same process.

VII. Conclusions

In this paper we proposed a new approach for routing in cognitive radio networks. When finding a route, our proposed approach considers all candidate channels whether they are known to be available at a node through sensing, or have not been sensed, but the probability distribution of their availabilities are known. Numerical comparison of our proposed approach with traditional approaches which build their routes based only on the channels availabilities through sensing, showed that our approach enhances the throughput and the stability of the routes being setup. Also, this approach increases the probability of finding an end-to-end path.

In the proposed approach, nodes can perform some of the sensing operations a posteriori, if needed, rather than a priori, hence saving sensing and switching times overhead. Also, sensing can be done concurrently, and not all nodes need to perform sensing. Moreover, sequential path selection may preclude setup of better paths, which is avoided by our proposed approach. Our approach is also more comprehensive in the sense that it can handle different quality metrics, and can also handle the cost of selecting a downstream relay node that is farther from the destination than the upstream node.

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