SEARCH: A Routing Protocol for Mobile Cognitive Radio Ad-hoc Networks

Kaushik R. Chowdhury, *Student Member, IEEE,* and Marco Di Felice

***Abstract*—Recent research in the emerging field of cognitive radio (CR) has mainly focused on spectrum sensing and sharing, that allow an opportunistic use of the vacant portions of the licensed frequency bands by the CR users. Efficiently leveraging this node channel information in order to provide timely end-to-end delivery over the network is a key concern for CR based routing protocols. In addition, the primary users (PUs) of the licensed band affect the channels to varying extents, depending on the proportion of the transmission power that gets leaked into the adjacent channels. This also effects the geographical region, in which, the channel is rendered unusable for the CR users. In this paper, a geographic forwarding based SpEctrum Aware Routing protocol for Cognitive ad-Hoc networks (SEARCH), is proposed that jointly undertakes path and channel selection to avoid regions of PU activity during route formation. Specifically, the optimal paths found by geographic forwarding on each channel are combined at the destination with an aim to minimize the hop count. By binding the route to regions found free of PU activity, rather than particular CR users, the effect of the PU activity is mitigated. Our proposed approach is thoroughly evaluated through simulation study.**

I. Introduction

The emerging field of Cognitive radio (CR) networks is geared to address the increasing congestion in the unlicensed band by opportunistically using vacant spectrum, such as, frequencies licensed for television broadcast, public service, among others [1]. While there has been considerable research effort in devising efficient spectrum sensing and sharing algorithms at the node level, it is important to seamlessly integrate these designs in the implementations of the end-to-end network protocols. As an example in a CR network, routes constructed at the network layer must not affect the ongoing transmission of the primary users (PUs) of the licensed spectrum and thus, they must have an awareness of the spectrum availability. Moreover, when a PU is detected, the routing protocol must make the key decision of either (i) switching the channel in the affected portion of the route, or (ii) passing through entirely different regions altogether, thus increasing the latency. The frequently changing PU activity and the mobility of the CR users make the problem of maintaining optimal routes in ad-hoc CR networks challenging. In this paper, we propose the SpEctrum Aware Routing for Cognitive ad-Hoc networks (SEARCH) protocol based on geographic routing, that adapts to the dynamic spectrum availability and the node mobility, while trying to maintain end-to-end connectivity.

A key problem faced in the design of distributed routing protocols in CR networks is that the path and channel decisions are made sequentially and not together. The best routing paths are first identified and *then* the preferred channels along the path are chosen in [2]. Here, the ad-hoc distance vector (AODV) routing protocol is modified to include the list of preferred channels by a given node as the route request (RREQ) is forwarded through the channel. Once the RREQ is received, the destination is aware of the channels that may be used to transmit at each hop and finds the optimal combination such that channel switching is minimized. If this RREQ is transmitted over the control channel and *not* on the channels actually used for routing, then the arrival time of the RREQs is not reflective of the true path latency. Moreover, the condition that there may not be any available channels in certain segments of the route is not considered.

The route formation in the SEARCH protocol is based, in part, on geographic routing. This principle is used in GPSR that undertakes greedy forwarding under normal conditions and enters into perimeter mode when a void (region with an absence of forwarding nodes) is encountered [3]. In order to circumvent this void, it requires the construction of a planar graph of the network at each node at all times or the creation of network-wide spanning trees [4]. However, this constitutes an overhead as only a few selected nodes need to participate in the perimeter forwarding mode. The classical GPSR has also been modified for particular application scenarios, such as, mobile vehicular networks in GPSRJ++ [6]. Though these efforts feature improved route maintenance ability under mobility assumptions and overcome the need to maintain the planar graphs, they need specialized street level knowledge.

We assume that each node has a single tunable radio and is location-aware. The location information is periodically exchanged between neighboring nodes through beacon updates. The primary band comprises of n possible CR channels. The PU activity results in a spectral overlap with the CR channels, which in turn, reduces with increasing separation from the transmission frequency. We consider the overlap factors as $1, 0.5$ and 0.25 for $0, 1$ and 2 channel spacings from the PU's central channel frequency, respectively.

The rest of this paper is organized as follows. In Section II, we present the route setup phase of SEARCH, our CR routing protocol in detail. A thorough performance evaluation is conducted in Section III. Finally, Section IV concludes our work.

Kaushik R. Chowdhury is with the Broadband Wireless Networking laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, 30332 USA. Marco Di Felice is with the Department of Computer Science, University of Bologna, Bologna, Italy. This work was completed when he was a visiting researcher at the BWN laboratory in 2008. e-mail: kaushikc@ece.gatech.edu, difelice@cs.unibo.it

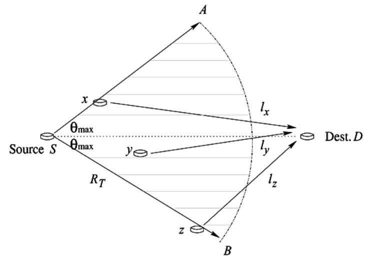


Fig. 1. Using greedy geographic forwarding on a given channel

II. SEARCH: A CR ROUTING PROTOCOL

First, the shortest paths to the destination, based on geographic forwarding and consideration of the PU activity, are identified on each channel. The destination then combines these paths by choosing the channel switching locations, with an aim to minimize the number of hops to the destination. In this section we shall describe the initial protocols functions in two parts: (i) the route setup phase and the (ii) route enhancement that is undertaken to improve the route, once it is in operation.

A. Route Setup:

In this stage, a route request (RREQ) is transmitted by the source on each channel that is not affected by the PU activity at its current location. It gets forwarded by intermediate hops till it reaches the destination, with each intermediate node adding in the packet its (i) ID, (ii) current location, (iii) time stamp and (iii) a flag status indicating the current propagation mode of the algorithm. The RREQ message may be forwarded by nodes only on the channels that are not affected by the PU activity. SEARCH operates in two modes - *Greedy Forwarding* and *PU Avoidance*, depending on whether the RREQ is propagating along the greedy shortest path to the destination or needs to circumvent a region of PU activity, respectively. Finally, the routes on the individual channels are combined at the destination by the *Joint Channel-Path Optimization* algorithm.

1) Greedy Forwarding: While SEARCH shares the principle of geographic forwarding with other related ad-hoc protocols like [3], the next hop is *not always* chosen purely on the greedy advance metric in our approach. The two distinguishing features are:

- The RREQ forwarding process must occur on the same channel and the chosen next hop must not be under a PU coverage region on the current transmission channel.
- The chosen forwarder must lie in a specific region around the current hop, called as the focus region, which we define later in this section.

In Figure 1, the source S has the nodes x, y and z within its transmission radius R_T. These nodes are at a straight line distance of l_x, l_y and l_z, respectively, from the destination D, where $l_x > l_y > l_z$. The focus region for S is shown by the sector $S - AB$ and extends to an angle of θ_{max} from the line SD. Classical geographic routing protocols like GPSR would have chosen node z at this stage, while SEARCH chooses the node with the greatest advance *within* its focus region, i.e. node y. If no such node exists, then SEARCH switches from the greedy forwarding phase to the PU avoidance phase.

We now define the focus region formally with reference to Figure 1,

Definition 1: **Focus Region:** Consider a straight line path, SD from a given node S to the destination D. The sector with transmission radius R_T, centered at node S and extending up to a maximum angular spread of θ_{max} on either side of SD, gives the focus region for this node.

Definition 2: **Decision Point:** A node that lies in the focus region of the previous hop along the path, but does not find a forwarding node for the RREQ in its own focus region, is called the decision point.

The focus region is shown as the shaded area in Figure 1. If the nodes x and y do not participate in the routing process, then node S would not have any candidate forwarder within its focus region. It would mark itself as a decision point, as per Definition 2.

Knowing the decision point (DP) gives an intuitive idea of the locations of the PUs and the occupied channels. We recall that the nodes within the coverage region of a PU do not take part in the RREQ forwarding process. Thus, they are virtually absent from the network topology on the affected channels and do not feature in the focus region as candidate forwarder nodes. Not finding any feasible node, this previous hop now labels itself as the DP and enters into the PU avoidance stage. When the RREQ is received at the destination, it knows the point on the route, i.e. the DP location, from which the path enters into a detour to avoid the PU region. SEARCH then attempts to find out alternate paths (and hence channels) at these detour locations.

2) PU Avoidance: When a PU region is encountered, rendering the channel in its vicinity unusable, the greedy forwarding towards the destination can no longer be carried out. This stage is called the PU avoidance stage as the RREQ now starts circumventing around the affected region. We explain this as follows:

Figure 2(a) shows the shaded circular area under the influence of a PU on the channel being used for forwarding the RREQ. In addition, the focus region for node x on this channel, from Definition 1, is given by the sector $x - AB$ with the maximum angle of $2 \cdot \theta_{max}$. Some of the nodes that sense the PUs and do not participate in the forwarding of the RREQ, lie in the focus region of the node x. Through the periodic beacon update, these affected nodes inform their one-hop neighbors, including node x, of the current state of the channel environment and of their current location. Thus, node x is aware that the closest node to the destination that can forward the RREQ (node a) lies outside its focus region. From Definition 2, node x concludes that it is a DP and sets the PU avoidance (PA) flag in the RREQ packet before re-transmitting it. The DP marks the point from which the route must circumvent the region of PU activity on the given channel. There may be several such DPs in the path to the destination and this information is collected by the RREQ as it traverses through the network. The PA flag in the RREQ

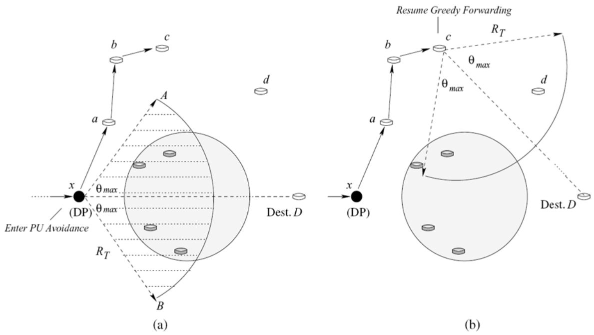


Fig. 2. The PU avoidance phase with the focus region

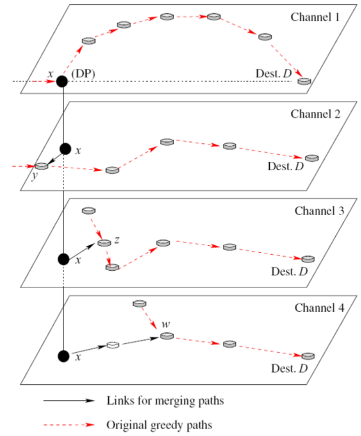


Fig. 3. The joint path and channel decisions at destination

remains set till a node is reached that has a candidate forwarder in its focus region. In the example shown in Figure 2(b), the RREQ traverses the node a, b and finally reaches node c. The latter has a candidate forwarder, node d, that lies in its focus region. At this point, i.e. at node d, the PA flag is reset, signaling the end of the avoidance phase and the greedy forwarding is resumed.

3) Joint Channel-Path Optimization: The optimization phase of the SEARCH protocol is designed to choose a combination of channels and the propagation paths along them that minimize the end-to-end latency.

In Figure 3, each plane represents a channel and the broken line shows the path obtained by the propagation of the RREQ on each of them. This path is limited on one channel and is a combination of the greedy forwarding and PU avoidance phases. Let the RREQ on channel 1 give the shortest path from the source to the destination D, among all the considered channels. A portion of this path from node x to D is shown. Let node x be the decision point (DP) where the path starts avoiding the PU affected region on channel 1. Our optimization framework tries to identify if a better channel (and hence, path) may be used at the DP, thereby preventing the additional hops incurred in channel 1. To allow a path switch at node x, the new path must have the node x in common, or must be within the transmission range of x. Thus, only the paths in channels 2 and 3 are considered as the nodes y and z are within range of x on these channels, respectively. The path on channel 4, being at a distance of at least two hops from node x cannot be included in this stage.

If the path on channel 1 is switched to a different channel, say channel 2, then the packet traverses on the path in channel 1 till node x and then on the path on channel 2 from node y to the destination. The channel, and hence, path change occurs at node x if the sum of the (i) path latency in the new channel from node y to the destination, (ii) the estimated time to reach node y from node x, and (iii) the cost of the switching the channel t_s is less than the path delay from node x to the destination in channel 1.

We define the variables used in the subsequent discussion as follows: The RREQ received on a given channel, say k, defines a path of l_k anchor points given by $P_k = \{A_k^1, A_k^2, \ldots, A_k^{l_k}\}$. The anchor points are the locations of the nodes that were chosen during the forwarding process of the RREQ packet and indicate the absence of PU activity. Some of these anchors may also serve as decision points (DP) depending on whether the path encounters a PU region. The optimal greedy path P_G is a combination (or union) of anchor points and the channel switching decisions shown by $C_j^{k,i}$, indicating that the channel is changed from k to i at the hop j. The transmission time for a packet on channel i is given as T_R^i and the total number of channels in the band is C.

We can formally express the route selection at the destination through the following algorithm steps.

- **Step 1. Initial Path Selection:** The destination D receives the RREQs on each channel $k \in C$ and extracts the path information P_k from it. The path P_k comprises of a set of nodes $\{A_k^j\}$ with their respective timestamps $\{t_k^j\}$, where $j = 1, \ldots, l_k$ and the final node is the destination, i.e., $A_k^{l_k} = D$. We first define the latency, L_k^m, from an intermediate point m to the final node l_k on the channel k based on their respective timestamps, t_k^m and $t_k^{l_k}$, as follows,

$$L_k^m = t_k^{l_k} - t_k^m \quad (1)$$

  As the first optimization step, considering the propagation from the first node of the route ($m = 1$), the least latency path L_k^m is chosen among all the available channels $k \in C$ using equation (1),

$$i = \arg_k \min\{L_k^1, \forall k \in C\} \quad (2)$$

  In this step, the greedy path solution P_G is initialized to the start node on the channel i as $P_G = A_i^1$. This set will grow as the choice of nodes and channel switching decisions are added progressively in the subsequent steps of the algorithm.
- **Step 2. Greedy Path Formation:** The least latency path may be further improved by switching to a different channel at the DPs. This is because the initial path having the minimum end-to-end delay, may not be continuously optimal through the intermediate path segments. In this step, SEARCH attempts to improve the chosen route by

considering intersecting paths on the other channels that may be locally optimal. The DPs are chosen for this optimization as the path starts curving at these locations and better paths on different channels that follow a shorter route to the destination may exist. Formally the next hop node, $A_i^{j=j+1}$, along the current chosen path on channel i is added to P_G, if it is not a DP. This step is repeated in a loop as long as a DP is not reached. Thus,

$$j = j + 1$$
$$P_G = P_G \bigcup A_i^j,\ if A_i^j \neq DP \quad (3)$$

If this next hop is the final destination, then the algorithm is terminated and the path is complete. In this case, SEARCH proceeds to Step 5 directly. If this is not so, and the next hop is indeed a DP, the local optimality condition is checked in Step 3.

- **Step 3. Optimization at the DP:** When a DP is reached, SEARCH attempts to find an *intersecting* path on a different channel at this location. A given path P_1 with node x is said to be *intersecting* with another path P_2, if the latter (i) has the node x common or (ii) has a node that is within transmission range of node x in path P_1. From Figure 3, the paths shown in channels 2 and 3 are intersecting with the path on channel 1 as the nodes y and z in these paths, respectively, are within transmission range of the node x. Given the channel switching time t_s and the time to transmit a packet T_R^k on channel k, the time overhead, δ_k, to reach the node in the intersecting path is $\delta_k = t_s + T_R^k$, $k \in C$.
The current channel i (and hence, the path) may be switched to an intersecting path (say, on channel k) at the node m in the transmission range of the DP j, only if the latter has a smaller latency to the destination measured from j. Also, the transmission range (R_T) constrains the allowed distance between the two nodes A_i^j and A_k^m by the inequality $dist(A_i^j, A_k^m) < R_T$. The total time taken to reach the destination is given by $L_k^m + \delta_k$, if channel k is chosen. Assuming the transmission range as R_T, the tuple $\{$hop number m', channel $k'\}$ is chosen that minimizes the total time $L_k^m + \delta_k$,

$$\{m', k'\} = \arg_{\{m,k\}} \min \{L_k^m + \delta_k\}$$
$$\text{dist}(A_i^j, A_k^m) < R_T,\ \forall k \in C \quad (4)$$

- **Step 4. Route Expansion:** The greedy path solution is updated with the new channel and path information. First, the channel switching decision shown by $C_j^{i,k'}$, is incorporated in the final path P_G, along with the node $A_{k'}^{m'}$ that serves as the next hop in the new path.

$$P_G = P_G \bigcup C_j^{i,k'} \bigcup A_{k'}^{m'} \quad (5)$$

Finally, the new channel k' is now the default channel, i.e., $i = k'$, $j = m$. The procedure of traversing the new path by checking the DPs is repeated from Step 2.
- **Step 5. Route Confirmation:** When the last hop i.e., the destination is reached, the route reply RREP is sent back to the source along the optimal route P_G. The RREP contains the IDs of the nodes, the anchor locations and the channel switching decisions. The routing of data packets can begin immediately when the source receives the RREP.

The next stage of optimization, route enhancement, occurs when the route is active and attempts to combine paths that are separated by more then one hop.

B. Route Enhancement

The route enhancement stage comes into operation *after* the initial route setup stage and conservatively explores the gains of linking together paths formed on different channels that are up to η hops away. From Figure 3, if the DP x is a part of the optimal route at the end of the route setup phase, this stage of the protocol may allow it to reach node w two hops away, on the least latency path in channel 4.

- In this phase, the currently used shortest path P_G is further optimized considering (i) all the remaining DPs on it, and (ii) the anchor points on the other routes (hence, on the other channels) that are within η hops of the considered DP. We assume that the currently used optimal path comprises of a set of anchor points given by $P_G = \{A_G^1, \ldots, A_G^q\}$. Formally, SEARCH chooses the DP on the optimal path (A_G^i) and the anchor A_k^m on channel k, that must be reached, to minimize the total distance to the destination. Here, the first constraint is that the node A_k^m must be within η hops of the DP A_G^i, i.e., $\text{dist}(A_G^i, A_k^m) < \eta \cdot R_T$. The maximum allowed physical distance between the two nodes is given by the product of the hop count η and the transmission range, R_T. On similar lines, the actual number of hops, $\eta_{i,m,k}$, between these two nodes is given by,

$$\eta_{i,m,k} = \frac{\text{dist}(A_G^i, A_k^m)}{R_T} < \eta \ where\ A_G^i = DP \quad (6)$$

If T_R^k is the transmission time for a packet on channel k' for a single hop, the total estimated time taken to traverse this distance of $\eta_{i,m,k}$ hops is $\eta_{i,m,k} \cdot T_R^k$. In order to find the tuple $\{i', m', k'\}$ that minimizes the total cost to the destination among all the possible combinations, we add the time to the destination from the new next hop m (L_k^m¡L_G^i) and the channel switching time t_s.
We formulate this optimization equation to find the tuple $\{i', m', k'\}$ as follows,

$$\{i', m', k'\} = \arg_{i,m,k} \min \{(\eta_{i,m,k} \cdot T_R^k + L_k^m + t_s) < L_G^i\}$$
$$\forall A_G^i \in P_G,\ and\ A_G^i = DP$$
$$\forall k \in C,\ \forall A_k^m \in P_k,\ \text{and}\, \eta_{i,m,k} < \eta \quad (7)$$

Summarizing the above discussion and from equation (6), we explain the constraints as follows: A node A_G^i in the optimal path P_G may be used in the minimization only if it is a DP. We consider the path P_k in each of the possible channels k in the channel set C. In these paths we allow the anchor points as a candidate solution if it is within η hops of the DP being considered.

- Once a feasible path is identified by the destination, it sends a route enhancement (ROP) message to the DP $A_G^{i'}$, found in the earlier step. The ROP contains (i) the ID of the node $A_{k'}^{m'}$ that must be reached on the new path, (ii) the path information in terms of successive next hop nodes from the intended node $A_{k'}^{m'}$ to the destination.
- The DP $A_G^{i'}$ receiving the ROP now sends an RREQ message with the node $A_{k'}^{m'}$ as the destination, similar to the route-setup phase involving greedy forwarding. The new path information received in the ROP is then included in the RREP and forwarded on channel k'.
- If the destination receives the forwarded RREQ, it checks if the actual latency on the new path is lower than the value on the current path from the DP $A_G^{i'}$. If so, an RREP is sent along the new route and an RERR is propagated along the earlier route indicating the formation and the teardown of the routes, respectively. In this process, the portion of the optimal path P_G after the DP $A_G^{i'}$ is deleted and the new path information is added. Thus, $P_G = P_G / \{A_G^{i'+1}, \dots, A_G^D\}$ followed by $P_G = P_G \bigcup \{A_{k'}^{m'+1}, \dots, A_{k'}^D\}$.
- This run-time optimization continues till all the DPs in the current optimal path P_G, have been explored and no further improvement in latency is observed.

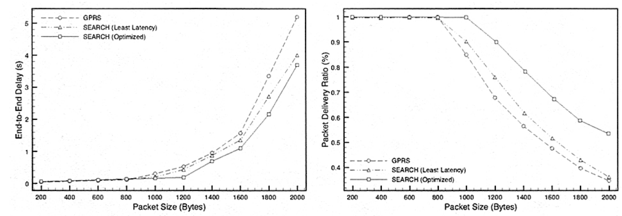
We next present the performance evaluation of SEARCH considering its different features and CR specific scenarios.

III. Performance Evaluation

In this section, we evaluate the performance of the SEARCH protocol under different network conditions, traffic loads and mobility factors. The simulation model is built in the NS-2 simulator with multi-radio multi-channel extensions. We model the primary users' activities by using the exponential ON-OFF process. Simulations are performed in random multi-hop network topologies, in which, 400 nodes are distributed in an area of $1000 \times 1000\,m^2$. The coverage range of the PU on its occupied channel is 300 m and the transmission range of the CR user is set at 120 m.

We demonstrate the performance improvement attained by SEARCH by comparative study of the following protocols:

1) **GPSR:** The classical GPSR [3] protocol is extended for a multi-channel environment. The least latency path over all the channels is considered as the final route chosen at the destination.
2) **SEARCH (Least Latency):** In this version of the SEARCH protocol, the route setup phase with the greedy forwarding (Section II-A1) and the PU avoidance components (Section II-A2) are retained. However, the path-channel optimization (Section II-A3) as well the route enhancement (Section II-B) is disabled. The final route chosen is the one that provides the least latency over all the available channels without any intermediate switching of channels.
3) **SEARCH (Optimized):** Here, all optimization modules are enabled and we assume $\eta = 2$ for the route enhancement function (Section II-B).



(a) (b)

Fig. 6. The effect of packet size on the end-to-end latency and the packet delivery ratio are shown in (a) and (b) respectively

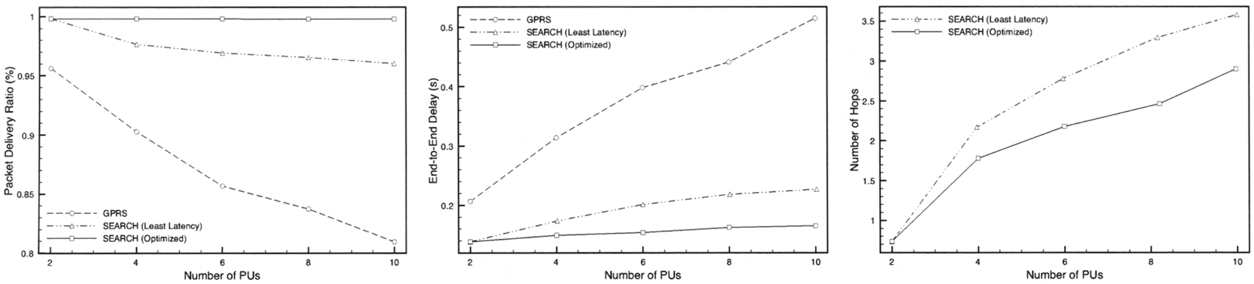
A. Effect of Number of Channels

We consider two separate cases of 5 and 10 channels, in which, a randomly chosen number of PUs is considered from the range $[1, 10]$. The PU is kept in the ON state for the duration of this experiment and the source and destination are initially separated by a distance of 850 m.

We first consider the packet delivery ratio (PDR) for 5 and 10 channels, as shown in Figures 4(a) and 5(a), respectively. We see a marked difference in PDR for the GPRS and the SEARCH protocols as the former does not account for the PU activity regions and may pass through them for the greatest advance to the destination. Apart from the effect on the CR user, a low PDR also implies that the PU reception is affected due to concurrent transmissions. Interestingly, SEARCH (least latency) does show a drop in the PDR as compared to the optimized case when PUs are increased. This is because with the increasing number of PUs renders large regions ineffective for transmission, even on the best available channel. Thus, there are some portions of the route that must intersect these PU affected region where detours are no longer possible. When more channels are present, the PU activity is shared among them and the region influenced by the PUs on any given channel is reduced. The ability to switch the channel in the optimized SEARCH allows the flexibility to maintain a high PDR, even under increasing number of PUs.

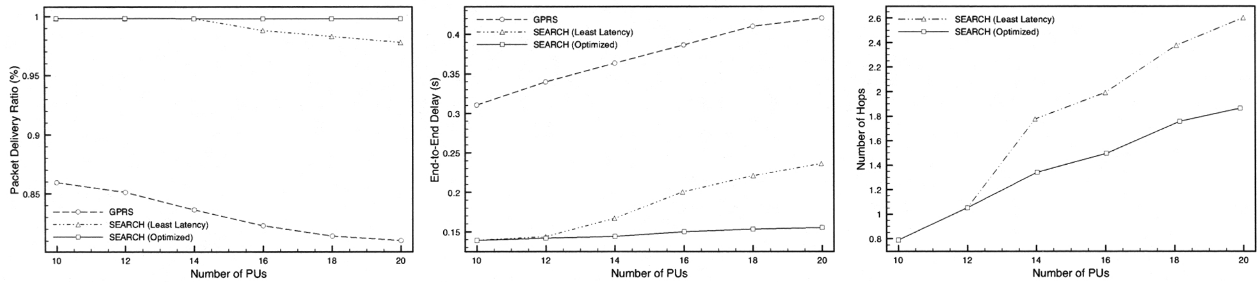
The difference in the end-to-end delay between GPRS and the SEARCH protocols is significant, as seen in Figures 4(b) and 5(b). This is counter-intuitive as the path to the destination for GPRS is the least in terms of hops, as it is not sensitive to the presence of the PUs. Here, the total link layer delay caused by packet re-transmissions at each hop is significantly larger than the latency due to path detour in SEARCH. Moreover, the difference between the two flavors of SEARCH demonstrates the benefit of optimizing the path over several channels. Thus, the optimized channel switching gives nearly 60% improvement in the optimized SEARCH over the single channel least latency configuration.

We defined the *path optimality* metric as the difference in terms of hops between the optimal shortest path that can be constructed considering the PU activity if the global topology is known, as against the path currently used for routing. In Figures 4(c) and 5(c), we show this metric for 5 and 10 channels respectively. Here we measure the difference in the number of hops of the two SEARCH protocols with the route that is constructed with the global topology knowledge. We



(a) (b) (c)

Fig. 4. The packet delivery ratio, the end-to-end latency, and the number of hops for the case of 5 channels are shown in (a), (b) and (c) respectively



(a) (b) (c)

Fig. 5. The packet delivery ratio, the end-to-end latency, and the number of hops for the case of 10 channels are shown in (a), (b) and (c) respectively

observe that the optimized SEARCH significantly reduces the average path length, due to Joint-Path Optimization described in Section II.A. In addition, we observe that the number of channels affects the path optimality condition to a greater extent than increasing the PUs in the network.

B. *Effect of Traffic Load*

In the Load Analysis, we consider 10 PUs inside the network, but vary the system load by modifying the packet size produced by the source node. We observe that both the end-to-end delay 6(a) and PDR 6(b) are optimal in the range of $900 - 1000\,\mathrm{Bytes}$. The least latency SEARCH protocol, as well as GPSR, suffer from self-contention among packets of the same flow as only one channel is used for data forwarding and no channel switching occurs. This is the key reason for the rapid decline in the PDR for higher packet sizes for these protocols. In comparison, the optimized SEARCH protocol uses path segments on different channels whenever PU regions are encountered. This alleviates the problem of self contention at the link layer thus giving a better PDR.

IV. Conclusions

In this paper, we presented SEARCH, a distributed routing protocol for mobile CR networks. Our approach jointly optimizes the path and channel decisions so that the end-to-end path latency is minimized. It is sensitive to the PR activity and ensures that the performance of the CR network is minimally affected as well as no interference is caused to the licensed users during their transmission. We believe that SEARCH can be further enhanced by incorporating a learning based approach that identifies the *type* of the PU, its duty cycle and times of operation.

Acknowledgement

This material is based upon work supported by the US National Science Foundation under Grant No: CNS-07251580. Marco Di Felice was supported by Italian Miur funds for the PRIN-2006 project NADIR.

References

[1] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty. NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey. *Elsevier Computer Networks Journal*, 50:2127–2159, September 2006.

[2] G. Cheng, W. Liu, Y. Li, and W. Cheng. Control Channel Based MAC-Layer Configuration, Routing and Situation Awareness for Cognitive Radio Networks. *In Proc. of IEEE DySPAN*, pp. 571-574, April 2007.

[3] B. Karp and H. T. Kung. GPSR: Greedy Perimeter Stateless Routing for Wireless Networks. *In Proc. of ACM MobiCom*, August 2000.

[4] B. Leong, B. Liskov and R. Morris. Geographic Routing without Planarization. *In Proc. of Symp. on Network Sys. Design and Implementation (NSDI 2006)*, San Jose, CA, May 2006.

[5] Q. Wang and H. Zheng. Route and Spectrum Selection in Dynamic Spectrum Networks. *In Proc. of IEEE Consumer Comm. and Networking Conf. (CNCC)*, pp. 625-629, Jan 2006.

[6] K C. Lee, J. Haerri, U. Lee and M. Gerla. Enhanced Perimeter Routing for Geographic Forwarding Protocols in Urban Vehicular Scenarios. *In Proc. of IEEE Wkshp on Automotive Networking and Applications, in conjunction with IEEE Globecom*, pp. 26-30, November 2007.

[7] IEEE Std 802.11b-1999/Cor 1-2001, 2001.

[8] Draft Standard for Low-Rate Personal Area Networks *IEEE 802.15.4/D17*, October 2002.

[9] C. Chereddi, P. Kyasanur and N. H. Vaidya Design and Implementation of a Multi-Channel Multi-Interface Network. *in ACM REALMAN Workshop*, May 2006.