# RACON: A Routing Protocol for Mobile Cognitive Radio Networks

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## ABSTRACT

Advancement of Cognitive Radio technology can remedy the problems encountered from bandwidth and spectrum access limitations. In Cognitive Radio Ad Hoc Networks routing is one of the most important issues to be addressed and desires deep investigation. Previously proposed routing protocols assume the presence of a connected path from the source to the destination. In some scenarios, due to the characteristics of ad hoc networks and the features of the used cognitive radios, this assumption is likely to be invalid. In this study, a novel routing algorithm for future multi-hop Cognitive Radio Networks is proposed. The main motivation is to maximize data rates and minimize data delivery latency for a set of user communication sessions to deliver messages for the case where there is no connected path from the source to the destination or when network is partitioned at the time a message is originated. Experimental evaluations are performed in the ns2 simulator. It has been shown that the proposed approach provides better adaptability to the environment and maximizes throughput in a number of realistic scenarios and outperforms recently proposed routing protocols for Cognitive Radio networks.

## Categories and Subject Descriptors

C.2.1, C.2.2 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless communication*, Network Protocols – *Routing protocols.*

## General Terms

Performance

## Keywords

Cognitive radio, routing, performance, wireless ad hoc networks

## 1. INTRODUCTION

Radio Spectrum is amongst the most heavily used and expensive natural resource around the world. Although almost all the spectrum suitable for wireless communications has been allocated, recent studies and observations indicate that many portions of the radio spectrum are not used for a significant amount of time or in certain geographical areas while unlicensed spectrum bands are always crowded. As a promising solution to scarce spectrum resource, Cognitive Radio (CR) [1] was proposed to enable unlicensed (secondary) users to sense and intelligently access the unoccupied spectrum portions that are not used by the licensed (primary) users at that specific time. The main components of an example Cognitive Radio Network (CRN), as shown in Fig. 1, can be classified as two groups: the licensed (primary) network and the CR (secondary or unlicensed network) network. The licensed network is referred to as an existing network, where the primary users have licenses to operate in certain spectrum bands. If a primary network has an infrastructure, primary user activities in the network are controlled through primary base stations. Due to their priority in spectrum access, the operations of primary users should not be affected by unlicensed users. The CR network does not have a license to operate in a desired band. As illustrated in Fig. 1, the CR users have the opportunity to access their own CR base stations, on both licensed and unlicensed spectrum bands. Because all interactions occur inside the CR network, their spectrum sharing policy can be independent of that of the primary network. The CR users can also access one of the licensed network's base stations through the licensed band, for this type of access roaming must be enabled. Another access type for a CR user is communicating with other CR users through an ad hoc connection on both licensed and unlicensed spectrum bands. In Multi-Hop Cognitive Radio Networks, the CR nodes sense spectrum and identify available frequency bands, named as Spectrum OPportunities (SOP) or white holes [2], then select one candidate from SOP via predetermined specific policy, which will not cause harmful interference to the licensed nodes. Based on the sensed information, CR users access the licensed band opportunistically when no primary users are using that band and vacate the band upon primary user activity detection. Using these unoccupied channels provides a more effective way to increase the overall network capacity.

A key distinguishing feature of a multi-hop mobile cognitive radio network is that there may never be a contemporaneous end-to-end path, but the union of network snapshots over the time may present an end-to-end path. The usage fluctuations of the available spectrum may lead to lack of communication for the CR user in a given time slot. However, using the key enabling technologies of CRNs, the capability to share the spectrum in an opportunistic manner, the CR user may find an appropriate communication channel in the consequent time slots that may

*CoRoNet'09*, September 21, 2009, Beijing, China.

establish an end-to-end path between source and destination. To explain it further, consider the three-node linear network where node *I* interchangeably finds access to temporally unused spectrum without interfering licensed users between nodes *S* and *D*. The corresponding link connectivity characteristics are shown in Fig. 2. Since there can never be a continuous end-to-end physical connection between *S* and *D*, conventional routing protocols typically drop packets in such situations, consequently will fail to deliver packets between *S* and *D*, and therefore, new routing protocols are needed to handle such situations. If it is feasible than just re-routing, a desirable routing approach will be to forward data from *S* to *I*, when they are connected, and then buffer it at *I* until the *I-D* link becomes up, at which point the data will be delivered to *D*.

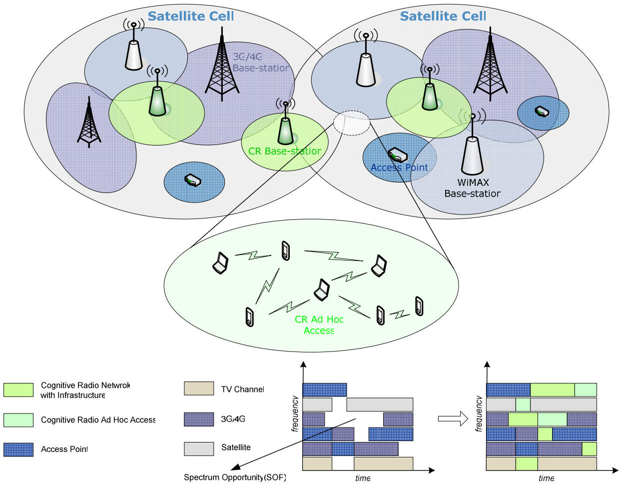

Figure 1. Example Cognitive Radio Network

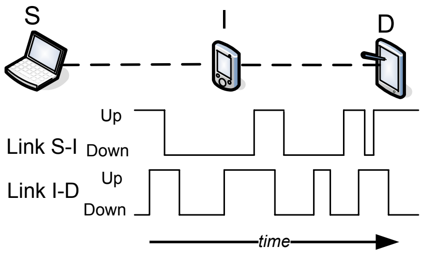

Figure 2. Link disconnectivity example.

In this paper, we present a routing protocol, RACON: A Routing Protocol for Mobile Cognitive Radio Networks, which is designed for data transportation in CRNs by making use of link modeling. The key idea is to design a link cost metric that is based on its spectrum usage history as opposed to its instantaneous state. RACON has the advantage of capturing any spatial and/or temporal locality of link disconnection and leveraging it for optimal route selection for CRNs. In reference to Fig. 2, modeling of the periodic link connectivity results in finite link costs for both links *S-I* and *I-D*. Hence at steady state, node S can compute a feasible path to *D* through node *I*. If node *S* finds the *S-I* link to be down, it buffers the packet for a predetermined certain short time and forwards it to *I* when the link is up. *I* will subsequently buffer the packet till the *I-D* link becomes up and eventually deliver the packet to *D*. Thus, with RACON a data packet is always routed closer to the destination even when the destination is not physically connected to the source or its current network partition.

The rest of this paper is organized as follows. In section II, we review some related work in this area. We describe the RACON: A Routing Protocol for Mobile Cognitive Radio Networks in Section III. We present the simulation environment in which we implemented RACON and the performance results of our protocol in Section IV. The paper concludes in Section V.

## 2. RELATED WORK

Routing constitutes an important yet not deeply investigated area of research in CRNs [3]. We would like to emphasize the need for simple and efficient routing algorithms in CRNs. There is only a limited amount of work available for the routing problem in multi-hop CR networks. In [4], a layered graph model was proposed for modeling network topology and routing in interference-based Dynamic Spectrum Access (DSA) networks. This model provides solutions for DSA networks with static link properties. Our routing strategy is more realistic in the sense that it considers the time-varying nature of the links as well as the intermittent connectivity in the network. Zheng et.al [5] proposed decoupled and joint route selection and spectrum management methodologies. The route selection in the decoupled case is performed by using the shortest path algorithm. However, authors in [6] show that the shortest path algorithm may not yield optimal solutions when both the link propagation time and the channel capacities are taken into account.

Some approaches [4], [5], [7] were proposed based on centralized infrastructure to achieve overall optimal network performance. However, those proactive methods cannot be deployed in multi-hop CRN, where both the node positions and spectrum distribution are hard to obtain. Other approaches [8-10] were proposed based on on-demand manner to reactively select routes and assign channels simultaneously. In these works, the information of channel usage is disseminated by on-demand routing process. Another approach, cognitive tree-based routing (CTBR) protocol [11], was proposed as an extension of tree based routing, which is taking the cognitive radio base-station as root and therefore can only be used for infrastructure CRNs. In [12], a delay motivated On-demand Routing Protocol (DORP) was proposed. They investigate the scheduling-based channel assignment, switching delay between channels and the back off delay within channel in CR nodes to select routes. The authors assume that each node has a traditional transceiver in addition to the Cognitive Radio transceiver to form a common control channel. Using two separate radios is costly, cumbersome, and consumes energy resources that are often limited. The common assumption behind these routing techniques is that there is always a connected path from source to destination. However, the short-range wireless communication environments and the wide physical range and circumstances over which such networks are deployed means that this assumption is not always valid in realistic scenarios. Besides, none of the above schemes target to maximize message delivery rate and minimize message delivery latency, while also minimizing the aggregate system resources consumed in message delivery.

# 3. THE RACON PROTOCOL

Cognitive radio users are not likely to access spectrum randomly, or have a path to a specific node definitely random but rather get connected in a predictable fashion based on repeating behavioral patterns such that if a node has gain opportunity to access a specific unused spectrum band and has connection to a specific node several times before, it is likely that it will gain connection to that node again. We would like to make use of these observations and information to improve routing performance by defining a cost metric and doing probabilistic routing. To accomplish this purpose, we establish spectrum availability and destination reachability prediction.

Our design for RACON routing associates a unique *message identifier*, a *hop count*, and an optional *ack request* with each message. This unique identifier is a concatenation of the host's ID and a locally-generated message ID (16 bits each). Assigning ID's to mobile hosts is beyond the scope of this paper. However, if hosts in an ad hoc network are assigned the same subnet mask, the remaining bits of the IP address can be used as the identifier. In our implementation, the hosts in the network are assigned ID's statically.

The hop count field determines the maximum number of exchanges that a particular message is subject to. While the hop count is alias to the TTL field in IP packets, messages with a hop count of one will only be delivered to their end destination. As discussed below, such packets are dropped subject to the requirements of locally available buffer space. Larger values for hop count will distribute a message through the network more quickly. This should typically reduce average delivery time, but will also increase total resource consumption in message delivery. Thus, high priority messages might be marked with a high hop count, while most messages can be marked with a value close to the expected number of hops for a given network configuration to minimize resource consumption.

Given that messages are delivered probabilistically in RACON, certain applications may require acknowledgments of message delivery. The *ack request* field signals the destination of a message to provide an acknowledgment of message delivery. These acknowledgments are modeled as simple return messages from receiver back to the sender. Of course, the acknowledgment can also be piggybacked with any other message destined back to the sender after the message is successfully delivered.

Each host reserves a maximum buffer size for message distribution. In general, hosts will drop older messages in favor of newer ones upon reaching their buffer's capacity. Of course, there is an inherent tradeoff between aggregate resource consumption and message delivery rate/latency. To ensure eventual delivery of all messages, the buffer size on at least a subset of nodes must be enough. Otherwise, it is possible for older messages to be flushed from all buffers before delivery in some scenarios. A number of buffer management strategies are possible for per-host basis. The simplest policy is well-known first-in-first-out (FIFO) technique. This policy is very simple to implement and bounds the amount of time that a particular message is resident in at least one buffer (i.e. live).

## 3.1 Spectrum Availability Cost

Spectrum availability is an inherent characteristic in CR Ad Hoc Networks where nodes usually get disconnected due to characteristics of ad hoc networks and CR technology like mobility, temporary obstructions, ability to find a non-interfering communication channel with the primary users etc. In RACON, we track a link's connectivity behavior and assign a persistent cost metric that gets updated periodically to reflect its overall state. Accordingly, if a link is disconnected for a long time, the cost is increased to a high value and for a well connected link the cost will be kept to a small value. In this way, a route can be found between a *source* and a *destination* even if there is no continuous end-to-end connectivity. The metric is specifically designed to minimize data delivery latency with minimal network buffer usage. We accomplish this by assigning larger costs to links with larger spectrum unavailability durations. Moreover, in situations where multiple such links have similar average spectrum unavailability durations the link with a history of less frequent disconnection-to-connection transition is assigned a lower cost. The rationale behind this is, for a given spectrum unavailability duration, a link that transitions' less frequently is a better link as it reflects a node has more opportunity to forward a packet to the other nodes. With these guiding principles, the cost of a directional link $L_{i,j}$ is defined as:

$$C_{i,j} = \frac{1 + \left( T_{\cos t\_window} - \sum_{k=1}^{N_{i,j}^{transition}} T_{i,j}^{k} \right)}{1 + N_{i,j}^{transition}} \qquad (1)$$

$C_{i,j}$, cost of link $L_{i,j}$, is dynamically computed by node *i* based on its spectrum usage history over a discrete sliding window of length $T_{cost\_window}$. Within a measurement window, the number of times the link status transitions from having opportunity to transmit without any interference to any primary user to causing interference is represented by the parameter $N_{i,j}^{transition}$, and the duration of the $k^{th}$ connectivity instance is represented by $T_{i,j}^{k}$. The term $\sum_{k=1}^{N_{i,j}^{transition}} T_{i,j}^{k}$ represents the total cumulative connectivity duration within the last measurement window. For a non-disturbed secondary link, this term equals the duration of the measurement window itself, and $N_{i,j}^{transition}$ equals to zero hence the cost reduces to unity. Since this is the minimum possible link cost, a fixed link will always be preferred over interfering links by any link state routing algorithm. Also, since the numerator of the expression for $C_{i,j}$ is dominated by the cumulative link primary user activity time, links with longer interfering times will have higher cost and thus will be avoided by the least cost algorithms. However, among multiple links with similar cumulative disconnectivity durations, the ones with lower transition counts $N_{i,j}^{transition}$ will have lower costs. This ensures that among all links that have similar cumulative disconnection periods, the least cost routing algorithms will not prefer links that cause interference with primary users more frequently. This should help minimize the data delivery latency. Note that the upper bound of the link cost will be decided by the parameter $T_{cost\_window}$ which is set dynamically by node i as a multiple of the measured periodicity of link Li, j.

When two nodes have an opportunity to access the spectrum without causing harmful interference to the primary users, they form two unidirectional links in the network. A node periodically computes the link cost (may be done at sensing period) and disseminates it. The outcome is that each node in the network maintains a directional link state database containing a subset of all directional links in the network with the following constraint: A node maintains the cost information of only those links that are at least one of all possible directional spanning trees rooted (going away from the root) at the node itself. In reference to the Figure 3, since the dotted links are not on any directional spanning tree rooted at *S,* they will never be on any routes between *S* and any other destination and hence will not be saved in the link state database of *S*. Each entry in the link state database has a timer so that if an update for the entry is not received before the timer expires, the information is removed.

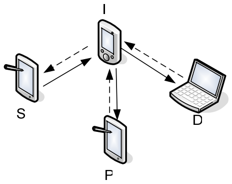

**Figure 3. Relevant links for the link state database of node S.**

After route computation, if a node finds that the next hop for the route is currently causes interference to the primary user, it buffers the packet for a predetermined short time and eventually forwards it when the link becomes available. A node keeps track of its currently active links using a simple *Hello* protocol (If the spectrum sensing algorithm uses beacons, there is no need to use additional beacon messages in the proposed scheme.) and a neighbor table that maintains the current instantaneous connectivity (as opposed to persistent connectivity) with all its neighbors. Additionally, any change in the link state database beyond a preset threshold triggers a fresh next-hop route computation for all the buffered packets. This ensures that any better route that appears as a result of network wide change in link connectivity will be utilized to forward the buffered packets.

## 3.2 Forwarding Strategy

In traditional routing protocols, choosing where to forward a message is usually a simple task; the message is sent to the neighbor that has the path to the destination with the lowest cost according to some metric. Normally the message is also only sent to a single node since the reliability of paths is relatively high. However, in the settings we envision here, things are completely different as stated before. First of all, when a message arrives at a node, there might not be a available path to the destination because of a primary activity so the node have to buffer the message and upon having an opportunity to use spectrum, the decision must be made on whether or not to transfer a particular message. Furthermore, it may also be sensible to forward a message to a number of nodes to increase the probability that a message is certainly delivered to its destination.

Unfortunately, these decisions are not so trivial to make. In the evaluations in this study, we have chosen a rather simple forwarding strategy – when forwarding a message to the node which is determined according to the link state algorithm, copy of the message is also sent to the other neighboring nodes if the spectrum availability cost is lower at these neighboring nodes. The first node does not delete the message after sending it as long as there is sufficient buffer space available (since it might encounter a better next hop, or even the final destination of the message in the future) for a predetermined short time. If buffers are full when a new message is received, a message must be dropped according to the queue management system used.

# 4. SIMULATION AND ANALYSIS

We have evaluated the performance of our protocol RACON through simulations using ns2 [13]. In our implementation, each simulated mobile node has a RACON routing agent layered on top of the Internet CRN Encapsulation Protocol (ICEP) layer. The ICEP layer is responsible for notifying the RACON agent when a new node becomes available by either coming into radio range or finding an available unoccupied channel by a primary user, and when a neighboring node becomes unavailable by either moving out of radio range or finding all the channels are occupied.

Unless otherwise noted, our simulations are run with the following parameters. Two-ray ground propagation model is used at the radio layer. The bit rate for each channel is 2Mbps. We model 50 mobile nodes moving in a rectangular area 1800m x 1800m in dimension. Each node picks a random spot in the rectangle and moves there with a speed uniformly distributed between 0-20 m/s. Upon reaching this point, the node picks a new destination and repeats the process. We use the following default communication pattern. Each source node generates and transmits constant bit rate (CBR) traffic and each message is 1 KB in length. The transmission interval for each node is set to 100ms. By default, each host allocates a 2,000-slot message buffer. We experiment with the effects of limiting buffer space below.

We will explore the characteristics of RACON routing under a number of different scenarios. We first explore the robustness of RACON to various radio transmission ranges, between 10-250 meters. 100% of the messages are delivered for all transmission ranges with the exception of the 10 m case as discussed below.

**Table 1.RACON characteristics as function of transmission range**

| Range | Delivery Rate % | Baseline Rate % | Latency | Hops |
|---|---|---|---|---|
| 250 m | 100 | 98 | 10,4 | 2.2 |
| 100 m | 100 | 36 | 28,2 | 6.2 |
| 50 m | 100 | 0.8 | 42,6 | 3.5 |
| 25 m | 100 | 0 | 168.6 | 3.1 |
| 10 m | 91.3 | 0 | 4126.3 | 3.1 |

Table I depicts the percentage of messages delivered under Delivery Rate column. As a point of comparison, Baseline Delivery shows the percentage of messages delivered using the well-known AODV routing protocol in our configuration. This comparison is not entirely fair to AODV because it is not designed to operate in cases where connected paths are unavailable. We include these results only to demonstrate that existing ad hoc routing protocols break down in the absence of sufficient wireless coverage, whereas RACON is able to continue communication. In addition, comparable results were readily available and because AODV had among one of the the highest delivery rates of the protocols studied. The Latency column shows average times in milliseconds, while the Hops column shows average number of hops that a message took in arriving at its destination. One interesting observation from the table is that the average number of hops increases to 6.2 for the 100 m range and drops back down to 3.5 for the 50 m range. In this case, nodes are on the verge of being fully connected as evidenced by the 36.3% of the packets that are successfully delivered using AODV (which requires full connectivity). At transmission ranges smaller than 100m, RACON relies upon node mobility and finding unoccupied spectrum to transport messages toward their destination, reducing the number of hops at the expense of increasing delivery latency.

**Table 2. Resource consumption characteristics of RACON for 50m transmission range, 4 hops Limit**

| Buffer Size | Delivery Rate % | Avg. Latency | Buffer Utilization | | | | |
|---|---|---|---|---|---|---|---|
| | | | Dead | Buffers | Lifetime | Live | Buffers |
| 2000 | 100 | 43.4 | 0 | N/A | N/A | 1980 | 45.1 |
| 1000 | 100 | 45.8 | 141 | 24.2 | 268 | 1876 | 30.7 |
| 500 | 100 | 46.1 | 762 | 18.9 | 162 | 1007 | 25.9 |
| 200 | 99.8 | 47.3 | 1397 | 12.7 | 95 | 523 | 19.5 |
| 100 | 95.5 | 47.7 | 1584 | 9.1 | 67 | 291 | 17.2 |
| 50 | 84.6 | 49.1 | 1721 | 6.4 | 48 | 176 | 15.4 |
| 20 | 58.7 | 48.4 | 1794 | 4.4 | 28 | 94 | 12.0 |
| 10 | 40.3 | 39.7 | 1823 | 3.3 | 22 | 54 | 10.3 |

Note that with a 10m transmission range, although coverage is very little compared to total area in the worst case, and also it takes over long to deliver a message in this scenario, 91.3% of messages are delivered within the lifetime of the simulation. We believe that without the availability of any routing infrastructure, such long delays are inherent given the low coverage densities. Finally, it is important to emphasize that our approach is sensitive to node density and transmission coverage as a function of the total target area. For example, we reran the 10m simulation in rather small area (i.e. 100m x 500m and we think it is still large for some scenarios, e.g. mobile sensors) with all other parameters set to their default values, and achieved 100% message delivery with a 452ms average delivery time.

Table II presents metrics of buffer consumption and explores this tradeoff for the case where each node has a 50m transmission with a variable amount of available buffer space. The second column, Delivery Rate, shows eventual delivery rate dropping from 100% to 40.3% for 10 per-node buffers. As noted above, delivery rate stays robust through a buffer size of 100 messages in this scenario. The third column shows average latency for delivered messages. The last five columns present a measure of the amount of memory resources consumed for the delivery of each message. The breakdown is split between two types of messages, Dead and Live, which is the number of each type of message at the end of the simulation. Dead messages are not present in the buffer of any node at the end of the simulation, while live messages that are present in at least one buffer at the end of the simulation. Note that a dead message does not imply that it was not delivered as copies of messages can continue to live in buffers long after message delivery. For larger buffer capacities, most messages are live because there is sufficient capacity to hold a message in at least one of the 50 nodes. For both types of messages, the Buffers column shows the average number of nodes that were buffering a particular message averaged across its entire lifetime. Finally, for dead messages, the Lifetime column depicts the amount of time the average message is stored in at least one host's buffer. Thus, for example, with 500-message buffers, 973 messages are eventually dropped from all hosts. Their average lifetime is 162ms and each message occupies an average of 18.9 buffers during this time. Similarly, there are 1007 live messages (still occupying at least one buffer) at the end of the simulation, each of which occupies an average of 25.9 buffers during its lifetime. To isolate the delivery behavior of a specific set of messages, nodes stop injecting new messages after a pre-determined amount of time. In steady state, if all nodes were to continuously inject new messages into the system (as would be the case for many real scenarios), we expect that all messages would eventually "die" (hopefully after delivery) as they get replaced in buffers by newer messages. Thus, in evaluating the tradeoff between resource consumption and message delivery, the resources consumed on behalf of dead messages are more interesting than those for live messages. It is likely that live messages occupy buffer space simply because they are not competing with any additional new messages. For dead messages, the buffer occupancy numbers multiplied by the average lifetime of the message measures the amount of memory resources required to achieve a given delivery rate and latency. In this way, we are able to capture the tradeoff between resource consumption and message delivery for a given scenario. For our trials, Table II shows that higher message delivery rates clearly require larger memory resources.

As noted earlier, we used AODV for a baseline comparison and besides not being the focus of this paper we evaluated a throughput comparison between AODV, and a recently proposed routing protocol DORP [12], and RACON to show that RACON can well fit the multi-flow multi-channel environment and effectively exploit the potential large communication capacity in CRNs. In the simulations, the rate of flows is varied from 100Kbps to 1800Kbps. The nodes are randomly placed in the area, and 8 flows having the same traffic generation rate. The result is shown in Figure 4.

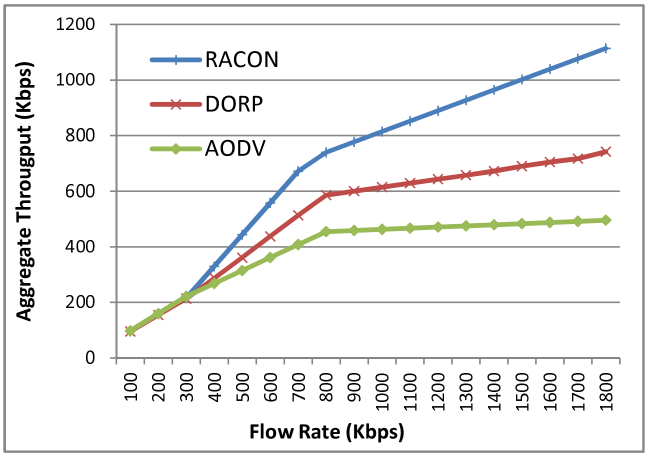

**Figure 4. RACON performance: throughput observed with different protocols**

## 5. CONCLUSION

In this paper, we have looked at Cognitive Radio Ad Hoc Networks, an area where a lot of promising new applications are evolving for an exciting future if the underlying mechanisms are implemented. Therefore, we have proposed RACON: A Routing Protocol for Mobile Cognitive Radio Networks. Due to the nature of ad hoc networks and cognitive radios used, in some scenarios, nodes can be unable to find unoccupied spectrum due to primary user activity causing partitioning in the network, making it virtually impossible to perform message delivery using current proposed routing protocols. The goals of RACON are to maximize message delivery rate, throughput and to minimize message latency while also minimizing the total resources (e.g., memory and network bandwidth) consumed. Through an implementation in the ns2 simulator, it has been shown that RACON achieves significant improvement on the throughput and delivers 100% of messages with reasonable aggregate resource consumption for scenarios where existing routing protocols are unable to deliver any messages because no end-to-end routes are available.

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