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Connectivity Driven Virtual Path Routing Protocol for Cognitive Radio Ad Hoc Networks

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Abstract—**One of the difficult challenge in Cognitive Radio Ad Hoc Networks (CRAHNs) is the throughput maximization in an environment with uncertain availability of spectrum resources and spatial diversity. Opportunistic spectrum utilization can alleviate the degradation in throughput by employing dynamic routing algorithm and accomplishing Virtual Path Routing (VPR). The VPR aims at finding the most reliable path for multi-hop communication between Secondary Users (SUs) in the presence of Primary Users (PUs) and other interfering SUs. By jointly routing and dynamic spectrum access with interference avoidance, VPR selects the path, which ensures optimal link throughput with minimum interference. In this work a utility function is introduced which incorporates probabilistic Signal to Interference Ratio (SIR), PU influence and channel switching time delay. The VPR performance is compared with other well known works in terms of throughput, Bit Error Rate (BER) and Packet Arrival Delay (PAD). The results suggest VPR provides better end-to-end throughput, BER and PAD by avoiding zones of PU presence and mitigating interference effects of neighboring SUs.**

Index Terms—**Cognitive Radio Ad Hoc Network, probabilistic Signal-to-Interference Ratio (SIR), Packet Arrival Delay (PAD).**

I. Introduction

Cognitive Radio Ad Hoc Network (CRAHN) [1] is a distributed multi hop mechanism consisting of transceivers, known as the Primary Users (PUs) and Secondary Users (SUs). The PUs are owners of spectrum with preference for spectrum usage, while SUs are unlicensed users who can utilize the unused spectrum bands for communication between nodes. The SUs opportunistically use available Spectrum Opportunities (SOPs) and establish communications. SOPs can be defined as the set of channels unoccupied by PUs and therefore open to SUs. CRAHN is a highly dynamic network paradigm where an SU can use a particular SOP until PU is absent and it has to immediately relinquish the used spectrum band as soon as PU becomes active.

The survey by Federal Communications Commission (FCC) [2] indicated that licensed spectrum is mostly underutilized, for instance in New York City the utilization of spectrum is less than 13.1 percent, and similarly in other areas the licensed bands are not properly utilized. Cognitive Radio (CR) [3] is an emergent field, which holds the potential to address the ever increasing radio spectrum demand. The ever changing behavior of communicating nodes in CRAHN warrants the need for efficient protocols and procedures where SUs can communicate efficiently without interfering with the PUs.

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CRAHNs are different from ‘classical’ ad hoc networks, because the communication among SUs heavily depends on the PU presence. In ad hoc networks, the nodes consider only the interference effects of other network nodes [4] and adopt techniques to avoid packet loss [5], by introducing cooperation among nodes. On the contrary, in CRAHNs, the spectrum usage and route maintenance entirely rely on the activity nature of PUs. It can vary from occasional mobility and channel use, to highly mobile and sporadic in terms of spectrum use. The local spectrum resource fluctuations due to infrequent nature of PUs and hop by hop interference caused by SUs have a deep impact on the overall link quality. These factors pose a major challenge to throughput optimization in CRAHNs.

In our work we introduce a utility function which senses the PU and SU activity probabilistically. The routing scheme introduced in this paper namely **Virtual Path Routing (VPR)**, works for throughput maximization based on link stability by considering the PU's presence and neighboring SUs' interference. The consideration of interference effects of other SUs is important because high level of interference on a particular channel renders it useless. The interference factors of all the network entities is considered statistically by computing the probabilistic SIR on the possible route. The proposed protocol tends to minimize the power utilization by penalizing paths with too much channel switching.

The simulations show that VPR can effectively avoid zones of PU presence along with selection of channel providing optimal SIR, which leads to better throughput, less BER and reduction in PAD.

The rest of the paper is organized as follows. In Section II we study the previously proposed routing algorithms based on PU and SU interference avoidance and throughput maximization. In Section III we discuss system model. In Section IV we discuss the VPR protocol and algorithm in detail. Section V presents the simulation results and Section VI concludes the paper.

II. Literature Review

Based on spectrum knowledge, CRAHN routing protocols are broadly classified in two major classes: *Network wide spectrum information* based solutions and *local spectrum information* based algorithms. In the former case, spectrum occupancy information is available to the nodes locally through network graphs or to the centrally controlling unit. While in the later case, spectrum availability data is constructed locally at each node in the network.

Dynamic Spectrum Access Protocol (DSAP) [6] is a centralized approach with a central base station to control spectrum allocation. This central base station contains network wide signaling information and manages spectrum bands utilization among nodes. DSAP comes with a major drawback as CRs are self-adaptive devices with no central body. Authors in [7] propose a protocol which works on the principle of layered graphs. Each layer corresponds to a channel and shortest path algorithm is used to find routes. Both [6] and [7] are centralized approaches and require spectrum information of the entire network for routing. Contrarily, the protocol proposed in this work is decentralized where SUs construct spectrum information locally.

Interference constraints form the basis of work presented in [8]. It is a decentralized algorithm in which minimum interference level avoidance is analyzed from PU's perspective. The paper lay down the basic principles for multi-hop route selection in CRAHNs, however SU interference impact is not discussed.

Minhas et al. in [9] present a game theoretic approach to introduce cooperation among SUs in a Cognitive Sensor Network. The authors argue that for efficient use of power and channel resources, cooperation among SUs is important. Therefore, the SUs are influenced to study the spectrum choice, as it has impact over the entire network. On the contrary in our work, all the SUs are considered as independent in their choice of channels. Their channel selection is observed probabilistically and the best channel is selected based on maximum SIR.

Protocol in [10] considers both per hop spectrum availability and source to destination shortest distance during route selection. The proposed algorithm creates a run time forwarding mesh consisting of shortest paths between source and destination and selects the best path to maximize throughput. However with increase in network size and highly mobile SU nodes, the performance of the said protocol degrades. Another spectrum aware technique is proposed in [11], which integrates the dynamic route functionality with per hop channel utilization to optimize throughput. In CRAHNs, channel availability changes hop by hop and SPEAR [11] addresses this heterogeneity by combining spectrum sensing with channel reservation for collision-free routing. Channel reservation is performed under the assumption of cooperation among SUs. In contrast, the routing protocol proposed in our work do not rely on cooperative scenario among SUs. It probabilistically analyzes the spectrum availability and forms the route to avoid interference.

Authors in [12] have introduced a routing protocol which aims at maximizing the throughput using better bandwidth utilization and by avoiding paths crisscrossing with PU receivers. The proposed algorithm defines two classes based on the preference given to PU. In the first class, decreasing end-to-end latency is given precedence over PU interference avoidance. In the second class, safeguarding PU communication is given more importance. It considers several metrics during spectrum selection stage but ignores the interference effect of neighboring SUs, which is discussed in our work.

Spectrum and Energy Aware Routing (SER) protocol proposed in [13] aims to efficiently use energy resources using TDMA style channel-time slot assignment to establish route. The utility function introduced in [13] selects the node, which satisfies the minimum threshold residual energy level. SER protocol generates Route Recovery (RREC) and Route Error (RRER) messages for route maintenance. The paper does not discuss the significant effect of overheads associated with these messages. Under a highly dynamic CRAHN scenario, increase in overheads will reduce the efficient use of energy resources of network nodes.

A clustered based technique; United Nodes [14] opts for paths offering least PU interference for maximizing throughput. Nodes run clustering algorithm and adjust themselves in clusters. Clustering algorithm considers node position, communication efficiency and interference for clustering. The metric in [14] considers the interference of PUs and SUs, but link restructuring depends on PU interference only. It does not account for the change in spectrum availability due to neighboring SUs presence after PU disruption period is over.

Link stability based routing protocol named Gymkhana is proposed in [15], [16]. The Gymkhana method calculates path connectivity by considering the second smallest eigenvalue of Laplacian of a graph. During route formation Gymkhana avoids zones of PU presence only, it considers neighboring SUs as inactive. Unlike Gymkhana we consider both the impact of PUs and SUs during route formation.

III. System Model

In this work, the network model assumed is cognitive in nature, in which N_s SUs coexist with N_p PUs, in a uniformly distributed environment. Each PU p uses a particular spectrum band ch_p and has transmission range r_p. We assume that each PU p uses the channel ch_p probabilistically defined by activity factor a_p. The activity factor a_p is classified by average *on* and *off* transmission. Mathematically it is defined as:

$$a_p = \frac{\bar{t}^p_{on}}{\bar{t}^p_{on} + \bar{t}^p_{off}} \quad (1)$$

$\bar{t}^p_{on}$ is the average time duration during which PU p is using ch_p for transmission and $\bar{t}^p_{off}$ is the average silent duration. The probability that p will not use its licensed spectrum ch_p is $1-a_p$. Each SU s ($s = 1, \ldots, N_s$) has a transmission range r_s and can use channel ch_p for communication if ch_p is not in use of PU p or it is not under its influence area. A simple path loss model is considered as defined in [17]. All SUs have same transmission power P_t. The power at the receiver [17] is given as,

$$P_r = \frac{P_t \lambda^2}{d^2} \quad (2)$$

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The received power is represented by P_r, the transmitted power is P_t, d is the distance between transmitter and receiver, λ is the wavelength, and α is the path loss coefficient. As it is a simplified path loss model, therefore propagation exponent α is assumed to be 2.

Link gain g_i [17] for transmitting SU s_i is defined as:

$$g_i = \frac{\lambda^2}{d^2} \tag{3}$$

modifying (2) in terms of link gain, we can write,

$$P_r = P_t g_i \tag{4}$$

The SIR between transmitting SU s_i and receiving SU s_j is measured probabilistically and is given as,

$$f[SIR]^{ij}_{ch} = \frac{(1-a_{p_i})g_{ij}P_t}{\sum_{n=1,n\neq i,j}^{N_s}(1-a_{p_n})g_{jn}P_t + a_p g_{jp} P_p} \tag{5}$$

where, $1-a_{p_i}$ and $1-a_{p_n}$ is the channel usage probability of SU s_i and n^{th} secondary node respectively. The second term $a_p g_{jp} P_p$ in the denominator of (5) shows the probabilistic interference of p PU, transmitting with P_p power.

The probabilistic SIR of (5) is channel based so each SU computes $f[SIR]$ for all the channels. It depends on the random activity of neighboring SUs and their interference. It also considers the influence and interference of licensed PU for that channel. The impact of each SU and the PU is inversely proportional to the square of the distance between interfering and transmitting nodes. According to the assumption, every SU transmits with same maximum power P_t, therefore distance and the channel usage probability plays major role in affecting the SIR between s_i and s_j.

IV. Virtual Path Routing

The objective of the VPR path establishment is to deliver information across the route that tries to avoid "hurdles," i.e. at the same time abstain from unstable areas where the risk of disconnectivity is high. These "hurdles" are in the form of zones (or channels) occupied by active PUs and high activity SUs. For illustration, cognitive network is drawn in Fig. (1) with three PU influence areas shown by blue, red and green colors. PUs can use only their licensed spectrum, therefore PU_1, PU_2 and PU_3 can use only channel 1, 2 and 3 respectively. A path between source Sx and destination Dx is drawn with per hop channel use information colored yellow. As it can be seen from the figure, VPR avoids PU interference by selecting a different channel in its zone.

VPR comprises of two phases. In the first phase, source initiates route discovery using *VPR Protocol* to gather information of all possible paths between source and destination. In the second stage of route selection, the destination chooses a path using *VPR Algorithm*.

A. VPR Protocol

The VPR requires information that is available via AODV protocol [11]. It is assumed that each SU is able to measure the influence of their transmissions on respective PU, and sense the PU activity factors, a_p, with $p = 1, \ldots, N_p$. Moreover it is also assumed that each SU s_i is able to compute SIR with other SU s_j, where $i, j \subseteq N_s$. In this work an assumption is made that each SU can probabilistically access a channel ch_p with probability $1-a_p$. Therefore all the available channels can be utilized by the SUs with some probability based on PU activity a_p.

The SUs utilize the important information of $f[SIR]$ and a_p, for calculating the link establishment possibility. These two important parameters are used to compute utility and stored in a *local utility* vector $\mathcal{LU}$. Each SU s maintains and periodically updates its own *local utility* vector $\mathcal{LU}_s$, where $s = 1, \ldots, N_s$. The length of $\mathcal{LU}_s$ vector is equal to the number of SUs, with each generic element $\mathcal{LU}_s(i)$, $(i = 1, \ldots, N_s)$ indicating the utility computed between two SUs. The formulation of $\mathcal{LU}$ is discussed in detail in the *VPR Algorithm*.

A route request is initiated by a source node $\mathcal{S}$ in order to update the routing table and renew information about the destination node $\mathcal{D}$. The criteria adopted for candidate path selection is maximum SIR on that path with minimal PU presence. Following this criteria, all possible paths leading to the destination are computed. Let K be the number of paths found between source and destination.

The RREQ, which reaches $\mathcal{D}$ for the k^{th} path contains three important information vectors.

- Node IDentity vector, NID_k, which contains the ID's of the relay nodes k. The nodes are assigned a unique tag. NID_k initializes with source ID and last element is the ID of destination node.
- Path Local Utility vector, $\mathcal{PLU}_k$, every secondary node on path k appends its local utility vector $\mathcal{LU}$ to form $\mathcal{PLU}_k$.

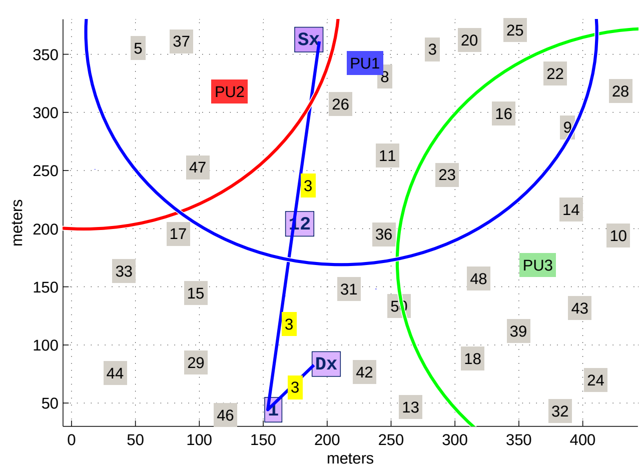

Fig. 1. Network Diagram

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- Path Channels vector, $PathCh_k$, which contains information about the possible hop by hop channel selection for a path k. This hop by hop channel adoption is defined by $max(\mathcal{L}U_k^{ij})$ between two communicating SUs s_i and s_j on a path k.

Each SU receiving the RREQ packet, checks if its ID has already been added in NID. If the ID exists the packet is dropped to avoid looping, in other case the node enters its ID in the NID and forwards the packet to the next candidate node. By using this methodology, destination $\mathcal{D}$ receives the number of packets that are within the threshold. The destination node uses the information received through RREQs to run VPR algorithm and selects the best path and channel that ensures maximum SIR and minimum PU activity. After selecting the best route, specific packets used for sending replies are send back via each node participating in the forward route.

B. VPR Algorithm

The destination $\mathcal{D}$ runs the algorithm for route selection on the basis of information stored in RREQ packet. Out of the three basic information RREQ packet holds, $\mathcal{L}U$ has the fundamental importance in the formulation of VPR Algorithm. Here we discuss in more detail the mathematical composition of local utility vector and the factors affecting it.

- ***Local Utility Vector*** ($\mathcal{L}U$): Each SU s_i calculates the 'utility' of choosing a particular channel ch, where $ch = 1, \ldots, N_p$, for communication with SU s_j, where $s_i, s_j \subseteq N_s$. This utility is based on the SIR which exists between s_i and s_j and the PU influence on the said nodes. Mathematically this utility is defined as:

$$\mathcal{L}U_{ch}^{ij} = \frac{f[SIR]_{ch}^{ij}}{a_p^i + a_p^j} \tag{6}$$

  where, a_p^i and a_p^j are the activity factors of PU p on s_i and s_j, respectively. $f[SIR]_{ch}^{ij}$ is channel based SIR, probabilistically computed between two SUs, s_i and s_j for channel ch.

  Each SU s_i calculates local utility with all other SUs s_j $(i \neq j = 1, \ldots, N_s)$ for all the channels available and selects the maximum utility $max(\mathcal{L}U_{ch}^{ij})$. This maximum value is stored in s_i's local utility vector $\mathcal{L}U_i$. The corresponding channel ch information is stored in *local channel* list. This local channel list provides channel usage information to $PathCh$ vector during route formation.

During RREQ initialization, source node $\mathcal{S}$ selects m best utility values from its local utility vector $\mathcal{L}U_i$ and forwards RREQ packets towards corresponding SUs. Thus m number of routes are selected between $\mathcal{S}$ and relaying nodes. The value of m can vary depending on network congestion and nodes' activity. During network congestion, value of m is increased so that more RREQ packets are forwarded to increase chances of successful path formation. When network dynamics are low, value of m is reduced to reach out only a selected group of nodes as chances of route formation are high with less usage of energy resources. Each RREQ packet contains utility information between source and m^{th} relaying node along with corresponding channel and node IDs information. The name ***Virtual Path*** comes from the fact that the algorithm opportunistically selects the path and channel (or virtual path) while relaying a RREQ packet. The relaying nodes receiving the RREQ packet selects the next best hop according to their local utility vector and broadcast RREQ to next candidate hops after inserting their local utility, channel and node ID information. Multiple route request packets are received by the destination pertaining to best possible routes.

The destination node $\mathcal{D}$ chooses the path which offers least channel switching delay with optimal end-to-end local utility. The path utility function is defined as:

$$\mathcal{U}_k = \frac{\sum_{i=1}^{H_k} \mathcal{L}U_k(i)}{\tau_{sw}} \tag{7}$$

where $\sum_{i=1}^{H_k} \mathcal{L}U_k(i)$ is the sum of local utility values of all the hops h_k on path k, with total number of hops H_k, $(h_k = 1, \ldots, H_k)$.

τ_{sw}, shows the switching time delay for path k. An important parameter considered is the amount of time required to vacate the band that is under use by other transmitters. The number of available channels determine the delay in switching between channels, if required.

The best value of $\mathcal{U}_k$ is considered from K possible paths. The utility in (7) is given by:

1) Total hops in a path k.
2) Number of channel switching occurring on path k.
3) PU activity and neighboring SU interference along the path k.

The goal of VPR is to optimize throughput by selecting the path which minimizes above three points and maximize SIR. After selecting the best route, RREP message is sent back along the selected route to initiate communication between source and destination.

V. Simulation Results

In this section, we experimentally evaluate the performance of VPR. We compare the working of VPR with *Gymkhana* routing protocol [15]. We consider the topology of the network and include parameters associated with it in the analysis. The selection of routes is also considered. We analyze the efficiency of the two protocols based on PU avoidance and maintaining optimum throughput along with BER and packet delay performance.

The VPR utility function that is defined in (7) selects the path with maximum utility value and is compared with Gymkhana routing protocol. Gymkhana utility function, defined as U^c [16], selects the path with maximum utility but considers the affect of PUs only to select the path.

The routing protocols are evaluated by generating different cognitive networks. The protocols under consideration derive all the possible paths between a given source and destination based on their respective criteria. A traffic session is simulated

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on the secondary network in which not only PUs can be active based on their activity factor a_p but neighboring SUs are also active and can use any available spectrum based on a_p.

We assume N_s SUs and N_p PUs are uniformly distributed in a square deployment region of area $500m^2$. Other simulation parameters are reported in Table I.

Fig. 2 and 4 report the performance of VPR and Gymkhana routing schemes in terms of throughput and BER. The resulting plots are for 100 networks, averaging them in case of 50 SUs and three PUs. The activity factors is kept constant with increasing Signal-to-Noise Ratio (SNR). VPR has better performance if its average value is considered.

Fig. 2 shows the throughput for the end-to-end paths. This is dependent on the SNR for the selected routes for the two methods. As it can be seen that when noise levels are high the success ratio of correct packet reception at destination is low and with increase in signal power, the throughput starts improving. But as seen from figure, the improvement in case of VPR is more as compared to the other routing protocol. In case of VPR the data is affected by noise only as it successfully avoids the PUs and neighboring SUs. Gymkhana avoids the PU interference but the interference from SUs corrupted the data.

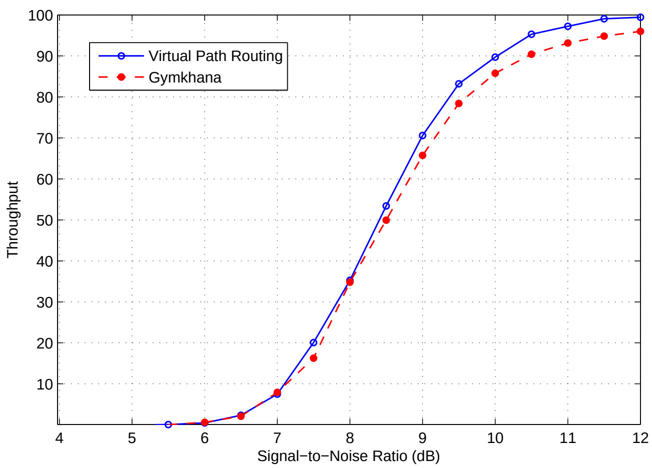

Fig. 2. Throughput comparison between VPR and Gymkhana

Performance comparison from percentage throughput perspective is reported in Fig. 3. During simulation, 100 data packets are sent across the 'best' routes selected by the two routing protocols. PU activity factor values during the experiment are $a_1 = 0.7$, $a_2 = 0.3$ and $a_3 = 0.4$. According to Fig. 3, VPR obtains better percentage throughput than Gymkhana because it successfully avoids the interference affects of SUs on the received data. The percentage throughput for the two routing schemes is computed for 10 dB SNR and averaged for 50 different networks.

Fig. 4 shows the BER for the routing algorithms, with BER plotted against SNR. In order to perform the experiment, 50 random networks are generated with simulation parameters reported in Table I. The SNR values are incremented from

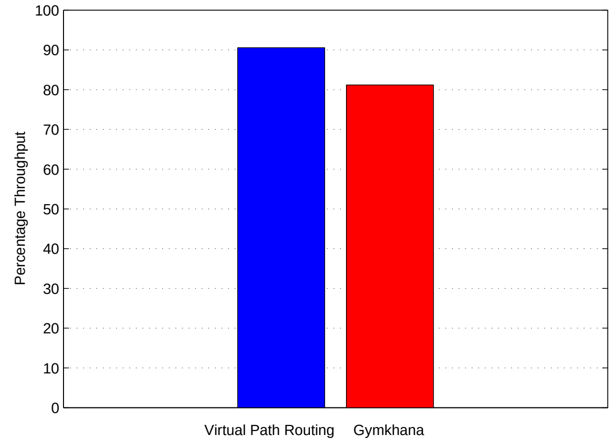

Fig. 3. Percentage throughput with activity factors: $a_1 = 0.7$, $a_2 = 0.3$, $a_3 = 0.4$

4 dB to 17 dB. Each random network generated BER plot and they are averaged to smooth out the results. From Fig. 4, it can be seen that at low SNR values the performance of both protocols is almost same. As the SNR increases, the interference effects become evident and VPR performance improves as compared to Gymkhana.

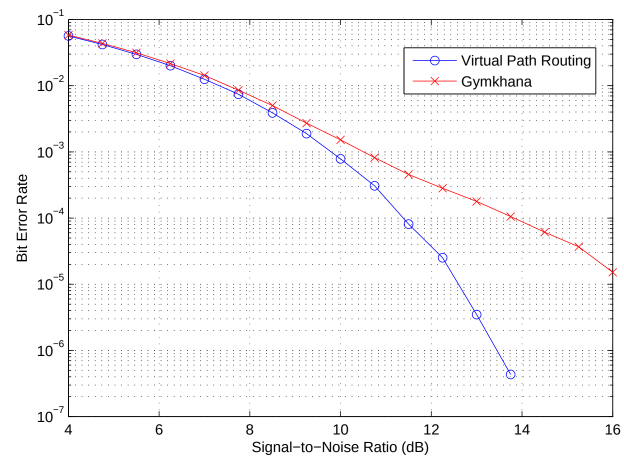

Fig. 4. Bit Error Rate (BER)

Fig. 5 reports the performance in terms of PAD. PAD is defined as the delay in the reception of packet at destination due to number of hops, PU presence and channel switching time delay. From the analysis shown in Fig. 5, it is evident that due to efficient route selection VPR is able to avoid zones of PU presence. The number of hops on the selected path are optimal and channel switching is not profound. Gymkhana is able to avoid the PU affected zones but slight increase in the PAD is due to higher number of hops on Gymkhana selected route.

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TABLE I
SIMULATION PARAMETERS

Parameters	Symbols	Values
Number of Secondary Users	N_s	50
Number of Primary Users	N_p	3
No of Channels	ch_p	3
Primary User Activity Factors	a_p	0.2-0.7
Range of Secondary Users	r_s	$75m$
Range of Primary Users	r_p	$150m$
Packet Size	Packet Size	256 bits
Channel Switching time delay	τ_{sw}	$25ms$

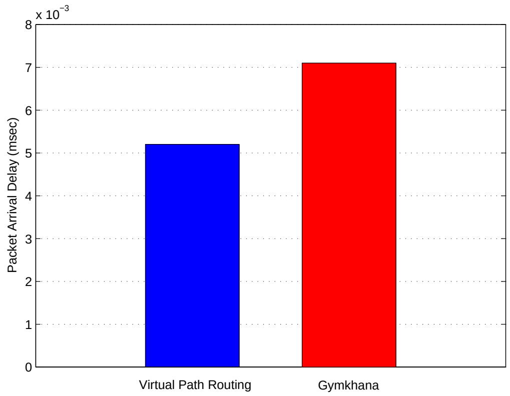

Fig. 5. Packet Arrival Delay (milliseconds)

VI. CONCLUSIONS

In this paper, we present interference and spectrum aware routing algorithm named as ***Virtual Path Routing (VPR)*** protocol. The VPR is a dynamic spectrum access routing solution which opportunistically selects paths offering least interference. The interference from both PUs and neighboring SUs is considered during route selection. We introduce a mathematical model, which combines the effects of PU activity and the neighboring SUs' interference impact for route selection. Secondary nodes in VPR take channel level decisions during path formation by selecting the channel that offers best SIR and is not under PU's use.

BER, throughput and latency are important parameters to measure the efficiency of any protocol. In CRAHNs, throughput, BER and PAD are directly affected by the presence of PUs. PUs affect the channel availability for SUs. Therefore communicating SUs not only face interference and contention from PUs but also neighboring SUs.

VPR performance is evaluated through simulations in a CRAHN scenario and comparison is made with Gymkhana routing protocol. In case of Gymkhana, it is observed that this protocol routes data based on minimum hops and considers the interference effects of PUs only. On the contrary, VPR considers the interference effects of all network entities and it is evident from throughput, BER and PAD results.

The future work will focus on thorough analysis of the working of VPR with further refinement of system model.

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