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RPCRAN: A ROUTING PROTOCOL FOR COGNITIVE RADIO AD HOC NETWORKS

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Abstract. *Cognitive Radio (CR) technology is an emerging and promising technology which enables the temporary use of the unused licensed spectrum without interfering with the transmissions of other users, thereby improving spectrum utilization. The spectrum is dynamically reused by the alteration of its power, frequency, modulation, and other operating parameters after sensing its radio frequency environment. Cognitive Radio Ad hoc Networks (CRAHNs) are ad hoc networks with CR capability. Routing is a critical issue in CRAHNs which has to be addressed, as the mechanism to form routes in the classical ad hoc networks is completely different from CRAHNs. This paper provides three main contributions. First, NS-2 has been extended to address CR routing by providing multi radio and multi-channel support. Secondly, the extended NS-2 provides a base for realistic simulation and performance evaluation of CR routing algorithms. Finally, in this paper, we have proposed a Routing Protocol for Cognitive Radio Ad hoc Network (RPCRAN) which considers CR users activity in CRAHNs. Evaluation of the proposed protocol has been compared against AODV under the extended NS-2 cognitive environment. Simulation results show our proposed protocol performs better.*
Keywords: CRAHNs, NS-2, DSA, Cognitive capability

1. **Introduction.** The usage of radio spectrum resources is controlled by national regulatory bodies such as the Federal Communication Commission (FCC). The FCC assigns radio spectrum to licensed holders also known as primary users on a long-term basis over vast geographical regions. There are portions of the assigned spectrums which are congested so much that there is interference while, on the other hand, large portions of the allocated spectrum are rarely used. On an average, the utilization of these bands lies between 15% and 85% [1]. The Cognitive radio (CR) term was first coined by Mitola in 1999 [2]. Cognitive Radio (CR) technology is an emerging technology which is envisaged to solve the problem of bandwidth scarcity and for an efficient use of the vacant licensed band. It is a well-known fact that the 2.4 GHz industrial, scientific and medical (ISM) band is heavily congested. So, to solve the problem of spectrum scarcity, Federal Communication Commission (FCC) has recently approved the use of unlicensed users, also called Secondary Users, to use the unused licensed band temporarily. Cognitive radio is the technology that enables Dynamic Spectrum Access (DSA) networks to make use of the radio spectrum efficiently without disturbing the transmission of primary or licensed users. This is done to provide a reliable communication for unlicensed users wherever and whenever required thereby effectively utilizing the radio spectrum.

CR accesses the unused spectrum temporarily which is called white space or spectrum holes [3]. We can say that the ultimate goal of the Cognitive Radio is to optimize the radio spectrum and enhance spectrum efficiency through cognitive capability and reconfigurability [4] from the surrounding medium in which it operates [5]. The major thrust in CR research has been on Medium Access Control (MAC) and physical layer [6,7].

The rest of the paper is organized as follows. In Section 2, we discuss routing challenges in CRAHNs and review some related work in this area. In Section 3, the network architecture of RPCRAN, our proposed routing protocol is presented. In Section 4, performance evaluation of RPCRAN is presented followed by Section 5, which concludes our work.

2. **Routing Challenges in CRAHNs and Related Work.** In Classical Ad hoc networks, there is a fixed spectrum for all the network nodes, e.g., WLAN uses 2.4 and 5 GHz bands, and GSM uses 900 and 1800 MHz bands. In DSA networks, there is no such pre allocated spectrum, instead the spectrum bands are distributed over a wide frequency range and may be different from node to node. In a traditional ad hoc network during routing over multiple hops, there may be disconnections when the node may have moved. This can only be detected, if the route reply packet is not received by the next hop node in the path after the retry interval has exceeded whereas in CRAHNs, even if there is no mobility, the node may be not able to transmit due to the presence of Primary Users (PU) activity. In traditional ad hoc network topology, information is gathered by sending beacons on the channel, but this is not feasible in CRAHNs as the licensed spectrum frequency range is quite large. This culminates in incomplete topology information eventually resulting in an increase in collisions among secondary users and causing interference to the primary users.

In CRAHNs routing is a challenging task as it is a twofold task. Firstly, a route discovery from CR source node to the destination has to be made avoiding interference to the primary users' activity and then at each intermediate node the bandwidth utilization has to be accounted for. During the network discovery phase, the critical issue is awareness of the spectrum, i.e., while finding an efficient routing solution, it has to monitor ceaselessly for the presence of PUs. This data can be communicated by the sensing mechanism which may be an external entity [8] or through the CUs itself.

A frequent presence of PUs [9] is a challenging problem as it causes the route breakup in CRAHNs and then the issue of route maintenance arises. Further other important characteristics of CRAHNs such as PU activity, node mobility, and variable link quality have to be encountered. CR technology can be applied in CR Mesh architecture [10,11] or in an ad hoc fashion [12].

Routing is an important aspect not yet researched fully in CRAHNs. Therefore, there is an essential need for a good efficient algorithm in such networks. Limited amount of work has been done on this aspect. In [13] for modeling network topology and routing in interference based DSA networks, a layered graphic model was proposed. This is based on a complex model. This approach was based on centralized infrastructure for achieving optimal network performance. The drawback of this approach is that it considers static links for modeling. Such approach which is based on a proactive method cannot be applied to CRAHNs as it is difficult to determine node position and spectrum availability. In [14], a protocol called SEARCH was proposed based on geographic routing. In this protocol, destination node position is known to the source and the intermediate nodes. There are some drawbacks of this protocol. It is difficult to obtain the location information and expensive as it employs GPS. Secondly, there is a key issue of functioning properly indoors. The methods employed to estimate locations (by the distance to certain anchors) are computations intensive, and without good accuracy. In [15], a protocol called spectrum and energy-aware routing (SER) protocol based on the dynamic source routing protocol was proposed. ROSA (routing and dynamic spectrum) allocation algorithm [16] was based on a distributed algorithm which used one or more radio interfaces for data transmission. It used a single dedicated radio interface for messages. Sheu and Lao [17] proposed a protocol which was based on cooperative benefit between two adjacent nodes and routing was done by evaluating the cost. In [18], authors proposed a dedicated channel for broadcasting route request and route reply packets. The demerit of this scheme was the transmission in untested channels. The Spectrum Aware Mesh Routing (SAMER) [19] considered those paths for routing where the spectrum was available in abundance. Our routing approach is more realistic in comparison to the above approaches, as we consider dynamic nature of the links and intermittent connectivity in CRAHNs.

3. Network Architecture.

In CRAHNs each secondary user should avoid interference to the primary users by periodically sensing the transmitting channel. Simultaneously, it

TABLE 1. RPCRAN algorithm for the best route discovery in CRAHNs

```
Source Node S broadcasts to Destination node D on all possible channels.
All channels may not be available to PU activity. If i^th channel is available and CU is the cognitive user and PU
is the primary user
    If (Intermediate CU Node I receives Route_Request) Then
      Create a Reverse Route to S
      Update its link_table
          If (Route_Request is duplicate) Then
            discard Route_Request Packet
          Else If the route is better Then
            update link_table
          If (I is D) Then
            unicast Route_Reply to S
          If (I receives Route_Reply) Then
            forward Route_Reply to S
          Else If (S does not receive Route_Reply for a certain time period t) then
            S broadcasts (Route_Request_Error)
    End If
          If (I senses PU activity) then
            Discard the route
            Update link_table
            Forward PU_Route_Request_Error
          Else
            Rebroadcast Route_Request to D
            D updates its link_table
      End If
```

has to monitor the availability of other bands, in order to detect spectrum holes and to switch to a new band, if it has to vacate this band. We assume that the network consists of PUs which are stationary and whose coverage area is known such as fixed television broadcast towers. The PUs are active or non-active working like on/off switch. The PU activity is sensed by a spectrum sensing mechanism, which is out of the scope of this paper. The route from the source node to the destination node in CRAHNs consists of multiple hops having multiple channels depending upon the spectrum availability. Each node is allowed a threshold transmission power to avoid interference to PUs in the vicinity. If, for example, there is PUs activity in j^{th} channel, transmission on the adjacent channels $j \pm 1$, $j \pm 2$ cannot be performed to avoid co channel interference. The route discovery is based on the following algorithm described in Table 1.

Figure 1 shows the Modified Mobile Node Architecture with multiple interface support. This is our CR Model. In this model, we have incorporated multiple channels. The channels represent the spectrum. This can be seen by the presence of multiple channels. The Routing agent differentiates between primary and cognitive users with a sub header. This has the ability of switching the channels according to the channel availability. Incoming packets come through the corresponding channels through the various entities in ascending order. All the packets are handled either by Routing protocol or by the application as the last module of every interface, i.e., the Link layer is connected to the common point (Address Multiplexer). For the outgoing traffic, the appropriate interface is selected by the routing protocol. The routing protocol uses the channel information transferred via MAC. In Routing Agent, we use our protocol RPCRAN. The network stack is composed

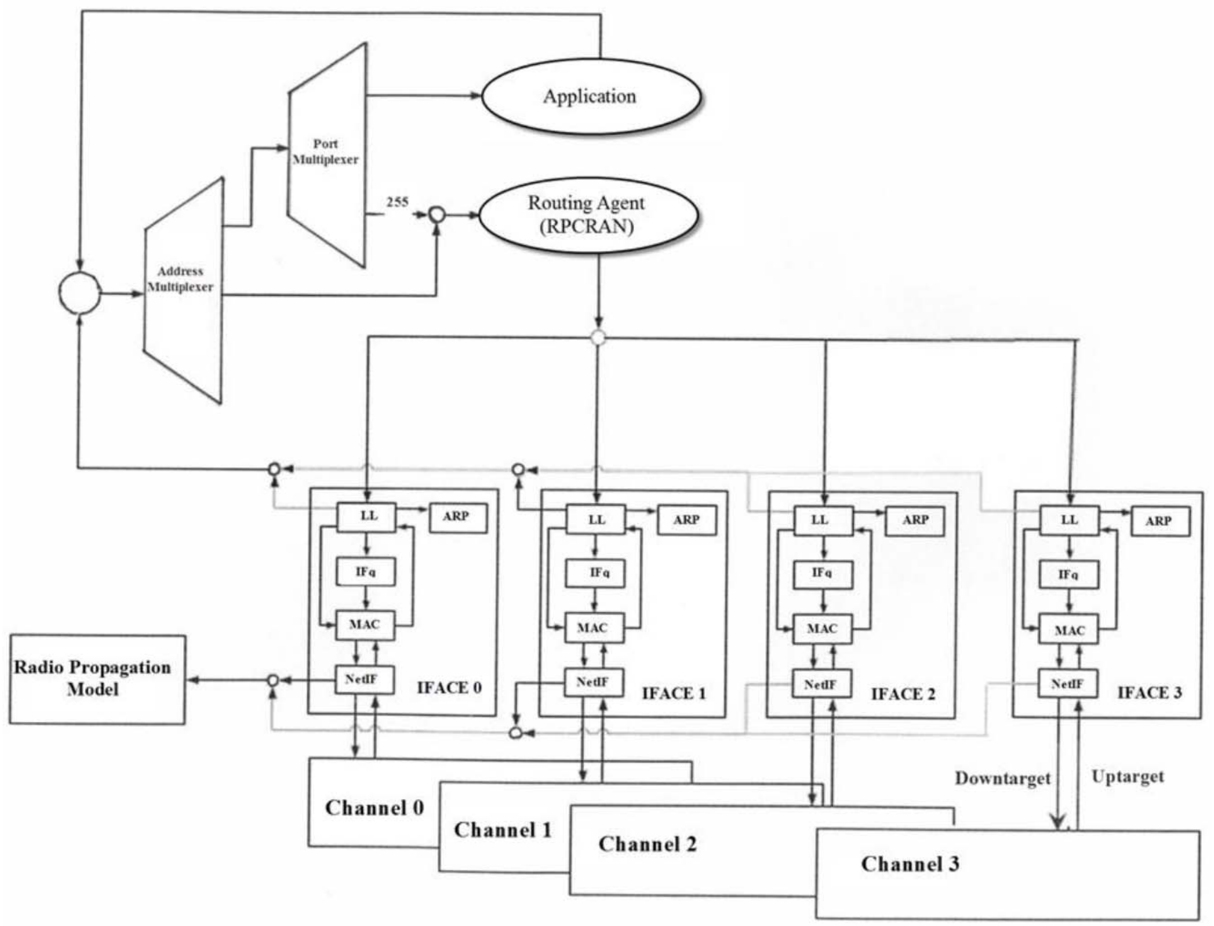


FIGURE 1. CR model

of a link layer (LL), an ARP (Address Resolution Protocol) module connected to LL, an interface priority queue (IFq), a mac layer (MAC) and a network interface (netIF), all connected with the channel. The job of the link-layer is responsible for simulating the data link protocols. It has an ARP module connected to it, which resolves all IP to hardware (Mac) address conversions. Normally, for all outgoing (into the channel) packets, the packets are handed downward to the LL by the Routing Agent. The LL hands down packets to the interface queue. The ARP receives queries from the Link layer. If ARP contains the hardware address for the destination, it writes it into the MAC header of the packet, otherwise it broadcasts an ARP query, temporarily caching the packet. There exists a buffer for a single packet for each unknown destination hardware address. If there are more packets sent to the same destination, the earlier buffered packet is dropped. Once the hardware address of a packet's next hop is known, the packet is inserted into the interface queue. The packets from the LL are handed down to the interface queue. It acts as a filter for all the packets in the queue. The Network Interface layer serves as a hardware interface which is used by mobile node to access the channel. The job of the MAC layer is to draw packets from the queue as it needs them. This is accomplished by a handshaking mechanism between the MAC and the queue. Thus, it can be said that MAC layer is responsible for transmitting the packet on the channel. For this, it has to follow a certain medium access protocol before transmitting the packet on the channel. While receiving, the MAC layer is responsible for delivering the packet to the link layer. The last object of the network stack is the network interface. The Network Interface layer is a hardware interface through which the mobile node accesses the channels which are connected to the physical layer. This interface is subject to collisions. The radio propagation model receives packets transmitted by other node interfaces, to the channel. The interface stamps each broadcasted packet with the meta-data related to the transmitting interface like the transmission power, wavelength, etc. This meta-data in the packet header is used by the propagation model in receiving network interface to determine if the packet has a minimum power to be received and/or captured and/or detected (carrier sense) by the receiving node.

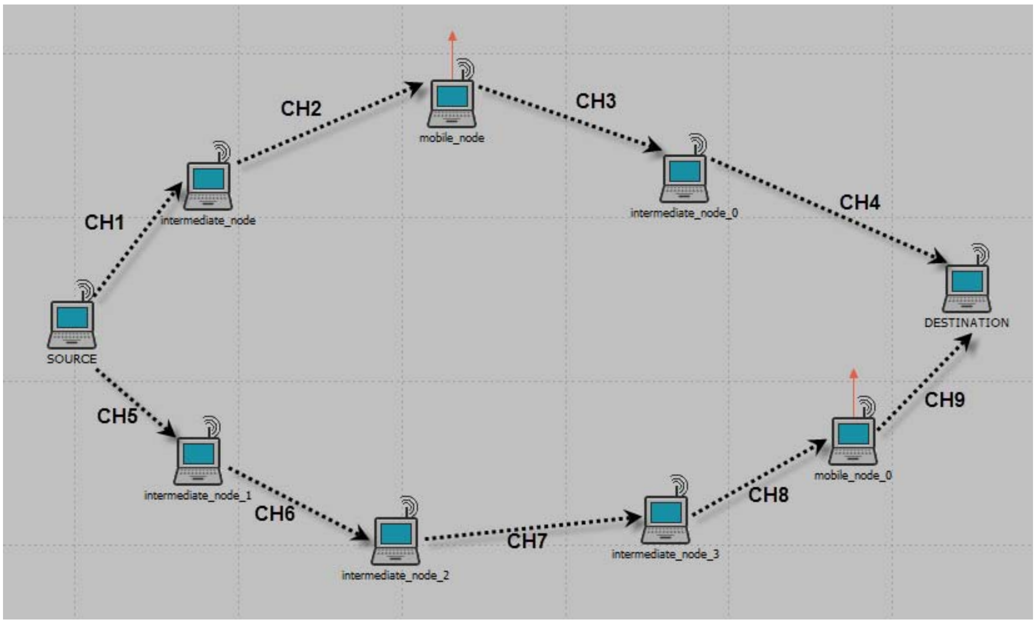


Figure 2. CR ad hoc network formation

Figure 2 shows formation of CRAHNs using nodes and channels. It also shows how data can be sent from the source to the destination. When the route request is broadcast it can take any path either through channel 1 or channel 5 depending on fewer hops which are dependent on availability of channels due to PU activity.

Figure 3 illustrates a successful transmission in a multi-channel MAC.

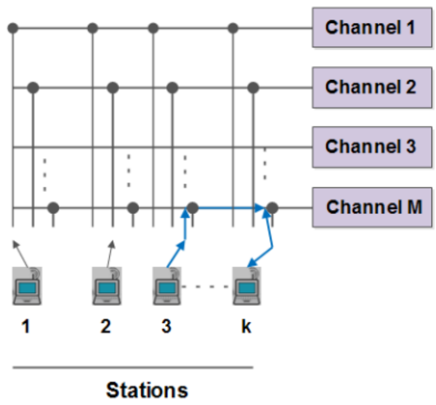


FIGURE 3. A successful transmission of node 3 to node k over channel M

4. **Performance Evaluation.** In this section, we evaluate the performance of our protocol under various network conditions and different traffic loads. The evaluation is done in Network Simulator 2 (NS 2.34) [20]. The NS2 code from [21] was extended to support multi radio multi-channel whose architecture is shown in Figure 1. Some of the key modifications were done in NS2 code, which are as follows. Channel selection mechanism was incorporated in the Routing Layer instead of the MAC layer. Modification of the mobile node was done to correctly associate with channel. Request sending method was modified. Furthermore, random time selection for sending packets for route discovery to all the interfaces was incorporated.

The simulations have been carried out in a multi hop network environment. The CU activity is modeled according to random Waypoint Model in 1000×1000 m^2 area. Nodes density distribution is 400 nodes/km^2. The transmission range of PU is assumed to be 120 m and the coverage area is 300 m. These parameters have been taken to have a comparative result with the current authors [14,22]. Their results cannot be validated as their code is not available. The stationary PUs (like fixed TV towers) has been modeled using exponential ON OFF Markovian process. The ON and OFF state $1/\alpha$ and $1/\beta$ is analogous to birth and death process. In cognitive environment ON state signifies the spectrum occupied by the PUs. The OFF state represents the unoccupied period of the PUs. Here we have taken $\alpha = 0.5$ and $\beta = 0.5$. The PUs packet is controlled by a broadcast timer. The simulation parameters are listed in Table 2. We consider three metrics for performance evaluation:

Packet Delivery ratio: Packet Delivery ratio (PDR) is defined as the ratio of packets, which are received at the destination node to the packets sent by the source node. PDR is calculated by dividing the number of packets received by the destination through the number of packets originated (generated by the CBR sources). It specifies the packet loss rate, which limits the maximum throughput of the network. The better the delivery ratio, the more complete and correct is the routing protocol.

Hop Count: Also called path length. Hop count is calculated by dividing the number of MAC transmission divided by Agent layer transmission.

TABLE 2. Simulation parameters

Simulation Area	1000×1000 m^2
Channel Type	Channel/Wireless Channel
Propagation Model	Two Ray Ground
Antenna Type	Omnidirectional
Network Interface Type	Phy/WirelessPhy
Routing Protocol	AODV/RPCRAN
Interface Queue Type	PriQueue
MAC Protocol	MAC/802_11
Max Packet in IFQ	100
Number of Mobile Nodes	10
Simulation Time	300 seconds
Mobility Model	Random Waypoint
Agent	UDP
CBR Packet Size	500
Coverage Area of PU in the Occupied Channel	300 m
Transmission Range of CR user	120 m
Physical Layer Noise	0.1

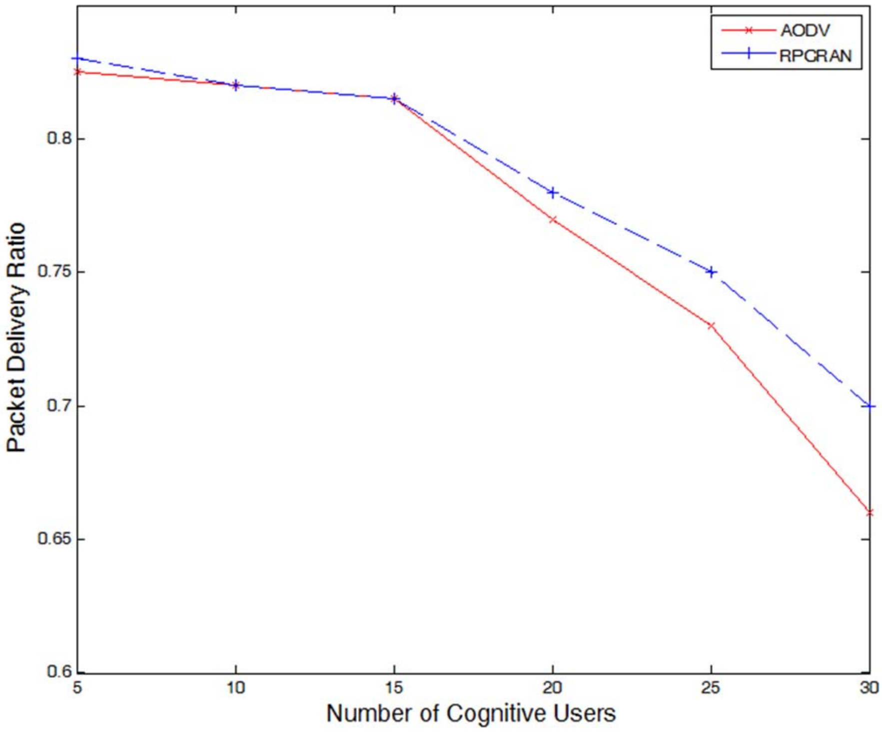
End to End Delay: End-to-end delay refers to the time taken for a packet to be transmitted across a network from source to destination.

We have created an AWK script which calculates the above three metrics from the trace file created. The selected application lists for each class and the number of applications in each class are shown in Table 2.

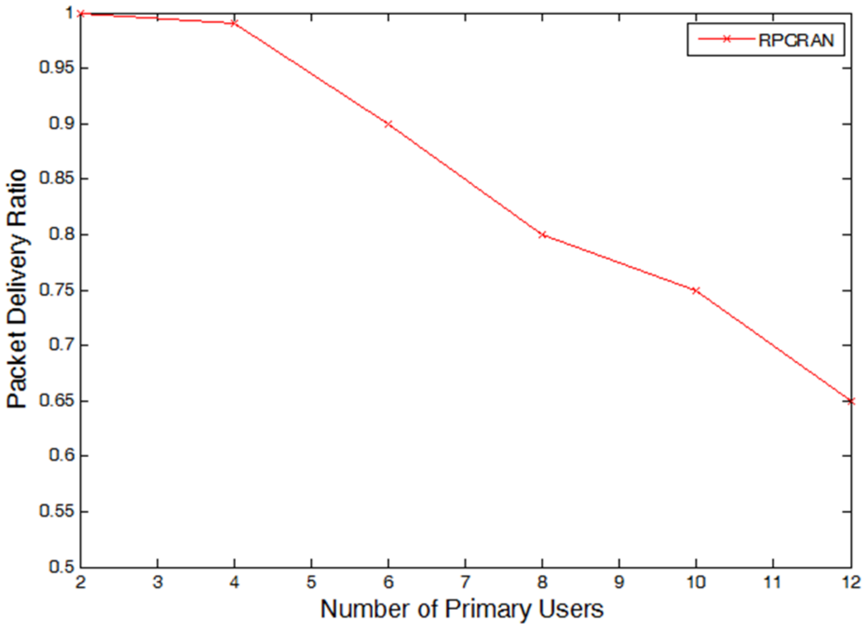
4.1. **Simulation results and analysis.**

4.1.1. *Packet delivery ratio.* Figure 4(a) shows the packet delivery ratio with respect to the cognitive users. In this scenario, no primary users' activity is there and the numbers of channel available are 4. We test our simulator with only cognitive users' present. This is to compare our proposed protocol RPCRAN with standard protocol AODV to test the functionality of our designed CRAHNs simulator. It is observed from Figure 4(a) that RPCRAN follows AODV thus validating our simulator. In Figure 4(b) numbers of cognitive users are fixed at 30 and PUs are present. It is observed that PDR lies between 1 and 0.65. This decrease in PDR can be attributed to the fact that with an increase in PU activity, free channels are not available to the CUs so the packets are delivered only when the channels are idle. Still the simulator can perform well keeping the PDR in the above mentioned range. RPCRAN can form another link for a different route with another channel when the PU becomes active on that channel, and the CUs have to vacate the spectrum for the PU.

4.1.2. *End to end delay.* Figure 5(a) shows the end to end delay when only cognitive users are present. The figure exhibits end to end delay for AODV and RPCRAN. Figure 5(b) exemplifies an end to end latency with the number of CUs fixed at 30 and number of CUs ranging from two to twelve. Initially, when the PUs are few, end to end delay is very less but with an increase in PUs it surges, but gradually it approaches stability. This increase is due to the Route Error. The stability which can be observed is after the route establishment. RPCRAN shows low end to end delay even when there is PU and CU activity.



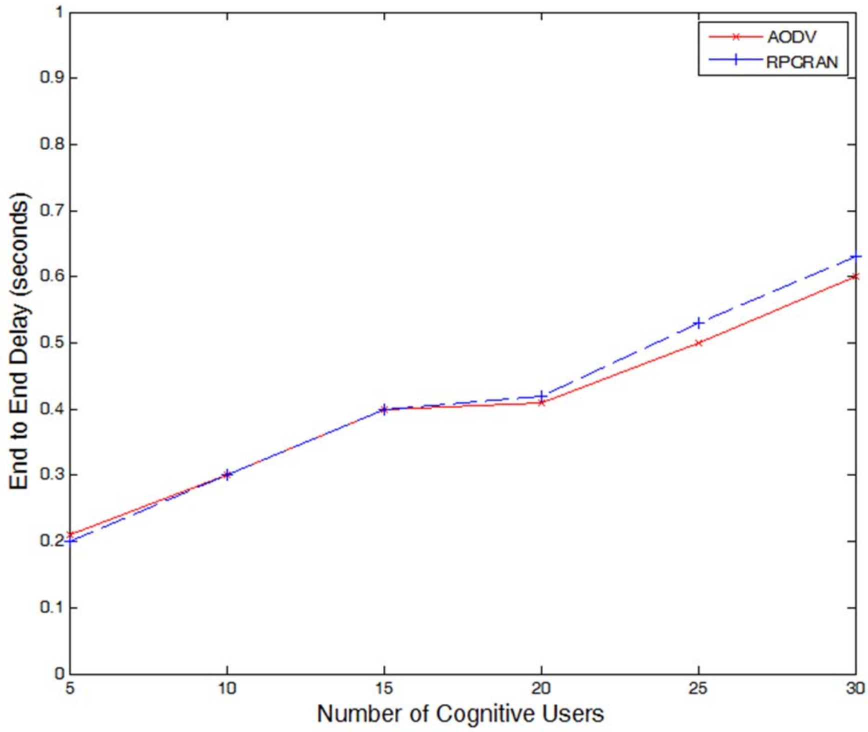
(a)



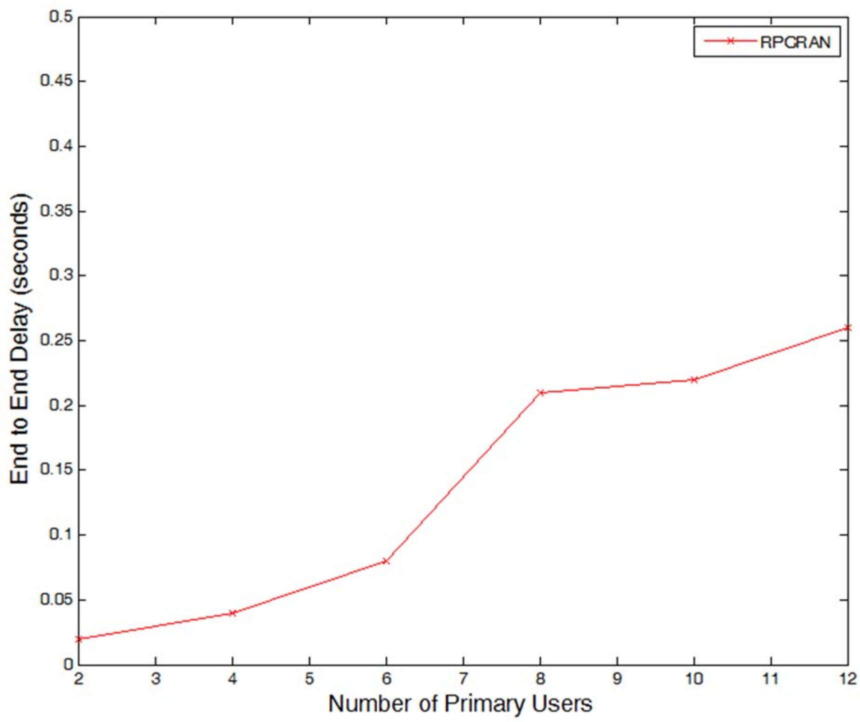
(b)

Figure 4. Packet delivery ratios: (a) only CUs present, (b) both CUs and PUs present

4.1.3. *Hop count.* Figure 6(a) shows the hop count for RPCRAN and AODV when only cognitive users are present. Figure 6(b) presents the hop count for RPCRAN with the number of CUs fixed at 30 and number of CUs ranging from two to twelve. It shows a low stable hop count due to node mobility. Hop count is an important factor depending upon the route discovery process. This process starts when the CUs have to search for

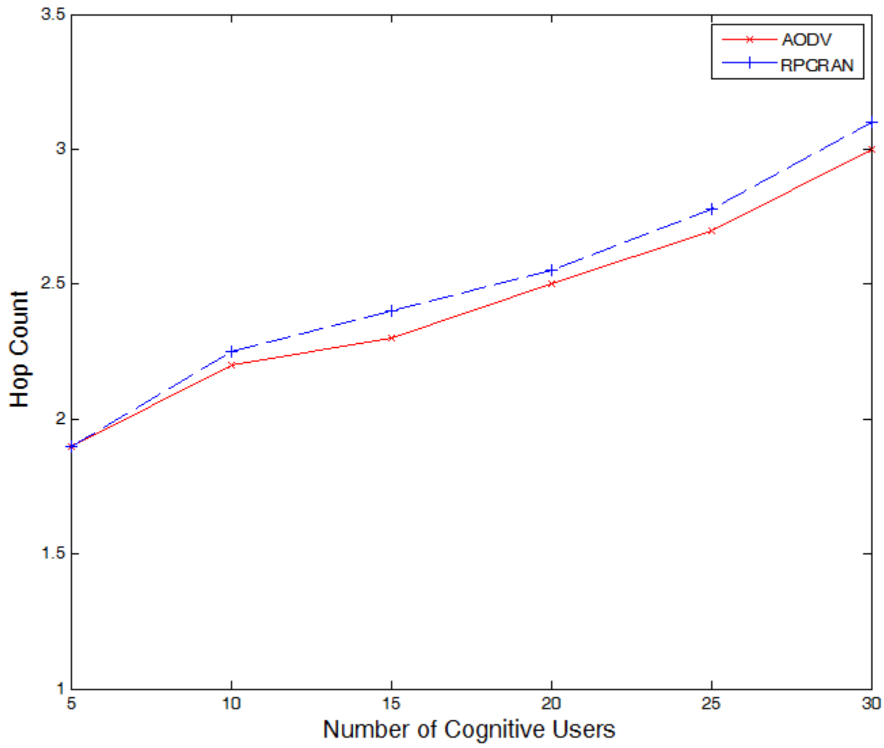


(a)

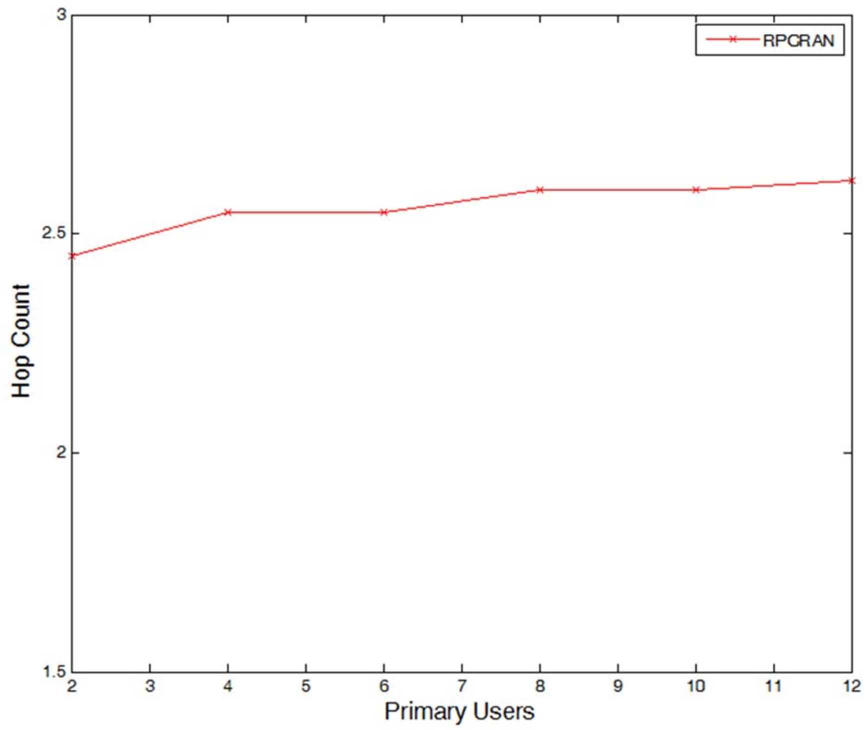


(b)

Figure 5. End to end delay: (a) only CUs present, (b) both CUs and PUs present



(a)



(b)

FIGURE 6. Hop count: (a) only CUs present, (b) both CUs and PUs present

other channels after vacating the channel allocated to the PUs. A low hop count implies that RPCRAN is relatively unaffected by joint PUs and CUs activity.

5. **Conclusion and Future Work.** In this paper, we have proposed RPCRAN, a routing protocol for mobile ad hoc cognitive radio network. This protocol is sensitive to the PR activity. The performance is not affected while ensuring no interference is caused to the licensed users. It utilizes multiple channels to enhance the performance of CRAHNs. A real validation of RPCRAN would come, if it is implemented in a real test bed. This protocol can further be enhanced by incorporating effective routing metrics. In future, we will implement this protocol in a test bed scenario and then compare the practical and simulated results.

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