A Multipath Routing Protocol for Cognitive Radio AdHoc Networks (CRAHNs)

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Abstract – **Cognitive Radio Networks (CRNs) increase spectrum utilization by opportunistically sharing licensed spectrum with cognitive capable devices. There are many routing algorithms proposed for CRNs so far. Most of these algorithms discover single path from source to destination and consume considerable amount of bandwidth during route discovery. On the other hand, the multipath algorithms designed for AdHoc networks show significant improvements in bandwidth utilization by discovering multiple paths using one route discovery process. So, it is believed that such multipath routing algorithm provides substantially resilient behavior to the channel dynamism because multiple paths are discovered within single round of path discovery. In this paper, a multipath routing protocol for Cognitive Radio Network (CRN) is proposed. The protocol considers channel stability for route formation and finds multiple disjoint paths between two nodes. The proposed multipath protocol is compared with Cognitive AODV (CAODV). Result shows that the performance of the proposed protocol is better in terms of packet loss rate, route discovery latency, route discovery frequency, and average delay.**

Key words: ***Cognitive, Multipath, Routing, Stability.***

I. Introduction

Cognitive Radio Network (CRN) has got considerable importance among researchers in the recent past [1, 2, 3]. The traditional wireless networks with fixed spectrum allocation policy enable only licensed users to access the allocated frequency band(s). However, spectrum usage census exhibits a large variation in both temporal and spatial dimensions [4]. This inefficient usage of licensed spectrum can be balanced through the use of cognitive communication. The new technology allows residing cognitive devices (called Secondary or Cognitive Uses (SUs or CUs)) along with licensed users (called Primary Users (PUs)). The CU with dynamic spectrum access capability opportunistically utilizes spectrum holes or white spaces, i.e. the unutilized frequency bands of licensed spectrum which is found due to lack of activities of licensed PUs. Moreover, a CU is capable of switching between channels based on the available signal strength and transmission quality of different bands. Research direction in CRN includes a wide range of areas like spectrum sensing and analysis, channel estimation, spectrum sharing, medium access control (MAC), and routing. However, in this paper we focus on routing method for CRN.

The primary objective of CRN is to utilize the spectrum hole to maximum possible extent. At the same time, it is important that the CUs make the best use of the spectrum hole with minimum wastage. Unfortunately, the single path routing protocols consume considerable bandwidth during the path discovery process of routing. On the other hand, the multipath routing protocols relatively reduce the overhead [5, 6] due to less frequent route discovery process compared to single path routing protocols. Because, the multipath routing protocols have the ability to discover multiple paths in one route discovery process and when there is a route failure the source node uses an alternate path rather than initiating a new route discovery process. Moreover, due to the existence of multiple paths, packets of same session may arrive in the destination quickly via different paths and hence reduces average end to end packet delay. Compared to Ad hoc networks, the route discovery is much more costly in CRN. Because, in CRN even to discover a route the Cognitive Radio Device (CRD) needs to use the primary channels opportunistically. Needless to say that due to discovery of multiple paths in single route discovery process, multipath approach is more effective for CRN.

Keeping the benefits of multipath algorithms in mind, this paper proposes an algorithm for discovering multiple paths in one route discovery process for CRN Ad hoc network. The protocol selects the most stable path from source to destination and ensures disjoint and loop free route. The PU activities and availability of channels for SUs are taken care of in the algorithm. The proposed scheme is compared with Cognitive AODV [7] protocol and results show an improvement of the new method over CAODV with respect to packet loss rate, route discovery latency, route discovery frequency and average delay.

Rest of the paper is organized as follows. Section II presents some related work. Section III states the system architecture followed by Section IV, in which proposed Multi Path Routing (MPR) protocol is discussed in detail. Section V shows the correctness (disjoint and loop free) of the algorithm. Simulation results are presented in Section VI. The paper is concluded in Section VII.

II. Related Work

Although, there are some single path routing protocols for CRN proposed in last decade [7, 8, 9, 10, 11], very few multipath protocols have been reported so far. These are available in [12,13]. Multipath Routing and Spectrum Access (MRSA) [12] and Multi-path Routing with end-to-end Statistical QoS Provisioning in Underlay Cognitive Radio Networks [13] are two routing protocols having significant contributions and novel ideas. A brief discussion on both of these two protocols is presented below.

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In [12], author describes an on demand multipath protocol that uses minimum hop count for selecting multiple paths. The proposed framework seeks to establish multiple paths that maximize spectrum wise disjointedness to minimize contention and interference among the links. The proposed framework is evaluated by simulation with simple network topology for illustration and a random topology for general performance tests. Through simulation, they have shown that MRSA achieves higher throughput than other reference routing approaches and also provides better resilience from the dynamic interruption of primary users. However, this protocol does not consider the CR dynamics or channel stability and hence in most of the cases unreliable paths are constructed.

In [13], two multipath routing schemes are proposed. In the first approach, named as duplication-based multi-path routing, identical packets are forwarded on multiple paths. The other approach called coding-aided multi-path routing, packets are stored in the buffer and then forwarded to the next hop when the SU gets activated. The proposal provides a statistical end-to-end delay model for multi-path routing with QoS provisioning by relating path diversity to end-to-end reliability. The protocol claims to enhance the end-to-end throughput by encoding packets on multiple paths. Although the approach has strong mathematical basis, it seems to be unrealistic for CRN. Because in duplication based approach the same packet is forwarded in multiple paths and hence, using multiple channels by the same packet is not an efficient approach. This happens in the environment where the channel is supposed to be used opportunistically and efficiently. Also the other approach where the packets are buffered is not suitable for delay sensitive applications.

The protocol proposed in this paper is a simple multipath routing mechanism and it is different form above mentioned two methods in many aspects. Unlike [12], we have considered channel stability as one of the prime criteria for selecting a path. Hence, it gives highly sustainable path. Our work follows simple route discovery method as is done in Ad hoc On-Demand Multipath Distance Vector AOMDV [17] protocol and uses sequence number of the route discovery packet to construct disjoint multiple paths. The paths discovered are used for transmission of unique packets rather than identical packets as done in [13]. As no buffering is done for forwarding packets as in [13], our proposal is suitable for delay sensitive applications. Although the proposed algorithm uses some of the managerial packets form AOMDV, the characteristics of CRN are taken care of in our approach. In fact, the disjoint multipath and loop free approach of our protocol is completely different from AOMDV.

III. System Model

The system model assumes a CRN with coexisting randomly distributed static PUs and mobile CUs. There are M non-overlapping channels denoted by $\boldsymbol{M} = \{1, 2, \ldots, M\}$ and each of the channels is for exclusive use by single PU. The coexisting CUs are equipped with a cognitive transceiver and can tune themselves to different channels for communication based on the availability of primary channels from the set *M*. Moreover, one CU can access only one channel at a time and can no way harm the PU conversation. We do not assume the existence of any Common Control Channel (CCC) for transmission of control messages. Rather, CUs use available free primary channels for communication of managerial packets related to route discovery. Further, two nodes need at least one common channel for transmission of information.

The protocol presented in this paper is an on demand protocol and hence a CU node initiates a route discovery process when there is a packet to transmit and it has no existing path to the destination. Algorithm works in the similar manner of AODV but CRN related characteristics like channel dynamism are taken into consideration for route formation. The CU nodes, before initiating the route discovery process, sense all the existing channels available for use and computes the stability of each channel using statistical calculation as explained in [14]. Since our main aim is to compute multipath for CRN routing, detail calculation of channel stability is not included in this paper. For understanding of the channel stability computation, a brief description is given in the next paragraph. The details of this process is available in [14].

A SU cannot use channel l if the node is under the coverage of PU_l (PU_l uses channel l) and the said PU is active. But SUs outside the coverage of PU_l (say radius of coverage is R_l) can obviously use channel l. Further, the discussion of [8] shows that due to neighbor channel interference, SU within R_l cannot use channel $l-2$, $l-1$, $l+1$ and $l+2$ if owner PUs of such channels are active. In other words, due to neighbor channel interference, PU activity in channel l will also affect the SUs using channel $l-1$, $l-2$, $l+1$ and $l+2$ [8]. However, affected region due to channel l will be smaller in other channels compared to the region of channel l. Using the idea presented in [8], a method of calculating channel state probability is explained in [14]. It is assumed that, Γ(i) represents the set of n-channels available in CR environment. There may be $j \leq n$ number of active channels between any two nodes at particular moment of time. Let say $\propto_i$ is a constant that represents the availability of a channel i such that $0 \leq \propto_i \leq 0.9$ and it is calculated from the previous history. Higher the value of $\propto_i$ more is the channel stable. The state probability of the channel i $(1 \leq i \leq n)$ is calculated as:

$$p_i = \frac{\sum_{k=i-2}^{i+2} \emptyset_k \times (A_A)_k \times \propto_k}{\sum_{k=i-2}^{i+2} \emptyset_k \times A_k} \quad (1)$$

Where,

$\emptyset_i$: is the PU density in channel i

$(A_A)_i$: Area in channel i that affects the SU in channel i, and computed as

$$(A_E)_i = \begin{cases} 1/4 \times A_i \ for\ i = i-2, i+2 \\ 1 \times A_i \ for\ i = i \\ 1/2 \times A_i \ for\ i = i-1, i-2 \end{cases} \quad (2)$$

$\propto_i$: as discussed above

A_i: is the actual coverage area of channel i

Each node while at power on mode, senses all the channels available in the environment and computes the state probability of each channel using equation (1). The computed probability is stored in a table maintained by each SU node. The information is also updated periodically determined by a timer. When the node needs to assign a channel for the route during route discovery phase, it selects the most stable channel from the set of available channels. Once the channel is assigned to a route it cannot be reassigned to another route. For the next route it selects the next available channel with next highest stability and so on. In the next section, various phases of the proposed MPR algorithm are described.

IV. The Proposed Multi Path Routing Protocol

The routing algorithm described here is an on demand and a node initiates the routing process whenever it has a packet to transmit. It uses various managerial packets of MAODV with few modifications that fit into CRN. Different phases of the algorithm are described below.

A. Route discovery

Source node with a packet to communicate but no path in its cache initiates a route discovery process. The node prepares a Route Request (RREQ) packet. Then it sends the packet to each of its neighbor *N(u)* through the most stable channel between them. The RREQ packet contains a sequence number, source and destination node address, the channel ID through which the RREQ is communicated and the stability value of that channel. The sequence number uniquely identifies a RREQ packet. A node receiving a RREQ checks its cache for a route to the destination specified in the packet. If it finds one, then it sends back a Route Reply (RRPLY) back to the source. Otherwise, the receiving node treats the RREQ message as its own message and repeats the route discovery process. However, if the node has already forwarded a RREQ with same sequence ID, it does not forward it again and drops the packet. A node can identify the previously forwarded RREQ from the sequence number of the packet. This process ensures unique multipath to same destination from same source. The RREQ message contains following information

```
<#Seq_id, src, dst, ch_id#,channel_stability>
```

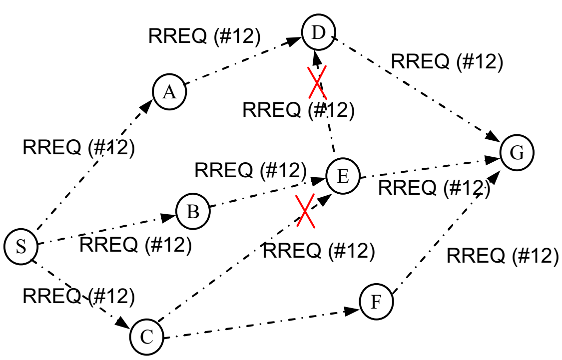

Fig. 1 Route discovery in proposed protocol

The Fig. 1 shows the flow of RREQ packet in the proposed protocol. The number inside bracket indicates the sequence number of the packet under consideration. Node S initiates the route discovery process and RREQ flows through various nodes to the destination G. We assume that no node has existing route in the cache. The node D drops the RREQ forwarded by E as it has already forwarded one RREQ with sequence number #12 which was earlier forwarded to D by A. Node E also drops one RREQ as shown in the diagram for similar reason. Each node (other than destination) receiving RREQ, records the reception of the packet and forwards the message to its open neighbors *N(u)* using the most stable channel. The destination node G receives three RREQ message from three different nodes and hence it prepares to send the RRPLY to all the three senders and hereby creates three paths. Further, the destination G assumes that all the three RREQs that it receives are disjoint. (Disjoint and loop free properties are proved in Section V).

B. Processing of RREQ

On receipt of the RREQ message, the destination node assigns a flow id and sends a Route Reply (RRPLY) to the node from which it has got the RREQ. The destination node can figure out that each of the RREQ messages are received through different paths and discovers a unique path. Otherwise, RREQ would have been dropped between source and destination. The RRPLY message contains the following information

```
<#Seq_id,#flow_id, src, dst, hop_cnt>
```

The RRPLY message is then propagated to the source through the reverse path of the RREQ message. Any intermediate node receiving the RRPLY message, updates the cache entry and sets the flow id as specified in the RRPLY message and hop count increases by 1. The intermediate node and the source on receipt of RRPLY message construct a table to the specified destination with following information

```
<#seq_id, #flow-id, dest, ch_id#, stability_val,
next-hop>
```

This table is used for forwarding packets from any node. However, if an intermediate node receives a RRPLY with a seq_ id# which is already passed through it, then the node drops the newly coming RRPLY. Otherwise, the protocol will produce multiple paths with joints.

C. Route Maintenance

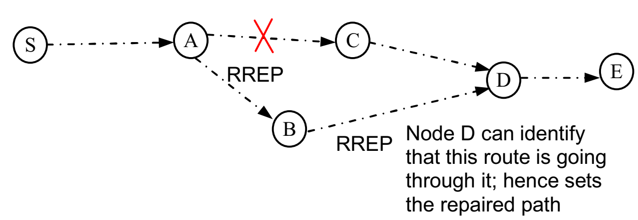

Fig. 2 Repair route during link fail

If a node notices a route failure, then it first checks if the failure is due to the channel occupancy by PU nodes. If it is so, then it checks available channel in its table and selects the one with the current high stability to the neighbor. If it cannot find any channel, then it assumes that the link failure may be due to the movement of the SU node. So, it initiates a route repair (RREP) process. It sends a RREP message to all its open neighbors *N(u)* with sequence ID and flow id of the failed link.

Every node receiving RREP message checks its cache for existing route to the destination. If an intermediate node receives a RREP with sequence ID already passing through it having different flow id, then it drops the RREP. Otherwise, if it has a path to the destination with same flow-ID of the RREP message then it connects the link to its existing sequence ID, flow ID and reverts one ROUTE-CORRECT message to the initiator of the RREP. If a node initiating RREP message does not get any reply within certain time interval then it sends Route Error (RTERR) message to the source node.

V. Algorithm Selects Disjoint Paths

In this section, it is shown that the proposed protocol produces disjoint and loop free multiple pats. Two most crucial topologies in CRAHN that may lead to formation of joint paths are shown in Fig. 3 and Fig. 4, respectively.

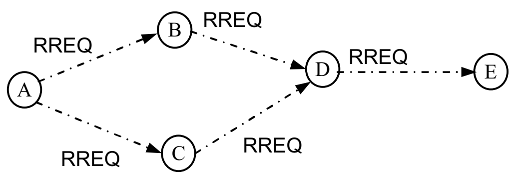

Fig. 3 Processing RREQ for disjoint path

As shown in Fig. 3, ABDE and ACDE are the two probable paths from A to D. However, the algorithm should not select two paths for the topology because DE is the joint path in both. To allow the two RREQs with same seq_id# by node D, they must have different sequence IDs. But, node A cannot generate the same RREQ with two different sequence numbers and hence one of the RREQ will be dropped in the node D. This shows that the algorithm will not select path with joints.

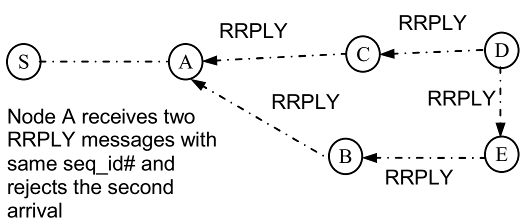

Fig. 4 Processing RRPLY for disjoint path

In another topology as depicted in Fig. 4, S to D has two paths S-A-C-D and S-A-B-E-D. In this topology, the common path SA cannot be detected during RREQ propagation. Because, at the time of RREQ propagation, node A could not figure out that the propagation of RREQ leads to the joint path. Again, the destination node D receives the RREQ from two distinct paths and no way can tell that both the RREQ have a common path from S to A, and hence sends RRPLY to both the requests. However, when RRPLY is processed by node A it can determine that the two reply packets are for the same seq_id#. So, node A drops one of the RRPLY and hence the possibility of establishing a joint path is eliminated. It proves that the algorithm generates disjoint unique multi paths.

Algorithm is loop free: To form a loop, one RREQ must go through at least one node twice, since a node does not allow one RREQ, with same sequence number twice so loop cannot be formed.

VI. Simulation Results

The proposed multipath routing protocol is simulated in *ns-2.31* [15] and *routing overhead, end-to-end packet delivery delay, packet loss ratio and route discovery frequency* are compared with CAODV [7]. During simulation, PUs and SUs are distributed uniformly across an area of 1000x1000 square meters with 11 primary channels. The PU activities are modeled as ON and OFF state. During ON state, PU access the channel and during OFF state SU gets opportunity. The transmission range of SUs and PU are 50m and 70m respectively. The SUs are initially placed uniformly and allowed to move according to the random walk model [16]. PU nodes are considered static in the simulation. The source and destination of each connection are also selected randomly. We have taken two scenarios with PU activities 15% and *85*% respectively, and simulated for 500secs. Details of simulation parameters are shown in TABLE I.

TABLE I
PARAMETERS AND THEIR TYPICAL VALUES USED IN THE EXPERIMENT

Parameter	Value range	Typical value (s)
Number of PUs	10-20	11
Number of SUs	20-50	30
PU transmission range	70m	70m
SU transmission range	50m	50m
Number of channels	11	11
Packet size	512Bytes	512Bytes
Session size	500-700 Pkts	600 Pkts
Simulation area	1000x1000	1000x1000
SU speed	2-10 m/s	variable
Active connections	10-20	15
Transmission bandwidth	5 MHz	5MHz

A. Average Packet loss

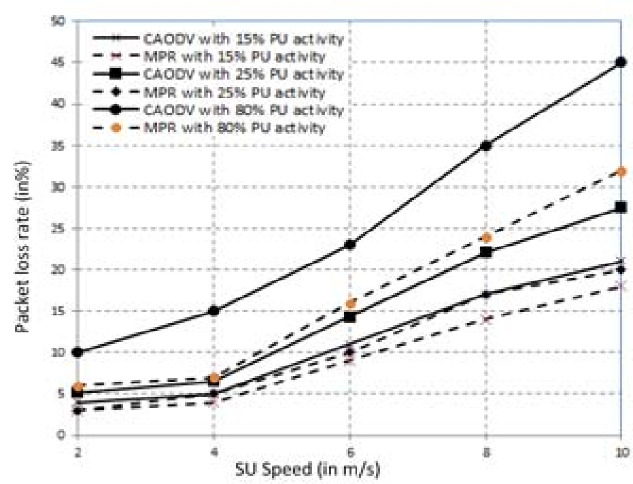

Fig. 5 Packet loss rate in CAODV and proposed MPR protocol

Packet loss occurs due to two reasons. Either the SU nodes go out of range, or PU node occupies channels and hence there is no room for SU node. Observation shows that the loss rate is more in CAODV than proposed MPR protocol. In MPR, since there are multiple paths discovered during route discovery phase, therefore, packets are delivered via different paths and hence it decreases packet loss rate. The speed of SU nodes and PU channel occupancy rate has large impact on packet loss. As the speed of SU increases, packet loss also increases. In this case, more breakage in path occurs as SU nodes go out of range leading to route failure. Also increased PU channel occupancy ignites loss rate. In this case, it is due to channel occupied by PU channel and SU does not get opportunities. However, in both these cases MRP performs better than CAODV, because of existence of multiple paths for data delivery.

B. Route discovery frequency

This parameter shows the rate at which route discovery packets are generated by various sources. When the source with a packet to transmit could not find a route in its cache it initiates a route discovery process (Section IV.A). CAODV generates more discovery packets per second compared to MPR. In the proposed MPR, the less frequency of route discovery may be justified with two major characteristics of itself. The protocol selects the most stable channel based on some statistical calculation (Section III.) and hence the route sustains for longer time. In CAODV, no route stability is considered and hence probability of route failure is more. Another reason is the discovery of multiple paths in one route discovery process in MPR, and if one route fails the source can still have option of alternate routes. However, observation reveals that increased SU speed and PU channel occupancy rate increase route discovery frequency. But MRP outperforms CAODV in all cases.

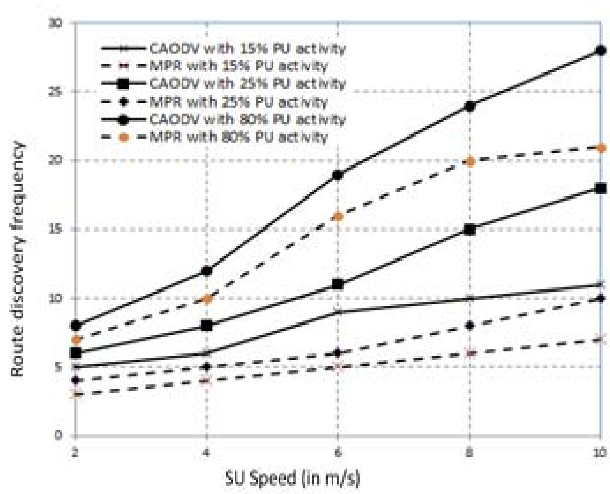

Fig. 6 Observation of route discovery frequency in CAODV and proposed MPR protocol

C. Average packet delay

Delay of MPR is less than CAODV because of multiple paths followed by packet in MPR and reaching the destination. On the other hand, CAODV follows the same path and packets suffer more queuing delay in the path and hence suffer more delay. However, in MPR, packets sometimes may take long route to reach the destination. In such cases, delay is more but despite of that it can outperform CAODV with respect to average packet delay. Further, increased speed and PU activities increase delay for both the protocols. In CAODV, the delay is worst as link failure occurs early. This is so because it does not consider the channel stability for selecting a route.

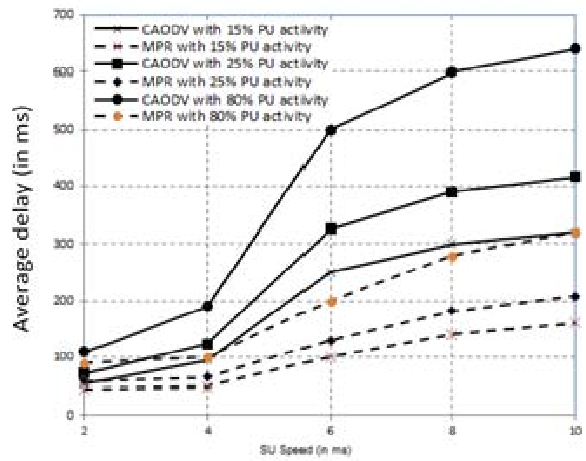

Fig. 7 Average delay in CAODV and proposed MPR protocol

D. Route discovery latency

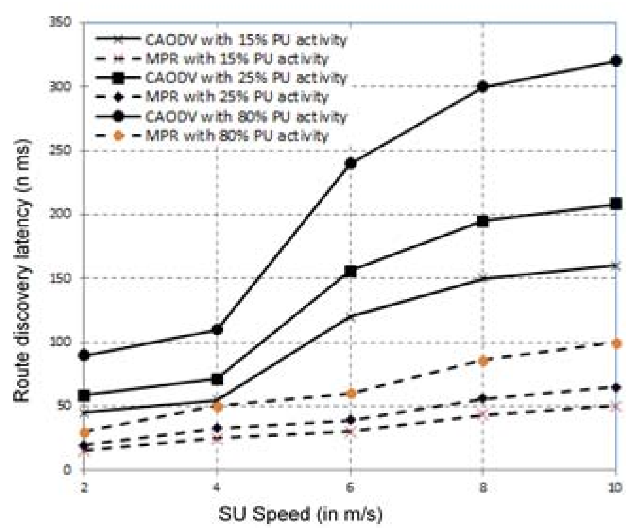

Fig. 8 Route discovery latency in CAODV and proposed MPR protocol

If a source node with a packet to transmit cannot find a route to destination in its cache then the packet has to wait in the queue till a new path is discovered. That waiting time is considered as route discovery latency. As expected, due to the existence of multiple routes in MPR, it shows lower latency compared to CAODV. Stable route selection is another reason for lower discovery latency in this protocol. As and when the speed of SU increases, the latency increases. This is so because the probability of not finding path in the cache of the source becomes higher. Again, with high PU activities, the latency increases accordingly.

E. Per route and average route discovery overhead

Since MPR needs to process multiple RRPLY messages therefore, the per-route overhead of MPR is more compared to CAODV (Fig. 9). However, the overall routing overhead is better in MPR (Fig. 10). Although MPR incurs more per route overhead as it generates multiple paths, it reduces route discovery frequency. On the other hand, the COADV leads to larger route discovery frequency and hence has greater average route discovery overhead.

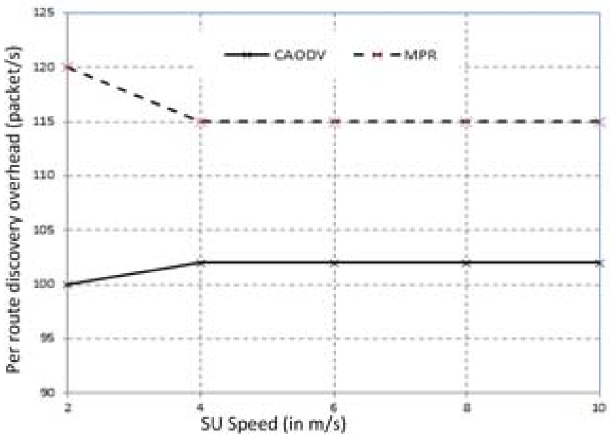

Fig. 9 Route discovery overhead (per route) in CAODV and MPR protocol

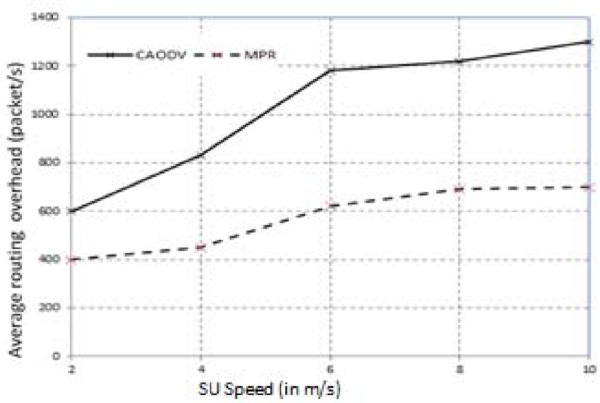

Fig. 10 Average routing overhead of CAODV and proposed MPR

VII. CONCLUSION

This paper describes a simple multipath protocol for CRN. The proposed protocol considers stability of channels during selection of route and ensures disjoint and loop free multiple paths from source to destination in one RREQ processing. The new protocol is simulated in *ns-2.31* and compared with CAODV. Results reveal that the new algorithm performs better than CAODV.

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