Location-Aware Probabilistic Route Discovery for Cognitive Radio Networks

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***Abstract*—Cognitive radios emerged as a solution for utilizing the spectrum which is considered a limited resource. Multi-hop routing in cognitive radio networks (CRNs) has been gaining increasing attention as it enables future large-scale CRNs. However, many existing protocols flood the network with control packets in route discovery phase, which leads to wasting bandwidth. In this paper, we introduce a location-aware probabilistic route discovery technique for CRNs that leverages gossiping with dynamic probabilities to reduce the flooding overhead without affecting the quality of the discovered routes. The proposed technique can be used on top of any routing protocol regardless of whether it relies on a common control channel or not. Evaluation of our technique through ns2 simulations for improving different classes of routing protocols shows a significant reduction in the number of control packets by up to 75% and an increase in throughput by up to 400%.**

I. INTRODUCTION

The exponential demand for portable and mobile devices increased the demand for high bandwidth wireless communications. Given that the spectrum is a limited natural resource, traditional static spectrum allocation mechanisms lead to the waste of this valuable resource. *Cognitive radios* emerged as a solution for enhancing spectrum utilization by allowing unlicensed users to opportunistically utilize unused portions of the spectrum. [1]–[3].

Multi-hop routing is one of the main directions that has been gaining increasing interest in cognitive radio networks research [4]–[8]. Many of the routing protocols for CRNs require either the source or the destination to discover different possible paths to select the best route. This approach requires the exchange of a large amount of information between the nodes in the network, usually by flooding the network with control packets, which leads to a large overhead.

In this paper, we present a new technique that reduces the overhead of global-view routing protocols in cognitive radio networks by probabilistically controlling the dissemination of control packets during route discovery. This allows for better utilization of the spectrum. Our technique builds on results of percolation theory which ensures full network reachibility if the rebroadcasting probability is larger than a critical value [9]–[11]. Gossiping based on percolation theory has been introduced in traditional ad-hoc networks to reduce the overhead of routing by probabilistically controlling the broadcast storm [12] of control packets. In [9] fixed probability gossiping was proposed to improve unicast communication in ad-hoc networks. A number of other metrics have been proposed to control the gossiping probability dynamically to better accommodate different models of ad-hoc networks [10], [11] including nodes density and battery power. Our proposed CRNs route discovery technique sets itself apart from other gossiping techniques by taking into account both the behavior of nearby primary users and the location of nodes. This allows for control packets to be disseminated through routes that are more likely to be shorter in terms of hop count and more stable, by avoiding primary users.

We present the details of the proposed technique for dynamically setting the probabilities based on the different nodes context as well as integrate it with two classes of routing protocols: those that use a common control channel and those that do not. Evaluation of the proposed gossiping technique through ns2 simulations shows that our technique can lead to up to 75% reduction in overhead under the different classes of routing protocols. In addition, this reduction in overhead leads to increasing the network throughput by up to 400%.

The paper is organized as follows: we introduce the necessary background on gossiping and our system model in Section II. Section III introduces the details of our proposed technique followed by the evaluation of it using ns2 simulations in Section IV. Finally Section V concludes the paper.

II. BACKGROUND AND SYSTEM MODEL

A. *Percolation Theory*

Global view on-demand protocols (e.g. AODV-like protocols) are a popular class of routing protocols in cognitive radio ad-hoc networks [2], [3]. Although these approaches find a globally optimal route by broadcasting control packets, they can cause the *Broadcast Storm* problem [12], where redundant packets flood the network. Percolation theory results were used as an approach to solve this problem: By probabilistically determining whether to re-broadcast a packet or not, a bimodal behavior [13] is predicted which shows that percolation occurs

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(i.e. a large portion of the nodes receives the broadcast packet) if the rebroadcast probability (p) at each node is larger than a critical value (p_c). Values much larger than p_c does not enhance coverage but increases the overhead. On the other hand, values for p less than p_c prevent percolation (i.e. only a small portion of the nodes receives the packet). These results show that ad-hoc networks exploit a phase transition phenomenon as small changes in rebroadcasting probability p result in significant changes in network reachability. By reducing the number of broadcast control packets, the medium contention is reduced. This improves spectrum utilization, network throughput, and delay.

Several approaches have been proposed either using a fixed probability [9] or dynamically changing probabilities. [10], [11]. Dynamic probabilities have been shown to fit the nature of wireless networks than fixed probabilities. Our contribution in this paper is to present a novel technique for dynamically setting the gossiping probability that fits the nature of CRNs. Our proposed technique takes both the observed stochastic behavior of primary users and the location information into account to reduce the route discovery overhead without affecting the route quality.

B. System Model

We consider an ad-hoc cognitive radio network with primary users (PUs) and secondary users (SUs). PUs hold the main license to access the spectrum and hence must be provided with a highly reliable communication environment. We model the presence of a PU on a certain channel c as a birth-death process [14] that alternates between busy and idle states. The periods at which the PU remains either busy or idle are modeled as two exponentially distributed random variables with parameters α and β respectively.

On the other hand, SUs are granted opportunistic access to the spectrum provided that PUs are not active. SUs are required to evade the spectrum as soon as a PU starts using it. Each SU is equipped with an agile-radio frontend that allows neighboring nodes to agree on the channel of communication [15]. Typically, there are two ways to coordinate between SUs for control purposes: (a) using a dedicated common control channel (CCC) and (b) in-band distributed coordination. Control packets for routing protocols include Route Request (RREQ) packets that disseminate through the network from the source in order to discover possible routes to the destination. Upon the reception of RREQs from different paths, the destination can select the best route, based on its specific metric, and sends back a Route Reply (RREP) to the source specifying the route to be used. This route selection process can also be performed at the source.

Each SU is capable of performing spectrum sensing and is aware of the stochastic behavior of the PUs surrounding it on each channel. Moreover, each SU is assumed to know its own location, the locations of its neighbors, and the location of the destination of the data. This location information is assumed to be broadcast through the network or obtained through out-of-band sources. These assumptions are valid for several applications of cognitive radio networks including Public Safety Networks [16] and Machine-to-Machine Communication [17].

III. PROBABILISTIC ROUTE DISCOVERY FOR COGNITIVE RADIO NETWORKS

In order to reduce the overhead of global-view routing protocols, we propose a novel technique to determine the gossiping probability dynamically at each node based on the observed stochastic behavior of primary users and the location of the destination of the broadcast packet. The intuition behind our technique is to make broadcast packets go with higher probability through hops which are most likely to be on the optimal route, i.e. hops that are closer to the destination and have low primary user activity nearby. Our proposed gossiping technique is generic and can be applied to a large class of CRN routing protocols to lower their route discovery overhead, without the need to change the protocol routing metric.

For the rest of the section, we first introduce how to select the dynamic gossiping probability for each channel. Then we introduce how to apply the proposed technique in case of the presence or lack of a common control channel.

A. Selecting the Dynamic Gossiping Probability

Assume each node x can access N channels and estimate the PUs' profiles PL_i for each channel $1 < i < N$, where the profile presents the probability of a PU becoming inactive on channel i during a predefined time period τ. Higher values of parameter τ represent higher path stability. Based on our system model, since each PU j is modeled as a two-state ON-OFF birth-death process with parameters α_j and β_j representing the parameters of the exponential distributions in the ON and OFF periods respectively, $PL_i = e^{-\tau \sum_j^n \beta_j}$

Upon the reception of broadcast packet from a neighbour y, x calculates the gossiping probability G_p, i.e. whether x will rebroadcast the packet or not, based on two factors:

- Location-based factor ($\delta_{x,s}$): which represents how close the current node (x) is to the destination compared to the previous node (y). This can be viewed as a greedy positive advance towards the destination (like geographic-based routing [18]). This factor is set to $\delta_{x,s} = \frac{(d_y - d_x)}{d_s}$, where d_y is the distance between y and the final destination, d_x is the distance between x and the final destination and d_s is the distance between s (source of the connection) and the final destination. This last term is used as a normalization factor to limit $\delta_{x,s}$ between -1 and 1 for the non-trivial case when the final destination is not within the transmission range of the source.
  This factor will favor nodes that are closer to the final destination than nodes that are further away from it.
- PU factor (ρ_i): which represents the stochastic behavior of PUs in the transmission range of node x. We choose $\rho_i = PL_i$, which is the probability of no PU becoming active on channel i.

To combine these two factors into a single value V_i, we set

$$V_i = \delta_{x,s} \times \rho_i$$

Algorithm 1 Gossiping on Channel i.

```
Before broadcasting a packet
Calculate $V_i = \delta_{x,s} \times \rho_i$
if $V_i < 0$ then
    $G_p = G_{min}$
else
    $G_p = G_{min} + \delta_{x,s}\rho_i \times (1 - G_{min})$
end if
```

Noting that $\delta_{x,s}$ can be negative in some cases, and that the gossiping probability (G_p) for a certain channel has to be above a threshold G_{min} to allow the back propagation effect [9]and guarantee coverage, we use a linear mapping to map V_i to the range $G_{\text{min}} \rightarrow 1$. That is

$$G_p = \begin{cases} G_{min} + \delta_{x,s}\rho_i \times (1 - G_{min}) & \text{if } V_i \geq 0 \\ G_{min} & \text{if } V_i < 0 \end{cases} \tag{1}$$

B. Integration with Routing Protocols

We discuss how to integrate the proposed gossiping technique into two different classes of routing protocols: those that use a Common Control Channel and those that do not.

1) Protocols with no common control channels: We take CAODV [3] as a representative protocol for this category and modify its route discovery process. Algorithm 1 summarizes the technique followed by each node. In the absence of a CCC, all control packets have to be broadcast on all or some of the available channels based on the routing protocol. For the modified CAODV protocol, the source node broadcasts a route request (RREQ) packet across all channels with probability 1. When an intermediate SU receives the first RREQ on channel i with no PU activity, If the receiving SU can supply a valid route for the desired destination, then it sends a unicast route reply (RREP) packet to the previous hop on the same channel. Otherwise, it broadcasts a copy of the RREQ packet through all available channels (i.e., with no current active PUs) using the calculated G_p for each channel.

Note that the standard unmodified CAODV protocol works exactly the same as the probabilistic CAODV but sets $G_p = 1$ for all nodes on all channels. By carefully and dynamically changing the value of G_p, the modified algorithm can significantly lower the overhead and enhance the performance as quantified in Section IV.

2) Protocols with a Common Control Channel: We take SPEAR [2] as a representative protocol for this category that has a separate unlicensed control channel from the data forwarding channels. Algorithm 2 summarizes the technique followed by each node. Each source node that wants to discover a route to a destination broadcasts a RREQ on the CCC with probability 1. The RREQ packet contains the node ID and its available channels. Upon the reception of this request by an intermediate node, the SU in SPEAR checks if there is common available channels (i.e. free from active PUs) between it and the previous node; If not, it drops the packet, otherwise it appends its ID and a list of its available channels to the packet. Each node rebroadcasts the RREQ if it did not hear it before until the RREQ reaches the final destination, which assigns channels to SUs on the selected path using a graph coloring approximation algorithm (where the color represents a channel).

Algorithm 2 Gossiping on a common control Channel.

```
Before broadcasting a packet
for Each data forwarding channel $i$ do
    Calculate $V_i = \delta_{x,s} \times \rho_i$
    if $V_i < G_{min}$ then
        $G_p(i) = G_{min}$
    else
        $G_p(i) = G_{min} + \delta_{x,s} \times \rho_i \times (1 - G_{min})$
    end if
end for
$G_p = \sum_{i=1}^{N} \frac{(G_p(i))}{N}$
```

Our proposed technique modifies the RREQ rebroadcasting step to reduce the number of rebroadcast RREQs. As in the CAODV protocol, the gossiping probability is calculated for each data forwarding channel ($G_p(i)$). However, there should be only one gossiping probability (G_p) used on the single common control channel. To fuse the different gossiping probabilities, we experimented with different options including using the maximum $G_p(i)$, minimum $G_p(i)$, and average $G_P(i)$. Through experimental evaluation we found that using the average probability showed superior performance. The intuition is that the other two options, i.e. using the max and min values, represent two extremes: one that overloads the CCC channel and the other reduces coverage respectively.

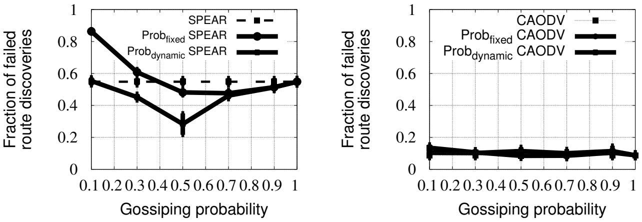
IV. PERFORMANCE EVALUATION

We evaluate our gossiping technique using ns2 simulations. We implemented two versions of the proposed probabilistic gossiping technique: one supporting the SPEAR [2] protocol that uses a CCC for control packets and another for the CAODV [3] which uses no control channel. The default values for the simulation parameters based on our system model are shown in Table I. We study the impact of changing the number of SU connections, the number of SUs, and number of available channels on different metrics. We start by defining the performance metrics and then evaluate the effect of the minimum gossiping probability (G_{min}) on performance. We then compare the modified version of the protocols based on our technique to the original versions. *Error bars in all plots represent the 95% confidence interval.*

A. Performance Metrics

We use the following metrics:

- Normalized overhead: which represents the ratio between the routing packets to the data packets.
- Total throughput: which is the number of delivered packets per unit time.
- Average packet delay: which captures the end-to-end delay.



(a) The fraction of failed route discoveries (CCC).

(b) The fraction of failed route discoveries (no CCC).

Fig. 1: Effect of changing the minimum gossiping probability G_{min}.

- Fraction of failed route discoveries: The ratio of connections that could not be established to the total number of connections.

B. Effect of changing G_{min}

In this section we analyze the effect of minimum gossiping probability (G_{min}) defined in Section III on performance. We also compare the performance of the proposed dynamic metric to gossiping with a fixed probability. The value of G_{min} or the fixed probability are shown on the x-axis of Figure 1. The figure shows that for the CCC case (Figure 1a), gossiping with a dynamic probability outperforms the fixed probability approach in terms of fraction of failed route discoveries. For a low value of G_{min} (less than 0.5) or the fixed gossiping probability, most RREQ packets are not rebroadcast, leading to a high fraction of failed route discoveries. This is enhanced as the gossiping probability increases till it reaches a certain value and the route discovery packets overload the limited CCC, leading to increasing the collisions and hence the fraction of the failed route discoveries.

On the other hand, for the protocols that do not use the CCC (Figure 1b), RREQ packets are sent over all channels and hence there is no single bottleneck. This leads to a significant reduction in the fraction of failed route discoveries and similar performance for all protocols under this metric. However, as we quantify in the next sections, the probabilistic CAODV leads to much less overhead in discovering these routes compared to the original version, which significantly enhances throughout.

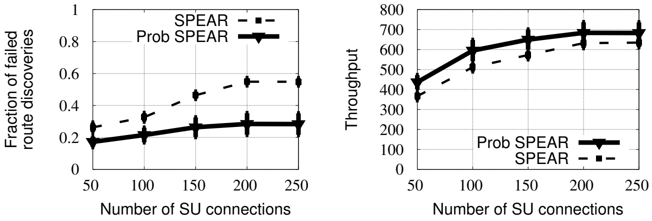
We use the optimal value of $G_{min} = 0.5$ for the rest of the paper.

C. Gossiping on a Common Control Channel

1) The effect of changing number of connections: Figure 2 shows the effect of changing the number of connections on the different metrics for the SPEAR protocol. As SPEAR sends the control packets on the common control channel and the number of these packets increases with increasing the number of connections (Figure 2c), this increases the congestion and number of packets dropped on the CCC. Hence, less route discoveries are successful as we increase the number of connections (Figure 2a). Since the proposed probabilistic technique reduces the number of control packets compared to the original SPEAR, it scales better and leads to higher throughput (Figure 2b). In addition, since probabilistic SPEAR discovers more routes and each source can send more packets, the queuing delay in probabilistic SPEAR is larger and this dominates the end to end delay (Figure 2d).

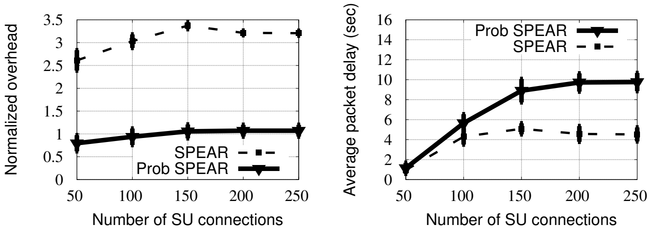
Parameter	Default value
Number of SUs	250
Number of SUs connections	200
Number of PUs	50
Number of channels	6
Traffic data type	UDP-CBR
Network size	1000* 1000 m^2
SU Tx range	125 m
PU Tx range	125 m
MAC Protocol	IEEE 802.11
Data rate (kbps)	4
$\alpha = \beta$	100
Simulation time(sec)	350
τ (sec)	1
G_{min}	0.5
Topology	Random

TABLE I: Parameters default values.



(a) Fraction of failed route discoveries.

(b) Total throughput.



(c) Normalized overhead.

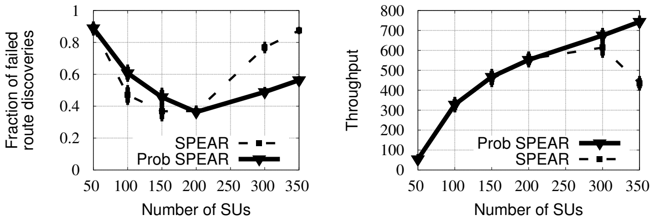
(d) Average packet delay.

Fig. 2: Effect of changing the number of connections on gossiping on a CCC.

2) The effect of changing number of SUs: In this experiment the number of SU connections is set to be 0.8× number of SUs. The number of PUs is set to be 0.2× number of SUs

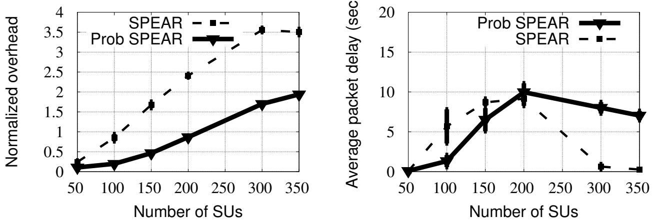
Increasing the number of SUs in the same area, i.e. increasing SU density, initially increases the connectivity and hence increases the fraction of found routes. However, increasing the density of SUs beyond a certain value increases the collisions and increases the number of failed route discoveries (Figure 3a). This correlates both with the throughput (Figure 3b) and the average packet delay (Figure 3d). Probabilistic SPEAR maintains its performance as compared to SPEAR.

3) Effect of changing number of channels: For Figure 4, the number of channels indicates the number of data channels



(a) Fraction of failed route discoveries.

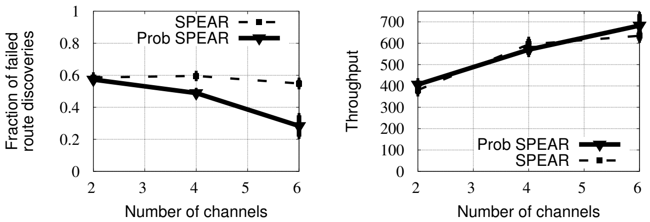
(b) Total throughput.



(c) Normalized overhead.

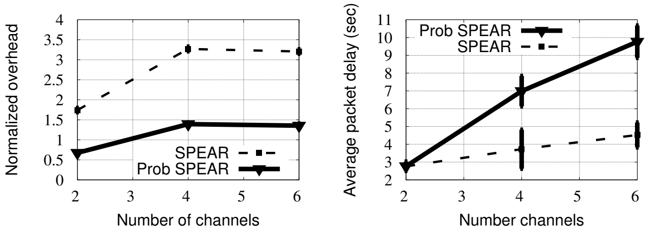
(d) Average packet delay.

Fig. 3: Effect of changing the number of SUs on gossiping on a CCC.



(a) Fraction of failed route discoveries.

(b) Total throughput.



(c) Normalized overhead.

(d) Average packet delay.

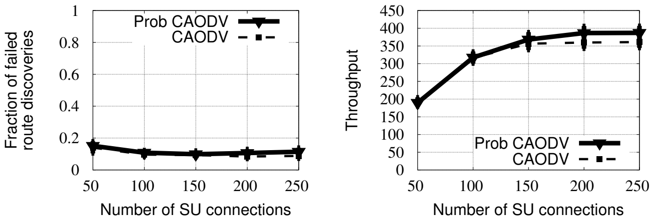
Fig. 4: Effect of changing the number of channels on gossiping on a CCC.

plus the CCC.

Increasing the number of channels increases the probability that two consecutive nodes will have common available channels and hence increases the fraction of successful route discoveries (Figure 4a). This also leads to increasing the throughput (Figure 4b) and the average packet delay (due to the queuing delay of the extra successful packets) (Figure 4d).

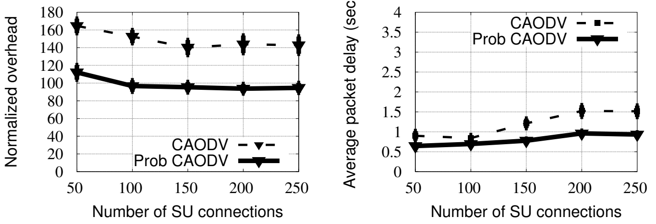
D. Gossiping with No Common Control Channel

1) Effect of changing number of connections: As CAODV sends the control packets on all the available channels, route discovery is not a bottleneck. Figure 5a shows that the difference in the fraction of failed route discoveries between CAODV and probabilistic CAODV is not large.



(a) Fraction of failed route discoveries.

(b) Total throughput.



(c) Normalized overhead.

(d) Average packet delay.

Fig. 5: Effect of changing the number of connections on gossiping with no CCC.

Contrary to the gossiping on the CCC case, since both the original and probabilistic CAODV discover the same number of routes, the number of data packets are the same and queuing delay does not dominate the end-to-end delay performance. The reduction of control packets (Figure 5c) in the probabilistic CAODV reduces the collisions with data packets, increasing throughout (Figure 5b) and reducing end-to-end delay (Figure 5d).

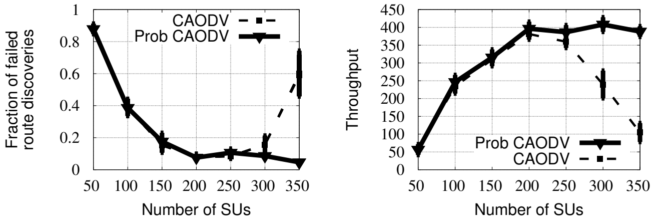
2) Effect of changing number of SUs: Similar to the CCC case, increasing the number of SUs initially increases reachability and throughput up to a certain value (Figure 6). After that, throughput and reachability decrease due to collisions. Increasing the throughout and reachability leads to increasing the number of sent packets, increasing the end-to-end delay of both techniques (Figure 6d). The probabilistic CAODV maintains its end-to-end delay advantage due to the reduction in overhead.

3) Effect of changing number of channels: In this case, the normalized overhead increases with increasing the number of channels (Figure 7c) as each node rebroadcasts the RREQ on all available channels. The throughput increases with increasing the number of channels (Figure 7b) as the routing opportunities increase with increasing the number of channels, which in turn results in increasing the delay (Figure 7d) due to the increased queuing delay.

E. Discussion

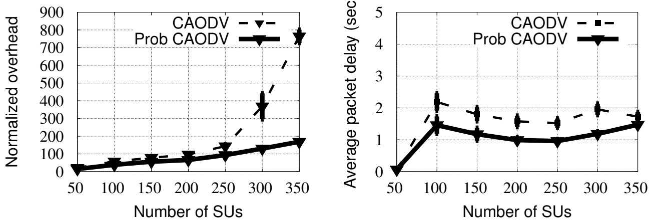
Our proposed probabilistic technique shows significant advantage in terms of increased throughput and reduced overhead for the two classes of routing protocols that use a CCC and those that do not.

For the case of using a CCC, this CCC becomes the bottleneck and hence our proposed probabilistic version significantly reduces the number of control packets, leading to discovering a higher number of routes. This is the main cause



(a) Fraction of failed route discoveries.

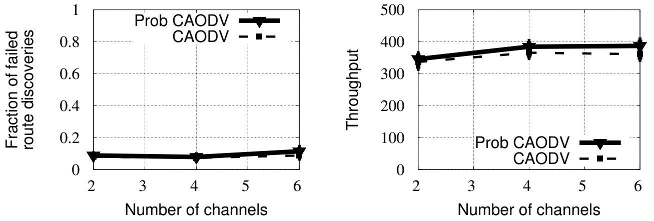
(b) Total throughput.



(c) Normalized overhead.

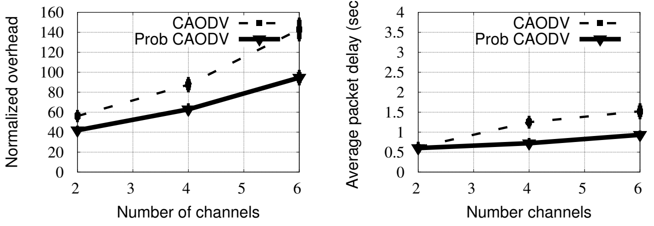
(d) Average packet delay.

Fig. 6: Effect of changing the number of SUs on gossiping with no CCC.



(a) Fraction of failed route discoveries.

(b) Total throughput.



(c) Normalized overhead.

(d) Average packet delay.

Fig. 7: Effect of changing the number of channels on gossiping with no CCC.

for the increased throughput compared to the original non-probabilistic version. However, this increases the end-to-end delay due to the increased number of data packets and the corresponding queuing delay.

On the other hand, for the case of not using a CCC, there is no bottleneck. Therefore, both the probabilistic and original version of the protocol discover almost the same number of routes. Our probabilistic version, however, does so with a much lower number of control packets, reducing the collision with data packets. This leads to both increased throughput and better end-to-end delay.

V. CONCLUSION

We proposed a routing metric-independent low overhead route discovery technique which can be used in the presence or absence of common control channel. In the proposed technique, each SU rebroadcasts control packets probabilistically based on the nodes relative location to the destination as well as the primary users activity. We showed how to integrate our technique with two classes of routing protocols: One that uses a common control channel for control packets and the other that does not. In both cases, our technique showed a significant reduction in the number of control packets by up to 75% and achieved up to 400% higher throughput. This is due to reducing the contention on the CCC and reducing the collisions between the control packets and data packets.

VI. ACKNOWLEDGMENT

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