Location-Aware Distributed Routing in Cognitive Radio Networks

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Abstract—**In cognitive radio networks, multi-hop communication with efficient routing can improve the connectivity and spectrum efficiency for cognitive users. Many routing algorithms have been proposed, but they may provide unnecessarily long routing paths as the existence of primary users and especially their locations have not been explicitly taken into consideration. In this paper, we investigate distributed routing in cognitive radio networks based on the location information of the primary users. The main idea is to navigate the routing path to avoid large interference to the primary users. We introduce a novel concept of guide strip as the navigation direction for routing. This guide strip is determined based on the visibility graph, which ensures a short packet travel distance, while the width of the guide strip is selected to guarantee a pre-defined successful routing probability. Simulation results demonstrate that the proposed distributed routing algorithm provides performance close to the globally optimal one.**

I. INTRODUCTION

Cognitive radio has been considered as a key enabling solution to the spectrum scarcity problem with spectrum sharing [1]. It allows cognitive users (CUs) to share the spectrum with primary users (PUs) if they do not cause large interference. Thus, the transmission power of the CUs should be constrained, which will degrade their connectivity.

Multi-hop transmission with routing in cognitive radio networks can reduce the transmission power and improve the connectivity and spectrum efficiency. To take this advantage, a global routing protocol based on common control channels was introduced in [2]. A minimum weighted routing protocol integrated with neighbor discovery was developed in [3], which is also based on a common control channel. Some other routing algorithms were considered with joint spectrum allocation to achieve higher spectrum efficiency, e.g., the multi-flow multi-frequency scheduling scheme in [4] and joint channel allocation and relay selection in [5].

Routing in cognitive radio networks is challenging when the CUs only have limited local information about their neighbors. There are only few related works on this aspect. The nearest-neighbor routing and farthest-neighbor routing strategies were proposed for a cognitive radio network coexisting with one primary source-destination pair in [6]. The sensor networks with some void areas are quite similar to the cognitive radio networks. In such sensor networks, a local rule that can help the packet get out of stuck nodes was developed for the greedy routing algorithm in [7], while the “right-hand rule” was used to bypass the void areas in [8]. With such simple local rules, the connectivity between the source and destination can be realized, though the packet may travel for a long distance.

Location-aware routing has the potential to improve the utilization of spectrum holes at different locations in cognitive radio networks, as it can avoid routing through those areas where PUs are located. In order to protect PUs, we introduce the concept of the guard zone [9] so that no CU can transmit if it is located within any PU guard zone. Full location information of the PU guard zones can be provided to the CUs, e.g., in the US such information can be obtained from the TV white space database maintained by Spectrum Bridge [10]. To reduce the packet travel distance, a compass routing algorithm was proposed for conventional networks in [11] and it always chooses the neighbor that is closest to the straight line between the transmitter and receiver. In the cognitive radio networks, the main challenge is how to explicitly consider the impact of the PU guard zones on the routing for the CUs and to find a short routing path.

In this paper, to minimize the packet travel distance, we propose a distributed routing algorithm for cognitive radio networks, which has two main steps: first planning a guide strip as a navigation direction to avoid the PU guard zones, which is based on the visibility graph; then applying a greedy forwarding strategy inside the guide strip. The guide strip is planned as short as possible so that the routing path will be short. The width of the guide strip is a key design parameter of the proposed routing algorithm, and we determine it based on a given constraint of the successful routing probability, i.e., the probability that we can successfully find a routing path from the cognitive source to the destination. We also introduce the multi-path routing technique to improve the connectivity. The proposed algorithm provides a systematic solution that achieves a high successful routing probability and returns a short routing path. In addition, simulation results demonstrate that the proposed distributed routing algorithm provides a good performance which is close to the globally optimal one.

This paper is organized as follows. Section II addresses the system model. In Section III, we describe the proposed routing algorithm, using the local information of the neighbors and full information about the spectrum environment. Simulation results of our algorithm are shown in Section IV. Finally, Section V presents the conclusions.

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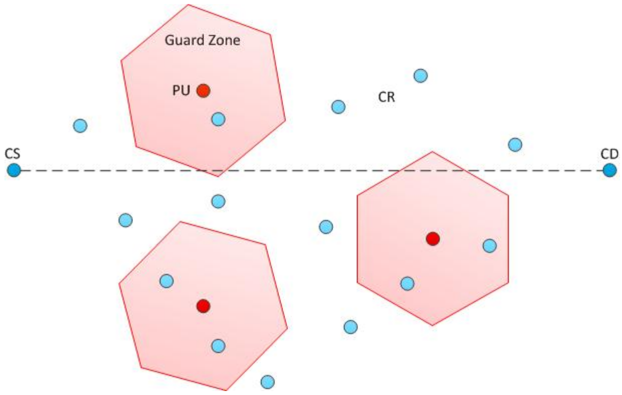

Figure 1. System model.

II. SYSTEM MODEL

In this paper we consider the cognitive radio network as shown in Fig. 1, where PUs and CUs coexist in the same area. Among the CUs, there is a cognitive source-destination pair (CS-CD) and all the others can be used as cognitive relays (CRs). The CUs are distributed according to a Poisson point process with density λ. Every CU has the same transmission range R, within which other CUs can successfully receive the transmitted message. The CS wants to deliver the packets to the CD with the help of the CRs, over the channel licensed to the PUs. With this kind of spectrum sharing, the transmissions of the CUs are not allowed to bring large interference to the PUs. We use guard zones to protect the PUs, i.e., the CUs in the guard zone of any PU can not transmit [9]. Hexagons with the same size[1] are used to describe the PU guard zones to simplify the model, as shown in Fig. 1. We assume that all the PUs work in the same frequency band and there is no overlap between different PU guard zones. We also assume that the CUs have full knowledge of the location information of the PU guard zones, e.g., through the white space services which are authorized by the Federal Communications Commission (FCC) [10]. The CUs also have the location information of their neighbors, i.e, the other CUs in their transmission range.

With this system model, the problem is how to design a distributed routing algorithm for the communication between the CS-CD. We have two objectives: 1) to accomplish the packet delivery from the CS to the CD; and 2) to make the packet travel distance as short as possible.

It is very difficult to find the shortest routing path since every CU only knows its local neighbors and there are some PU guard zones that need to be avoided. If applying the existing routing algorithms directly, the packet may get stuck in front of a PU guard zone and it may then detour and arrive at the CD with a very long path. Therefore, the impact of PU guard zones should be explicitly taken into consideration, based on which we will design a distributed routing algorithm in the next section.

III. DISTRIBUTED ROUTING ALGORITHM

Based on the location information of the cognitive neighbors and the PU guard zones, we will develop a distributed routing algorithm that follows a navigation direction, which is given as a narrow strip from the CS to the CD while avoiding the PU guard zones. This will provide a systematic solution for routing in cognitive radio networks.

A. Navigation Direction: the Guide Path and Guide Strip

We will first plan a navigation direction from the CS to the CD for the routing. Since the CUs have the full location information of the PU guard zones, they can determine the shortest geometric path between the CS and CD, without passing through the PU guard zones. We define the shortest geometric path between the CS and CD while avoiding the PU guard zones as the *guide path*. However, it is difficult for routing if we directly follow this line. Since the CRs are randomly distributed, it is almost impossible to compose a route with the CRs on the shortest geometric path. However, this guide path can still help the routing. Regarding this path as a navigation direction, we will next introduce a guide strip and the CUs will forward the packet within this strip. The routing path would be very short if it follows the navigation direction tightly.

Regarding the PU guard zones as obstacles, the guide path can be planned with the visibility graph. A visibility graph $\mathcal{VG}\left(N,\ L\right)$ is a graph of N vertices (K of which are the vertices of the obstacles) containing L edges between the vertices that can see each other, i.e., the edges do not pass through the obstacles. In this paper, the N vertices are composed of the CS, CD and the vertices of the PU guard zones (obstacles), as shown in Fig. 2(a). Then the shortest collision-free path is the shortest path in $\mathcal{VG}\left(N,\ L\right)$ and there always exists such a path. We can apply a navigating SHAKEY algorithm [12] to find the guide path.

Given the guide path as the navigation direction, the routing path depends on the density of the CUs, as well as the topology of the network. Since the CUs have only local neighbor information, it is hard to deliver the packet following the guide path. We propose to implement the routing in a guide strip instead of following a guide path, where a *guide strip* is defined as a narrow strip in the navigation direction from the CS to the CD. To put it simply, the guide strip is obtained by growing the guide path from a line to a 2-D area, as shown in Fig. 2(b). Then the distributed routing is performed inside the guide strip. Since the guide strip is narrow, the routing path can follow the navigation direction easily. Since the strip is bounded by two parallel lines, the CUs in the strip have the same ability to forward the packet.

The discussion about narrow strip routing in the following section can help us plan the guide strip and implement the distributed routing.

B. Narrow Strip Routing

First let us describe the routing in a narrow strip without the primary network. As shown in Fig. 3. the CS-CD are

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[1] The proposed routing solution is applicable when each PU guard zone is a polygon of any shape and size.

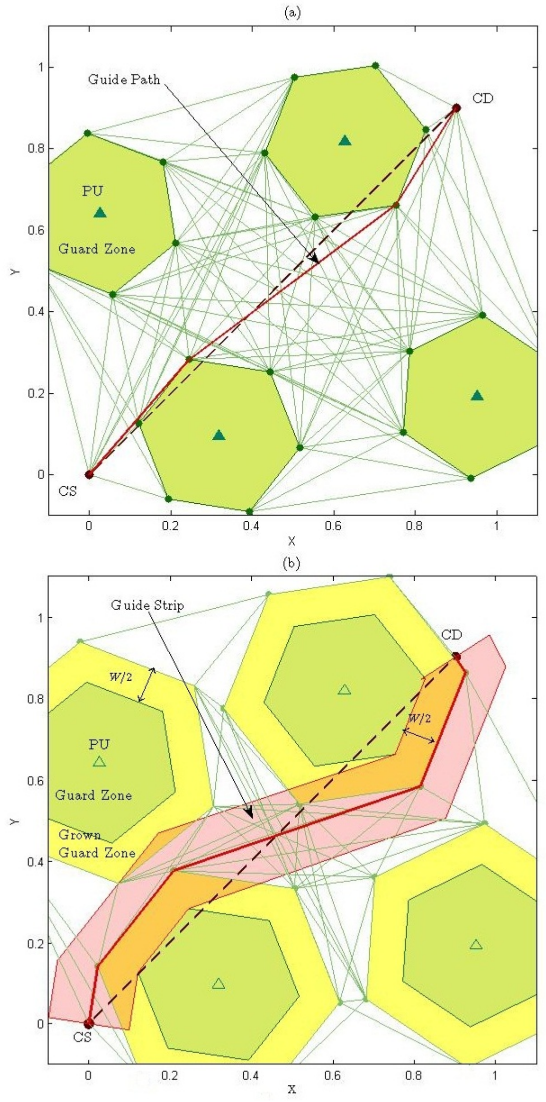

Figure 2. (a) The visibility graph and guide path: the vertices of the visibility graph are composed of the CS, CD and the vertices of the PU guard zones and the green lines are the edges between the vertices that can see each other; the guide path is the shortest path from the CS to the CD in the visibility graph. (b) The new visibility graph and guide strip: the vertices of the new visibility graph is replaced by the vertices of the grown guard zone; the guide strip is generated by expanding the shortest path from CS to CD with a width of $W/2$.

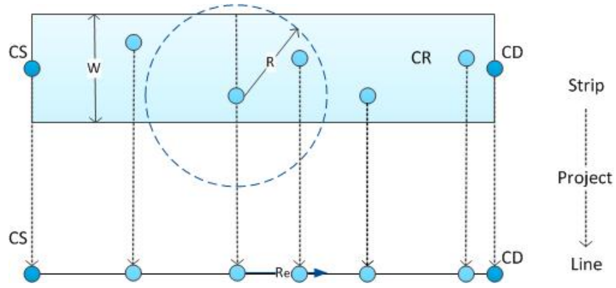

Figure 3. Narrow strip routing from CS to CD, which are in the middle of the left and right sides of the strip respectively. We project the nodes in the strip to a straight line.

at a distance L of each other and the CRs are in the strip with a finite width W. The spatial distribution, the density and the communication radius of the CUs are the same as the system model in Section II. There is a nice property for routing in a strip that is relatively narrow. If the strip is not wider than $W_c = \frac{\sqrt{3}}{2}R$ and if there exists a routing path in it, the existing route can be found by a greedy forwarding algorithm, e.g., the GEEDY4 in [13]. This means that the connectivity performance of the distributed routing algorithm in a narrow strip is the same as the centralized optimal one, which is a desirable property for our system where distributed routing is inevitable. In addition, routing in a narrow strip can guarantee that the routing path we get will be close to the shortest visibility path between CS and CD. In the following part, we will focus on routing in a narrow strip with width at most W_c.

The next question is how to pick the width W of the guide strip, and we will determine it to guarantee a certain successful routing probability. Since the greedy forwarding algorithm can always get a route if there exists one, it has the same probability of successful forwarding from the CS to the CD in the narrow strip as the centralized algorithm. It is very difficult to get an exact expression of this probability since the strip is two dimensional and bounded. However, we can still get an approximation for it. The method is to project the nodes in the strip to the horizontal axis (a straight line). Then we can apply the connectivity result of the straight line routing, which is given as the following theorem in [14].

Theorem 1. *For a given relay density λ and a given transmission range R for each node, the probability $P_l(L)$ that two nodes at a distant of L from each other are connected is*

$$P_l(L) = \begin{cases} 1, & \text{if } 0 \le L < R, \\ \sum\limits_{i=0}^{\lfloor L/R \rfloor} \frac{\left(-\lambda e^{-\lambda R}(L-iR)\right)^i}{i!} \\ \quad - e^{-\lambda R} \sum\limits_{i=0}^{\lfloor L/R \rfloor - 1} \frac{\left(-\lambda e^{-\lambda R}(L-(i+1)R)\right)^i}{i!}, & \text{if } L \ge R, \end{cases} \tag{1}$$

with $\lfloor L/R \rfloor$ denoting the largest integer not larger than L/R [14].

With this theorem, we can calculate the connectivity probability of the narrow strip routing by projecting the nodes in the strip to a straight line as shown in Fig. 3. By replacing the density λ and the communication radius R with the projected values $\widetilde{\lambda}$ and $\widetilde{R}$ respectively in Eq. (1), we get the following proposition.

Proposition 2. *Suppose that two nodes are at the left and right sides of a strip with distance L and width W respectively, and the relay density is λ. The probability $P_S(L,W)$ that these two nodes are connected can be approximated by $\widetilde{P}_S(L,W)$, which is given by*

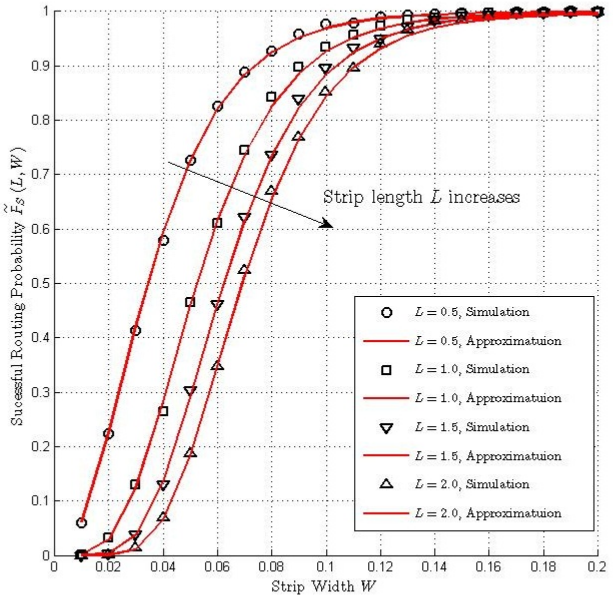

Figure 4. Narrow strip routing: the density of the CUs $\lambda = 300$ and their transmission range $R = 0.2$. The critical width $\frac{\sqrt{3}}{2}R$ is roughly 0.1732. The side length of the PU guard zones is 0.2.

$$\widetilde{P}_S(L,W) = \begin{cases} 1, & \textit{if } 0 \le L < \widetilde{R}, \\ \sum_{i=0}^{\lfloor L/\widetilde{R} \rfloor} \frac{\left(-\widetilde{\lambda} e^{-\widetilde{\lambda}\widetilde{R}}(L - i\widetilde{R})\right)^i}{i!} & \\ \quad -e^{-\widetilde{\lambda}\widetilde{R}} \sum_{i=0}^{\lfloor L/\widetilde{R} \rfloor - 1} \frac{\left(-\widetilde{\lambda} e^{-\widetilde{\lambda}\widetilde{R}}(L - (i+1)\widetilde{R})\right)^i}{i!}, & \textit{if } L \ge \widetilde{R}, \end{cases} \tag{2}$$

where $\widetilde{\lambda} = \lambda W$ *and*
$\widetilde{R} = \left(\frac{1}{2}\arcsin\left(W^2\right)R + \left(\frac{1}{3}R^2\right)^{3/2} - \frac{1}{3}\left(R^2 - W^2\right)^{3/2}\right)W^{-2}$.

As shown in Fig. 4, the approximation $\widetilde{P}_S(L,W)$ is always very close to the actual successful routing probability for strips with different widths and different lengths. The approximation is better when the strip is narrower. It is also easy to see that the shorter or the wider the narrow strip is, the better connectivity we have.

As a summary, we have 2 nice features for the narrow strip routing: 1) the distributed greedy forwarding algorithm can get the route if there exists one; and 2) there is a nice approximation for the successful routing probability, which quantifies the relationship between the connectivity probability and different parameters, e.g., the relay density, the length and the width of the strip.

C. Guide Strip Planning and Distributed Routing Algorithm

We will use a guide strip as the navigation direction and implement a distributed routing algorithm in this strip. To improve the successful routing probability and get a short routing path, we must plan a good guide strip. First, we will determine the width of the guide strip. There is a tradeoff in selecting the width. If the width of the strip is large, it will increase the successful routing probability in the guide strip. However, we can not make it as large as possible since there may be an upper bound for the strip width in a given navigation direction (refer to Fig. 2(b)). In addition, if the strip is too wide, the routing path will deviate from the guide path, which is the shortest visibility path from the CS to the CD, i.e., the travel distance will be long. Thus, we propose to set a threshold for the successful routing probability in the strip and take the smallest width that can achieve the threshold.

A guide strip can be planned with the same navigation direction with one guide path. But we can not expand the guide path directly because it is not easy to determine the expanding side, left or right, and it may lead the guide strip cross the guard zones. We will use the visibility graph to get the guide strip. The guide strip with width W is equivalent to the guide path of moving a circle with radius $W/2$ from the CS to the CD. The technique of the path planning for a circular object was introduced in [12]. First the visibility graph should be adjusted: the PU guard zones are grown by adding a width of $W/2$, as the new visibility graph shown in Fig. 2(b). By applying the navigating SHAKEY algorithm [12] on the new visibility graph, we will get a new guide path. Expanding the new path at both sides with width $W/2$ generates the guide strip.

To improve the connectivity, we will follow a multi-path routing scheme: if the distributed routing in the planned guide strip fails, we can use the second shortest strip, which can be got from the visibility graph, to replace the shortest one. This process can be repeated until we find a routing path or until we reach some pre-defined threshold on the number of trials. This scheme can help us to improve the successful routing probability from the CS to the CD.

With all the previous discussion, we now present the distributed routing algorithm for the cognitive radio networks as Algorithm 1.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of the proposed distributed routing algorithm under various realizations of the cognitive radio networks. We will show that the location-aware distributed routing algorithm can help to get a short routing path and provide the performance close to the globally optimal one.

In our experiments, the PUs and CUs are distributed randomly in a square area, whose size is normalized, i.e. 1×1. The CS and CD are deployed at position $(0,0)$ and $(0.9,0.9)$ respectively. There are 4 PUs in this area, with 4 disjoint PU guard zones, whose length of edge is 0.15. The threshold for the successful routing probability in the narrow strip is set to be 0.9.

Firstly, let us show an example for the routing path found by our algorithm. As shown in Fig. 5, all the CRs are classified into 3 types: the CRs in the PU guard zones, which are

Algorithm 1 Distributed Routing Algorithm for Cognitive Radio Networks

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1) Define a variable $n$ as the serial number for different navigation directions and let $n = 1$. Construct the visibility graph $\mathcal{VG}(N,\ L)$ based on the locations of the CS-CD and the PU guard zones.
2) If $n$ is larger than a pre-defined number $N$, return that there is no qualified guide strip.
3) The CS computes the $n$th shortest path of $\mathcal{VG}(N,\ L)$ as the guide path and its length $L_{\text{guide}}$, by applying the navigating SHAKEY algorithm [12].
4) With the length of the guide path $L_{\text{guide}}$, the density of the CUs $\lambda$, the transmission radius $R$, and the pre-defined successful routing probability $\text{Pr}_{th}$, compute the minimum required width $W_{\text{guide}}$ of the guide strip according to Eq. (2). Check whether $W_{\text{guide}}$ is smaller than $\frac{\sqrt{3}}{2}R$. If not, $n = n + 1$ and go to Step 2.
5) Adjust the visibility graph with growing the PU guard zones with width $W_{\text{guide}}$ and compute the guide strip. Check whether the strip has the same navigation direction with the corresponding guide path. If not, $n = n+1$ and go to Step 2.
6) The CS put the information of the guide strip into the packet head.
7) Each selected CR decodes the packet and gets the guide strip information, and implement the routing with a greedy forwarding algorithm.
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forbidden to transmit; the CRs in the guide strip, which are the candidate relays; and all the other CRs, which are relatively far from the guide path and will not be used for relaying. The strip information is enclosed into the packet so that each hop can navigate following the direction of the guide path. In the figure, the blue line is the final routing path and it fits the guide path well.

Next, we compute the packet travel distance with our proposed algorithm and compare it with the globally optimal one. The globally optimal routing path can be found by applying the shortest path search algorithm for the network topology composed of the CRs outside the PU guard zones. As we drop the nodes randomly, not all the network realizations give a route from the CS to the CD, even with the globally optimal routing algorithm. We run 5000 simulations for different realizations of the networks and 4658 of them have global routing paths, while 3779 of them have distributed routing paths with the proposed algorithm. Roughly, the proposed algorithm can handle $3779/4658 \approx 81.13\%$ of different scenarios. There are two main reasons that the proposed algorithm can not always get the route when the global algorithm can. The first reason is that the guide strip width is set to be bounded, but there may exist a successful routing path outside the strip. However, a narrow strip can provide us other advantages as mentioned in Section III-B. The second reason is that we have set a threshold for the successful routing probability in the strip. We can enlarge the threshold and increase the strip width to improve the connectivity, but these changes will also make it hard to control the navigation direction and result in a long routing path.

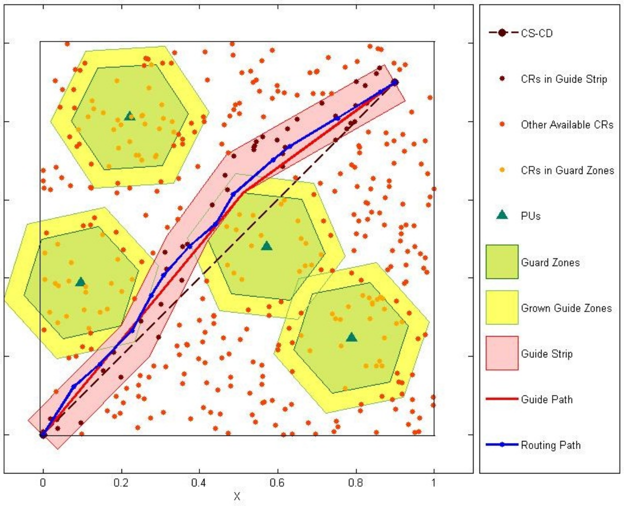

Figure 5. An example of the distributed routing. The density of the CUs is 400 and their transmission range is 0.15.

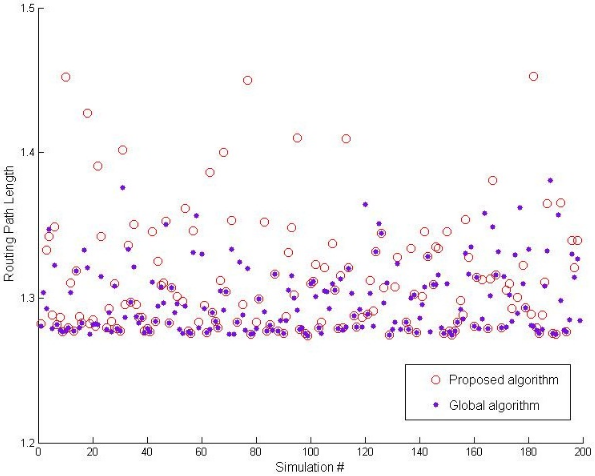

Figure 6. Comparing the packet travel distance with the globally optimal one. The density of the CUs is 400 and their transmission range is 0.15.

Fig. 6 shows the travel distances of the routing paths for 200 realizations, for both the globally optimal routing algorithm and the proposed distributed one. We can see that the routing paths of the proposed distributed algorithm achieve the shortest distance, or a distance close to the shortest one. We can get some statistics by comparing the results when both algorithms can get a route. Over the 5000 simulation results, the mean of the difference between the travel distances of the routing paths provided by two algorithms paths is 0.0193, while the variance is 0.0015. Compared with the mean of the length of the shortest routing path, which is 1.2941, the difference between results from the two algorithms is relatively small. It indicates that the proposed algorithm will give a short routing path if it can successfully deliver the packet.

V. CONCLUSIONS

In this paper, we proposed a distributed routing algorithm for cognitive radio networks. The algorithm is based on path planning with the visibility graph and narrow strip routing. It can help the packet to get a short travel path and a high probability of successful delivering when the density of the cognitive users is large. Applying a large strip width may improve the connectivity of the distributed routing in the strip, but it will also increase the packet travel distance. Therefore, there exists a tradeoff in picking the strip width, which is an interesting future research direction.

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