# Destination-Region-Based Local Minimum Aware Geometric Routing

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***Abstract*— Geometric routing algorithms in mobile ad-hoc networks (MANETs) contain two forwarding modes: greedy forwarding and face forwarding. It is well known that face forwarding is inefficient and fails frequently in practical situations. A previous work, NEAR [2], avoids switching to face forwarding by predicting local minima and not forwarding messages to them. However, NEAR predicts excessive local minima, which degrades routing performance. Also, NEAR is not localized due to its bridge detection scheme. Aiming to further improve the performance of NEAR, we propose a destination-region-based Local minimum AwaRe GEometric Routing (LARGER) algorithm which improves the accuracy of the local minima prediction by dividing the network into a number of regions and predicting local minima based on the region where the destination is located. Simulation results show that LARGER substantially improves the prediction accuracy and the routing performance of NEAR and other state-of-the-art geometric routing algorithms in terms of route length.**

**Keywords: Bridge detection, destination region, geometric routing, local minimum prediction, MANETs**

## I. Introduction

Geometric routing [3], [8], [11] has been widely accepted as the most promising generally scalable wireless routing method in mobile ad-hoc networks (MANETs). Geometric routing (see Figure 1 for an example) is a distributed routing algorithm, in which each node along a source-destination path (which is shown by thick lines in the figure) makes a message-forwarding decision based on some position information. Each message is forwarded in either greedy forwarding mode or face forwarding mode.

Greedy forwarding is the default mode. In greedy forwarding, a node forwards the message to another node that is the closest to the destination and that is within its transmission range (i.e.: its neighbor node). No greedy forwarding can be made by a node that is closer to the destination than any of its neighbors. Such a node is called a local minimum.

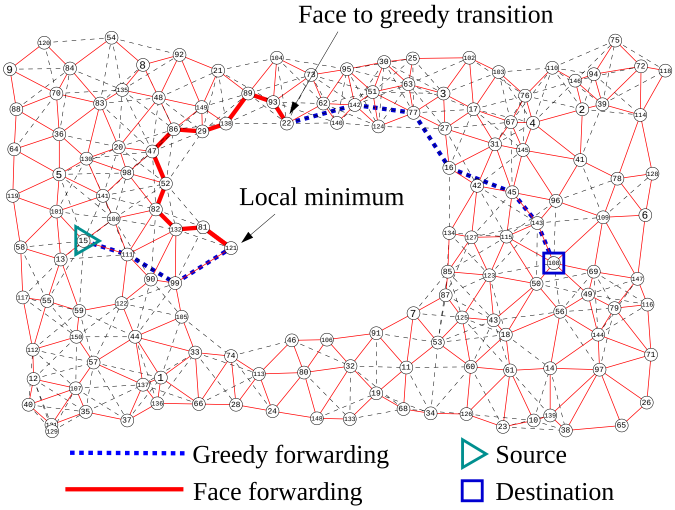


Fig. 1. An example of geometric routing.

As shown in Figure 1, a message starts from the source 15 and is forwarded by a number of greedy forwardings to the local minimum 121. The forwarding mode is then changed to face forwarding. Face forwarding forwards the message along the perimeter of the void area in the network which is next to the local minimum in the direction of the destination. Face forwarding can forward the message in either direction along the perimeter. The traversal uses either the left-hand rule or the right-hand rule. In the left (right) hand rule traversal, the traveler travels around the perimeter placing its left (right) hand on the perimeter.

In face forwarding mode, when the message is forwarded around the void area to the first node (such as node 22 in Figure 1) that is closer to the destination than the local minimum, the forwarding mode reverts back to greedy. Geometric routing switches between greedy forwarding and face forwarding in order to make

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sure that the message continuously gets closer to the destination. The algorithm described above is the first geometric routing algorithm that guarantees delivery of the messages, which is called Greedy-Face-Greedy (GFG) routing [3].

To avoid loops in face forwarding, messages can only be forwarded along the edges in the planar subgraph of the original network graph. A planar graph is a graph without crossing edges, which can be produced by several localized algorithms which retain the connectivity of the original graph. In Figure 1, the thin solid lines make up the edges of the planar subgraph. Faces, including the single outer face, are defined as the areas surrounded by the edges in the planar subgraph.

Despite half a decade of research on geometric routing, it is difficult to implement and deploy in realistic environments. Most problems in geometric routing are related to face forwarding which has been reviewed in several publications [2], [9], [14]. Also, face forwarding is inefficient: the diameter of the planar subgraph is larger than the original graph. Also, a recovery from a local minimum usually produces a detour from the shortest path, as can be seen in Figure 1.

To prevent some of the situations where a geometric routing algorithm encounters a local minimum and switches to face forwarding mode, Arad et al. [2] proposed *Node Elevation Ad-hoc Routing* (NEAR). NEAR predicts (in a wide sense) local minima and does not forward messages to them. In NEAR, local minima are defined in a wide sense where a forwarding to a local minimum may not cause an immediate failure of greedy forwarding, but will incur one within several consecutive forwardings. While a local minimum is defined regarding a given destination, a predicted local minimum in NEAR is defined for the network as a node that is probably a local minimum for some nodes in the network. Therefore, the prediction is usually inaccurate: excessive local minima are predicted. Since the predicted local minima are disabled in routing, predicting excessive local minima degrades the routing performance. Moreover, NEAR relies on a void discovery process similar to the one in [9] which makes it a non-localized algorithm.

The main objective of this paper is to further reduce the unnecessary transitions to face forwarding by improving the accuracy of local minimum prediction. We propose an effective localized routing algorithm, which is called destination-region-based Local minimum AwaRe GEometric Routing (LARGER). Since both LARGER and NEAR improve the performance of geometric routing by preventing message-forwarding to the predicted local minima, the routing performance is closely related to the accuracy of the local minima prediction. LARGER increases the prediction accuracy by dividing the network into $k$ regions and predicting, in each node, $k$ local minimum statuses, one for each region, as opposed to predicting local minima for the network as a whole. Simulation results show LARGER's substantial improvements in prediction accuracy and routing performance.

Our contributions in LARGER are summarized as follows:

- LARGER uses a destination-region-based local minimum prediction scheme which increases the accuracy of the local minimum prediction and reduces the excessive amount of predicted local minima, which is a problem in NEAR.
- LARGER uses a localized scheme to prevent routing failures caused by the inaccurate prediction of some local minima. Here, if these local minima are excluded from the network, no path can exist between certain source and destination nodes.
- LARGER does not have additional assumptions to the state-of-the-art geometric routing algorithms. Moreover, all of the messages that it uses are small in size and can be piggy-backed to the existing messages used in the geometric routing algorithm.
- Simulations are performed to evaluate the effectiveness of the different components in LARGER. Other routing protocols, including NEAR, GFG, and GOAFR, are implemented for comparison to the improved routing performance of LARGER

The rest of this paper is organized as follows. Section II reviews related works. Section III presents LARGER with some preliminary experimental analysis. Simulations and results are shown in Section IV. Finally, Section V concludes the paper with a discussion of possible future work.

## II. Related Works

Geographic routing requires each node to be able to determine its coordinates by means such as the use of global positioning systems (GPS), virtual positions [15], or relative positioning based on signal strength estimation [7]. In order to perform a greedy forwarding in which a message is forwarded to another node that is as close to the destination as possible, each node needs to know the positions of its neighbors and that of the message's destination. All nodes can exchange hello messages to discover neighbors' positions. With the assumption that the destination's globally unique ID is known to the source, the destination's position can be queried from a location service. The location service, which provides a map from node IDs to their current positions, is a building block of geometric routing.

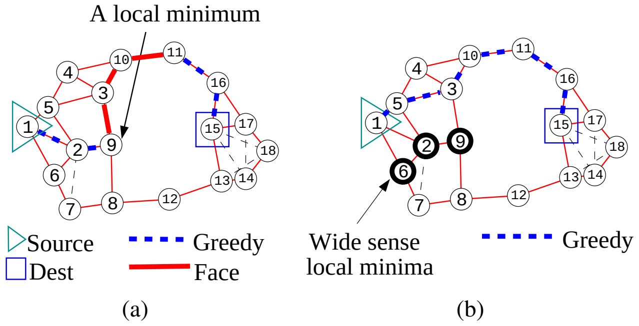



Fig. 2. Geometric routing with (b) and without (a) wide sense local minima.

In the home-based location service, each node is assigned (usually by hashing its node ID) a globally known home (a geometric region). All nodes in the home region of a node act as location servers of the node, to which the node can send its updated location information. When a source wants to send a message to a destination, it first sends a query to the home of the destination to obtain the destination's position information from some servers there. Then, the source stores the position information of the destination in the message and sends it using a geometric routing algorithm. Improved home-based location services include GLS [12], DLM [17], HIGHGRADE [18], and LLS [1].

Variants of geometric routing include Greedy-Face-Greedy (GFG) [3], Compass Routing II [10], Greedy Perimeter Stateless Routing (GPSR) [8], and Greedy Other Adaptive Face Routing (GOAFR) [11]. Interested readers may refer to [4] for additional information. GOAFR, which is implemented in our simulation, uses a distance-bounded face traversal. This traversal iteratively traverses both sides of the face for a bounded distance with the right-hand rule and the left-hand rule respectively, and increases the bound if the condition to return to greedy forwarding mode is not satisfied after each iteration. The resulting paths of GOAFR are asymptotically optimal and are shorter than those of GFG on average.

The connectivity graphs of wireless networks typically contain many crossing edges. While greedy routing runs on the arbitrary wireless network graphs, to work correctly, face routing must run on a planar subgraph of a given wireless network graph. Localized methods for obtaining a planar subgraph include Gabriel Graph (GG) [5], Relative Neighborhood Graph (RNG) [16], and Localized Delaunay Triangulation (LDT) [6], [13].

## III. Destination-Region-Based Local Minimum Aware Geometric Routing

LARGER is developed based on a previous work, NEAR [2]. We will first represent some important and useful ideas in NEAR in Section III-A and III-B. Then, we will present our work in the rest of the section.

### A. *Wide sense local minimum*

First, we assume that each node has the position information of all possible destinations.

*Definition 1:* (*Wide sense local minimum* [2]): A wide sense local minimum for a given destination is a node that is unable to send a message to the destination solely by greedy forwarding. A traditional sense local minimum is a wide sense local minimum. An node whose neighbors that are closer to the destination are all wide sense local minima is also a wide sense local minimum.

In Figure 2(b), nodes 9, 2, and 6 are the wide sense local minima, respectively, for the destination 15. In the rest of this paper, we will simply use local minimum to refer to wide sense local minimum. Note that if the destination is node 8, nodes 2, 6, 9 are no longer local minima. Therefore, the status of local minimum is sensitive to the location of the destination.

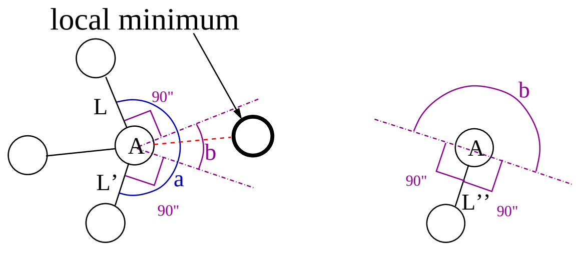
If neither the source nor the destination is a local minima, a greedy routing which forwards messages only to non-local minima can deliver messages successfully. This is because each non-local minimum always has some non-local minimum neighbor that is closer to the destination. An example to compare routing with and without local minimum information is shown in Figures 2(a) and 2(b). As shown in the figures, with predicted local minima, the routing algorithm does not enter face forwarding mode and results in a shorter path.

However, it is infeasible for a node to calculate whether it is a local minimum for any other node, since the amount of information required violates the goal of geometric routing – scalability.

### B. *Predicted local minimum in NEAR*

A global prediction scheme is proposed in NEAR to predict the local minimum status of a node. By global prediction, we mean that a local minimum is predicted without referring to any particular destination. By prediction, we mean that a node is labeled as a local minimum when it is a possible local minimum for some nodes.

In this scheme (as illustrated in Figure 3(a)), each node calculates the maximal angle $a$ between a pair of its




(a) (b)

Fig. 3. The local minimum status of node $A$ is predicted solely based on angle $a$ in NEAR (a). the local minimum angle $b$ of node $A$ in LARGER (a, b).

adjacent links, say $L$ and $L'$, where $L$ and $L'$ do not include the links with the neighbors that were already predicted as local minima. A node is predicted as a local minimum if $a$ is greater than a given threshold angle $p_a$ ($p_s > \pi$.).

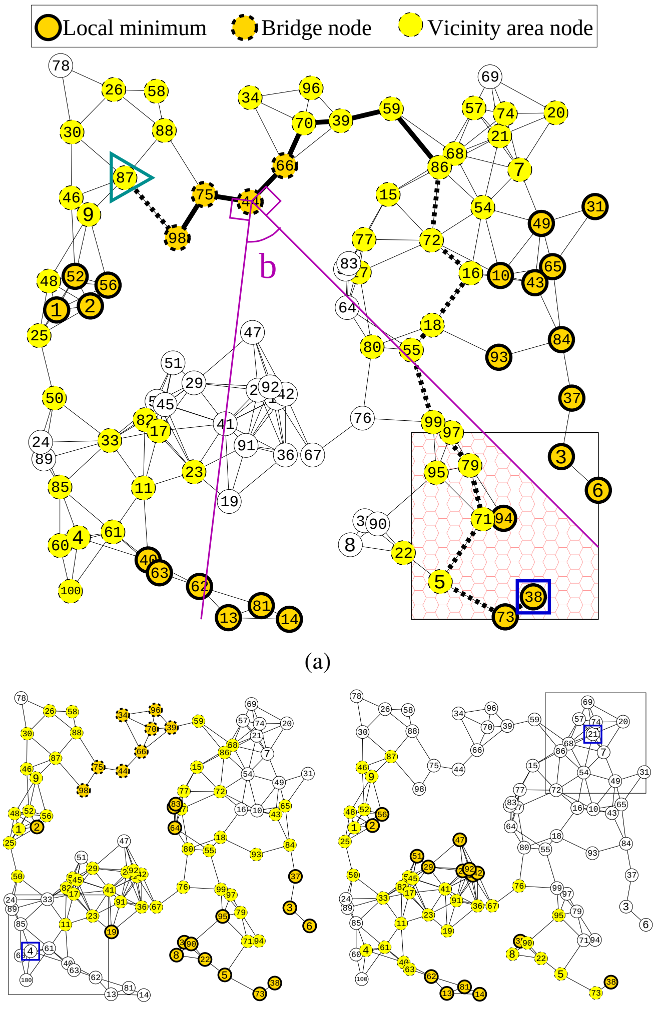
The idea of this scheme is that, the larger is angle $a$ the greater is the node's probability to be a local minimum of some other nodes.

### C. *Destination-region-based predicted local minima*

To improve the accuracy of the global prediction scheme in NEAR, LARGER uses a destination-region-based local minimum prediction scheme. We partition the network into $k$ *destination regions* and assume each node has a prior knowledge about this partition. Each node then has a status vector of length $k$ to indicate its local minimum statuses for these $k$ destination regions. If a node is a local minimum for the $i^{th}$ ($1 \leq i \leq k$) destination region, the $i^{th}$ status in the status vector is set to 1. Otherwise it is 0. In a routing process where the message is destined for a destination inside the $i^{th}$ destination region, LARGER makes forwarding decisions on the nodes' local minimum statuses according to their $i^{th}$ status on the status vectors.

The destination-region-based local minimum prediction scheme of LARGER is presented as follows. First, we define the *local minimum angle* of a node for a given destination region, which is used to determine whether the node is a predicted local minimum.

*Definition 2 (Local minimum angle):* A local minimum angle $b$ of a node $A$ is an angle whose vertex is at $A$ and whose rays are given according to the following situations : (1) if $A$ has more than two links (as in Figure 3(a)), and $L$ and $L'$ are two adjacent links of $A$ such that the angle between them is greater than $\pi$, the two rays of $b$ are perpendicular to $L$ and $L'$ respectively; (2) if $A$ has only one link $L''$ (as in Figure 3(b)), then both of the rays of $b$ are perpendicular to $L''$. Here, $L$, $L'$ and $L''$ do not include the links with the neighbors of $A$ that were already predicted as local minima.




(a)

(b) (c)

Fig. 4. Examples of the prediction scheme and routing schemes in LARGER. Each node is labeled (predicted) differently with respect to different destination regions.

If a node $A$ has a local minimum angle $b$, node $A$ is a local minimum for all of the nodes within $b$. A node might not have a local minimum angle if all of the angles between its adjacent links are less than $\pi$.

The definition of local minimum angle is only complete with the following definition of the destination-region-based predicted local minimum, since it relies on the predicted local minimum status of the neighbors which is in turn determined by the local minimum angles of these neighbors.

*Definition 3:* (*Destination-region-based predicted local minimum*): For a given destination region, a node is labeled as a destination-region-based predicted local minimum if the percentage of the destination region that is covered by the node's local minimum angle is greater than a constant threshold $p$ ($0 \leq p \leq 1$) – the *local minimum threshold*.

An example to illustrate how to determine whether a node is a destination-region-based predicted local minimum is shown in Figure 4(a) where the network is divided into $3 \times 3$ equal-sized, square destination regions. Among these regions, the one containing the destination (node 38) is delimited by a square in the bottom right of the network. The local minimum angle of node 44 for this destination region is labeled by $b$. The area of the destination region that is covered by $b$ is shown by the shadow inside the destination region. If this shadowed area accounts for a percentage of the destination region that is greater than the local minimum threshold $p$, node 44 will be labeled a destination-region-based predicted local minimum.

Given that the local minimum threshold $p$ equals 0.1, all destination-region-based predicted local minima for the above destination region are shown in Figure 4(a) with thick rings. Different collections of destination-region-based predicted local minima are labeled for two other destination regions in Figures 4(b) and 4(c). If the destination regions are ordered from top to bottom and from left to right, the $7^{rd}$ and the $9^{th}$ statuses on the status vector of node 44 are 1, and the $3^{th}$ status is 0.

Our prediction scheme is based on the fact that the percentage of a destination region being covered by the local minimum angle of a node is a good estimation of the probability that the node is a real local minimum of a destination chosen randomly from the destination region, if the destinations are evenly located inside the destination region.

The prediction scheme in NEAR is a special case of our scheme, where the network has a single infinitely large destination region and the local minimum threshold $p = \frac{p_a - \pi}{2\pi}$, where $p_a$ is the threshold angle in NEAR.

Note that our local minimum prediction scheme is only intended to increase the prediction accuracy of the previous schemes, and it is possible that, given a destination region, a node that is a real local minimum for some destination does not necessary have a local minimum angle and therefore will not be labeled as a predicted local minimum.

### D. Evaluation of the Prediction

We evaluate the prediction scheme in LARGER by comparing it with the one in NEAR. As presented in the last subsection, LARGER has two additional features that NEAR lacks: (1) it uses multiple destination regions, and (2) it predicts based on a coverage percentage.

The metrics in our evaluation are: (1) *hit-rate* (recall), which is the proportion of a destination's real local minima that are labeled as predicted local minima for the destination region where the destination is located; (2) *precision*, which is the proportion of predicted local minima that are real local minima for a destination; and (3) *local minimum percentage*, which is the percentage of per node predicted local minima over the total number of nodes. Hit-rate and precision together measure the *accuracy* of prediction, which can be measured as a monotonously increasing function of both hit-rate and precision. Local minimum percentage is an indicator of the amount of control overhead in the algorithms.

Since NEAR does not use destination regions, in the first experiment, we use the whole network as a single destination region to compare LARGER against NEAR. The experimental variable $p$ ($0 < p \leq \frac{1}{2}$) is the local minimum threshold for LARGER, and $2\pi p + \pi$ (which ranges between $\pi$ and $2\pi$) is the threshold for the maximal angle $p_a$ in NEAR.

Our experiments are repeated over 30 randomly generated connected networks (with network degree $\approx 3.5$), and the numbers of real and predicted local minima for each node (as a destination) are recorded and averaged. The simulation settings are shown in Table I. The results in Figures 7(a) and 7(d) show that LARGER has a larger hit-rate than NEAR most of the time and it always has a larger accuracy and smaller percentage of local minimum.

The second experiment evaluates the effect of using multiple ($n \times n$) destination regions in LARGER. As shown in Figures 7(b) and 7(e), the hit-rate and the precision in LARGER is further increased by using more destination regions.

### E. Bridge Detection

Ideally, if neither the source nor the destination of a message is labeled as predicted local minimum, then the message can be sent to the destination solely in greedy forwarding. However, due to the inaccuracy in the prediction based on the destination region instead of the actual destination, a rare situation might occur in which the message must be forwarded by some predicted local minima.

*Definition 4 (Bridge):* A bridge for a destination region is made up of a number of connected, predicted local minima of the destination region. If these local minima are removed from the network, for some source-destination pair, no path will exist between them.

An example of a bridge is shown in Figure 5. In the figure, if the bridge, which is not supposed to participate in the message-forwarding, is removed, there is no path from the source $S$ to the destination $D$.

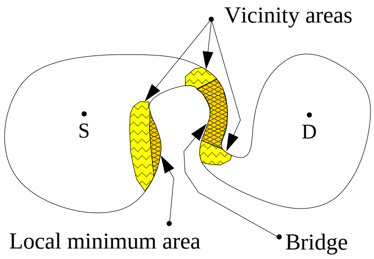



Fig. 5. Local minimum area, vicinity area, and bridge. A bridge is characterized by having at least two adjacent vicinity areas.

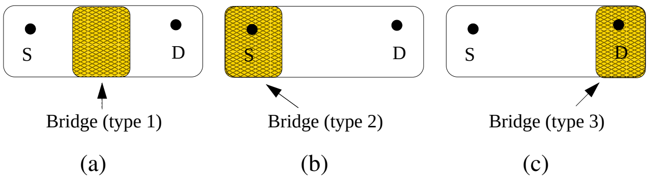



Fig. 6. Three types of bridges.

We classify three type of bridges, which are shown in Figure 6. The first type does not contain the source or the destination. The second type contains the source node. The third type contains the destination. A bridge can belong to the second and the third type simultaneously, in which case both the source and the destination are in the same bridge. Nodes in these bridges are labeled via different methods.

To label the first type of bridge, we need to define some additional node groups in the network, which are illustrated in Figure 5. Similar to the definition of local minimum angle and the definition of predicted local minima, each of these node groups is defined with respect to a particular destination region.

- **Local minimum area**: a group that consists of a set of connected predicted local minima.
- **Vicinity area**: a group that consists of a set of connected nodes that are not predicted local minima and are within $k$ ($k = 2$) hops away from a predicted local minimum

For vicinity area, a small $k$ results in a large number of vicinity areas (that could be connected together if $k$ is larger), while a large $k$ results in a large propagation overhead. In our implementation, we choose $k = 2$.

Our algorithm requires that the nodes in each of these areas (groups) to select a unique area ID, which we call *local minimum area ID* and *vicinity area ID* respectively. These ID selection processes need some cooperation and message propagation among the nodes in the same area, but we will not get into this due to space limitation. We can assume that these processes converge quickly if the local minimum areas are not large, which is usually the case in practical situations.

The first type of bridge can be identified for having at least two neighboring vicinity areas. This is a necessary but not a sufficient condition, but it satisfies our goal of not missing any bridge. An algorithm just needs to count the number of vicinity area IDs to know the number of neighboring vicinity areas.

The second type of bridge is simple to detect: a predicted local minimum area is a second type of bridge if the current node is inside it.

For the third type of bridge, each destination needs to append its local minimum area ID (if any) to the messages containing its current position which it sends periodically to its location server. The source of the message can obtain the local minimum area ID of the destination together with the position of the destination from the location service. This way, a node having the message stamped with the local minimum area ID of the message's destination is able to identify the third type of bridge for the destination.

Figures 4(a), 4(b), and 4(c) show how the nodes are labeled in a real network. Note that only the nodes in the first type of bridge are shown as thick dashed rings since they can be labeled independent of any destination.

### *F. Routing in LARGER*

Now that the destination-region-based predicted local minima (which we will simply call predicted local minima is the rest of this paper) and the nodes in the bridges are labeled, we can define LARGER routing in Algorithm 1. Note that since the prediction of local minima is not perfectly accurate, LARGER (as well as NEAR) might switch to face routing mode occasionally, but with a lower frequency. Algorithm 1 is basically a variation of GFG which makes use of the predicted local minima to prevent from entering face routing. Variations of other geometric routing schemes, such as GOAFR, can be defined similarly to make use of the predicted local minima.

Note that in Algorithm 1, if the source of a message is a predicted local minimum, then all the other nodes in the same local minimum area as the source will be regarded as the second type of bridge, and the message can be sent to these predicted local minima.

A LARGER routing process can be illustrated using the example in Figure 4(a). In Figure 4(a), the source 87 sends a message to the destination 38. Before the routing starts, the source obtains the position and the local minimum area ID of the destination from the location service. In the routing process, the message first travels in greedy forwarding mode to 98. Then it travels

**Algorithm 1** routing in LARGER (basic)

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Init: Query the position information and the local minimum area ID of the destination from the location service. Set forwarding mode to GREEDY.
if the current node is the destination then
    consume the message and exit;
end if
if forwarding mode is GREEDY then
    Let N be the set of neighbors that are not predicted local minima (excluding nodes in bridge) and that are closer to the destination than the current node.
    if N is not empty then
        send the message to the node in N that is the closest to the destination.
    else
        store the current destination distance D and change forwarding mode to FACE;
    end if
end if
if forwarding mode is FACE then
    send the message to the next node according to face routing.
    if the destination distance of new node is smaller than D then
        change forwarding mode to GREEDY;
    end if
end if
```

from 98 to 86 in face forwarding mode. In 86, the routing protocol returns to greedy mode and travels from 86 to 5. The message is then forwarded to 73 and later to the destination. Here, 73 is in a bridge of the third type which contains the destination.

Note that in the example above, the message passes through a bridge of the first type. As we have mentioned, our bridge detection condition is sufficient but not necessary condition, which means that some local minimum might be detected as bridges unnecessarily. However, this does not affect the delivery of messages in LARGER.

LARGER guarantees delivery. It can be proven from the definition of the three types of bridges that by removing any local minimum area (excluding bridges) the network will not partition since none of the local minimum areas have more than one adjacent area. Therefore, if the underlying geometric routing guarantees delivery, LARGER also guarantees delivery.

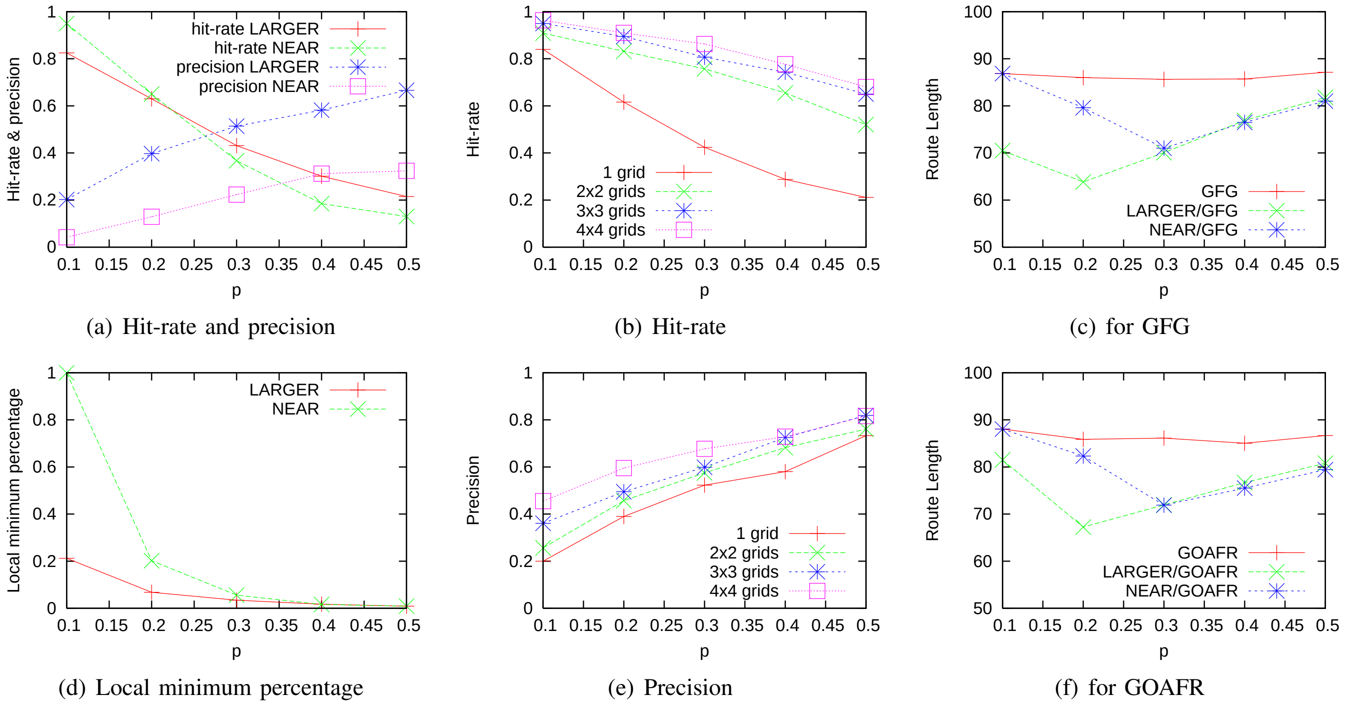
There are two additional improvements in our routing algorithm. First, if the current node is a node in the same local minimum area as the destination, it will not send the message to any non-local minimum node. This rule restricts the path to a small area of the network and reduces unnecessary face forwarding. The second improvement is that the routing algorithm returns to greedy mode faster, once the message is sent from a (non-bridge) local minimum to a non-local minimum, or once the message is sent from a non-local minimum to a local minimum (which must be in the local minimum area where the destination is located). The second improvement is based on the first improvement. It can be easily proved that adding these two improvements will not cause routing loops in LARGER.

### *G. Remarks*

LARGER has very little additional overhead and it is localized and scalable. LARGER uses hello messages to propagate information in the selection process of the local minimum areas, the vicinity areas and the bridge detection process. The amount of messages that need to be added to each hello message is very small and their size is constantly bounded: in our implementation, at most six values (totally 18 bytes) for each destination region. If there are $4 \times 4$ destination regions, the maximal bytes added to a hello message is only 96 bytes. Compression techniques can make it even smaller. Since the local minima usually account for a very small portion of the nodes, the average additional information is even smaller. The amount of information added to the hello message does not increase as the network size increases. The detection method used for the third type of bridge adds an ID to each location service message. Location service protocols that are scalable for local traffic patterns are available, and we expect improvements in this research field in the near future.

While LARGER improves the routing performance, it has almost no additional assumptions to the existing routing protocols. The assumption of nodes' prior knowledge of the destination regions is the same as the prior knowledge assumptions used in the home-based location services and their variants which are the most popular form of location services. For instance, LARGER can use the home-regions in a home-based location service as the destination regions. The registration and the query of the local minimum area ID of the destination in LARGER reuses the same location service for nodes' position.

LARGER improves the efficiency of geometric routing by preventing entering face forwarding mode which has a greater number of transmissions that the greedy forwarding. Thus, LARGER increases the routing speed and decreases the network energy consumption. Also, face forwarding depletes the energy of the nodes on the perimeter quicker which causes bigger voids and even network partition as the those nodes die out. The location errors and the asymmetric links all cause the




(a) Hit-rate and precision (b) Hit-rate (c) for GFG

(d) Local minimum percentage (e) Precision (f) for GOAFR

Fig. 7. (a, d) Comparison of LARGER and NEAR. (b, e) Comparison of LARGER with $n \times n$ destination regions. (c, f) Route length in LARGER and NEAR (network degree $\approx 3.5$.)

delivery failures of face routing in practice. To sum up, by reducing face forwarding, LARGER increases delivery efficiency and the delivery ratio both in the short term and in the long term.

## IV. Simulation

In this section we observe how LARGER improves the routing performance of geometric routing. We use GFG and GOAFR as the underlying geometric routing algorithm of LARGER respectively and compare their performance with the original GFG and GOAFR. We observe the routing performance in terms of the route length. The parameters in our simulation are the number of nodes in the network (or network density), the local minima threshold $p$, and the number of destination regions in the network. Our simulation is implemented on a packet level event-driven MANET simulator we developed which provides a real-time graphical interface for easy debugging.

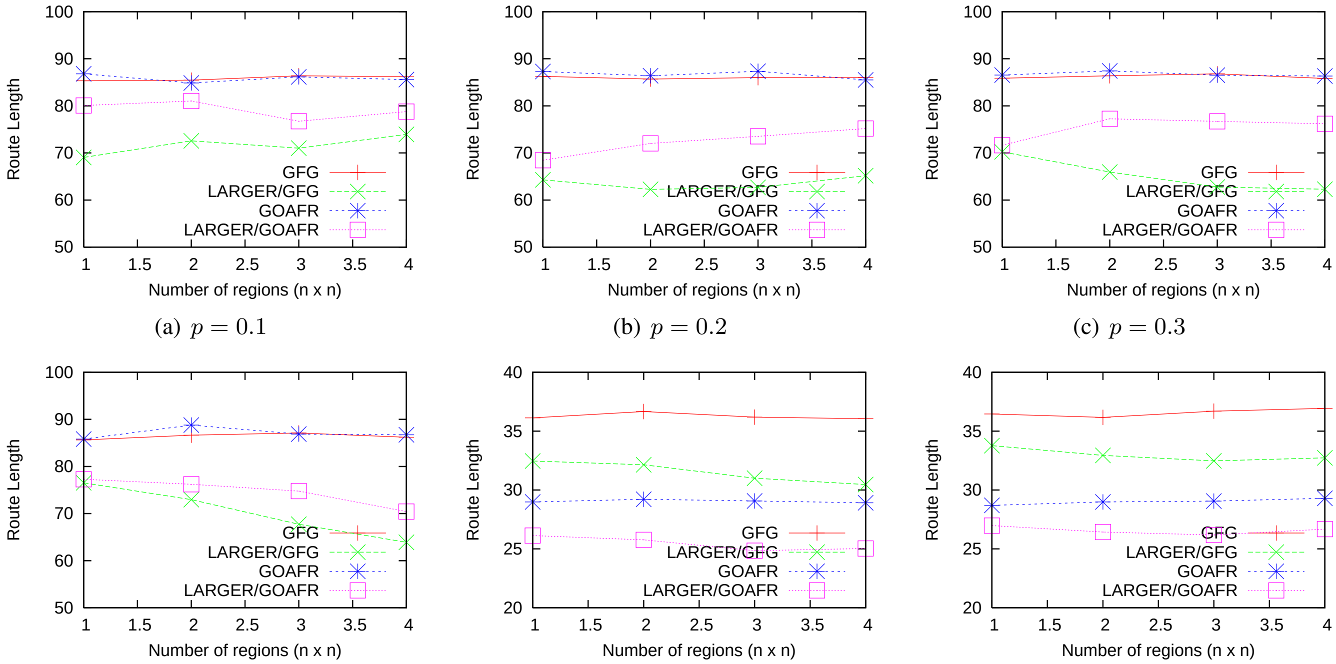
Instead of dealing with the problems in face routing, we simplify our experiment environment to better estimate the efficiency of our algorithm in bypassing obstacles and improving the routing performance. We use the ideal radio model and the static mobility model. We use randomly generated connected networks of different densities in our simulation. Each network is randomly generated by placing nodes in random positions. The connectivity is checked, and disconnected networks are discarded. The network degree ranges from 3.5 to 7 neighbors per node. Networks of different densities contain voids of different sizes and a different number of voids. Table I shows the simulation setting.

TABLE I
SIMULATION SETTING

| **Parameter** | **Value** |
|---|---|
| network size | $2,000m \times 2,000m$ |
| radio range | 200m |
| network density | 3.5/7 neighbors per node |
| number of destination regions | $1 \times 1, 2 \times 2, 3 \times 3, 4 \times 4$ |
| local-minimum threshold ($p$) | $0.1, 0.2, 0.3, 0.4, 0.5$ |

Each simulation result is averaged over 30 different networks of identical settings. We let each node be the destination and select ten other nodes to send ten messages using GFG, GOAFR, LARGER/GFG, and LARGER/GOAFR respectively. Here LARGER/GFG and LARGER/GOAFR are the implementations of LARGER with the underlying geometric routing protocols being GFG and GOAFR respectively.

In the first simulation, we evaluate the efficiency of our local minima prediction algorithm. Bear in mind that it is based on the percentage of area of the destination region that is covered by the local minimum angle of the node. We use the method in NEAR, which predicts based on the size of the maximal angle between adjacent links, to compare to ours in terms of route length. There




(a) $p = 0.1$ (b) $p = 0.2$ (c) $p = 0.3$

(d) $p = 0.4$ (e) $p = 0.2$ (f) $p = 0.4$

Fig. 8. Route length vs. number of destination regions. In (a-d) network degree $\approx 3.5$. In (e-f) network degree $\approx 7$.

is a non-localized void discovery process in NEAR that always enables it to choose the shorter side of a face. To ensure fairness, we implement a version of NEAR that only replaces the local minimum prediction algorithm of LARGER. Moreover, we use a single destination region in this experiment. The experiments use a varying parameter $p$, which is the local minimum threshold for LARGER and for NEAR $2\pi p + \pi$ is the threshold of the maximal angle.

The simulation results are shown in Figures 7(c) and 7(f). The results show that the performance of LARGER is better than or equal to that of NEAR in all cases. These results are consistent with our previous experiment on the accuracy of local minimum prediction, where LARGER shows better hit-rate and precision. Here, GOAFR does not outperform GFG since the network is not dense enough. Note that in all of these figures, the routing performance of GOAFR and GFG do not change as the local minimum threshold or the number of destination regions changes.

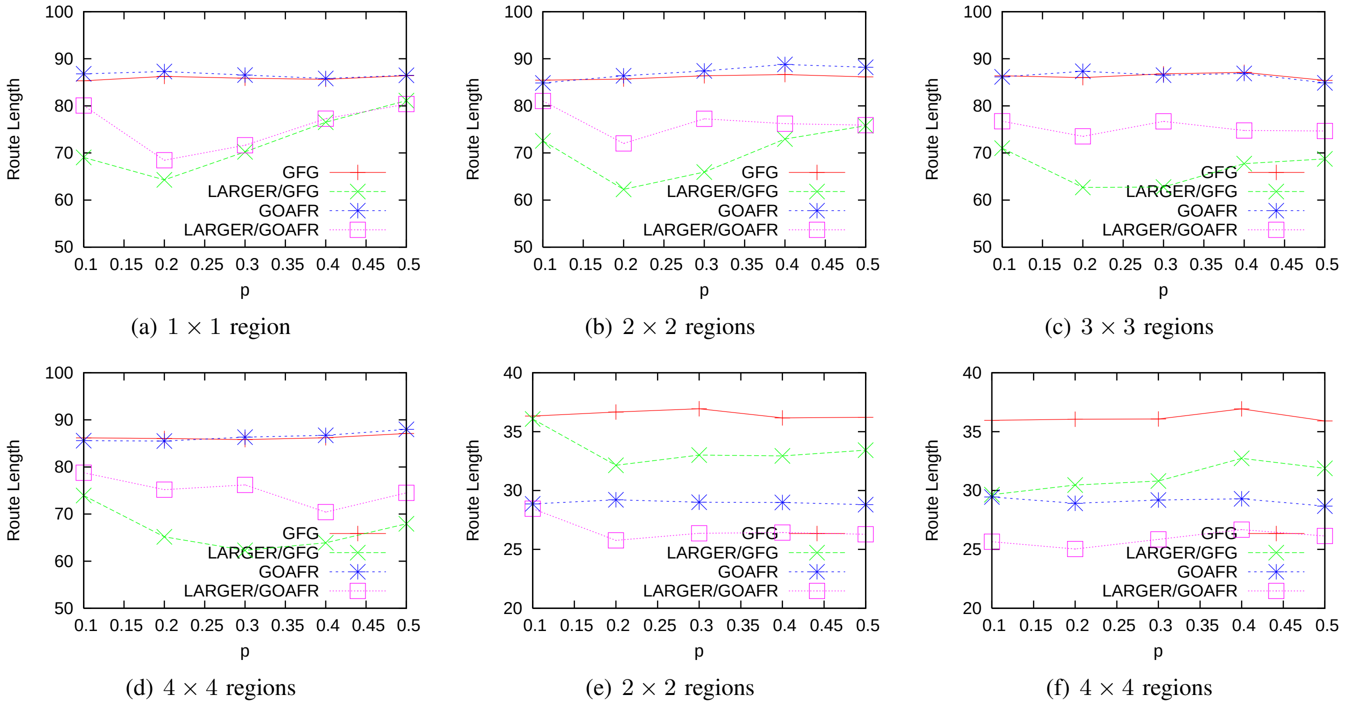
In the second experiment, we compare the performance of LARGER using the number of destination regions and the local minimum threshold as the varying parameters. Figures 8(a) to 8(d) show the results on route length when varying the number of destination regions under different local minimum threshold. Figures 9(a) to 9(d) show the results on route length when varying the local minimum threshold under different numbers of destination regions.

Figures 8(a) to 8(d) show that the performance of LARGER is better in most cases when the number of destination regions increases. When the local minimum threshold is not very small, increasing the number of destination regions improves the performance substantially. We conclude that using more destination regions has a positive effect on performance.

Figures 9(a) to 9(d) show two facts. The first fact is that, with a larger number of destination regions the route length is less affected by the local minimum threshold. The second fact is that, with a larger number of destination regions the average route length is smaller under different local minimum thresholds. Thusly, we get the same conclusion that a larger number of destinations benefits the routing performance.

Figures 8(e), 8(f), 9(e), and 9(f) show the results of similar simulations that are performed in networks of a higher density (network degree $\approx$ 7). Due to space limitations, only selected figures are shown for these results. Note that in the dense networks, GOAFR has a much better performance than GFG. In dense networks, the trends of performance changes of LARGER under various local minimum threshold and number of destination regions are the same as it is in the sparse networks.

To sum up, both of our algorithms in LARGER, the local minimum prediction algorithm and the multiple destination region scheme, are shown to be effective in our simulation results.




(a) $1 \times 1$ region (b) $2 \times 2$ regions (c) $3 \times 3$ regions

(d) $4 \times 4$ regions (e) $2 \times 2$ regions (f) $4 \times 4$ regions

Fig. 9. Route length vs. local minimum threshold. In (a-d) network degree $\approx 3.5$. In (e-f) network degree $\approx 7$.

## V. Conclusions

We have presented LARGER which improves the accuracy of the local minimum prediction by dividing the network into a number of regions and predicting local minimum based on the region where the destination is located. Simulation results show that LARGER substantially improves the prediction accuracy and the routing performance of NEAR, GFG and GOAFR in terms of route length. Other polygon tessellations, such as hexagons, might be better than squares for dividing destination regions. Therefore, in future works, we will also evaluate the effect of using different polygon tessellations as destination regions in our simulations.

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