A Hop Count Based Greedy Face Greedy Routing Protocol on Localized Geometric Spanners

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***Abstract*—We describe a Fast Delivery Guaranteed Face Routing (FDGF) in ad hoc wireless networks. Since it is expensive for wireless nodes to get the whole network topology information, geometric routing decisions should be made locally by nodes using location information of neighboring nodes which are at most k hops away. In this paper, we first define k-local algorithm and obtain two local geometric graphs, i.e., k-Local Delauany Triangulation Graph (k-LDTG) and k-Local Minimum Weight Spanning Tree (k-LMWST), which are more efficient than existing definitions. We present problems with existing face routing protocols and propose FDGF to counter possible long delivery delay with high probability. The performance of face routing differs on different planar graphs. We compare face routing characteristics of four different underlying routing graphs which include k-LDTG, Gabriel Graph (GG), Relative Neighbor Graph (RNG) and k-LMWST. Due to different attributes of these graphs, the message delivery delay, routing hop and minimum energy consumption differ greatly. Through experimentation in the NS-2 simulator, we have shown that the proposed face routing protocol achieves 100% delivery ratio on Unit Disk Graph (UDG) when source to destination connection path exists. Face routing on k-LDTG is fast with less relay hops and face routing on k-LMWST is energy efficient. RNG achieves desirable minimum energy consumption attribute, better than all the others when the propagation model is free space and close to k-LMWST when the propagation model is Two Ray Ground.**

***Keywords*-face routing, localized algorithm, Delaunay triangulation, minimum spanning tree, relative neighbor graph, Gabriel graph.**

I. Introduction

Geographic routing protocols use node location information to make routing decisions. One simple way is to deliver message to a neighboring node that is closer to the destination in every routing step. But this greedy approach suffers from the local minimum problem, in which a message reaches a node that does not have a closer neighbor to the destination although source to destination path exists. Another way of applying geographic routing is to route messages face by face along the source to destination line which guarantees delivery. The local minimum problem also could be solved by face routing. For efficient face routing, planar sub-graph (the sub-graph without crossing edges) should be extracted from the original graph. A combination of the above two geographic routing approaches is also available [5], [11], i.e., a node performs simple geographic routing whenever there are closer neighbors to the destination and switches to face routing upon local minimum. Since it is expensive or even impossible for nodes to get entire network topology information, routing decisions should be made locally by nodes using only distance k (for some small value of k) neighborhood information in such a situation.

In this paper, we first define the concept of k-Local algorithm, which is different from similar definitions in the literature [9], [10]. By applying k-local minimum weight spanning tree and k-local Delaunay triangulation algorithms, k-LMWST and k-LDTG are obtained. The properties of these two local geometric graphs are presented for further use in the routing process. We show that the proposed definitions are more efficient than existing definitions, with uniformly simplified expressions.

After that, we propose a Fast Delivery Guaranteed Face Routing (FDGF) scheme which guarantees delivery and reduces delay with high probability by increasing the number of copies of the same message in transit at edges which cross with source to destination line. Performances of the proposed face routing protocol under the local minimum weight spanning tree, Gabriel Graph, Relative Neighbor Graph and local Delaunay triangulation graph are also evaluated.

Simulation results show that the proposed face routing technique achieves 100% delivery ratio when source and destination node connection exists. Face routing on k-LDTG travels less routing hops than all other graphs and hence is the fastest. Face routing on k-LMWST is the most energy efficient when the propagation model is *Two Ray Ground*, which considers both the direct path and a ground reflection path, with the cost of longest delay and largest routing hops. RNG is an ideal face routing graph in terms of minimum energy consumption: it is close to LMWST when the propagation model is *Two Ray Ground* and it is the best of all the routing graphs when the propagation model is *Free Space*.

The rest of the paper is organized as follows. Section

2 gives the k-Local Algorithm definition and the local geometric spanners, i.e., k-LDTG and k-LMWST. Section 3 reviews some of the existing face routing protocols. Section 4 elaborates on our proposed solutions. Following that, Section 5 presents the details of experimental results and performance analysis. Section 6 concludes by summarizing our findings and points out the possible future directions that we could work on.

II. Definitions, Properties and Relations of Local Graphs

Various planar graphs could be used for face routing. Gabriel Graph (GG), Relative Neighbor Graph (RNG), Minimum Spanning Tree (MST) and Delaunay Triangulation (DT) are all planar graphs. GG is a certain graph that connects a set of points in the Euclidean plane. Two points u and v are connected by an edge in the Gabriel graph whenever the disk having line segment uv as its diameter contains no other points from the given point set. RNG of a graph $G = (V, E)$ with V the vertex set and E the edge set, denoted by $RNG(G)$, is the set of all edges $uv \in E$ such that there is no vertex or point w where $uw \in E$, $wv \in E$ and $|uw| < |uv|$ and $|wv| < |uv|$. MST is the spanning tree with minimum total weight and DT is a triangulated planar graph in which no point is in the disk determined by three vertices of any triangle of the triangulation. Among all these routing graphs, the performance of face routing on them differs from each other. MST is energy efficient and DT is fast for face routing protocols. But it is very expensive or even impossible for nodes to get entire network knowledge to extract these two graphs.

Researchers have been working on the local construction of these graphs. In [9], Li *et al.* defined k-localized Delaunay triangle and k-localized Delaunay graph in their own way. They have proved that the UDel (it is the Delaunay triangulation in which we keep only edges of length at most one) is a t-spanner. A triangle Δuvw is called k-localized triangle if $disk(u, v, w)$ does not contain any node in node set P that is in distance k neighborhood of u, v, or w. The k-localized Delaunay graph over a node set P (denoted as $LDel^{(k)}(P)$) has exactly all Gabriel edges and edges of all k-localized Delaunay triangles. Restricted Delaunay Graph (RDG) [4] is another localized Delaunay triangulation defined by Gao *et al.*

In [8], Li *et al.* proposed a local algorithm which constructed a localized minimum spanning tree (LMST) for topology control. In [10], Li *et al.* proposed the idea of k-local LMST ($LMST_k$), extending LMST to distance k neighborhood. In the $LMST_k$ definition, a node u collects its distance k neighborhood $N_k(u)$ and constructs locally MST $T_k(u)$ of $N_k(u)$. An edge is selected in the final local graph if it was retained by both of its incident nodes.

To simplify the construction of local graphs, we define k-local algorithm which could be used in obtaining both local minimum spanning tree graph and local Delaunay triangulation graph. Our definitions are different from the k-local algorithms used in [9] and [10], with uniformly simplified expressions and increased efficiency(all proofs in the paper are omitted due to space limitations).

A. k-Local Algorithm

If taking any algorithm A such that on input node set V of Unit Disk Graph (UDG, all edge lengths are at most one unit) G, the algorithm could output a graph $A(V)$ of V, then k-Local Algorithm can be defined as follows:

- For any node u, $\forall u \in V$
  - u collects its distance k neighborhood $N_k(u)$.
  - u constructs $A(N_k(u))$.
- A link uv is accepted in the local graph if it is in $A(N_k(u))$ and $A(N_k(w))$, $\forall w \in N_1(u)$ if $u \in N_k(w)$ and $v \in N_k(w)$.

B. k-LDTG Definition and Its Properties

The k-Local Delaunay Triangulation Graph (k-LDTG) can be obtained by using k-local algorithm (Definition II-A, with $k = 1, 2, ..., d$.) of Delaunay triangulation construction. For simplicity, LDTG refers to our k-local Delaunay triangulation graph definition in the rest of the paper. The properties of LDTG are listed in the following theorem.

Theorem II.1. *If G is a UDG, by applying k-Local Delaunay triangulation algorithm, the obtained graph has the following properties.*
a) It is connected if the original graph is connected;
b) It is planar;
b) It is t-spanner, $t \leq \frac{4\sqrt{3}}{9}\pi$.

If only considering clusterheads and gateway nodes in [4], 1-LDTG is the same as RDG.

C. k-Local Minimum Weight Spanning Tree

We define k-Local Minimum Weight Spanning Tree (k-LMWST) by applying k-local algorithm (Definition II-A) of minimum spanning tree construction. Node ids are used to break the balance when two edges have the same weight. Larger id number is assumed to have larger weight. We show that the constructed k-LMWST of UDG has interesting properties summarized in the following theorem. LMWST refers to our k-local minimum weight spanning tree definition in the reminder of the paper.

Theorem II.2. *If G is a UDG, by applying k-Local minimum weight spanning tree algorithm, the obtained graph has the following properties.*
a) It is a planar;
b) It is a superset of minimum spanning tree.

We also can show that k-LMWST is a superset of $(k+1)$-LMWST (with $k = 1, 2, ..., d$). Larger k will make the LMWST closer to MST with the increase in communication costs.

D. Definition Comparisons and Relationships of Geometric Graphs

The goal of the local construction is to obtain graphs which are supersets of the global graph and are "as close to it" as possible. Apparently, a local algorithm is more efficient than another one if its output graph is closer to the global one when nodes collect the distance k neighborhood (for the same value of k) information. Compared with existing definitions $LDel^{(k)}(P)$ and LMST$_k$, LDTG and LMWST show uniformly simplified definitions and increased efficiency. We can prove the following relationships when comparing $LDel^{(k)}(P)$ and LMST$_k$ with k-LDTG and k-LMWST.

$LDel^{(k+1)}(P) \subseteq k$-LDTG$\subseteq LDel^{(k)}(P)$

LMST$_{k+1} \subseteq k$-LMWST$\subseteq$LMST$_k$

The following relationships can also be obtained among all the geometric graphs of MST, LMWST, RNG, GG, UDel, LDTG.

MST$\subseteq$ LMWST $\subseteq$ RNG $\subseteq$ GG $\subseteq$ UDel $\subseteq$ LDTG

III. Problems with Face Routing Protocols

A. Face Routing Definition

In face routing, a message follows a sequence of adjacent planar faces which are intersected by the straight line ST connecting the source node S with the destination node T. Face routing was first proposed by Kranakis *et al.* [6], called Compass Routing II. This routing protocol explores a face completely before switching to the adjacent face. To accelerate message delivery, variations of face routing without exploring complete faces have been proposed. Although some of them use techniques to avoid face routing loops caused by a non-planar graph without really constructing the planar graph itself, only face routing protocols in planar subdivision are discussed in this paper.

B. Existing Face Routing Protocols

Greedy Face Greedy (GFG) routing was proposed by Bose *et al.* [2]. The GFG routing logic works in the following way, as shown in Figure 1.

1) *P← S*
2) *repeat*
3) *Let F be the face with P on boundary and intersecting PT*
4) *Traverse F until reaching an edge that intersects PT at some point Q≠ P*
5) *P← Q*
6) *until P=T*

In [5], Karp *et al.* proposed greedy perimeter stateless routing (GPSR) for routing in MANET. Their routing logic

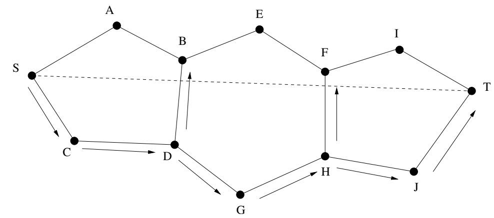

Figure 1. GFG routing

is defined as follows: On each face, the traversal uses the right-hand rule (referred as left hand rule by other face routing protocols because the routing logic could be considered as walking along the inner faces by using left hand touching the edges.) to reach an edge that crosses source node S to destination node T line segment $\overline{ST}$. At that edge, the traversal moves to the adjacent face crossed by $\overline{ST}$ by using the right hand rule. The combination of simple greedy routing and face routing upon local minimum is part of their routing logic.

In [7], Leong *et al.* proposed Greedy path vector face routing (GPVFR). The routing logic defined in GPVFR is (see Figure 2):

1) *Find the face F containing the line segment ST. Let A and B be the clockwise and anti-clockwise nodes. If $|AT| \leq |BT|$, forward the packet clockwise along F; if $|AT| > |BT|$, forward the packet anti-clockwise.*
2) *If any adjacent edge intersects the line segment ST then set S to current node C and go to step 1.*

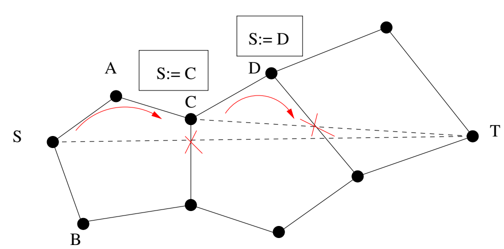

Figure 2. GPVFR routing logic

C. Pitfalls for Some Face Routing Protocols

Existing face routing protocols could fail to deliver message even if source and destination connection exists. In Figure 3, when source node S has message for destination node T, GPSR and GPVFR face routing protocols fail to reach destination.

In GPSR, right-hand rule (defined in [5]) is applied at crossing edges. When a message reaches node A, A continue to use right-hand rule to deliver the message to node C, C to D and finally the message is routed back to source node. The combination of simple greedy and face routing also fails because node C is closer to destination node T than node B.

In GPVFR, node A chooses node C as the next hop because of $|CT| \leq |BT|$. Face routing fails in GPVFR as a result.

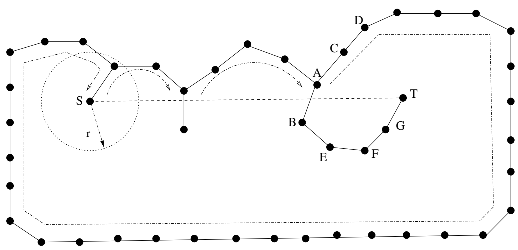

Figure 3. Face routing examples

D. Possible Long Face Routing Delays

GFG assumes routing could use either left hand rule or right hand rule upon an edge which intersects with the source to destination line segment. In [3], Frey and Stojmenovic have proved that GFG guarantees delivery. However, with only one rule (right or left hand rule), routing may not reach the destination at one routing cycle (reach back to source node). In Figure 3, since node A could choose either node C or node B as the next hop, routing will return back to source node if A chooses node C by using the left hand rule. Thus long delay is inevitable in this case, although delivery is guaranteed through proper bookkeeping (remember the closest crossing edge with the source to destination line).

IV. A Fast Delivery Guaranteed Face Routing (FDGF)

Greedy face greedy (GFG) works fine in most scenarios. But as mentioned in section III-D, GFG routing can experience long delivery delay. To increase the probability of a faster routing path selection, two copies approach could be adopted, i.e., upon a crossing edge, left hand rule and right hand rule are applied at the same time.

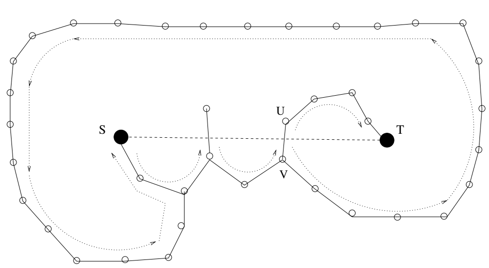

Figure 4. FDGF routing

In Figure 4, when edge UV crosses line ST, one message traverses to the next hop using left hand rule from node U above line ST and another same copy from node V traverses to the next hop using right hand rule (see dashed line).

The proposed FDGF routing is based on GFG [2], [3], with reduced routing hop count by using additional message copies, which we call continuation copy. If a message is supposed to be delivered to a node in the other side of an edge which crosses with source to destination line segment, a continuation copy will also be transmitted at the same side of the sender (two sides are separated by the source to destination line). Our goal is a fast delivery guaranteed face routing and we want to evaluate the characteristics of different local graphs when this face routing logic is applied on them. The routing process is shown in Algorithm 1.

Algorithm 1 Fast Delivery Guaranteed Face Routing

```
procedure FDGF ROUTING
    while (Messagecount ≠ 0) do
        if (Source node & message starting) then
            Send message to left hand neighbor
            Send message to right hand neighbor
        else
            if (Connection with previous node crosses ST) then    ▷ ST: source destination line
                Change rule
            end if
            Decide next hop node
            if (Connection with next hop crosses ST) then
                Decide continuation node
                Send message to continuation node
            end if
            Send message to next hop node
        end if
    end while
end procedure
```

A node keeps a record of all the messages it has received for some time. If the same message arrives with the same rule from the same node, it is just discarded. Also, a node keeps another record of all the messages that have been sent. If a node has delivered a message to another node for a specified rule, it will not send the message to the same node again if the rule is the same. In this way, the total number of duplicate messages will be reduced. These two records can be represented as queues to save storage space.

To deal with the situation that the record of a message is deleted from nodes due to space limitation of queues while the message never ends up at the destination node, hop count is used to terminate the message. After exceeding a specified maximum hop count (e.g., 2×number of nodes), the message is simply discarded.

V. Experimental Evaluation

In the simulation, FDGF routing logic is applied on the 1-LMWST, RNG, GG and 1-LDTG underlying graphs. Delivery latency, hop count and energy consumption of *Two Ray Ground* model and *Free Space* model are compared between these different local graphs.

A. *Simulation Environment*

The proposed FDGF Routing is implemented using the NS-2 [1] simulator. This simulation environment includes full simulation of the IEEE 802.11 physical and MAC layers, which makes the simulation better reflects the real world.

In the simulation, we choose parameters according to Table I. A subset of nodes act as sources and another subset of nodes act as destinations, with each source node sends one and only one message to each destination node (other than the source node itself).

Table I
PARAMETERS OF THE SIMULATIONS.

Parameter	Value
Number of mobile nodes	50
Transmission range	250m
Data rate	1 Mbps
Simulation time	1700-11900 seconds
Link layer queue length	150
Topology size	1500m $\times$300m
Packet payload size	1000 bytes
Antenna model	OmniAntenna

For the simulation results, all numbers in all the figures are obtained as an average of 10 different runs with 10 different randomly generated network graphs. The confidence intervals for numbers are calculated at 95% confidence level.

B. *Face Routing Delay and Hop Comparison*

Face routing under local minimum weight spanning tree, Gabriel graph, relative neighbor graph and local Delaunay triangulation are implemented. Simulation results show that face routing using LDTG outperforms LMWST in both the delivery delay and the number of hop count. GG and RNG are in between LDTG and LMWST in terms of delivery delay and hop count. Delivery ratios using the proposed face routing strategy on all graphs are 100% guaranteed. Figure 5 and 6 are the face routing comparisons of delivery delay and hop count among LDTG, GG, RNG and LMWST graphs.

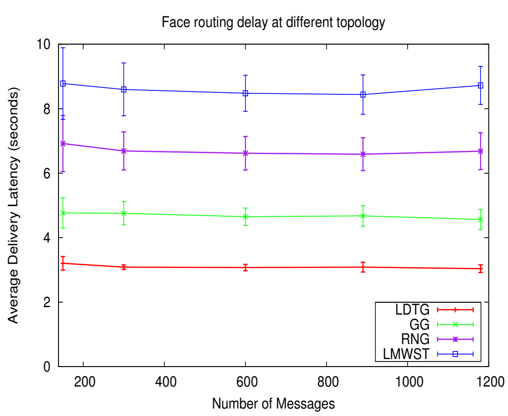

Figure 5. The graph of delay comparison

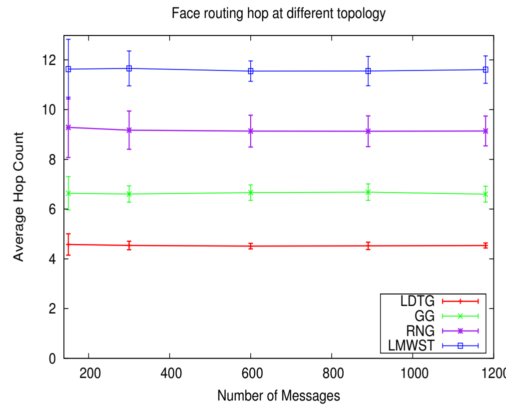

Figure 6. The graph of hop count comparison

C. *Face Routing Energy Comparison*

Although face routing delivery latency using LMWST is larger than the delivery latency of using RNG, GG and LDTG, the energy consumption using LMWST is less than that of the RNG, GG and LDTG when the propagation model is *Two Ray Ground* . We collect data and calculate the sum of path distance's fourth power, which is shown in Figure 7 below.

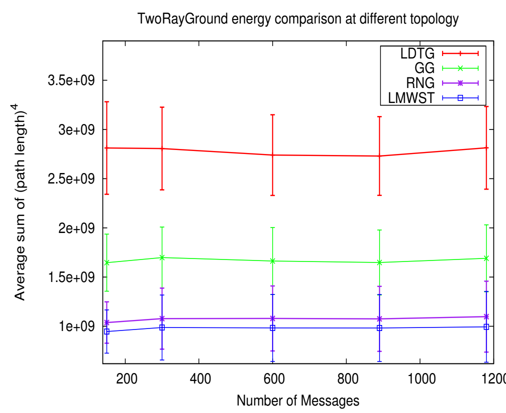

Figure 7. The graph of energy comparison (Two Ray Ground)

It is known that in the *Two Ray Ground* propagation model, the relation between the power used to transmit packets, P_t and the received power P_r can be characterized as

$$P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{1}$$

where G_t is the antenna gain of the transmitter, G_r is the antenna gain of the receiver, λ is the wave length, d is the distance between the antenna of the transmitter and that of the receiver, and L is the system loss, h_t is the antenna height of the transmitter and h_r is the antenna height of the receiver.

According to Equation 1 and Figure 7 it is clear that the minimum energy consumption for message transmission in LMWST is less than the minimum energy consumption in RNG, GG and LDTG if the propagation model is *Two Ray Ground* and if node radius could be adjusted properly after knowing the distance between two neighboring nodes.

When the propagation model is *Free Space*, it turns out that RNG performs best in terms of energy consumption. The results of energy comparisons are shown in Figure 8.

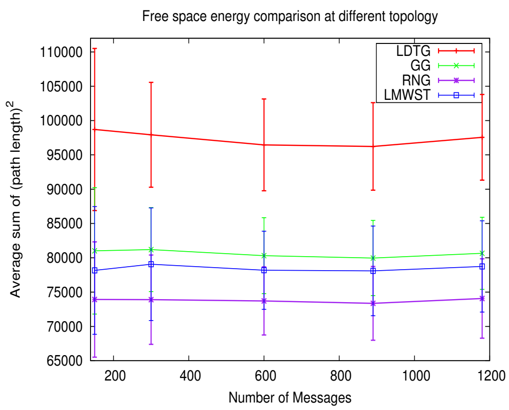

Figure 8. The graph of energy comparison (Free Space)

It is known that in the *Free Space* propagation model, the relation between the power used to transmit packets, P_t and the power received P_r can be characterized as

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L} \tag{2}$$

According to Equation 2 and Figure 8, it is clear that minimum energy consumption in LMWST is less than the minimum energy consumption in LDTG in *Free Space* propagation model if radius could be adjusted properly. And it turns out that RNG is the best in energy consumption out of the four local graphs.

Although LMWST is the graph with minimum total weight, it is not necessarily the best energy efficient graph when multiple source nodes and destination nodes are randomly selected, just as the case shown in the *Free Space* propagation model.

VI. Conclusions and Future Directions

In this paper, we first define k-local algorithm upon which k-LDTG and k-LMWST are obtained and properties of these two graphs are presented. Compared with existing definitions, our definitions are uniformly simplified and efficient.

After that, we propose a FDGF routing logic which accelerates and guarantees message delivery on UDG. Face routing is an important aspect of geographic routing in wireless ad hoc networks where nodes make routing decisions locally, which has been carefully studied in the last couple of years. However, the face routing energy consumption on different local routing graphs, including LDTG and LMWST, has never been compared before. In the paper, face routing properties, including delay as well as hop count and energy consumption on LDTG, GG, RNG and LMWST, are well examined. Simulation results show that FDGF routing on LDTG is the fastest. LMWST is the most energy efficient when propagation model is *Two Ray Ground*. Although RNG is easy to construct, face routing on this graph achieves desirable energy consumption attribute when propagation model is *Free Space*.

Although current face routing protocols usually assume reliable communication channels, it would be interesting if the routing logic could be extended to delay tolerant networks (DTN). How to properly apply face routing in DTN is within our future research direction.

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