Contention-based Georouting with Guaranteed Delivery, Minimal Communication Overhead, and Shorter Paths in Wireless Sensor Networks

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***Abstract*—Nodes in contention-based (beaconless) georouting forward packets towards a known destination position without the knowledge of the neighborhood. The only existing methods [17], [20] that guarantee delivery in unit disk graphs (UDG) require runtime planarization of the communication graph with either unbounded message overhead per hop while preserving the Gabriel graph property of the subgraph, or a constant overhead per hop with up to 13 control messages.**

In this paper we show that the next hop can be selected directly by a contention mechanism and without prior planarization. Existing greedy routing methods select the next hop with 3 messages using a RTS-CTS-DATA scheme in a timer-based contention where only the next hop neighbor responds. We extend this to provide also recovery from local minima with 3 messages per hop by the Rotational Sweep algorithm. We prove that our algorithm guarantees delivery in UDGs, and also yields routes that are shorter than or equal to the combined greedy and face routing with Gabriel graph planarization. Simulation results show that especially the duration of the contention process can be significantly reduced.

Our algorithm can be also used for conventional beacon-based routing with guaranteed delivery without prior planarization, replacing the complicated implementation from [19] by a very simple method which evaluates angular distances to select the proper forwarding neighbor. It also provides a simple network boundary detection algorithm, with or without beacons.

***Keywords*-Geographic Routing, Contention-based Forwarding, Wireless Networks**

I. Introduction

Wireless ad hoc and sensor networks consist of nodes that are equipped with very limited resources. They usually have a wireless transceiver with limited transmission range, restricted memory and processing capabilities, and limited energy resources. Even when relaxing such restrictions, a shared communication medium where a message by one node is received by all its neighbors dictates the design of algorithms with minimal communication overhead, to prevent message failures due to collisions. A lot of effort has been invested in developing topology control strategies and routing protocols in order to reduce communication overhead, guarantee message delivery, and reduce route lengths. In this paper we focus on contention-based (beaconless) geographic routing, a completely reactive approach for multi-hop communication in wireless ad hoc and sensor networks, that relies on position information and reduces the overhead for the exchange of topology and routing information to a minimum.

Existing contention-based georouting strategies are mainly greedy algorithms. The forwarding node, which currently holds the packet, issues a Request-to-send (RTS) announcing its location and the destination location, upon which its neighbors contend for becoming the next hop. The contention round is timer-based: the closer a neighbor to the destination, the shorter its timeout; thus, the neighbor closest to the destination answers first with a Clear-to-send (CTS) and obtains the data packet. Decisions are locally optimal, but local minima cannot be handled and require a separate *recovery* strategy.

Because of the problem of local minima, face routing [2] has become an established technique in geographic routing. It guides packets along the faces of the network communication graph and provides guaranteed delivery if this graph is planar. The planarity of the underlying graph is obtained by using local proximity graph constructions such as the Gabriel graph or relative neighborhood graphs (see Def. 1 and [16]). Long time it was believed that face routing is not possible by exchanging only messages between the forwarder and the next hop without knowing the neighborhood. This is indeed true for the classic face routing based on the construction of planar subgraphs as shown in [17], [20]. In this paper we show that it is not necessary to use these underlying proximity graphs and that a correct next hop of a boundary traversal can be selected by a contention mechanism. As byproduct we produce improvements even for conventional beacon-based georouting by simplifying recovery and constructing boundaries with a reduced or equal number of edges than boundaries of Gabriel subgraphs, and consequently recovery from local minima with fewer hops leading to overall shorter paths.

Our main contribution is a contention-based recovery algorithm that in conjunction with a contention-based greedy strategy allows completely reactive georouting without knowledge of the neighborhood. It has the following features:

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- proven delivery guarantee for the unit disk graph model (standard model where transmission ranges are assumed to be uniform and of constant radius r)
- no neighboring nodes other than the nodes on the message path are actively involved in communication
- RTS-CTS-DATA scheme with 3 messages per hop (no neighborhood discovery, no further control messages)
- shorter or equal hop count than face routing based on Gabriel graph planarization
- easy-to-implement algorithm for selecting the forwarding neighbor, based merely on a timer delay function.

Instead of letting each neighbor answer with a delay proportional to its *geographic* distance to the destination (greedy approach), our delay function is (for recovery phase) based on the distance to the forwarder d and the *angular* distance θ to the previous hop. This information is sufficient for ordering the forwarder's neighbors such that the first neighbor in this order is the correct next hop on a boundary traversal.

II. Related Work

A. Geographic routing

One of the earliest approaches in geographic routing is the *greedy method* [7] that makes locally optimal decisions to select next-hop neighbors with the goal to minimize the distance to the destination in each step. Greedy routing is very effective as long as there are no local minima, i.e. nodes that have no neighbor closer to the destination than themselves. Local minima can be observed at the boundary of void regions in the network. Such situations require a *recovery* strategy. One of the first strategies of this kind is face routing, which guarantees delivery and forms the basis of the well known GFG (greedy-face-greedy) algorithm [2]. Face routing performs a traversal of faces of the communication graph, i.e. a message is passed along the nodes incident to the face, while each edge is selected in counter-clockwise order w.r.t. the previous edge. Void regions in the networks are faces of the communication graph, thus a face traversal guides the message around such regions (see Fig. 1). Face traversals guarantee loop freedom and progress towards the destination as long as the graph is planar. Therefore, localized planarization strategies such as Gabriel graph (GG) [12] (Def. 1) and relative neighborhood graph (RNG) [16] constructions were developed along with these routing strategies. A detailed description of the building blocks of recovery strategies with proofs on delivery guarantees are presented in [10]. It is shown that using a planar graph is a sufficient condition to guarantee message delivery of GFG and some other geographic routing algorithms. Comprehensive overviews of planar graph routing and recovery strategies are given in [9], [3].

Recently Liu and Feng introduced an algorithm that uses a rolling-ball scheme to identify neighboring nodes which are part of a boundary traversal around a void region [19].

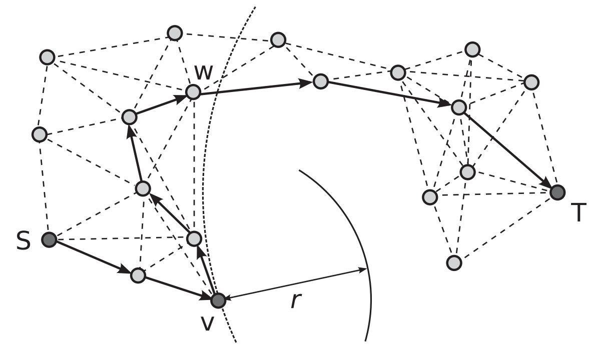


Figure 1. Combined greedy and face routing (GFG): Starting from node S, the message follows a greedy path until local minimum node v. After a recovery path that traverses the boundary of a Gabriel subgraph, greedy routing is resumed after node w.

Instead of identifying the adjacent nodes on a planar face, nodes determine the neighbors that are hit by rolling a ball around the node set. The resulting set of edges (node pairs) matches the definition of a so called α-shape (see Fig. 3 and Section II-C). The algorithm in [19] is quite complicated and needs the knowledge of the neighbors' locations as other conventional georouting algorithms. Our algorithm traverses the nodes on the α-shape as well, but with a different method, which does not need the a priori knowledge of the neighborhood (it is also applicable in beacon-based georouting). Moreover it is easier to implement, as the neighbor selection can be reduced to the evaluation of just one function. Proposed extensions in [19] such as short-cutting and probing packets, which identify whether a left-hand or right-hand traversal is a better choice after a local minimum, can be applied to many single-path georouting algorithms; therefore we do not discuss them here. Our proof of guaranteed delivery use similar arguments as in [19] and [10]. We repeat some arguments here for completeness. In addition we prove that our traversal paths are of the same length or even shorter than a face routing traversal on a Gabriel subgraph and explain why our algorithm has a better performance than the original face routing.

B. Contention-based georouting

In 2003 the first fully reactive geographic routing schemes were published independently by three groups and under the names beacon-less routing (BLR) [14], contention-based forwarding (CBF) [11], and implicit geographic forwarding (IGF) [1]. The basic idea behind these schemes is that the next hop can select itself using a contention-mechanism. First, the forwarder broadcasts a request to send (RTS) and the candidates start a timer. The timer depends on the advance a of the candidates, which is $a := |vT| - |wT|$, where v is the forwarder position, w the candidate, and T the target. The candidate with the largest advance has the shortest timeout. After the timer expires, the candidate answers with a CTS and immediately obtains the DATA message from the forwarder. Other nodes that overhear these messages stop their timers and cancel their scheduled responses. This way, the next hop is selected without knowing of or hearing from other neighbors.

For the greedy algorithm, the delay function t (as function of the advance) is defined as follows, based on the transmission range r, and the maximum timeout $t_{\max}$, which defines the length of the contention period:

$$t_{\text{greedy}}(a) = \frac{a}{r} \cdot t_{\max}.$$

Both r and $t_{\max}$ are considered fixed parameters.

In a previous work [17], [20] contention-based recovery methods were presented that determine the next hop of a planar subgraph traversal in a reactive way. The Angular Relaying algorithm uses a delay function that depends on the angle between previous hop, forwarder and next hop, such that the first hop in counter-clockwise order responds first. This node is not always a neighbor in the Gabriel subgraph, but the forwarder knows only previous hop and the candidate so far and cannot check the Gabriel condition without knowing other neighbors. Therefore, the neighbors that detect the violation of the Gabriel graph condition, answer with a protest message. These protests are again scheduled in counter-clockwise order such that a protesting node directly becomes the next hop candidate, unless there are further protests. This scheme is the first contention-based recovery algorithm that does not involve the complete neighborhood in the contention-process and guarantees delivery.

C. Boundary detection

The problem of identifying the boundary of a void region is similar to finding the convex hull of a point set. The main problem here is to identify nodes on the boundary which are connected by edges that do not intersect other edges between boundary nodes.

Fang et al. introduced the notion of 'stuck nodes' which identify themselves by a geometric criterion using the position information of the 1-hop neighborhood [6]. A node u is a (strongly) stuck node, if there is a location outside its transmission radius where none of u's 1-hop neighbors is closer to. However, this criterion does not forbid edge intersections, and these intersections cannot be removed by a localized algorithm (see Fig. 1).

In the 1980s Edelsbrunner et al. [5] introduced the notion of α-shapes and α-hulls, the latter being a generalization of the convex hull of a point set. For arbitrary negative α, the α-hull is the intersection of all closed complements of discs with radius $-1/\alpha$ such that the complement contains all points of S. Intuitively, the α-hull with a negative α contains everything which is not touched by a disc that is moved around the point set (see Fig. 3). An α-shape is the boundary which connects the points on the α-hull.

Our algorithm traverses the boundary of the network along the α-shape. It identifies such intersection-free boundary

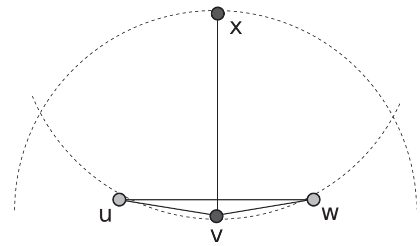


Figure 2. u and w are stuck nodes, but they cannot identify the edge intersection of (u, w) and (v, x) locally.

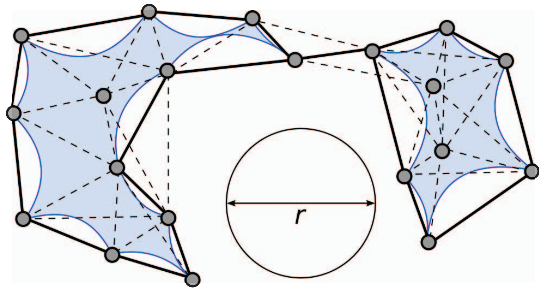


Figure 3. Unit disk graph with radius r, α-hull (shaded area) and α-shape (solid edges) with $\alpha = -\frac{2}{r}$ of a point set.

edges rather than constructing a local planar subgraph and can thus reduce the communication overhead.

III. The Rotational Sweep Boundary Traversal and Routing

The Rotational Sweep (RS) algorithm identifies the next hop in counter-clockwise order and generates (when applied by subsequent hops) a boundary traversal path along a void region. This serves as recovery from local minima and forms in conjunction with contention-based greedy forwarding the RS routing algorithm. Different particular ways of rotational sweeps lead to different recovery schemes, and here we describe a novel way.

A. The RS Boundary Traversal Algorithm

A contention-based sweep circle algorithm is the continuation of an idea proposed in [17], [20]. There, the sweep circle method was used to construct a Gabriel subgraph as part of the so-called Angular Relaying algorithm. This algorithm finds the next node on the boundary traversal of a void region by rotating a curve from the previous node to the next node. As it is not possible to directly determine Gabriel neighbors through the contention mechanism, this curve does not immediately select the desired neighbor, leading to a round of potential protest messages. The RS algorithm originates from the observation that the Gabriel graph planarization is in fact not necessary: the selected neighbor can actually be used as the next hop.

The RS algorithm is started by a local minimum node with direction toward destination T serving as the artificial

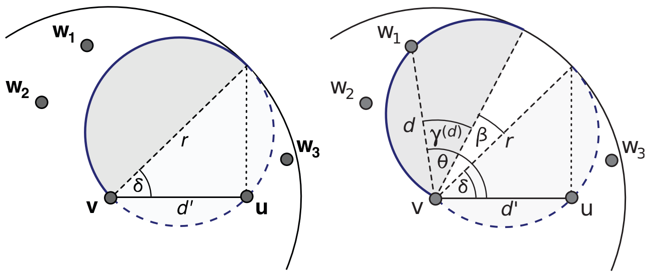


Figure 4. Sweep Circle starting at current node v with u as previous hop and δ being the start angle. The relative position of candidate w_1 is given by distance d and angle θ.

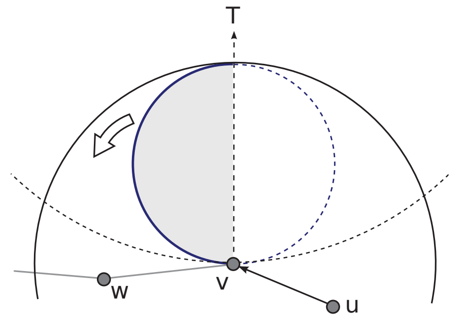


Figure 5. Initialization of the RS algorithm when starting the sweep at a local minimum node v.

previous hop (Figure 5) and initiates the next hop selection through a contention-mechanism, which works as follows. The forwarder broadcasts a RTS announcing its own position, the position of the previous hop, and the position of the packet destination. The neighboring nodes start a timer and respond with a CTS after timer expiry, unless the forwarder has stopped the contention or another has responded before. The timer delay for each neighbor is given by a delay function as described in the following sections. This delay function causes the neighboring nodes to schedule their responses in a specific order, which reflects more or less a counter-clockwise order starting from the previous hop. After the first neighbor answers with a CTS, the forwarder immediately sends the DATA packet. All other neighbors cancel their scheduled transmissions. Thus the message exchange of the RS algorithm is a RTS–CTS–DATA sequence. In a graphical representation, this timer mechanism works like rotating a sweep curve around the forwarder, where the curve indicates positions where the timer of possible nodes is currently expiring. Intuitively, in the graphical representation, the first node hit by the rotating sweep curve, is the one that answers first.

Our main contribution is the Rotational Sweep (RS) algorithm, which determines the next hop without leading to any protests. It has therefore a minimal communication overhead. Furthermore, it preserves guaranteed delivery and reduces the number of hops for recovery. Using a rotating sweep circle leads to a traversal of the α-shape, and forms in conjunction with a greedy strategy the combined RS routing algorithm.

B. Sweep Circle

The Sweep Circle (actually a semi-circle) is defined by a delay function which depends on two variables d and θ, where $d = |vw|$ and $\theta = \angle uvw$. The angle between the edge vw connecting forwarder and candidate and the diameter of the sweep circle is given by $\gamma(d) = \arccos(d/r)$, where r is the communication radius (Figure 4). The delay for the candidate w is proportional to the angle β between the diameter of the Sweep Circle and the start line. The start line depends on the location of the previous hop u and is defined by the angle $\delta = \arccos(d'/r)$, where $d' = |uv|$.

Given the start angle δ (provided by the forwarder), the candidate node w can calculate its delay based on its relative location by the following function:

$$t(d,\theta) = \frac{\beta}{2\pi} t_{\max}.$$

More precisely, it can be describes as:

$$t(d,\theta) = \begin{cases} \dfrac{\theta - \gamma(d) - \delta}{2\pi} t_{\max} & \text{if } \theta - \gamma(d) > \delta \\ \left(1 + \dfrac{\theta - \gamma(d) - \delta}{2\pi}\right) t_{\max} & \text{otherwise.} \end{cases}$$

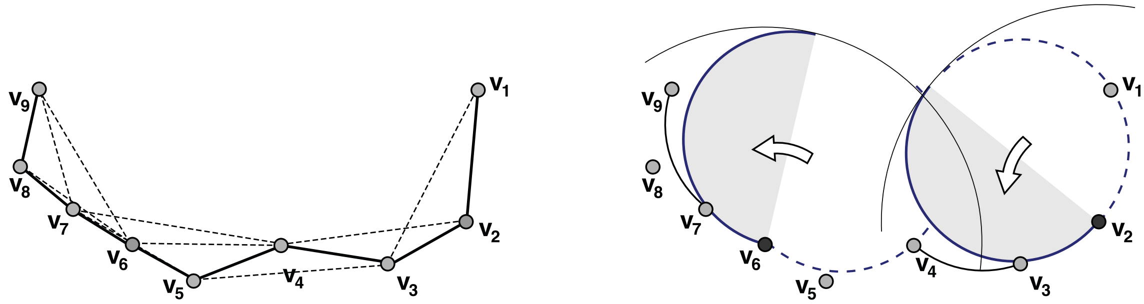
If the position of the candidate is behind the start position of the sweep circle, i.e. if $\theta - \gamma(d) < \delta$, then the delay would be negative. Instead, we let this candidate answer with a positive, but longer delay by adding $t_{\max}$.

When applied by subsequent nodes, the RS algorithm yields a boundary traversal of a void region. The traversal path of the sweep circle traversal is a subsequence of the Gabriel graph traversal as shown in Figure 6.

C. Combined RS routing

The combined RS routing is a combination of contention-based greedy forwarding and the RS algorithm (described in Subsection III-A) as a recovery strategy. The effective greedy forwarding is used whenever possible. In case of a local minimum, the RS algorithm traverses the boundary of a void region until greedy forwarding can be resumed. Table I shows pseudo code for the combined algorithm.

When the RS algorithm is started at a local minimum node, the destination node is assumed as previous hop (Figure 5). For a local minimum node v, the intersection of its transmission area and the circle around the destination node T with radius $|vT|$ is always empty. As $|vT|$ is always larger than the diameter of the Sweep Circle, the sweep curve always starts in an empty region with the Sweep Circle being empty, such that no node is skipped unintentionally.



(a) Unit disk graph of a point set and Gabriel subgraph (solid edges) (b) Sweep Circle Traversal

Figure 6. Unit disk graph and traversals. The boundary of the Gabriel subgraph contains all nodes $v_1, ..., v_9$. The Sweep Circle skips node v_5 and v_8 in this sequence.

IV. Guaranteed Delivery

Existing claims for guaranteed delivery localized routing are based on the unit disk graph model, where two nodes communicate if and only if the distance between them is at most r, the communication radius. We also use the same model in our analysis. The first thorough analysis of delivery guarantees of face routing and combined greedy/face routing has been presented in [10]. The proofs presented there rely on planar graphs and their structural properties. Therefore we can follow some proof ideas, but not use them directly for the RS algorithm. Furthermore we do not prove delivery guarantees for the RS algorithm on its own. This algorithm is meant to be used in combination with a greedy strategy. As an outline, we show that RS produces a closed curve along the boundary of a void region, which is not intersected by itself nor by any other edge that could lead to the target. This forms the foundation for showing that the destination node can be reached as long as the network is connected. The fact that the destination is indeed reached follows then by the progress criterion, which is applied here (and in most combined greedy/face routing algorithms in the literature).

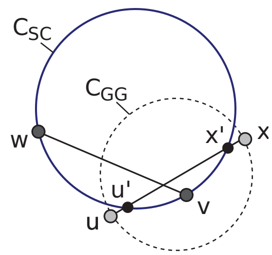
Definitions and preliminaries

We call the sequence of edges that results by applying the RS algorithm a *traversal path*. If not stated otherwise, the traversal is performed according to the right-hand rule (the next hop is found in counter-clockwise direction).

A Gabriel (sub)graph traversal is a right-hand traversal of a Gabriel subgraph. The Gabriel graph is defined as follows:

Definition 1: The *Gabriel graph* (GG) of a node set V contains an edge uv, iff $|uv|^2 \leq |uw|^2 + |vw|^2$ for all $w \in V$ and $w \neq u, v$.

In other words, GG contains an edge uv if the circle having uv as diameter is empty. The GG definition also applies to subgraphs of the unit disk graph; then all edges have an additional length restriction of at most r.



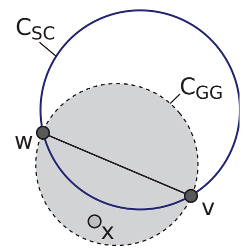


Figure 7. Illustration for Lemma 1 Figure 8. Illlustration for Lemma 2

Lemma 1: An edge vw of a Sweep Circle (SC) traversal path is never intersected by an edge ux of the Gabriel subgraph.

Proof: Let C_{SC} be the Sweep Circle with v and w on its perimeter, ux and edge of the Gabriel subgraph, and C_{GG} the Gabriel circle having ux as diameter (see Figure 7). Consider the quadrangle $wuvx$. Angles at w and v ($\angle uwx$ and $\angle uvx$) are smaller than $\pi/2$ since w and v are outside the circle C_{GG} due to the Gabriel graph condition. Suppose the edge ux intersects the circle C_{SC} in points u' and x'. The sum of the angles $\angle wu'v$ and $\angle wx'v$ is π. Then the sum of the angles $\angle wuv$ and $\angle wxv$ is then smaller than π. This means that the sum of all angles in the quadrangle $wuvx$ is smaller than 2π, which is a contradiction. ■

Lemma 2: Let S_{GG} be a sequence of nodes by a face traversal on a Gabriel subgraph. Let S_{SC} be the sequence of nodes obtained by the RS algorithm applied on the same nodes. Then $S_{\mathrm{SC}} \subseteq S_{\mathrm{GG}}$.

Proof: Let w be the next node in S_{SC} after node v. Then w and v are on the perimeter of the empty Sweep Circle C_{SC} with diameter r. Consider the Grabriel circle C_{GG} having vw as diameter (i.e. its radius is $\leq r$) as shown in Figure 8. There are no points above vw that are contained in both circles. Below vw there are two areas, one is their common intersection, which does not contain any point. There is another area which is in C_{GG} but not in C_{SC}. If in that area there is a node x then vw is not in the Gabriel subgraph but

The Combined RS Routing Algorithm
Variables: previous hop u, current node v, neighbor w, target T, first edge in recovery mode e_r and recovery distance d_r to target

Action of forwarder v
on reception of a data packet from node u

if packet in greedy mode
  send RTS[greedy, v] and wait for CTS by neighbor w
  (neighbor w calculates the delay w.r.t. the advance)
  if no such neighbor exists (i.e. on timeout $t_{\max}$)
    switch packet to recovery mode
    send RTS[recovery, t, v] and wait for CTS by neighbor w
    (neighbor w calculates the delay using the RS algorithm)
    store current distance to the destination d_r
      and $e_r \leftarrow (v, w)$ in the packet header
  endif
else (packet is in recovery mode)
  send RTS[recovery, u, v] and wait for CTS by neighbor w
  (neighbor w calculates the delay using the RS algorithm)
  if for w holds $||w - T|| < d_r$
    switch packet to greedy mode
  else
    if (v, w) equals the first edge e_r in recovery mode
      drop packet; return
    endif
  endif
endif
forward DATA packet to w

Action of candidate w
on reception of RTS[mode, u, v]

if mode = greedy
  $a = |vT| - |wT|$
  if $(a > 0)$
    wait $t_{\text{greedy}}(a)$ time steps (t as a function of the advance)
  else return
else (mode = recovery)
  wait for $t(|vw|, \angle uvw)$ time steps
endif
if no other candidate has responded before
  send CTS packet to v

Table I
THE COMBINED RS ROUTING ALGORITHM

there is a path from v via x to w in the Gabriel subgraph, and the SC traversal path containing the edge vw becomes a subsequence of the path along the Gabriel subgraph. The latter path cannot intersect vw by Lemma 1. If there is no such node x then vw is also in the Gabriel subgraph. ■

Corollary 1: The Sweep Circle traversal path is of the same length or shorter than a face traversal on a Gabriel subgraph.

Proof: This follows directly from Lemma 2. An example is shown in Figure 6. ■

Lemma 3: Let F be the face enclosed by an SC traversal path. Then there is no path from the boundary of F to the interior of F.

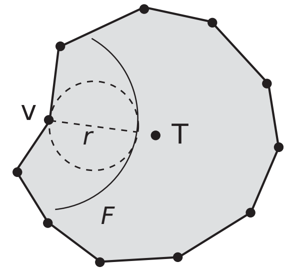


Figure 9. Illustration for Lemma 3. A node x in the interior of F is reachable from the boundary, if its distance to one of the boundary nodes is $< r$. But then it would become part of the traversal path and part of the boundary.

Proof: Assume that there is a node T in the interior of F (see Figure 9). The boundary nodes of F have an empty 'sweep area' around each boundary node v, which is determined by the intersection of empty circles with radius r having v on its boundary. Assume T can be reached from the boundary. As the boundary is not intersected, T must have a connection to a boundary node v, i.e. $|vT| < r$. But then T is in the 'sweep area', i.e. T would be touched by the Sweep Circle of radius r and thus become a part of the traversal path or part of the boundary. Note that similar proof is given in [19] (with their Fig. 2 as illustration). ■

Lemma 4: Let v and T be two nodes in a network graph that can reach each other and v a local minimum node. When starting the RS algorithm at v, the traversal path leads to a node v' with $|v'T| < |vT|$.

Proof: The traversal path is a closed polygon with T in its exterior. If T is in its interior, it would not be reachable (follows from Lemma 3). Imagine a circle around T with radius $|vT|$. The traversal path contains a node v' inside this circle, otherwise t would be in the interior of F and not reachable. Illustration is given in Figure 10. Similar argument is given in [19] (as part of their Theorem 2). ■

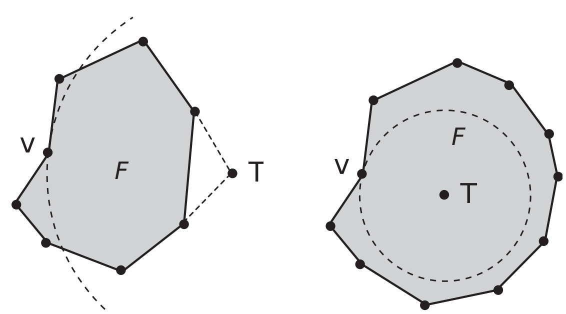


Figure 10. Illustration for Lemma 4.

Theorem 1: The combination of greedy forwarding and Rotational Sweep guarantees delivery in connected unit disk graphs.

Proof: Greedy forwarding and recovery by RS are used alternatingly. Each greedy step reduces the distance to the destination. In a local minimum, RS is started and the traversal path leads to a node that is closer to the destination than the local minimum node (Lemma 4). Greedy forwarding is resumed only if the next hop node is closer to the target than the local minimum node that started recovery (progress criterion). Thus in each step of this alternating greedy and recovery sequence the message gets closer to the destination. As the number of nodes in the network is finite, the message is finally delivered to the destination. ■

V. Simulations

For comparison with existing approaches we have selected the following algorithms:

BLR Request-response [15]: BLR is one of the three first contention-based greedy routing methods. It was complemented by a backup mode, also called request-response approach. In this mode, the forwarder broadcasts a request and *all* neighboring nodes respond. If a node is closer to the destination, it responds immediately and becomes the next hop. Otherwise the forwarder constructs a local planar subgraph (GG) from the position information of the neighbors and forwards the packet using the right-hand rule. The position when entering backup mode is stored in the packet. Greedy forwarding is resumed when a node is closer to the destination. BLR Request-Response is essentially a reactive beaconing, because all neighbors are involved the exchange of position information.

Angular Relaying [17], [20]: Angular Relaying (AR) is a *Select-and-Protest* algorithm proposed in a previous work and, to the best of our knowledge, the most efficient contention-based recovery algorithm so far. This algorithm determines possible neighbors of a Gabriel subgraph by a contention process using the sweep circle method. As Gabriel neighbors cannot be determined directly, it allows protests in a second phase to correct wrong decisions.

For all three algorithms (BLR, Angular Relaying and RS routing) we use the same greedy part, as we want to point out the differences in the efficiency of recovery. The greedy part uses an RTS-CTS scheme as described in the pseudo code in Table I.

We have performed simulations using a custom simulation environment for wireless networks based on the unit disk graph model. The transmission power is fixed for all nodes and chosen before starting the simulations such that the resulting network has a certain density (average number of neighbors). Nodes are placed randomly and uniformly in the simulation area. For the simulations we generated 100 random unit disk graphs with 100 nodes for network densities (i.e. avg. number of neighbors) ranging from 4 to 12. With density 4 the networks are quite sparse with local minima being more likely, and thus the recovery mode is used more often, whereas in networks with density 12 greedy routing

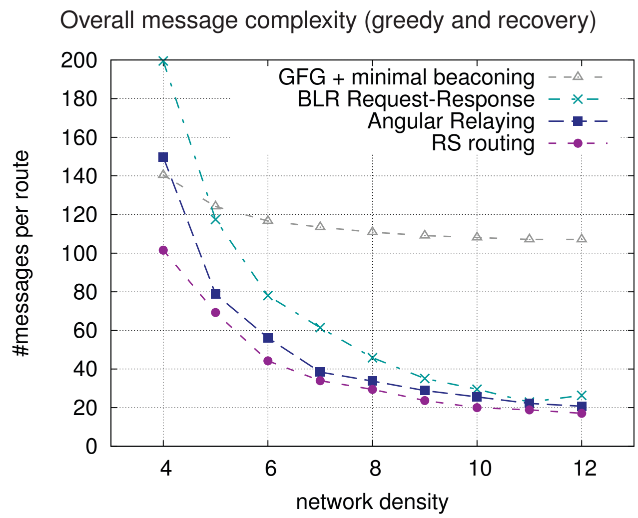


Figure 11. Overall message complexity (including greedy forwarding).

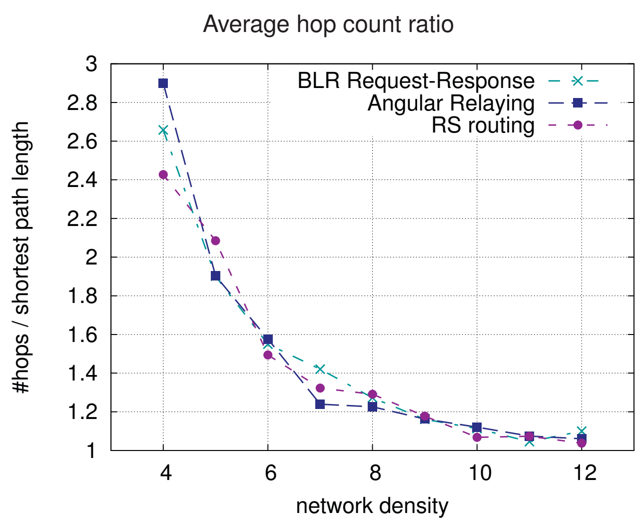


Figure 12. Path length efficiency: ratio of hop count and shortest path length.

almost always succeeds and the recovery mode is seldom used. For each random graph (or random node placement), a message is sent from the leftmost to the rightmost node using RS routing and the aforementioned algorithms. The greedy part is identically for each algorithm, the recovery is performed by BLR Request-response, Angular Relaying using sweep line and sweep curve, and the new RS routing.

In our simulations we are using a maximum contention timeout $t_{\max}$ that is long enough to avoid unwanted collisions between responding candidates. Collisions of control packets due to short contention timeouts are a general problem of contention-based strategies and already discussed in [20]. Without such collisions all messages could be delivered as long as the unit disk graph was connected.

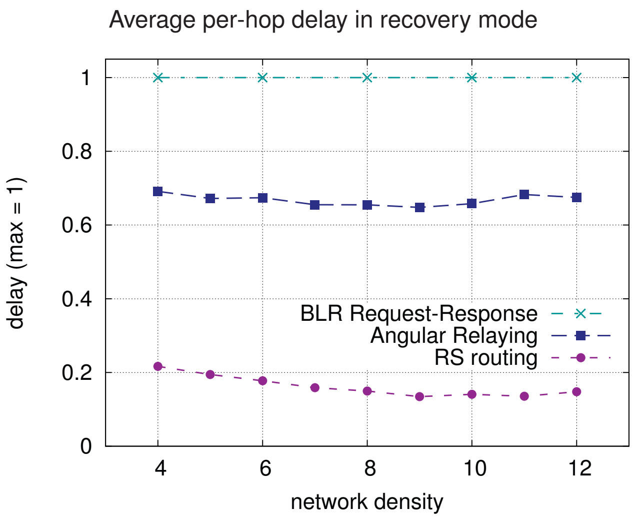


Figure 13. Per-hop delay in recovery mode (normalized).

Therefore, we can focus on the path length (hop count) and the message overhead. The path length of all three strategies is more or less the same. In certain cases the RS algorithm is able to skip some nodes that are used in Angular Relaying and BLR that are based on Gabriel graph traversals. But in random networks this gain seems to be within the normal variation (Figure 12). The most important improvement is the reduced per-hop delay: Here the RS algorithm could produce a reduction of around 70% compared to Angular Relaying and around 80% compared to the Request-response approach of BLR (Figure 13). BLR has to wait until all neighbors respond, which takes the whole contention period. In Angular Relaying the forwarder can select an appropriate candidate earlier, but has to wait for possible protests; in addition, Angular Relaying uses other start angles that cause a larger delay for a 'typical' next hop in recovery mode.

As RS routing always uses the RTS/CTS/DATA scheme with 3 messages per hop, a reduction of the message complexity is also visible (Fig. 11). By contrast, in BLR all neighbors have to respond in each routing step and in Angular Relaying at least a small overhead of protest messages is required.

Figure 11 shows also a comparison with a conventional (beacon-based) GFG algorithm, denoted as 'GFG + minimal beaconing'. Minimal beaconing means that every node in the network sends one beacon once to announce its position to its neighbors so that GFG can continue properly. The results show that for one or two routing tasks in a static network, a contention-based scheme is more efficient. Beacon-based algorithms save the RTS/CTS messaging which is advantageous in scenarios with higher load; but then, a contention-based scheme can possibly benefit from cached position data of the neighbors.

VI. Adaptation to Conventional (Beacon-Based) Georouting

The basic idea of the RS algorithm is ideally suited to be used in conventional (beacon-based) forwarding. In this case we assume that a node receives beacons by its neighbors, including their positions, and that it uses this data to maintain a neighbor table (including locations). The following algorithm can be used in conjunction with a greedy algorithm. It is started in a local minimum situation and repeated as long as no further progress towards the destination compared to the local minimum node is made.

After receiving a packet from node u in recovery mode, node v checks whether the recovery mode has to be continued. If this is the case, it determines the next hop by evaluating the following function t' for all its neighbors w. This function is a simplified form of the delay function given in Section III-B (with start angle $\delta = \arccos(d'/r)$, where $d' = |uv|$, $d = |vw|$ and $\theta = \angle uvw$ being the angular distance to the previous hop):

$$t'(d,\theta) = \begin{cases} \theta - \arccos(d/r) & \text{if } \theta - \arccos(d/r) > \delta \\ \theta - \arccos(d/r) + 2\pi & \text{otherwise.} \end{cases}$$

After evaluating this function, the neighbor with the minimum $t'(d,\theta)$ is selected as the next hop.

We note that Liu and Feng recently [19] described a beacon-based georouting algorithm based on a similar concept that produces the same hop sequence. However, going carefully through lengthy and technical details, we were not able to extract a simple algorithm as presented here.

VII. Conclusion

We have presented a new contention-based algorithm for geographic routing that works reactively and has guaranteed delivery. It requires no knowledge of the neighborhood and its distinctive property, compared to previous algorithms, is that no other nodes than the ones on the message path are actively involved in the communication. We proved that the resulting paths are of the same length or even shorter than the ones produced by face routing using the standard Gabriel graph planarization. This makes Gabriel graph planarization obsolete, regardless of whether the neighborhood is known (by beaconing) or not. The reason for the efficiency of RS routing is that for a boundary traversal just the next intersection-free edge has to be determined rather than identifying all neighbors of a planar subgraph.

In conventional beacon-based georouting algorithms, the Sweep Circle algorithm can be run solely by the forwarder without RTS/CTS and by using the knowledge of the neighborhood: For each entry in the neighbor list, the forwarder evaluates the delay function and finally selects the neighbor with the minimum value as the next hop. Shortcutting techniques [4] and distributed dominating set constructions [13] can be applied to further reduce the hop count especially in dense networks.

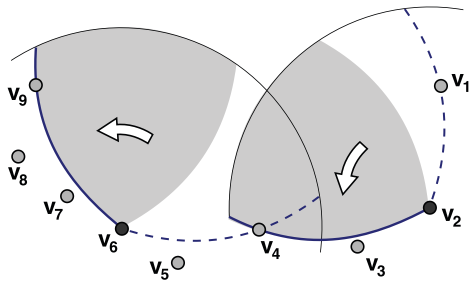


Figure 14. Rotational Sweep using the edge of a Reuleaux triangle.

The RS algorithm with its present delay function leaves some room for further optimizations. For example, by using the edge of a Reuleaux triangle (a triangle formed by the intersection of three circles placed on an equilateral unit triangle) as a sweep curve, as depicted in Fig. 14, one can expect a further reduction of the number of hops. We will elaborate on this approach in our continuation of this work.

The presented RS algorithm solves the problem of reactive recovery for contention-based or beaconless routing algorithms. This gives new impulses to the application of contention-based strategies in non-ideal networks (non-uniform transmission radii and lossy links) where loop detection, traversal-based recovery, or virtual node routing [18] might use the technique presented here. Our technique also gives a strategy that can be applied in real sensor networks, where positions of sensors are recorded as part of their deployment. It might also influence the search for reactive network spanner constructions [8].

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