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Geographic Routing With Minimal Local Geometry

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Abstract—Geographic routing based on virtual coordinates has been studied extensively, especially in environments expensive localization techniques are infeasible. Even though, the construction of virtual coordinate system is theoretically understood, their practical deployment is questionable due to computational requirements. An alternative approach is to use raw range measures from a special set of nodes called “anchors” as virtual coordinates, which only preserve partial geographic knowledge. In this paper we follow a similar approach, but focus on answering the question “what are the minimal geometric primitives required to perform geometric routing?”. We take the first step towards answering this question, based on a node centric local geometric view of localized nodes. We define local geometric primitives and show that geographic face routing can be performed with those primitives.

Index Terms—Wireless ad-hoc routing, Geographic Routing, Localization, Virtual Coordinates, Geometric Primitives

I. INTRODUCTION

Geographic routing is a routing paradigm proposed for wireless ad-hoc networks, which are capable of geographically locating nodes in the network [1], [2]. This approach is promising due to its scalability and efficiency in the face of network dynamics, compared to the on-demand routing schemes proposed for wireless ad-hoc networks. Even though its seminal work on geographic routing focused on one-to-one routing, subsequent proposals on routing schemes like multicast [3] were proposed later. Further more geographic aware mechanisms are used to build higher level communication abstractions like geographic hash tables, following a data centric approach.

Geographic routing relies on geographic information of nodes in the network. Therefore it should be supported by an auxiliary localization service. Localization is an independent problem, which was extensively studied, especially for the networks where expensive localization methods are not feasible. Thus most of the localization schemes assume that, only a small number of nodes (referred as beacons or anchors) know their exact geographic location information and they propagate this information so that the rest of the nodes can derive their geographic information with certain geometric computations. Alternatively some other schemes localize nodes purely based on connectivity information (neighborhood) available to the nodes.

Virtual coordinate based localization is an approach which deviates from both these approaches. It suggests to derive a virtual coordinate system which corresponds with the physical space. Virtual coordinate systems can be categorized as either topological or metric based. Topological virtual coordinates use topology information and arrive on a virtual coordinate

space, without any geometric correspondence with the physical space. Contrarily metric based systems derive virtual coordinate systems which bare correspondence with the physical space.

In this paper, we present key geometric constructs required to perform geographic routing when minimal geometric knowledge is locally available. In other words we rely on a virtual coordinate system which uses raw distance measures as coordinates, rather than using localization techniques like trilateration.

II. BACKGROUND

A. Geographic Routing

Compass routing [4] was the first geographic routing algorithm proposed for the broader context of geometric networks. Conceptually this scheme is considered to be a local routing scheme, since it does not need to keep any routing information other than its one-hop neighborhood. It performs a “greedy” selection on its next hop in a point to point routing scenario, based on the angle towards the destination, hence called compass routing. GPSR/GFG are the first notable geographic routing schemes which promise delivery inaugurates, specifically in the context of wireless ad-hoc networks. Both these approaches initially continue with forwarding the point to point traffic to the geographically closest neighbor to the destination. Subsequently they suggest *face routing*, when greedy forwarding hits a dead end (local minima). “sentence on face routing extensions”. In [5], they further studied and reports a comprehensive analysis of delivery guarantees in all the well established face routing schemes, based on planarity sub graphs. Furthermore it provides an insight into the required geometric properties of the underlying planar sub graphs.

B. Localization

Even though localization is assumed by all geographic routing algorithms, making nodes available with location information is not straight forward in environments like wireless sensor networks. WSNs are equipped with tiny embedded devices with limited processing and communication capabilities, which are powered by limited energy sources. Therefore, localization in these devices is always not trivial due to their intrinsic resource constraints. For instance, localization based on globally adopted technologies like Global Positioning System (GPS) has not become a viable candidate for WSNs. On the other hand due to extreme nature of these networks and the large number of nodes in a deployment, it is not possible to statically assign locations for each node in the network. A typical solution is to equip small number of devices (so called

anchor nodes) with location information (with GPS or with other locating mechanism), and let the rest of the nodes (non-anchor nodes) to derive their location. In order to calculate their position, non-anchor nodes have to measure the distances from anchor nodes (from minimum of three anchors in a two dimensional surface) and utilize basic algebraic principles to arrive on their coordinates. This is called *trilateration* in the literature, while measurements from more than three anchors are used to get more accurate positions in the presence of erroneous range measures, which is called *multilateration*.

C. Virtual Coordinate Systems

A rather different direction of localization research is to localize nodes with a virtual coordinate systems (VCS), which is different from the Euclidean system. VCS, as opposed to real coordinates are desirable in some applications, which only need to preserve topological structure rather than their exact geographic locations. Geographic routing is one such application of this nature. Rao et.al proposed a mechanism to assign synthetic coordinates to perform geographic routing, commonly referred to as NoGeo [6]. NoGeo computes an embedding of the network on the Euclidean space, starting from an initial coordinate assignment at each node. It models the coordinate assignment problem as a mass-spring model and performs an iterative relaxation algorithm to achieve an approximation of the optimum coordinate assignment. Shang et.al have incorporated inter distances between nodes into the coordinate construction problem, hence to compute an embedding of the network preserving the topological structure of the network [7]. The problem formulation was based on a technique borrowed from psychometrics called multi dimensional scaling and based on an iterative approach. These virtual coordinate systems does not to bare any correspondence with their geographic coordinates in the Euclidean space. Therefore on these coordinate systems, it is not possible to perform operations which resemble geometric relationships with the physical topology. Specifically when considering geographic routing, face routing as a local minima recovery scheme is not a candidate, thus failing to provide delivery guarantees.

D. Virtual Raw Anchor Coordinates

Even though virtual coordinate systems offer sound grounding to the localization problem, in a more realistic setting their applicability is questionable. This is mainly due to most of these mechanisms being iterative in nature, making them impractical for large networks. Additionally individual nodes would be computationally burdened with the numerical calculations involved in such algorithms. Identifying these discrepancies, [8] and [9] have independently proposed a virtual coordinate scheme relying only on the raw measures from anchor nodes. Both these mechanisms assign nodes their coordinates, simply as a hop-count vector from the anchors. Therefore this mechanism does not demand any further computational manipulations as in virtual coordinate construction schemes. It is similar to VCS, as it does not physically related to the geographic locations. Huc et.al have

studied its physically consistent counter part with raw distances from anchors as the coordinates; VRAC [10]. Further more they have proposed a combinatorial approach to planarity a network, localized with raw anchor coordinates.

E. Minimal Geometry for Geographic Routing

In this paper we emphasis that, non of the virtual coordinate system approaches do not construct coordinates, which correspond to their physical locations. Therefore important geometric routing notions like face routing are not able to perform on virtual coordinates studied up to now. In this respect we further state that, topological structure of a virtual coordinate space which consists minimal geometry for geographic routing is to be understood, while we take the first step forward.

III. VIRTUAL LOCAL GEOMETRY

In this section we present a virtual coordinate system and the associated geometric concepts. We follow a node centric approach and define local geometric constructs in order to be utilized in geographic routing.

A. Raw distance measurements as virtual coordinates

Virtual Raw Anchor Coordinate system (VRAC), which was introduced in [10], assigns coordinates based on the raw distance measurements from anchor nodes. Use of raw distance measures as its coordinates alleviate several problems associated with other localization schemes like trilateration. Most importantly it is the cheapest possible way to assign coordinates to the nodes, since no further processing is needed when the raw distances are obtained. Furthermore it does not propagate raw measurement errors as there is no further processing takes place.

Without loss of generality, VRAC can be considered as a mapping between the physical space (either three or two dimensional) and a n dimensional virtual space, where n is the number of nodes which serve as anchors. Anchor nodes are pre-configured and know that they serve as anchors. Both anchor nodes and non-anchor nodes are able to estimate the distances between nodes. Anchor nodes either know their geographic location or not depending on the application requirement. In both cases they preserve the topology and the physical correspondence, hence local geometric notions can be defined. As the first attempt to understand the nature of the problem, we assumes that nodes locate inside the convex triangle formed by the anchors and distributed on a two dimensional surface. According to the definition, VRAC is a multi dimensional coordinate system (depends on the number of anchor nodes), which can represent the physical space of three dimensions, but in this paper, we focus on two dimensional case as most of the routing algorithms are well established and evaluated for such networks.

Coordinate construction is simple and does not need any further processing once the distances estimated from the anchor nodes are available. Figure 1, illustrates an example coordinate assignment, where the distances formed into a vector serves as the coordinate of a node. Note that we adopt a slightly varied version of the original VRAC system, where

we derive the perpendicular distance from the edges of the bounding triangle as depicted in Figure 1. The three components of a VRAC coordinate is denoted as x, y, z representing a coordinate of a given node as (x, y, z) . There are several properties, which make this coordinate system different from the euclidean coordinate system. Most importantly it is not possible to define an unique origin (zero vector in vector space terminology) not adhering to the fundamental properties of algebra. As a result, the notion of distance and angle is not implicit in this coordinate system as in the Euclidean system. We take an alternative approach to define required geometric concepts in the presence of partial geographic knowledge. In the next section we present a construction of local geometric view of a node and how it corresponds with the global geometry of the network.

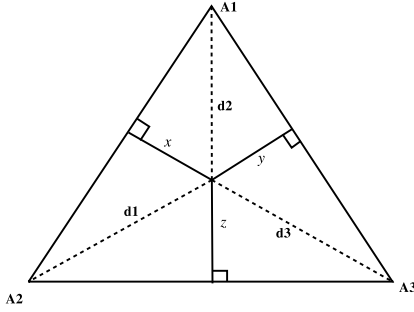


Fig. 1: Coordinate assignment in VRAC; it uses the raw distances d_1, d_2 and d_3 and calculates x, y and z , which is assigned as the coordinate

B. Local Geometric View of VRAC Nodes

In order to tackle described deviations from standard euclidean geometry and algebraic concepts, we consider a local view point of a node. Therefore it can be stated that, our approach is *node centric* in contrary to the euclidean space which is build upon the central definitions. Our aim is to define the notion of an angle (hence rotation) based on the local view of the space. As illustrated in Figure 2, a node divides the physical space into six sectors based on its coordinate value. Sectors are numbered according to the Figure 2, and two of the components of the coordinate happen to be the borders of the sector.

Drawing a similar analogy with the Euclidean space, we treat those two components as axes. In order to incorporate the notion of direction, we define the left borders of a sector as follows. Due to the symmetry of the sector definition of right borders are trivial.

$$\text{border left}(u, \text{sector}) = \begin{cases} x, & \text{if sector} = 1 \text{ or } 4. \\ y, & \text{if sector} = 2 \text{ or } 5. \\ z, & \text{if sector} = 3 \text{ or } 6. \end{cases} \quad (1)$$

A sector preserves some important Euclidean geometric relationships, which are crucial in bridging the two spaces. We exploit these similarities and define the following geometric primitives.

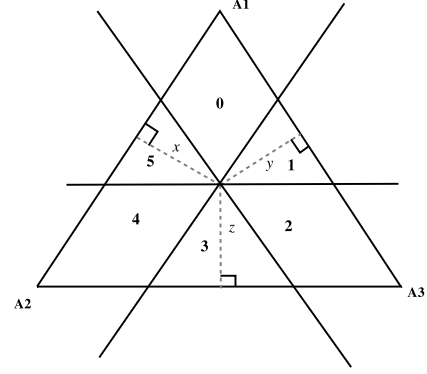


Fig. 2: Sectors are numbered from 0 to 6 and the sector borders are implicitly defined

1) *Sector Gradient*: Consider any sector s of a given node $u = (x_u, y_u, z_u)$ and a neighboring node $v = (x_v, y_v, z_v)$ lying in the same sector. We observe that any point on the line connecting u and v (extended edge), can be represented by a unique ratio, namely the *sector gradient*. Sector gradient is a similar notion to the gradient of a line in the euclidean space, but only valid with in a given sector. We formally define the sector gradient of a line, as follows.

$$\text{Gradient}(u, v) = \frac{\text{border left}(u, s) - \text{border left}(v, s)}{\text{border right}(u, s) - \text{border right}(v, s)} \quad (2)$$

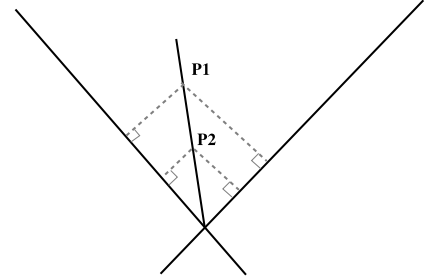


Fig. 3: Concept of gradient which is due to the equi faced triangle properties observed in the triangles along the line

This geometrically represents the ratio between the differences from sector borders at a given point on a line, as illustrated in Figure 3. Sector gradient can only represents a line passes through the origin of the sector (node it self of concern). Similar to the analogous euclidean notion of the gradient, sector gradient has a correspondence with the rising angle from the left sector border and a given line. This relationship is used to make the comparison between two angles created by two different nodes with in a given sector.

2) *Sector Angle*: Comparing the angle between two or more network edges is an important geometric primitive, in the geographic routing context. Even though sector angle provides a sector dependent notion of the angle, it is not sufficient to compare two angles. This is due to the non orthogonal shape of the sectors, as opposed to the orthogonal Euclidean space.

Consider another neighboring node w in the sector of the node u . In order to make $u - v$ line and $u - w$ line (edges in

the network) comparable, we project the node w onto the line segment $u-v$. Trivial geometric relationships can be used to calculate the projection of w on to line segment $u-v$ is defined as below.

$$\text{Projection}(w, u, v) = \text{Sector Gradient}(u, v) \times \text{border left}(u, s) - \text{border left}(w, s) \quad (3)$$

Once the value of the projection is calculated, considering the sector gradient of $u-v$ and the value of $\text{right}(v)$, rising angle of the two edges $u-v$ and $u-w$ can be compared. Algorithm 1 illustrates the angle comparison within a sector.

Data: u, v, w

Result: Node which makes the biggest angle with the sector border

```

 $p = \text{Projeccion}(w, u, v);$ 
if  $p > \text{border right}(w, s) - \text{border right}(u, s)$  then
  | return  $v$ ;
else
  | return  $w$ ;
end

```

Algorithm 1: Comparison of angles within a sector

3) *Clockwise/Counter-clockwise Rotation:* Rotation about a given edge in the network is a fundamental operation used in geographic routing. Once the comparison between two or more angles is defined as above, it is possible to construct an algorithm for rotation about an edge. Rotation algorithm uses the pre-defined sector numbering scheme and angle comparison algorithm. Ideally a node starts rotation algorithm about a given edge, and recursively searches for the first incident edge clockwise or counter-clockwise as required. Due to the symmetry of the geometry utilized in the derivation, it is easy to flip the direction of the rotation. Rotation algorithm is illustrated in Algorithm 2.

Data: u, v

Result: First edge towards the clockwise direction

```

 $N = \text{Neighbors in the sector of } v;$ 
for each node in  $N$ ;
   $n = \text{node locates with the smallest angle //Algorithm 1};$ 
if  $n \neq \text{NULL}$  then
  | return  $n$ 
else
  | return
  |  $n = \text{Recursively call Algorithm 1 on sectors}$ 
end

```

Algorithm 2: Rotation clockwise/counter-clockwise

Proposition suggests that two line segments get intersected, when the two line segment end points do not locate in the same side of the other line segment. We illustrate this proposition in Figure 4. In order to detect whether the two points are in the same side of a line segment or not, we define the Algorithm 3. It initially attempt to determine this by sector numbers if the two points are not in the same sector, while the two points are in the same sector it uses the sector gradients of edges.

4) *Line Segment Intersection:* Detecting line segment intersection is often performed in geometric algorithms for various reasons. We construct a line segment detection

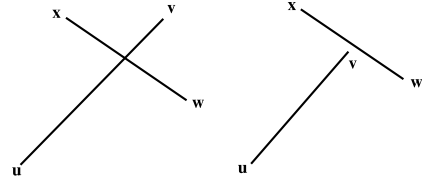


Fig. 4: Detection of intersection of line segments

algorithm based on the geometric concepts defined so far. More specifically, we utilize a classical proposition in geometry to decide the intersection.

Data: u, v, w, x

Result: True or False

```

if  $w, x$  in intersecting sectors compared to  $u, v$  then
  if  $u, v$  in intersecting sectors compared to  $w, x$ 
  then
    | return TRUE
  else
    | return FALSE
  end
else
  if  $w, x$  in same sector as  $v$  then
    if  $\text{Algorithm1}(v, w)$  AND  $\text{Algorithm1}(v, x)$ 
    then
      | return TRUE
    else
      | return FALSE
    end
  else
    end
  end
end

```

Algorithm 3: Check Intersection

IV. ROUTING WITH VIRTUAL LOCAL GEOMETRY

In this section we utilize the local geometric constructs defined in previous section in geographic routing algorithms. In general, point to point geographic routing algorithms operate in two phases; forwarding greedily and avoiding local minima (routing voids), when greedy forwarding is not able to proceed further. Face routing proposed in [1] and [2], is a delivery guaranteed mechanism to recover from routing voids, which employs right/left hand rule on a planarized subgraph. In this section we show that with local geometry defined in VRAC, it is possible to perform necessary and sufficient geometric operations in order to perform geometric face routing guaranteeing the delivery of point to point traffic.

A. Greedy Forwarding

Greedy forwarding is a simple forwarding mechanism, where it sends the packet to the closest neighbor to the destination. As VRAC is a non-metric space, defining a metric to perform greedy forwarding (i.e to find the closest neighbor to the destination) is not trivial. In order to overcome this limitation, we defined a greedy region based on the local geometric knowledge of a node as depicted in the Figure 5. In

greedy forwarding, it maintains a progress condition based on the geographic distance towards the destination, similarly we use this greedy region which progressively shrinks and hence ultimately lead to arrive at the destination.

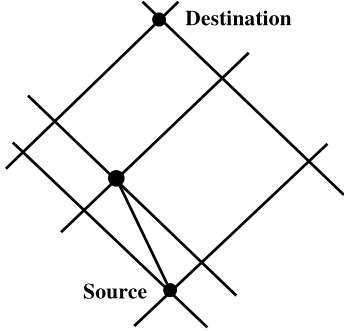


Fig. 5: Greedy region based on the local geometric view of a node

In order to define the greedy region a node identifies the sector where the destination resides according to it. Since a node has the coordinate of the destination node during a routing session, it identifies the sector of it self according to the destination node. We define the intersecting region of those two sectors as the greedy region. hence a node looks for greedy neighbors in this region. As shown in the Figure 5, if there are nodes in this region, progressing in this manner will shrink the region and eventually reach the destination. Since a node does not forward the packet to the closest neighbor, this approach differs from standard greedy forwarding. We analyze the difference based on our simulation environment and which is presented in Section V.

B. Face Routing

We consider face routing on a planarized sub graphs. Distributed planarization on VRAC was proposed in [11], is used as the planarization algorithm, as VRAC explicitly consists of necessary geometric properties. Face traversal performed with the classical right/left hand rule, where a node rotates according to the rule and finds the first neighbor clockwise or counter clockwise. In addition to the face traversal, face changes should be performed accordingly. While there are several variants of the face changing criteria, all of them checks whether whether the face traversal intersects with the connecting line between current local minima and the destination. We use the defined geometric concepts to implement the face routing algorithm proposed in GFG, which is proven its delivery grantees in an arbitrary graph. Face routing algorithm is illustrated in Algorithm 4. It uses the rotation algorithm to search its neighbors clockwise or counter-clockwise and check for intersections based on the Algorithm 3. If it detects an intersection, following the GFG algorithm it changes the rotation direction accordingly.

Data: *current, previous, localmin, destination, direction*

Result: Next hop

if *current* $\neq$ *localmin* **then**

repeat

 | *n* = Rotate(*current*, *previous*)

until Check Intersection(*n*, *localmin*, *destination*) ;

 Intersection detected, changing the rotation direction

 Face

 Routing(*current*, *previous*, *localmin*, *dest*, *opposite*)

else

end

Algorithm 4: Face routing utilizing local geometric properties

V. ROUTING PERFORMANCE EVALUATION

In this section we evaluate geographic routing performance over VRAC system. Evaluation is done in a simulation environment, which purely focuses on routing algorithms, while ideal radio characteristics and link layer complexities are abstracted. We consider greedy and face routing phases separately and compare them with geographic routing done over Euclidean coordinates. An important point is that, our approach differs from geographic routing over Euclidean coordinates only in the greedy phase, as described in earlier sections. As proved earlier with the local geometric primitives, on VRAC system it is possible to perform face routing algorithms exactly as in the Euclidean coordinate system. Therefore to compare the overall performance, we analyze a metric called *stretch factor* which is commonly used in performance analysis of geographic routing. Stretch factor represents the ratio between the number of hops required by the geographic routing over the shortest path from the source to the destination node. Further more to illustrate face routing behavior on VRAC system and Euclidean coordinates, we present two example simulation outputs.

A. Stretch factor

We perform simulations varying the node density within an area of 400X400. Radio ranges of nodes are set to be 50 units and nodes are spread uniformly throughout the area. Shortest path is found between two randomly selected source and destination nodes in the randomly deployed topology using the Dijkstra's algorithm in a centralized manner.

B. Face routing

In order to demonstrate the performance of face routing over VRAC is exactly same as in the Euclidean space, we present two examples of face routing when the node density is 1/1600 nodes per unit area. We perform only face routing to highlight that both approaches follow exactly the same path towards the destination. Figure 7 shows an outer face traversal until it reaches the destination while Figure 8 shows a face traversal through an inner face of the graph with face switchings taking place.

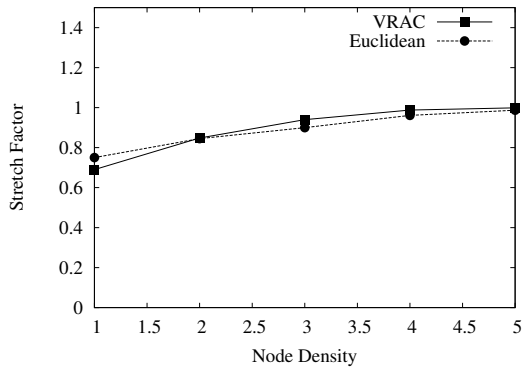


Fig. 6: Stretch factor vs node density for VRAC and Euclidean coordinate systems

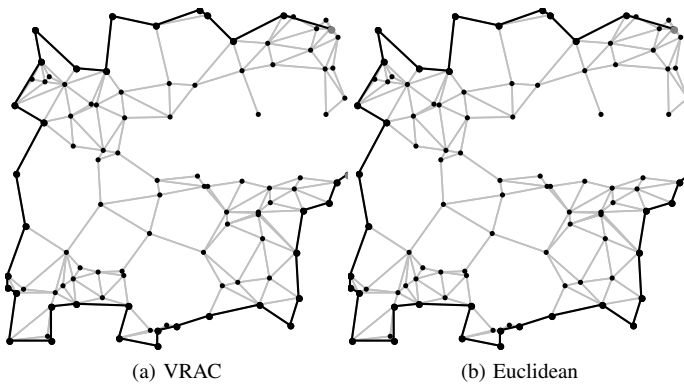


Fig. 7: Face routing along the outer face of the graph

VI. CONCLUSIONS AND FUTURE WORK

In this paper we outline a new direction of research in the context of virtual coordinate based geographic routing. Most of the current work on virtual coordinates calculates a graph embedding on the Euclidean space, which should follow an iterative mechanism. Therefore none of the virtual coordinate systems have not succeeded in practice. A relatively straight forward idea is to use raw distance measures from pre configured anchor nodes as coordinates, which does not require any further processing. It only maintains partial geographic knowledge and hence performing classical geometric operations poses a challenge. Our main contribution is to take the first step towards answering the question "what is the minimal geometric knowledge needed to perform geometric routing?". In order to tackle the question, we propose a node centric mechanism and define local geometric concepts associated with it. These constructs are carefully constructed such that they bare a correspondance to the physical geometric structure of the network. We apply these constructs to implement face routing variant adopted by GFG scheme.

In order to understand the problems associated, we took a simple approach and hence simplified the problem. For example we only consider routing within a convex triangle of anchors. Most importantly our on-going work relies on analyzing these local geometric concepts in the presence of noisy range measurements. Therefore we are yet to identify

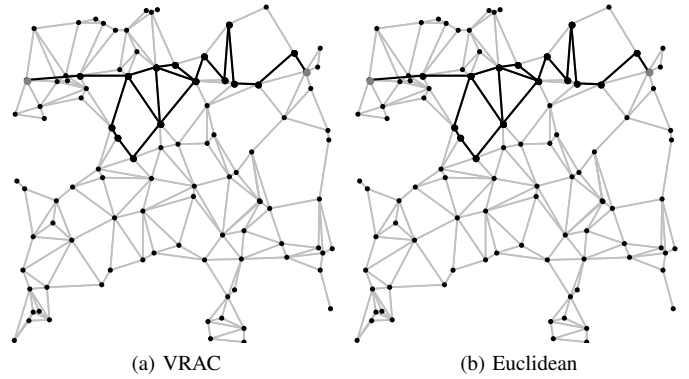


Fig. 8: Face routing along an inner face of the graph

how well these geometric primitive perform in the presence of errors. Once the effect of errors are identified, implementing a localization protocol in real wireless environment would be a possible future work.

VII. ACKNOWLEDGEMENT

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