An Alpha-Shapes based Technique for Detecting Boundaries of a Wireless Sensor Network

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ABSTRACT
Nodes along the boundaries of a Wireless Sensor Network (WSN) play some other important roles in addition to their routine tasks. A prior knowledge of the WSN boundaries can effectively be utilized in numerous WSN aspects pertaining to mobile events, mobile nodes, geographic routing, shape and coverage maintenance, barrier coverage etc. In this paper, we present a localized method based on actual connectivity graph and nodes' locations to detect the boundaries of a WSN. The proposed scheme does not make any idealistic assumption like Unit Disk Graph (UDG) model, uniform node deployment, or specific node degrees. The method is based on the idea of alpha-shapes – geometric structures used to capture the shapes formed by a set of points in space. With an appropriate value of alpha, alpha-shapes capture the meaningful boundaries of a point cloud. The value for the parameter alpha is computed locally by each node as $\sqrt{2}/d$ where d is the distance between the node and its farthest neighbor. The analytical and simulated results show the robustness of the proposed scheme under dynamic network conditions.

General Terms
Wireless Sensor Network

Keywords
Wireless sensor network, alpha-shape, boundary detection

1. INTRODUCTION
A Wireless Sensor Network (WSN) is an ad-hoc wireless network formed by a multitude of nodes called sensor nodes, each equipped with microcontroller, sensors, short-range RF-transceiver, and powered by on-board limited energy supply [1]. Sensor nodes are unobtrusively deployed inside or near some phenomenon of interest and tasked to collaboratively gather relevant sensory data like temperature, pressure, humidity, light, sound etc. The sensory data gathered by the nodes is routed over multiple hops to a specially designated node called a sink node that acts as a gateway between the WSN and the end-user space. This emerging data acquisition paradigm is envisaged as a potential enabler for many applications. Some of the major application areas of WSNs are [7]: surveillance, environment monitoring, habitat monitoring, smart buildings, structural health monitoring, facility management, industrial process automation, precision agriculture, health-care, logistics, critical infrastructure protection, disaster relief etc.

The nodes along the boundaries of a WSN are tasked with a few other important roles in addition to their normal role of sensing and communication. Various factors for extra importance of these nodes are: i) boundary nodes capture the map that represents significant features of the underlying environment like obstacles, buildings, terrain variations, physical boundaries etc., ii) nodes along the exterior boundary enable the detection of entry and exit events of a moving target in a barrier coverage, iii) interior boundaries provides a good approximation of the general health of the WSN in terms of sensing and connectivity coverage, iv) nodes on the boundaries are considered to be most suitable beacons for virtual coordinate constructions, and v) interior boundaries bound the routing voids present in the network. A prior knowledge of boundary nodes can be utilized in a number of ways in various WSN applications.

1.1 Importance of WSN boundaries
Interior boundaries may denote clusters of failed nodes due to power depletion, external attack, or physical destruction caused by events like fire or structure collapse etc. [18]; and indicate the deployment of additional nodes.

The dead-end situation in greedy forwarding is also attributable to concave formations at the boundaries of the network [5]. A prior knowledge about the boundaries can enable geographic routing to avoid or recover from dead-end situations.

The intrusion detection and target tracking applications are more interested in the entry and exit events [4, 6] of an intruder through the boundaries of the monitored region.

In node localization using virtual coordinates, it is assumed that the finest resolution in coordinates appear using a set of beacons that are farthest apart [3] i.e. on the boundary of the network.

Mobile nodes may be benefited by the knowledge about the boundaries of obstacles present in the region [19].

The importance of boundary detection is therefore advocated by a variety of situations at both network and application levels, that may be benefited by such knowledge.

Alpha shape (α-shape) [8] is a geometric structure used to capture the shape rendered by a set of points in space. For a disc of radius $1/\alpha$, an α-shape is a graph consisting of nodes and joining edges that lie on the boundary of the discs that contain no other nodes in the network. With an appropriate value of α, α-shapes can capture the meaningful internal and external boundaries of given point cloud. α-shapes are extensively used in the field of geometric modeling, medical imaging, graphics, and molecular structure modeling.

A WSN is often modeled as a geometric graph where vertices represent nodes and the edges represent the communication links between nodes. So, effectively a WSN is a candidate for another application of α- shapes.

2. RELATED WORK
According to the taxonomy suggested by Wang et al. [9], the existing methods for boundary detection of sensor networks

can be broadly classified into three categories: geometric methods, statistical methods, and topological methods.

2.1 Geometric Methods

Geometric methods are guided by the location information of the nodes to detect the boundaries of the network. Fang et al. [5] was one of the earliest to use geometric aspects of the network to identify routing holes using a method called tent-rule. The tent-rule identifies all unreachable regions w.r.t. greedy forwarding assuming Unit Disk Graph (UDG) model for node ranges. It works by sorting neighbors angularly about a node. If the bisectors of edges to contiguous neighbors intersect outside the range of the node, then the node is around an unreachable region. Fayed et al.[10] proposed a localized α-shape based boundary detection method by taking α as $2/R$ where R is the normalized transmission range of the nodes. Liu et al.[11] proposed Rolling-ball UDG boundary Traversal (RUT) based on α-shape for finding the boundaries of WSN for the purpose of recovering from dead-end during greedy forwarding. Rührup et al. [2] also used the notion of α-shapes to determine the next boundary node for recovering from dead-end during greedy forwarding. These methods rely heavily on the assumption of UDG model for node ranges, which is often criticized to be too unrealistic in practice [12, 13, 20].

2.2 Statistical Methods

The statistical methods are based on the probability distribution of various network aspects. A boundary node is identified based on some statistical properties under certain prevailing conditions. The statistical data like node degrees and path lengths are used to infer whether the node is an interior or a boundary node. Fekete et al.[14] proposed a solution to detect the boundary nodes based on the assumption that the nodes are uniformly distributed over the deployment field. The method is motivated by the fact that the average node degree of an interior node is much higher as compared to the nodes on the boundaries of the network. A suitable degree threshold then can be used to identify the boundaries. Chen et al. [16] improved the Fekete's work by extending the notion of node degrees to 2-hop neighbors and achieved a better detection rate especially in low-density networks. Fekete et al. [15] proposed another statistical method based on the concept of "*restricted stress centrality*" of nodes with the assumption that each node sends a message to every other node along all shortest paths. The restricted stress centrality is the measure of the number of shortest paths going through the node. An interior node tends to have a higher centrality as compared to the nodes on the boundaries. This very property can then be used to detect boundary nodes. The drawback of statistical methods is the unrealistic assumptions about node distributions, node degrees, and routing methods.

2.3 Topological Methods

Topological methods rely on the information about actual connectivity graph of the network to detect boundaries. Ghrist et al. [14] proposed an algorithm that detects boundaries via homology without any knowledge of sensor locations; however, the algorithm assumes that the node ranges are discs with precise radii. Funke [10] proposed a method to identify boundaries by constructing iso-contours based on hop count from a root node and identifying where the contours break. The proposed method assumes UDG model of connectivity and high node degrees. Kröller et al. [17] proposed a solution that detects network boundaries by searching for special combinatorial structures called flowers. The communication ranges in this work are modeled by a quasi-unit disk graph (qUDG) [20], with nodes u and v definitely connected if $|uv| \leq 1/\sqrt{2}$ and not connected if $|uv| \geq 1$. The success of this algorithm depends on the identification of at least one flower structure, which may not always be present especially in a sparse network. Wang et al. [9] proposed a topological method to detect holes that is purely driven by the communication graph only. The scheme constructs shortest path trees by flooding packets throughout the network. The "flow" of tree forks near a hole, continues along opposite sides of the hole and then meets again past the hole. By detecting the nodes where the shortest paths fork and meet, the boundaries of the hole are detected.

The proposed scheme is motivated by the fact that the location awareness is a fundamental requirement in many WSN applications (e.g. tracking, monitoring etc.) where data without information of its originating node is not as useful. So, location information is inherently available at each node. Instead of making any idealistic assumption about the transmission ranges of the nodes, we use a loose notion of locality in wireless communications – nearby nodes are connected by direct communication links, and distant nodes generally are not. We have used qUDG [20] model for wireless connectivity while simulating our scheme. The proposed method makes use of both geometric as well as topological aspects of the nodes to detect the boundaries of the network. The proposed method is based on the connectivity graph and nodes' locations information locally available.

3. SYSTEM MODEL AND TERMINOLOGY

Sensor nodes are deployed randomly in a 2D Euclidean plane. Presence of obstacles, environmental conditions, and other RF impairments make the nodes' ranges to deviate from the Unit Disk Graph (UDG) model. The terrain variations, obstacles, uneven node densities, node failures etc. give rise to the formation of holes in the WSNs. The network thus formed is modeled using a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V} \subset \mathbb{R}^2$, is the set of vertices representing the sensor nodes and $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$, is the set of edges representing wireless links between the nodes. The communication links are assumed to be symmetric, i.e. if u is a neighbor of v then v is also a neighbor of u. The nodes are aware of their locations in the form of their Cartesian coordinates and completely devoid of any information other than the locations of their immediate neighbors.

3.1 Alpha-shapes

Given a set of points $\mathcal{S}$ in a plane and $\alpha \geq 0$, a point $p \in \mathcal{S}$ is said to be an *α-extreme* if it sits on the boundary of a disc with radius $1/\alpha$ that contains no other point in $\mathcal{S}$. Two neighbors u and v in the set $\mathcal{S}$ that lie on the boundary of an empty disc of radius $1/\alpha$ are said to be *α-neighbors*. An *α-shape* is a graph whose vertices are α-extremes and whose edges connect α-neighbors.

Figure 1(c) depicts a set of points rendered as equivalent α-shape by applying the empty disc condition between each pair of points. When α approaches zero, the α-shape approximates the boundary of the convex hull (Figure 1(b)) of the points, and for a large value of α every point in the space is on the boundary. So, a proper value of α (Figure 1(c)) is the key for detection of meaningful boundaries.

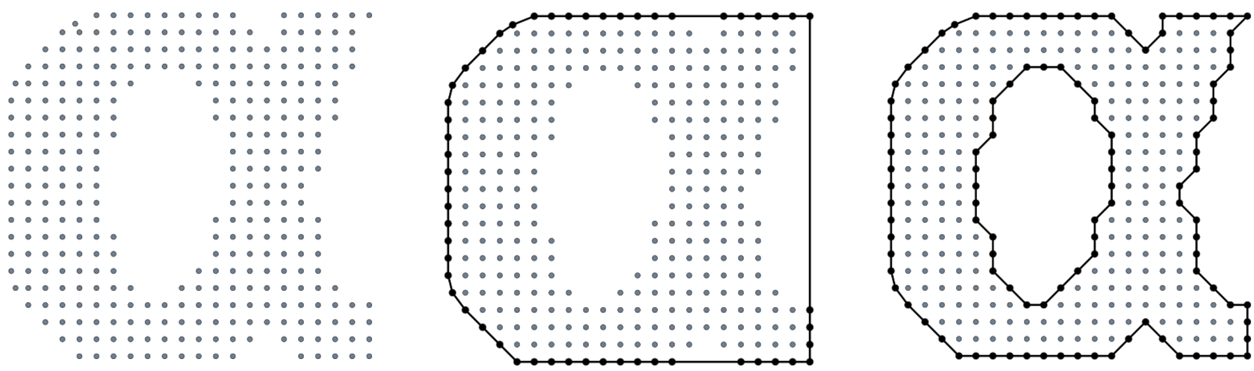

Figure 1. (a) Given point cloud **(b) Convex hull ($\alpha = 0$)** **(c) α-shape ($\alpha = \sqrt{2}/r$)**

3.2 Applying α-shapes to WSNs

The α-shape computation requires a global view of precise points' locations in space. However, the nodes beyond the transmission range are not considered by a node during α-shape computation. Hence, α-shape computation is very much localized to 1-hop neighbors of a node. α-shape computation is also immune to translations and rotations in space, hence is applicable to absolute as well as relative coordinate systems for the points. A WSN is often modeled as a geometric graph where vertices represent nodes and the edges represent the communication links between the nodes. In WSN applications, it is impractical for a node to have information about the global topology or nodes' locations for entire network. Further, the location information available at nodes may be faulty due to localization errors. So, at first sight it may appear that a WSN is not a potential candidate for α-shape application. However, for a value of the radius of the disc comparable to the transmission range, a node only needs to consider its nearby neighbors for α-shape computations, thereby relaxing the global view requirement. The localized computation for determination of α-extremes is a property that motivates the use of α-shapes in WSN applications.

4. α-SHAPES BOUNDARY DETECTION

Each node maintains a vector $\mathcal{N}$ of locations information of its 1-hop neighbors. This information is utilized to perform the computation of the parameter α and to test the condition of α-shapes. If a node is able to identify at least one such disc that satisfies the α-shape condition, it tags itself as a boundary node. In presence of variable node ranges, it is challenging to have an optimum value of α that can be applied throughout the network. In this work we argue that it is not necessary to have same value of α for each node in the WSN, rather a node may determine its own value of α based on the local topology and the locations of its 1-hop neighbors by taking the distance to its farthest neighbor as an approximation of its range. The value of α is computed as $\sqrt{2}/\mathrm{d}$ where d is the Euclidean distance between the node and its farthest neighbor. The choice of the value for α is motivated by the fact that four circles of radius $\sqrt{2}/\mathrm{d}$ can fully cover a circle of radius d. It is also argued in [21] that a ratio of $\sqrt{2}$ (≅ 40% variation) between maximum and minimum transmission range of a node is a good enough assumption for modeling range variations. The presence of localization errors may affect the working of the proposed method. Hence, for this study it is assumed that localization errors are to the extent of only a small fraction of the communication ranges of the nodes.

The algorithm for boundary detection is described below:

Ignoring isolated nodes: If a node does not have any neighbor (i.e. $\mathcal{N}(\mathrm{u}) = \phi$) then it identifies itself as an isolated node and need not to perform the disc test.

Computing α: A node u computes the Euclidean distances between itself and all its neighbors, and selects the maximum distance so obtained for computing the value of α. Let $\mathcal{N}(\mathrm{u})$ be the set of neighbors of u, v be the farthest neighbor of u, the Euclidean distance between u and v be |uv|, then α is computed as:

$$\alpha = \frac{\sqrt{2}}{|\mathrm{uv}|} \quad \text{where} \quad \mathrm{v} \in \mathcal{N}(\mathrm{u}) \wedge |\mathrm{uv}| = \max_{\mathrm{x} \in \mathcal{N}(\mathrm{u})}(|\mathrm{ux}|)$$

The value of α will vary from node to node, and this aspect of the proposed algorithm makes it resilient to the variable transmission ranges of nodes.

α-extreme detection: Based on the value of α, own location, and locations of its neighbors, the node $\mathrm{u}(\mathrm{x_u}, \mathrm{y_u})$ checks whether it is an α-neighbor with any of its neighbors. The condition for α-neighbor with a neighbor $\mathrm{v}(\mathrm{x_v}, \mathrm{y_v})$ is tested by computing the center of the disc of radius 1/α passing through u and v and applying the empty-disc test. The center of the disc $\mathrm{c}(\mathrm{x_c}, \mathrm{y_c})$ is calculated as (Figure. 2):

$$x_c \leftarrow x_u + \frac{|uv|}{2}\cos(\theta) - l\,\sin(\theta)$$

$$y_c \leftarrow y_u + \frac{|uv|}{2}\sin(\theta) + l\,\cos(\theta)$$

where $\mathrm{r} = \frac{1}{\alpha}$, $l = \sqrt{r^2 - \left(\frac{|uv|}{2}\right)^2}$, $\theta = \tan^{-1}\left(\frac{y_u - y_v}{x_u - x_v}\right)$,

and $|uv| = \sqrt{(x_u - x_v)^2 + (y_u - y_v)^2}$

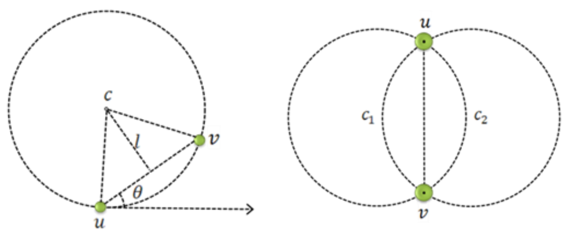

Figure 2. α-shape computation

There will be two such discs (Figure. 2), one on either side of the line joining the two nodes. If some of the neighbors of u other than v, exist inside each of the discs then the node v is not an α-neighbor of u.

Given two neighbors u and v, radius of the disc r, and centers of the discs c_1 and c_2 passing through u and v, the condition given below determines whether u and v are not α-neighbors.

$$\exists w \in \mathcal{N}(u)(|c_1 w| < r) \wedge \exists x \in \mathcal{N}(u)(|c_2 x| < r)$$

If none of the neighbors of u satisfies the condition in above equation then nodes u and v are identified as α-neighbors and included in the α-shape.

Boundary detection: A sequence of edges in the α-shapes of adjacent nodes forms a boundary of the network. Each node computes its local α-shape and thus is aware of its local boundaries only. The boundary of the network is then identified by sending probe packets through a sequence of successively adjacent α-neighbor nodes.

5. SIMULATION

The simulation of the proposed method is carried out for different node densities and distributions under varying terrain topographies. Nodes are distributed in a terrain ranging from 50×50 to 250×250 square units Euclidean plane. Network sizes are varied from 50 to 1800 nodes. Nodes locations are chosen from normal or uniform random distributions. Quasi Unit Disc Graph (qUDG) model is used for nodes connectivity. As proposed in [21], the ratio between maximum and minimum node range is considered as $\sqrt{2}$. The simulation is carried out for following cases: (i) strategic deployment in hole-free environment (Figure. 3), (ii) strategic deployment in regions with well-defined holes (Figure. 4), (iii) uniform random deployment (Figure. 5), and (iv) normally distributed nodes around a given point (Figure. 6).

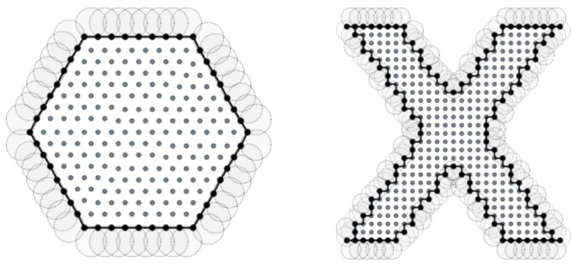

Figure 3. Strategic deployment in obstacle-free terrain

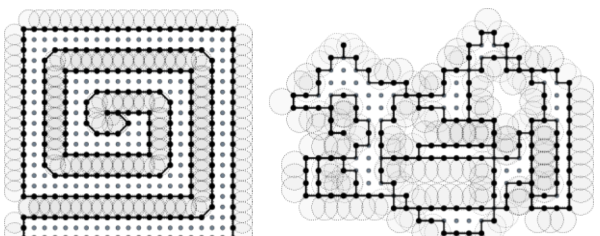

Figure 4. Strategic deployment in regions with obstacles

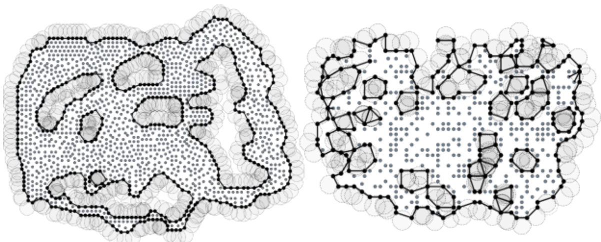

Figure 5. Uniform deployment (1500 and 500 nodes)

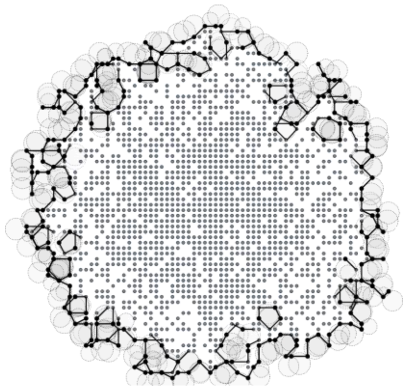

Figure 6. Random normal deployment (1800 nodes)

It was observed that the proposed scheme could efficiently detect meaningful internal and external boundaries when nodes are precisely localized. A graceful degradation was noticed when the localization errors were confined to only a small fraction of the nodes' ranges.

In all the cases of strategic deployment, the proposed method could find boundaries with 98.9% accuracy. Random uniform and random normal distributions of nodes yielded 97.7% and 96.1% accuracy.

6. CONCLUSION

In this paper, an algorithm is proposed to identify nodes and edges along the boundaries of a WSN based on the well-known concept of α-shapes. The proposed method could find the meaningful internal and external boundaries of a network by utilizing the local information at the nodes. Instead of making any assumption about the node ranges, the proposed scheme uses the connectivity graph and nodes' locations to compute α-discs radii. It is also observed that the knowledge about the exact transmission range of a node is not critical, instead a lose notion of the transmission range serves the purpose of computing an appropriate value for α. The simulation results of the proposed scheme have demonstrated satisfactory performance under different node densities and distributions. Though, the proposed scheme has shown graceful degradation in presence of localization errors, a systematic study on the effects of such errors on the proposed scheme is still to be explored.

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