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Detection of Boundaries in 3-D Wireless Sensor Networks

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ABSTRACT:

This research focuses on distributed and localized algorithms for precise boundary detection in 3-D wireless networks. Our objectives are twofold. First, we aim to identify the nodes on the boundaries of a 3-D network, which serve as a key attribute that characterizes the network, especially in such geographic exploration tasks as terrain and underwater reconnaissance. Second, we construct locally planarized 2-manifold surfaces for inner and outer boundaries in order to enable available graph theory tools to be applied on 3-D surfaces, such as embedding, localization, partition, and greedy routing among many others.

To achieve the first objective, we propose a Unit Ball Fitting (UBF) algorithm that discovers a majority of boundary nodes, followed by a refinement algorithm, named Isolated Fragment Filtering (IFF), to remove isolated nodes that are misinterpreted as boundary nodes. Based on the identified boundary nodes, we develop an algorithm that constructs a locally planarized triangular mesh surface for each 3-D boundary. Our proposed scheme is localized, requiring information within 1-hop neighborhood only. We further extend the schemes for online boundary detection in mobile sensor networks aiming to achieve low overhead. Our simulation and experimental results demonstrate that the proposed algorithms can effectively identify boundary nodes and surfaces, even under high measurement errors.

Index Terms:

Boundary detection, triangulation, wireless sensor networks.

INTRODUCTION:

MANY wireless networks exhibit substantial randomness, due to the lack of precise nodal deployment and the nondeterministic failures and channel dynamics. Therefore, the final formation of a wireless network heavily depends onits underlying environment. Consequently, there is a primary interest to discover the unknown geometry and topology of a wireless network formation (or a subnetwork formation), which provide salient information for understanding its environment and for efficient operation of the network itself. In particular, boundary is one of the key attributes that characterize the network in two- (2-D) or three-dimensional (3-D) space, especially in such geographic exploration tasks as terrain and underwater reconnaissance.

Existing System:

The quest for efficient boundary detection in wireless networks has led to two research thrusts outlined here.Detection of Event Boundary: The investigation on boundary detection started from the estimation and localization of events in sensor networks. The spatially distributed sensors usually report different measurements in respond to an event. For example, upon a fire, the sensors located in the fire are likely destroyed (and thus resulting a void area of failed nodes), while the sensors close to the fire region measure higher temperature and smoke density than the faraway sensors do. Boundary detection is to delineate the regions of distinct behavior in a sensor network [1]. Achieving accurate detection of event boundary is challenging because the sampling density is limited, the sensor readings are noisy, the delivery of sensor data is unreliable, and the computation power of individual sensors is extremely low [1], [2].

To this end, a series of studies has been carried out to explore efficient information processing and modeling techniques to analyze sensor data in order to estimate the boundary of events [1]–[5].Due to inevitable errors in raw sensor data, these approaches do not yield precise boundary. Instead, they aim at a close-enough estimation that correctly identifies the events frontier, based on either global or local data collected from a set of sensors.Detection of Network Boundary: Besides the researchdiscussed above that is mainly from the data processing perspective, interests are also developed to precisely locate theboundary of the network based on geometric or topology information of a wireless network. Noise in sensor data is no longer a concern here because such boundary detection is not based on sensor measurement. However, new challenges arise due to the required accuracy of the identified boundary, especially in networks with complex inner boundary (i.e., “holes”) or in high-dimensional space.

Proposed System:

Most proposed network boundary detection algorithms are based on 2-D graphic tools. For example, Voronoi diagrams are employed in [6] and [7] to discover coverage holes in sensor networks. Delaunay triangulation is adopted in [8] to identify communication voids. In contrast to [6]–[8] that exploit sensor positions, two distributed algorithms are proposed in [9] by utilizing distance and/or angle information between nodes to discover coverage boundary.There are increasing interests in 3-D wireless networks, with several areas such as routing [19]–[24], localization [14], [25], nodal placement [26], [27], physical-layer investigation [28], and applications [28], [29] being explored recently. This research aims to develop distributed and localized algorithms forprecise boundary detection in 3-D wireless networks. Our objectives are twofold.

1) First, we aim to identify the nodes on the boundaries of a 3-D network based on local information.

2) Second, we construct locally planarized 2-manifold surfaces for inner and outer boundaries.

To achieve the first objective, we propose a Unit Ball Fitting (UBF) algorithm that discovers a set of boundary nodes, followed by a refinement algorithms, named Isolated Fragment Filtering (IFF), which removes isolated nodes that are misinterpreted as boundary nodes by UBF. Our proposed scheme is localized, requiring information within 1-hop neighborhood only. This quality is highly desired to enable fast and low-cost boundary detection.

BOUNDARY NODE IDENTIFICATION:

The proposed boundary node identification algorithm involves two phases. The first phase is the Unit Ball Fitting, which aims to discover a set of boundary nodes. The second phase is Isolated Fragment Filtering, which removes isolated nodes that are misinterpreted as boundary nodes in Phase 1.

A. Phase 1: UBF

We present the UBF algorithm in this section. The related definitions, theories, and algorithm description are elaborated sequentially.

1) Definitions: To facilitate our exposition, we first introduce several basic definitions.

Definition 1: The nodal radio transmission range is assumed a constant. Without loss of generality, we normalize it to be 1.

Definition 2: The nodal density, denoted by , is the average number of nodes in a unit volume.

Definition 3: A well-connected network is a network where: 1) no nodes are isolated; and 2) there are no degenerated line segments. In other words, given a line segment between two

nodes, e.g., Nodes i and j , theremust be at least one node whose distances to Nodes i and j are less than , where denotes the distance between Nodes i and j.

We consider well-connected networks only in this work because the isolated nodes and degenerated line segments are swingable, causing ambiguity in boundary definition and detection.

Definition 4: A unit ball is a ball with a radius of , where is an arbitrarily small constant.

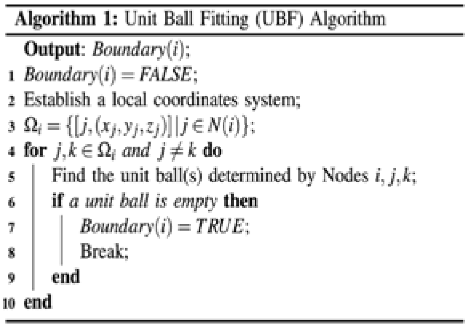
Definition 5: An empty unit ball is a unit ball with no nodes located inside.

Definition 6: We say a unit ball touches a node if the node is on the surface of the ball.

Definition 7: A hole is an empty space that is greater than a unit ball. The space outside the network is treated as a special hole. With the above definitions, we next discuss the motivations to develop the UBF algorithm and the theories that prove its correctness and computing complexity. Subsequently, we give the formal algorithm description.

2) Motivations and Theoretic Insights: The proposed UBF algorithm is motivated by the fact that a hole can always contain an empty unit ball. Therefore, we can search for empty unit balls in order to identify holes and

boundary nodes.More specifically, a node can test if it is on a boundary by constructing a unit ball with itself on the ball's surface. If at least one such ball can be found that no nodes are located inside, a hole is identified, and the node is a boundary node



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Algorithm 1: Unit Ball Fitting (UBF) Algorithm
Output: $Boundary(i)$;
$Boundary(i) = FALSE$;
Establish a local coordinates system;
$\Omega_i = \{[j, (x_j, y_j, z_j)] | j \in N(i)\}$;
for $j, k \in \Omega_i$ and $j \neq k$ do
    Find the unit ball(s) determined by Nodes $i, j, k$;
    if a unit ball is empty then
        $Boundary(i) = TRUE$;
        Break;
    end
end
```

TRIANGULAR BOUNDARY SURFACE CONSTRUCTION:

The boundary nodes identified so far are discrete. They largely depict the network boundaries.However, many applicationsrequire not only discrete boundary nodes, but also closed boundary surfaces. Moreover, it is highly desirable that such surfaces are locally planarized 2-manifold in order to apply available 2-D graphic tools on 3-D surfaces. In this research, we implement an algorithm that constructs locally planarized triangular meshes on the identified 3-D boundaries. We adopt the method proposed in [30] that can produce a 2-D planar subgraph (which, however, is not a triangular mesh) and extend it to 3-D surfaces to achieve complete triangulation without degenerated edges. The algorithm is localized and based on connectivity only.

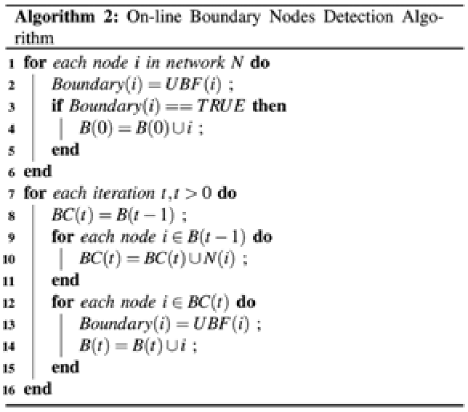
BOUNDARY DETECTION IN DYNAMIC WIRELESS SENSOR NETWORKS:

Over time due to environment dynamics (such as, water flow, wind, and animal movement) or the evolvement of the network itself (as links break or nodes run out of batteries). Topology dynamics often cause the change of network boundary, calling for an effective online boundary detection algorithm, with low overhead and high energy efficiency. In this work, we consider a general random mobility model, where a node moves for a distance of that is (less than transmission range) to any direction in a time unit. Note that we do not consider any special radio model constraints here, except the maximum radio transmission range . The sensors' mobility is constrained by their container (e.g., seabed and shore).

The UBF algorithm is localized only involving 1-hop neighbor nodes. Although sensors are mobile, the current boundary nodes give valuable clues to find the boundary nodes in the near future. More specifically, even though some old boundary nodes might have moved inside and not be boundary nodes anymore, they should still be located near the boundary and thus help to narrow down the boundary candidates. As a matter of fact, the previous boundary nodes and their neighbor nodes are good candidates for identifying the new boundary nodes.

The UBF algorithm can be applied only to these candidate nodes instead of all nodes in the network in order to reduce energy consumption.While we can simply reconstruct the triangle mesh based on the newly identified boundary nodes, a more effective approach is to maintain the triangle mesh constructed previously and update it according to the new boundary. We observe that the Voronoi cells are more stable than boundary nodes, and the triangle mesh is only determined by the Voronoi cells, more specifically the landmarks of the cells. How to update the landmarks forming the triangle mesh is the key to solve this problem efficiently.

However, the selection of new landmark is not trivial because new triangle mesh must satisfy two properties. First, all of the landmarks must be boundary nodes. Second, there are no crossing edges between landmarks. Some landmarks in the previous round might not be boundary nodes in this round due to mobility, and thus are not eligible for new landmarks. Therefore, we have to find a new boundary node as a new landmark to replace the old one, if the old landmark is not on the boundary anymore. Picking the boundary node closest to the old landmark is a straightforward way to fulfill the mission.



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Algorithm 2: On-line Boundary Nodes Detection Algorithm
for each node $i$ in network $N$ do
    $Boundary(i) = UBF(i)$ ;
    if $Boundary(i) == TRUE$ then
        $B(0) = B(0) \cup i$ ;
    end
end
for each iteration $t, t > 0$ do
    $BC(t) = B(t-1)$ ;
    for each node $i \in B(t-1)$ do
        $BC(t) = BC(t) \cup N(i)$ ;
    end
    for each node $i \in BC(t)$ do
        $Boundary(i) = UBF(i)$ ;
        $B(t) = B(t) \cup i$ ;
    end
end
```

SIMULATIONS AND EXPERIMENTS:

To evaluate the effectiveness of our proposed boundary detection algorithms, we have carried out extensive simulations under various 3-D wireless networks and studied the impact of a wide range of distance measurement errors. The algorithm is also implemented in real sensor motes. In this section, we will first introduce our simulation setup. Then, we present the simulation and experiment results and discuss our observations.The 3-D networks used in our simulations are constructed by using a set of 3-D graphic tools (including TetGen [38]). First, a 3-D model is developed to represent a given network scenario (e.g., an underwater network, a 3-D network in space, and general 3-D networks with arbitrary shapes of our interest). A set of nodes are randomly uniformly distributed on the surface of the 3-D model. They are marked as boundary nodes, serving as ground truth to evaluate our algorithm. A cloud of nodes is then deployed inside the 3-D model. Again, the nodes are randomly uniformly distributed. Once the nodes are determined, an appropriate radio transmission range is chosen according to nodal density, such that the network is connected.

Each node connects to its neighbors within its radio transmission range. In our simulated networks, nodal degree ranges from 5 to 45, with an average of 18.5. A node also estimates its distance to each neighbor. While our simulations do not involve physical-layer modeling, we introduce a wide range of random errors, from 0% to 100% of the radio transmission radius, in the distance measurement.For each simulated network, the input includes a set of the nodes (both interior and boundary nodes), the local 1-hop connectivity of each node, and the distance measurement (with various errors) within 1-hop neighborhood. We run our proposed distributed and localized algorithms for boundary node detection and surface construction. First, each node establishes a local coordinates system by using distributed multidimensional scaling [36] based on local distance measurement. Then, boundary node identification is performed, followed by the triangular mesh algorithm.

CONCLUSIONS:

We have proposed distributed and localized algorithms for precise boundary detection in 3-D wireless networks. Our objectives have been twofold. First, we have aimed to identify the nodes on the boundaries of a 3-D network, which serve as a key attribute that characterizes the network, especially in such geographic exploration tasks as terrain and underwater reconnaissance. Second, we have intended to construct locally planarized 2-manifold surfaces for inner and outer boundaries in order to enable available graph theory tools to be applied on 3-D surfaces, such as embedding, localization, partition, and greedy routing among many others. To achieve the first objective, we have proposed a Unit Ball Fitting algorithm that discovers a set of potential boundary nodes, followed by a refinement algorithm, named Isolated Fragment Filtering, which removes isolated nodes that are misinterpreted asboundary nodes by UBF. Based on the identified boundary nodes, we have developed an algorithm that constructs a locally planarized triangular mesh surface for each 3-D boundary. Our proposed scheme is localized, requiring information within 1-hop neighborhood only. We have further extended the schemes for online boundary detection in mobile sensor networks aiming to achieve low overhead. Our simulation and experimental results have shown that the proposed algorithms can effectively identify boundary nodes and surfaces, even under high measurement errors.

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