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Boundary Detection in 2-D and 3-D Wireless Sensor Networks

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Abstract—*In order to track and detect continuous natured objects in wireless sensor networks, large number of sensor nodes are involved. These continuous objects like bio-chemical diffusions, forest fires, oil spills usually spread over larger area. The nodes that sense the phenomena need to communicate with each other for exchanging the information and also send sensing information to sink, possibly by passing through many intermediate nodes. In this paper, we have reviewed boundary detection in 2-D wireless sensor networks as well as in 3-D wireless sensor networks. A comparative study between the both has also been shown. The various challenges encountered in 3-D wireless sensor networks have also been discussed.*

Keywords— Boundary detection, Delaunay Triangulation, Event Boundary, Network Boundary.

I. INTRODUCTION

Boundary detection plays a crucial role in information fusion and dissemination in 2D and 3D Wireless Sensor Network (WSN) applications such as target tracking, plume tracking, forest fires, animal migration, underwater WSNs and surveillance applications. It is also often important for self-organization of networks. A network has a specific embedding and can have three different types of boundaries which the scheme presented in this paper aims at detecting.

First is network's outer boundary which consists of a unique subset of nodes. Second is an inner boundary. The last type of boundary is an event boundary. For example events such as mobile targets or forest fires have highly dynamic event boundaries while an underground chemical plume may have boundaries that change gradually over time.

Currently available boundary detection schemes that have been targeted exclusively at 2D networks can be broadly categorized as physical information-based and topological/connectivity information-based [2][5] schemes. The former uses physical position of nodes to identify the boundary while the latter uses topological/connectivity information of the network. Physical domain schemes rely on node location or physical position information obtained using localization algorithms or GPS. Providing nodes with GPS is expensive and infeasible for many applications. Localization based on parameters such as RSSI/time delay is error-prone even for 2D networks of modest size, is susceptible to interference, multipath and fading, which makes it impractical in many environments. Future sensor networks may have thousands or even millions of sensors, and hence distributed strategies that do not accumulate errors, and scalable in cost and complexity are of significant interest.

An alternative approach is connectivity based boundary detection [19-20]. A connectivity domain description of a network can have more than one valid embedding (configurations) [20] in physical domain, even though only one of them corresponds to the physical network. The actual embedding is one out of the many, but identifying the correct embedding solely based on the connectivity information is challenging. Hence, connectivity information based boundary identification captures a union of boundary nodes in every embedding. As a result the actual set of boundary nodes is a subset of it which leads to identifying a band of nodes as boundary nodes [20]. Due to such difficulties there is no connectivity based approach available to identify boundaries on 3D surfaces to the best of our knowledge.

Boundary detection in connectivity domain requires two steps:

(1) Identifying the correct embedding, and

(2) Detecting boundary.

A novel two step connectivity based approach for boundary detection is proposed. It produces highly accurate results by overcoming the ambiguity of network boundary due to multiple embedding in connectivity domain. It uses a Virtual Coordinate System (VCS) to generate a Topology Preserving Map (TPM) that identifies the correct physical embedding. In VCS, a subset of nodes is selected as anchors. Then all the nodes in the network including anchors estimate their shortest path hop distance to the anchors and use those values as virtual coordinates. Number of anchors is the cardinality of the coordinates. TPM is simply a map of the original network, in the original physical dimensionality, in which the neighbourhood is preserved. 2D topology preserving map (TPM) generation based on virtual coordinate system

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(VCS) is discussed in [2]. The technique does not involve measuring signal strengths or time delays, which are costly and often impractical to implement in large scale networks.

Emerging technologies point to many applications for such networks. For example, an oil pipeline, a boiler or a bridge that needs to be monitored for corrosion, temperature distribution, or structural integrity. Tiny nano-sensors capable of wireless communication and minimal computation capability can be deployed in massive quantities on their surfaces.

II. BOUNDARY DETECTION

1. Detection of Event Boundary

The research 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 instance, in case of fire, the sensors located in the fire are likely to be 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 unavoidable errors in the 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.

2. Detection of Network Boundary

Besides the research discussed above that is mainly from the data processing perspective, interests are also developed to precisely locate the boundary 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. Nevertheless, various challenges arise due to the required precision of the required boundary, especially in networks with complex inner boundary (i.e., “holes”) or in high-dimensional space.

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 locations, other two distributed algorithms are proposed in [9] by utilizing distance and/or angle information between nodes to discover coverage boundary.

In [10], an algebraic topological invariant called homology is computed to detect holes. The algorithm is generally applicable to networks in any dimensional space. However, it is a centralized approach, and there is significant challenge to decentralize its computation as pointed out in [10]. In [11], the isosets (each of which consists of nodes with the same hop distance to a beacon node) are identified. The disconnection in an isoset indicates the boundary nodes of holes. Multiple beacons can be employed to locate the boundary nodes at different directions of a hole. This approach does not guarantee to discover the complete boundary of every hole. Higher accuracy can be achieved if more beacons are employed or when the network is denser. Reference [12] introduces a deterministic algorithm for boundary detection. It searches for a special subgraph structure, called m-flower, which is bounded by a circle. Once an m-flower is identified, the algorithm can subsequently find the boundary nodes through a number of iterations of augmentation of the circle. However, not every graph has an m-flower structure. Therefore, the algorithm may fail especially when the nodal density is low. In [13], a shortest path tree is built to find the shortest circle, which is then refined to discover the tight boundaries of the inner holes.

All of the network boundary detection approaches discussed above are developed for networks in 2-D space. Except for [10], which is centralized, none of them can be readily applied to 3-D networks since higher-dimension space introduces significant complexity in searching for boundaries, and many topological and geometrical tools cannot be extended from 2-D to 3-D.

III. COMPARISON BETWEEN 2-D AND 3-D WSN

A wireless sensor network is built upon a large number of low cost sensor nodes. Although a two-dimensional (2D) planar setting is assumed in most earlier studies on wireless sensor networks, there have been increasing interests in deploying sensors in three-dimensional (3D) space for such applications as underwater reconnaissance and atmospheric monitoring [1]– [12]. While the third dimension appears irrelevant to network communication and management protocols at the first glance, surprising challenges are observed in efforts to extend many 2D networking techniques to 3D space.

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This work focuses on boundary detection in 3D wireless sensor networks. Boundary is a key attribute that characterizes a sensor network, providing salient information for understanding environmental data and for efficient operation of the network itself, especially in geographic exploration and monitoring tasks. Due to the lack of precise nodal deployment and the nondeterministic sensor failures and channel dynamics, many wireless sensor networks exhibit substantial randomness, with their final formations heavily dependent on underlying environment. Consequently, the boundaries are often unknown before network deployment, calling for distributed and autonomous algorithms for efficient boundary detection.

1. Challenges in Connectivity-Based 3D Boundary Detection

Let's first look back upon the development of boundary detection algorithms in wireless sensor networks, which offers a full-spectrum understanding of the boundary detection problem and the limitation of existing boundary detection solutions.

2. Boundary Detection in 2D Sensor Networks

The problem of boundary detection has been extensively studied in 2D wireless sensor networks, covering the detection of eventboundariesand network boundaries. Events are reported according to sensor readings. A sensor is called an event sensor if it detects the target event based on its measurement (e.g., high temperature and smoke density upon a fire). An event sensor declares itself on the event boundary if it has non-event sensors in its neighbourhood. While the basic idea appears straightforward, event boundary detection is challenging, due to limited sampling density, noisy sensor readings, lossy data delivery, and low computation power of individual sensors [13], [14], calling for efficient information processing and modeling techniques to analyze sensor data, in order to estimate the boundary of events [13]–[17].

The detection of network boundary is to locate the outmost nodes in a sensor network, irrespective of sensor data or events. Without the facilitation of neighbouring sensor readings, a sensor node depends on geometric or topological information to determine if it is on a boundary. The geometry-basedapproachesrequire the knowledge of location or distance for localized boundary detection [18], [19]. On the other hand, the topology-based schemesachieve location/distance-free by exploiting topological characteristics of the network [20][22].

3. Hurdles to Extending Topology-Based Schemes to 3D

Topology-based boundary detection is intrinsically challenging in 3D wireless sensor networks, because higher dimension space introduces significant complexity in searching for boundaries and many topological tools cannot be extended from 2D to 3D, rendering none of the available topology based schemes [19]–[20] readily applicable for distributed and autonomous boundary detection in 3D sensor networks.

For example, the fundamental group persevering (FGP) transformation is adopted in [20] to produce a reduced topology graph with all holes preserved. It can effectively identify fine-grained boundaries, but the transformation and further refinement techniques are usable on 2D plane only.

The algorithm in [22] exploits the fact that, on a 2D plane with holes, the branches of a shortest path tree belong to different homotopy types, which cannot be continuously deformed from one to another. Thus two paths with distinct homotopy types are connected to form a circle around an inner hole, which is further refined to discover tight boundaries. However, similar concept no longer holds in 3D, where the shortest paths around a hole are homotopy equivalent. Similarly, the m-flower structure employed in [20] is effective in 2D only.

In [20], isosets are identified for boundary detection. An isoset consists of nodes with the same hop distance to a beacon node. The disconnection in an isoset indicates a boundary.

While similar ideas can be applied in 3D, it becomes nontrivial to test disconnections in 3D isosets, and moreover the scheme does not guarantee to discover complete boundaries.

Finally, a whole detection algorithm based on homology is proposed in [20]. It is generally applicable to networks in any dimensional space, but it is a centralized approach and there exists significant challenge to decentralize its computation.

4. 3D Open Research Challenges

Although the sensor nodes are located in a 3D environment in real UWSNs and AANETs applications, most of the existing studies assume 2D wireless network topology structures. The characteristics of the physical layer affect the design of the other layers and the overall 3D wireless ad hoc and sensor networks performance directly. So a key research is required in the physical layer and antenna propagation for 3D environments. Another challenge is the MAC layer which faces link breakage and poor quality due to the high mobility and longer distances between nodes of the 3D networks. There are very few studies available in the area of MAC

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layer in 3D environment. Therefore, 3D UWSNs and AANETs call for efficient research on testbeds and directional antennas. Furthermore, location estimation of the nodes and sharing of information are vital issues for directed antenna based MAC layers, and they are more challenging for AANETs especially because of highly mobile nodes, such UAV.

As discussed previously that routing is one of the most challenging issues for 3D UWSNs and AANETs due to the unique 3D wireless networks characteristics, the existing 3D wireless networks routing solutions are limited and have a lot of drawbacks. LOS communication is essential for collaborative coordination and collision avoidance between the nodes of UWSNs and AANETs. Thus, developing novel routing algorithms that can support LOS communication and manage huge traffic is still an open issue. Reliability is a critical issue for 3D wireless ad hoc and sensor networks transport layers. 3D applications use different types of data such as target images, acoustic signals, or video captures of a moving target. These applications require different high levels of reliability. Such reliability is not fulfilling with the existing transport layer protocols.

During the packet delivery in AANETs, the changes of aircraft trajectory will affect the accuracy of routing protocol. Thus, the accuracy of aircraft mobility is very important because all traffic advisories are based on the current state estimates of the aircraft. Clearly, a major challenge in aircraft tracking is thus to provide accurate state estimates of aircraft. However, it is difficult to obtain precise aircraft state estimates when the aircraft changes a flight mode. Due to high speeds nodes, the 3D network is highly dynamic with constantly changing topology. Furthermore, a severe bandwidth constraint occurs in the network, due to the high volume of data that needs to be transfer in a limited allocated spectrum.

IV. CONCLUSION

With the growing 3D applications, new 3D UWSNs (Underwater Wireless Sensor Networks) and AANETs (Airborne Ad Hoc Networks) have been developed and deployed in recent years. Due to the distinctive features of 3D wireless ad hoc and sensor networks and the complex deployment environment in 3D ocean spaces and sky spaces, various efficient and reliable 3D communication and networking protocols have been proposed. In this paper, 2D wireless sensor networks, 3D wireless sensor network, boundary detection and issues related to 2D and 3D networks have been surveyed as a separate network family for efficient communication. Furthermore, we present an overview of the challenges faced during boundary detection in 3-D wireless sensor networks. We have a strong belief that more promising developments and significant improvements of 3D wireless networks will be achieved in the near future. This will greatly enhance human's abilities in investigation and manipulation of the 3D environment.

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