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Coordinate-free Distributed Algorithm for Boundary Detection in Wireless Sensor Networks

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***Abstract*—In this paper, we propose a coordinate-free distributed boundary detection algorithm (CDBD). It adopts general sensing and communication models and exploits two centrality measures, i.e., *betweenness* and *closeness*. For CDBD, each node only needs to communicate with its k-hop neighbors twice and makes decision whether it itself is a boundary node independently. CDBD has advantages of fast convergence and low communication overhead. Extensive simulation demonstrates the desirable performance of CDBD.**

***Index Terms*—Boundary detection; distributed algorithms; coordinate-free; wireless sensor networks**

I. Introduction

Wireless sensor networks (WSNs) have been widely adopted to collect physical information about a region of interest (RoI) [1][2][3][4][5]. In most of their applications, the global network topology is of a major concern, as it is closely related to the basic network functionalities such as coverage and data communications [6]. Boundary detection is therefore an important topic in WSNs. Strictly speaking, boundary detection includes sensing boundary detection [7] and communication boundary detection [8]. The former strives to find the nodes whose sensing ranges are part of the sensing boundary of the network; the latter deal with finding the boundary nodes of the communication graph of the network. In this paper, we focus on sensing boundary detection. Without ambiguity, we will use sensing boundary and boundary interchangeably.

However, boundary detection can not be solved precisely without knowing the coordinations the nodes. By exploiting location information and computational geometry, the problem can actually be addressed in a distributed way under some specific assumptions, e.g., location awareness and perfect disc sensing/communication models. In [7], it is shown that a distributed algorithm for accurate boundary detection can be obtained if and only if the communication range is at least two times of the sensing range. In some applications, detection accuracy is however not a concern, and the assumptions can be relaxed. An example is a sensor network deployed for habitat monitoring. The boundary nodes may be only in charge of counting the entry and departure number of the animals in the RoI, and give a rough estimate about the total number of animals living in the RoI. An approximation algorithm that finds most of the boundary nodes can still give a good estimate, and will not incur much performance degradation. Motivated by these considerations, in this paper we devise an approximation solution, named coordinate-free distributed boundary detection (CDBD).

CDBD does not assume node location information or any specific sensing/communication model. Instead, it exploits two centrality measures in graph theory, i.e., *betweenness* and *closeness*, to achieve the goal. These two centrality measures quantify to what extent a node lies in the center of the graph. As calculating the betweenness and closeness for each node using the global topology information is practically infeasible, in CDBD each node determines which nodes are boundary nodes in its k-hop neighborhood graph (referred to as local boundary nodes). It informs the local boundary nodes about this determination. A node is identified local boundary node by every k-hop neighbor considers itself a global boundary node. CDBD only involves two rounds of local communication (within k-hop neighborhood), thus converging fast and having low communication overhead. Through extensive simulation, we demonstrate the effectiveness of CDBD. Our simulation results indicate that CDBD is able to find most of the boundary nodes, and the detected nodes that are not boundary nodes are located closely to the network boundary. By tuning the threshold values of betweenness and closeness, CDBD can achieve different level of detection accuracy. Further, our results indicate that CDBD may have desirable performance by using a small-value k (e.g., 2 or 3).

The remainder of the paper is organized as follows. We will give a brief description about previous work on boundary detection in Section II. We formulate the problem in Section III, and propose CDBD in Section IV. We report our simulation study in Section V and conclude the paper in Section VI.

II. Related Work

Boundary detection and coverage in WSNs are closely related problems, and are often addressed at the same time. The basic idea lies in that when there is a coverage hole in the network, the nodes which are nearest to some points in the coverage hole are the boundary nodes [8]. Therefore, methods that are used for coverage hole verification can be easily modified to detect boundary nodes. Mainly, there are two approaches to address the problem [7]: i) perimeter-based approach [9][10][11], and ii) Voronoi polygon based approach [7][12][13][14]. In the first approach, the sensing border of each node is checked for boundary detection. Huang *et al.* [10] show that a node is a boundary node if and only if

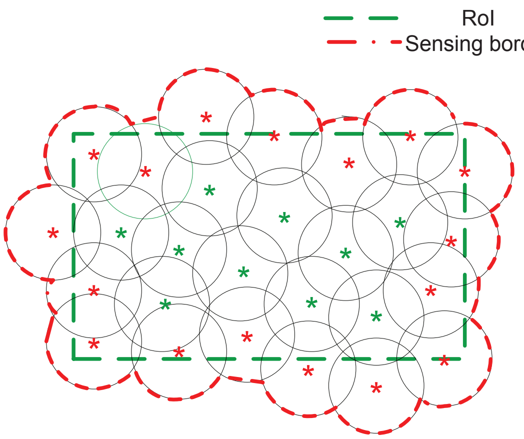

Fig. 1. An illustration of sensing border and boundary nodes

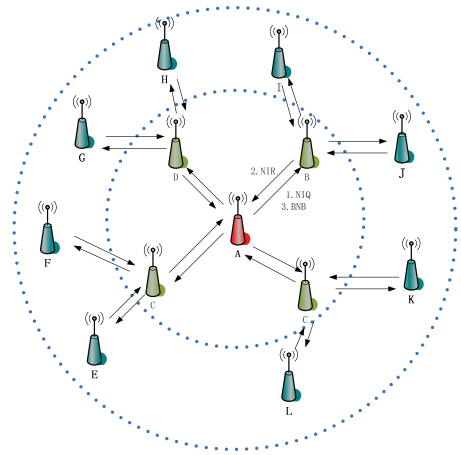

Fig. 2. The communication process of CDBD when $k = 2$.

there is a point on its sensing border not covered by any of its direct neighboring node. Zhang *et al.* [9] further show that the intersection points between two sensors instead of their sensing border can be used for boundary detection, which greatly simplifies the computational complexity. Two nodes i and j are boundary nodes when at least one of their intersection points can not be covered by their direct neighbors (excluding nodes i and j). Recently, Kasbekar *et al.* [11] exploits this principle to obtain a coordinate-free distributed algorithm under the assumption of an open disc sensing model. In the second approach, location information is required, and a Voronoi diagram is constructed. Each node decides independently whether or not it is a boundary node, by checking if every point in its voronoi polygon is covered [7][12][13]. Our work to be presented here differ from the aforementioned work in that we propose a distributed approximation algorithm without knowing nodal location or assuming any sensing/communication model.

III. Problem Formulation

We consider a WSN of N nodes. We do not assume any specific sensing model such as disc sensing model [15][16] or probabilistic sensing model [17]. A node may have a communication range of any shape. Nodes are not aware of their own location and thus have no clue about the distances or angles from their neighbors. Each node has a unique ID. Denote the k-hop neighborhood communication graph of node i by $G_i(L_i, N_i)$, where N_i is the number nodes (including node i) and L_i the edge set. The communication graph of the network is similarly represented by $G(L, N)$.

Let R_i be the sensing region of node i. The sensing region of the entire network is $R = \cup_{i=1}^{N} R_i$. Denote the boundary set (or simply boundary) of R by ∂R. The definition of boundary nodes is given below, and an illustration of the boundary and boundary nodes of a WSN is plotted in Fig. 1.

Definition 1: Nodes i is a boundary node if and only if there is a point p in its sensing region such that $p \in \partial R$.

With perfect disc sensing and communication models and even with location information, previous research [7] shows that there exist an accurate distributed algorithm for boundary detection if and only if the communication range is at least twice of the sensing range. The goal of this paper is to solve this problem without these specific models or assumptions. And, we aim to develop a distributed approximation solution based on two centrality measures in graph theory, i.e., *betweenness* and *closeness*.

Definition 2: The betweenness BET_i of node i in $G(L, N)$ is defined as

$$BET_i = \sum_{s,t \in N | s \neq t \neq i} \frac{|\mathcal{P}_{st}(i)|}{|\mathcal{P}_{st}|}, \tag{1}$$

where $\mathcal{P}_{st}$ is the set of shortest paths from s to t, $\mathcal{P}_{st}(i)$ the subset of $\mathcal{P}_{st}$ through node i, and $|\cdot|$ the cardinality of a set.

Definition 3: The closeness CLO_i of node i in $G(L, N)$ is the average weight of the shortest path between node i and all other reachable nodes, i.e.,

$$CLO_i = \frac{\sum\limits_{t,t \in N | d \neq i} w(\mathcal{P}_{it})}{N - 1}, \tag{2}$$

where $w(\mathcal{P}_{it})$ is the aggregate weight of links in $\mathcal{P}_{it}$.

From the definitions of *betweenness* and *closeness*, we know that the larger the betweenness, or the smaller the closeness, of a node, the higher probability that the node lies near the center of the network. Denote the thresholds of betweenness and closeness by th_{bet} and th_{clo}, respectively. We may use them to evaluate the "distance" of a node from the center of the network, and thus decide which node are boundary nodes.

IV. Distribution Algorithm

In this section, we propose an approximation solution, named Coordinate-free Distributed Boundary Detection algorithm (CDBD), to the above formulated problem. We will demonstrate in the next section that CDBD has a desired performance compared to the accurate algorithm.

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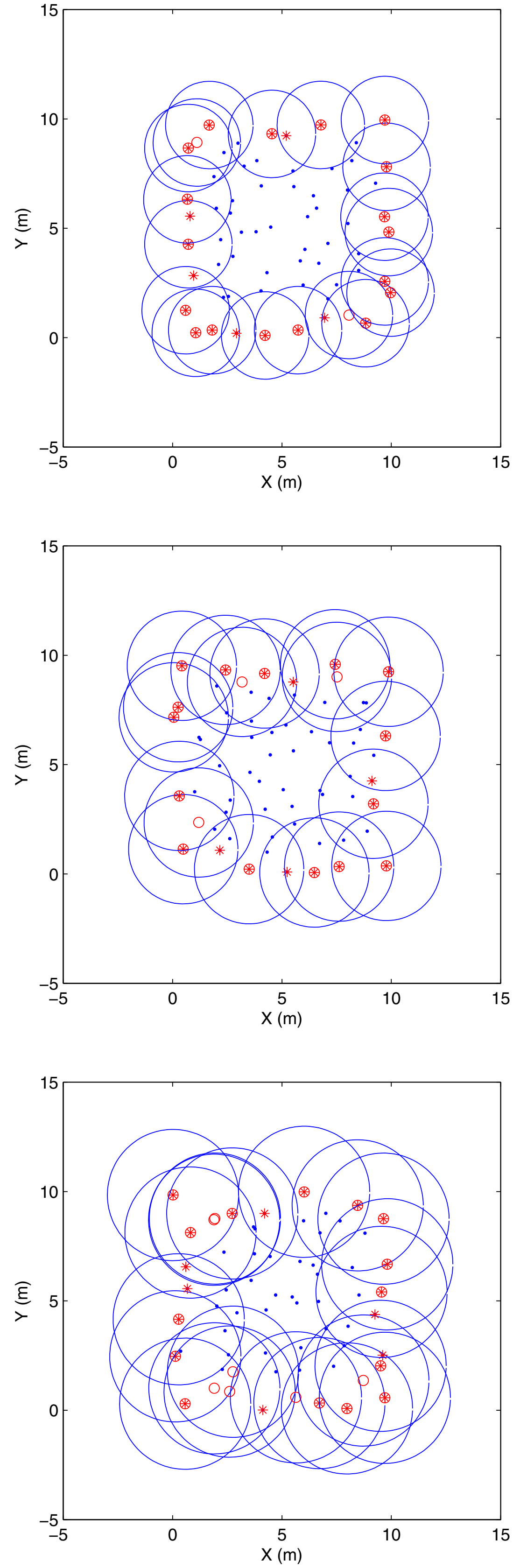
CDBD exploits the aforementioned two centrality measures betweenness and closeness. The basic idea lies in that a bound ary node will have a low value of betweenness, and a higl value of closeness. To facilitate the distributed detection o the boundary nodes, each node i builds a k-hop neighborhooc graph $G_i(L_i, N_i)$. In this graph, it calculates the betweennes and closeness for all the nodes including itself, determine which of them are boundary nodes and inform these node by communication. Each node finally knows about its statu (boundary node or not) in the k-hop neighborhood graphs o every k-hop neighbor. It marks itself a global boundary nod if it is considered a boundary node in all these sub graphs. Th pusydo codes of CDBD is given in Algorithm 1, from whicl we can see that the communication process of CDBD involve three subprocesses: i) neighborhood information query (NIQ) ii) neighborhood information report (NIR), and iii) boundar node broadcasting (BNB). See an illustration of in Fig. 2.

Algorithm 1 Coordinate-free Distributed Boundary Detectio

1) Initially, each node broadcasts a HELLO message t nodes in its k-hop neighborhood. Each node receivin the message will reply a message including its II through multihops.
2) Each node i constructs a virtual graph $G_i(L_i, N_i)$ b using the information obtained at step 1), and find the shortest paths for any pair of nodes in the grap by Floyd-Warshall algorithm. Then it calculates th betweenness and closeness for every nodes in th $G_i(L_i, N_i)$ in a centralized way.
3) If the betweenness of a node j is larger than a pre defined threshold th_{bet}, node i declares j is a boundar node and send a YES-BET message to j; otherwise it sends a NO-BET message to node j. In the sam way, node i will send j a YES-CLO message when th value of closeness of node j is less than a pre-define threshold th_{clo}.
4) Upon receiving the decision messages from nodes i its k-hop neighborhood, node i decides that it itself i a boundary node if it receives either all YES-BET o all YES-CLO messages. Otherwise, it consider itsel an interior node.

Remarks: i) Each node makes protocol decisions indepen dently and distributively, only using information in its k-ho neighborhood. CDBD is therefore a distributed algorithm; ii each node only needs to broadcast messages to its k-ho neighborhood for two rounds, and therefore CDBD is com munication efficient; iii) the computation time for calculatin of betweenness and closeness and communication cost wil increase when k becomes large, but nevertheless, according t our simulation, a small k (e.g., 2 or 3) may yield desirable results; and iv) th_{bet} and th_{clo} are important parameters and need to be carefully chosen in order to get good performance.



(c) $r_s = 3$.

Fig. 3. Nodes marked by red circle are obtained by CDBD when $r_s = 2, 2.5, 3$ with other parameters being fixed. Their sensing regions are indicated by blue circles. Nodes marked by red star are the true boundary nodes.

V. Simulation Results

In this section, we perform extensive simulation to demonstrate the effectiveness of CDBD. The simulation settings are given as follows. We deploy n sensor nodes in a square area of 10×10 m^2 randomly. The sensing and communication regions of all nodes are homogeneous and are assumed to be the circular areas centered at each node. Denote the sensing and communication ranges of by r_s and r_c, respectively. We will mainly focus on the impacts of the three parameters r_s, n and k, on the performance of boundary detection, and simply let $r_s = r_c$. To evaluate the effectiveness of CDBD, we use two performance metrics, i) RTCA, the ratio of total number of nodes identified by CDBD as boundary nodes to the number of actual boundary nodes, and ii) ABD, the average distance of the set of nodes obtained by CDBD to the boundary node set. We study CDBD under simulation settings: i) varying sensing range r_s while other parameters are fixed, ii) varying network size n while other parameters are fixed, and iii) varying locality parameter k while other parameters are fixed.

We first fix $n = 64$, $k = 2$ and carry our simulations for different r_s, $r = 2, 2.5, 3$. The threshold th_{bet} for $r_s = 2, 2.5, 3$ are set to $5, 3.47, 2.22$, and the threshold th_{clo} for $r_s = 2, 2.5, 3$ are set to $1.76, 2.53, 3.964$, respectively. We plot several randomly generated network topologies in the Fig. 3, and the metric comparison results are shown in the Tab. I. From Tab. I, most of the nodes obtained by CDBD are boundary nodes and those that are not boundary node are near the boundary nodes. In Fig. 3, we mark the nodes obtained by CDBD by red circles and the true boundary nodes by red stars. We also plot the sensing region of nodes obtained by CDBD in blue circles in the figure. From Fig. 3, we can see that CDBD has a quite accurate detection performance. What is more, the nodes obtained by CDBD are all near the sensing border of the network, and their sensing region forms a boundary barrier [18]. In our previous example of habitat monitoring, these nodes can be sufficient for estimating animals entering and departure form the RoI. Therefore, though CDBD does not find all absolute boundary nodes, it is desirable in terms of low communication overhead and minor degradation of application requirements. With the increase of sensing range r_s, the number of boundary nodes will decrease, while the number of k-hop neighboring nodes of a node will increase. However, by carefully choosing th_{bet} and th_{clo}, CDBD can still obtain a desired performance, and thus is robust to the parameter of sensing range.

We proceed to evaluate the impact of network size n on the boundary detection performance of CDBD. We fix $k = 2$, $r = 2.5$, and conduct simulation for $n = 49, 64, 81$ (results of case $n = 64$ can be found in Fig. 3). The threshold th_{bet} for $n = 49, 81$ are set to $1.65, 3.00$, and the threshold th_{clo} for $n = 49, 81$ are set to $1.75, 1.80$, respectively. The corresponding results are shown in Fig. 4 and Tab. I. Similar satisfactory performance is observed again. At last, we study the impact of k. We fix $n = 64$, $r = 2$, and perform simulation for $k = 2, 3, 4$ (results of case $k = 2$ can be found in Fig. 3). The threshold th_{bet} for $k = 3, 4$ are set $7.00, 9.50$, and the threshold th_{clo} are set $2.50, 3.80$, respectively. The corresponding results are shown in Fig. 5 and Tab. I. When k increases, the number of k-hop neighboring nodes of a node increases, thus the computation and communication cost of CDBD increases. From Fig. 5, we see that the performance however is not improved with k. Therefore, a small-value k (e.g., 2 or 3 in our simulation) is preferred in order to trade off communication cost and detection accuracy.

TABLE I
RTCO and ABD under different parameters

Parameters (varying r_s)	$r = 2$	$r = 2.5$	$r = 3$
RTCO	0.7826	0.7895	0.7143
ABD	0.1000	0.1667	0.3636
Parameters (varying n)	$n = 49$	$n = 64$	$n = 81$
RTCO	0.6875	0.7895	0.7727
ABD	0.1538	0.1667	0.1905
Parameters (varying k)	$k = 2$	$k = 3$	$k = 4$
RTCO	0.7826	0.7600	0.6667
ABD	0.1000	0.2800	0.2000

VI. Conclusions

In this paper, we have proposed a coordinate-free distributed boundary detection algorithm (CDBD). Our algorithm does not require nodal location information or rely on any specific sensing and communication models. It is very simple and can converge fast with low communication overhead for algorithm execution. Our extensive simulations validate the effectiveness of CDBD and its scalability as well as robustness. In the future, it will be interesting to investigate the relation between the thresholds th_{bet} and th_{clo} and the network parameters r_s, n and k, in order to improve CDBD's performance under different network settings, and develop a parameterless approach that dynamically adjusts the two thresholds to (near) optimal values according to the network conditions.

Acknowledgements

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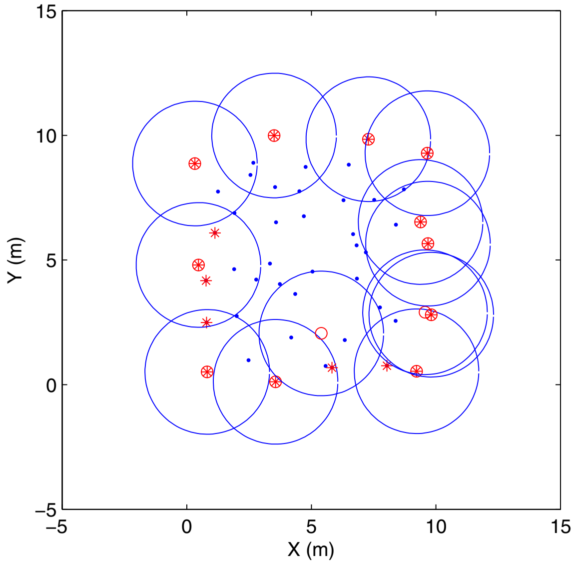
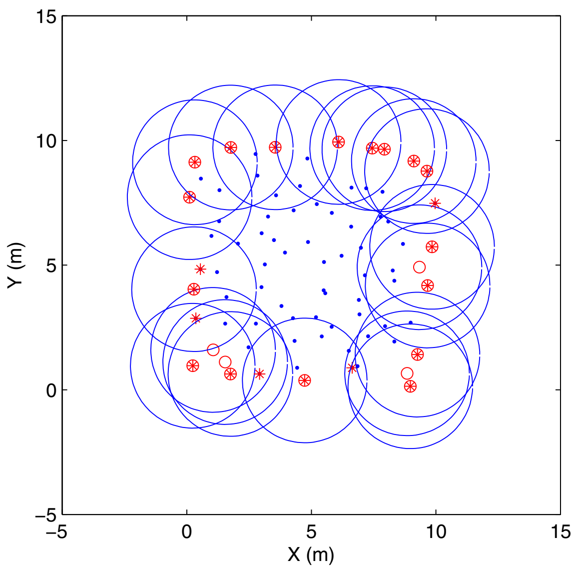
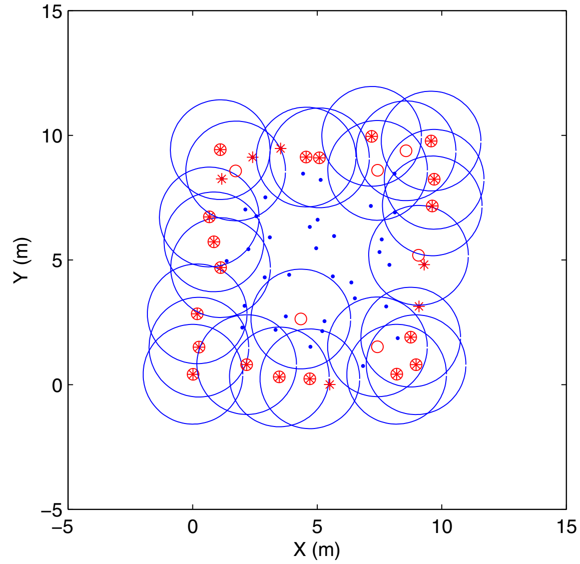
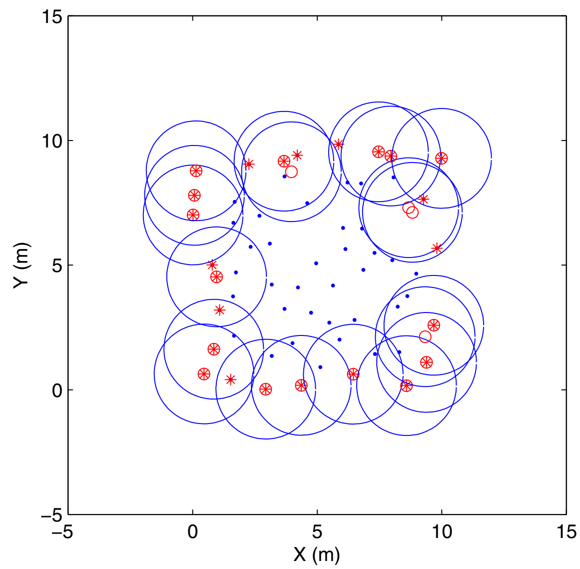




(b) $n = 81$.

Fig. 4. Nodes marked by red circle are obtained by CDBD when $n = 49, 81$ with other parameters being fixed. Their sensing regions are indicated by blue circles. Nodes marked by red star are the true boundary nodes.





(b) $k = 4$.

Fig. 5. Nodes marked by red circle are obtained by CDBD when $k = 3, 4$ with other parameters being fixed. Their sensing regions are indicated by blue circles. Nodes marked by red star are the true boundary nodes.

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