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Tree-based coverage hole detection and healing method in wireless sensor networks

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ABSTRACT

In wireless sensor networks, coverage is a fundamental issue affecting the quality of service. A coverage hole may appear anywhere in the area being monitored at any time because of many reasons. Thus, hole detection and healing have become major challenges towards achieving perfect coverage. This study provides a novel algorithm using trees and graph theory to detect and describe the existing holes in the region of interest. Simulation results show that the tree-based method can indicate the location, size, and shape of coverage holes accurately. Based on the results for hole detection, a tree-based healing method is also proposed. The method is divided into two phases, namely, hole dissection and optimal patch position determination. Results obtained from the experimental evaluation reveal that the proposed healing method can increase the coverage rate with only a few additional sensors compared to other related methods.

1. Introduction

Wireless sensor networks (WSNs) have excellent capabilities in monitoring physical environments. For this reason, WSNs have been extensively applied in both the civil and military fields, such as habitat monitoring, industrial diagnosis, ambient assisted living, and disaster recovery. In WSNs, sensor nodes are scattered across regions of interest (ROIs) to detect events and collect information. Covering the ROI adequately and capturing events and information efficiently are desirable. A complete coverage of the region guarantees the achievement of such requirements. However, coverage holes unavoidably appear in the ROI because of many reasons, such as random deployment, sensor destruction, and energy exhaustion of nodes [1]. The existence of coverage holes dramatically affects the performance of WSNs. For example, coverage holes aggravate the transmission burden of the boundary nodes of holes, which leads to hole diffusion because the energy of nodes on hole boundaries will be consumed rapidly [2]. Therefore, coverage hole detection and healing are major issues in WSNs.

The sensing range of any node in a WSN is commonly assumed to be a disk, with which the sensor collects the information on the surroundings [3, 4], such as temperature, humidity, concentration, and radiation. Due to their nature, the values of such data change in a continuous fashion. Therefore, their values on locations which are close to sensor nodes can be derived from nearby nodes, even though these locations are not directly sensed by any node. For instance, if we obtain the temperature of the nodes on the boundary of a hole, then the temperature of nearby points inside the coverage hole can also be derived [5]. In other words, the performance damage induced by small coverage holes can be ignored in WSNs. However, conventional methods for coverage hole detection and healing always concentrate on how to achieve 100% sensing coverage, thereby incurring unnecessary consumption of resources.

In this study, we mainly focus on the issue of coverage hole detection and healing in WSNs and ignore the effects of small coverage holes on the overall performance of a network. On one hand, coverage hole detection is a fundamental problem in evaluating the quality of services in WSNs. If the information about coverage holes, such as positions, sizes, and shapes, is inaccurately detected, then we cannot provide relevant methods to patch the uncovered regions. On the other hand, deploying only a few additional sensors to reduce the uncovered areas as much as possible is desirable. Therefore, determining the optimal patch positions for healing holes is another key issue in WSNs. The main contributions of this study include: (1) We propose a tree-based method to detect and describe the existing coverage holes in WSNs. The tree can accurately indicate the locations, sizes, and shapes of coverage holes. (2) On the basis of this tree description, we propose a method to dissect a large hole into several smaller holes. We determine the optimal patch position of each small sub-coverage hole to deploy additional sensors. Thus, multiple patch positions can be

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Table 1
Comparisons of coverage hole detection methods.

Proposed solution	Distributed /Centralized	Advantages	Drawbacks
Zhang [6]	Distributed	Positions of one-hop neighbors are needed	Coverage hole described with boundary nodes
Ma [7]	Distributed	Every hole inside the WSN can be found	Requires the absolute location Hole described with boundary nodes
Qiu [8]	Distributed	Detects holes without the requirement of accurate location	Does not provide the global view of holes Hole described with boundary nodes
Liu [9]	Centralized	Describes the sizes of holes accurately	High computational complexity
Bejerano [10]	Distributed	Provides accurate size estimations of holes.	High computational complexity May fail in sparse WSN
Kroller [11]	Distributed	No need about location information of sensor nodes	Require a high density of nodes
Saukh [12]	Distributed	Applies in both sparse and dense networks	Do not provide the accurate boundaries of coverage holes
Ghrist [13], Yan [14]	Distributed	Constructs complexes to detect holes	Miss several coverage holes

simultaneously determined at each round of iteration with low complexity.

The remainder of the paper is organized as follows: Section 2 summarizes the related work on the detection, description, and healing of coverage hole. Section 3 provides the preliminaries used in the study. Section 4 describes in detail the tree-based coverage hole detection method. In Section 5, we propose a hole healing method based on trees. Section 6 includes the simulations conducted to assess the performance of the proposed method. Finally, Section 7 concludes the paper.

2. Related work

Given that coverage is one of the important issues in WSNs, a large number of studies on detecting and healing coverage holes have been previously conducted.

The most common method to detect and describe coverage holes is by directly determining the boundary nodes of the holes. If boundary nodes are recognized, the coverage holes contained by the boundary nodes can be detected. Zhang *et al.*, proposed a localized method for detecting the boundary nodes of coverage holes through the Voronoi and neighbor-embracing polygons [6]. This method can be extended to monitor irregular ROIs, but to implement it, each node needs the position information of its one-hop neighbors. Ma *et al.*, provided a geometry-based distributed hole detection algorithm to determine the coverage holes in a post-deployment scenario and used the boundary nodes to describe the coverage holes [7]. In their method, each sensor node knows its absolute location information. Qiu *et al.*, proposed a Delaunay-based coordinate-free mechanism to detect coverage holes, and the boundary nodes were used to indicate the locations of holes [8]. However, this method cannot provide the global view of holes. The preceding works used the boundary nodes to describe the coverage holes. This is a common approach in hole detection. However, this kind of methods has a drawback: the coverage hole, which is surrounded by the boundary nodes, does not describe accurately the uncovered region. The estimated sizes of the coverage holes are always larger than the actual sizes of the corresponding coverage holes. Furthermore, in several cases, the coverage holes surrounded by boundary nodes may contain several sensor nodes inside themselves, which will be discussed in the subsequent section.

Many existing approaches utilize the intersections of the sensing disks of sensors to detect and heal coverage holes. In this type of approaches, the intersections of the sensing disks of the boundary nodes of holes are calculated. The unions of such intersection points are used to describe the holes. For example, Liu *et al.*, used the intersections of sensing disks to determine the locations and sizes of holes and employed a greedy method to patch the holes [9]. Yigal introduced the concept of the cycling segment sequence, which was used to construct a localized and efficient algorithm for coverage hole detection [10]. This algorithm is also based on the intersections of sensing borders. The coverage hole description using the intersections of sensing disks can provide accurate size estimations of holes. However, the coverage hole description using the intersections requires burdensome computation and estimation. This method may be impossible to implement locally in sensors and may also be ineffective in determining coverage holes in sparse deployments of sensor nodes. In sparse deployments, isolated sensors, whose coverage regions do not intersect with any other sensors, may appear. Thus, the isolated sensors cannot work with other nodes to determine the boundary of coverage holes.

The topological properties of WSNs are also adopted in several studies to detect and describe the coverage holes. Kroller *et al.*, presented an algorithm to search for several types of patterns, so-called flowers, which were further extended and merged in the augmenting phase of the algorithm to form a boundary of the network [11]. Saukh *et al.*, provided a solution for boundary recognition that approximates the boundary of the sensor network by determining the majority of the inner nodes through geometric constructions [12]. However, these types of methods require a high density of nodes. These methods may also fail to recognize the boundaries of holes accurately. Ghrist *et al.*, introduced the nerve complex and the Rips complex to indicate hole locations. They used homology to describe the detected coverage holes [13]. Yan *et al.*, proved that coverage holes can be detected through the use of the Cech and Rips complexes. Therefore, they proposed a homology-based distributed method to determine coverage holes [14]. Topology-based methods have an evident advantage: no accurate location information of sensor nodes is needed. However, these methods may miss several coverage holes. As shown in the literature [14], a homology-based algorithm can only detect non-triangular holes with the probability of 99% and cannot detect triangular holes.

Table 1 summarizes the main advantages and drawbacks of the aforementioned coverage hole detection methods. To avoid the drawbacks, we present a distributed method to detect all types of coverage holes and provide a tree-based description method to determine the locations and sizes of coverage holes accurately.

Several studies simply focused on the solutions of coverage hole healing. Wu *et al.*, proposed an iterative Delaunay triangulation-based method to eliminate existing coverage holes [15]. In their method, an optimal patch position was obtained in each iteration. A viable solution involves enhancing several sensors with mobile capability; then, the mobile sensors are relocated to heal the holes. For instance, Shen *et al.*, partitioned the area of a WSN into a number of grids and developed a method to move the sensors to the desired grids, thereby meeting the optimization requirements [16]. Wang *et al.*, provided a bidding protocol for mobile sensor deployment to achieve a balance between sensor coverage and sensor cost [4]. This protocol chooses the farthest Voronoi vertex from sensors as the target location of the additional sensor. Wang *et al.*, proposed a deterministic method to achieve a multilevel coverage