Computer Communications 81 (2016) 52–60

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Constrained node-weighted Steiner tree based algorithms for constructing a wireless sensor network to cover maximum weighted critical square grids

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ARTICLE INFO

Article history:
Received 2 April 2015
Revised 29 July 2015
Accepted 29 July 2015
Available online 6 August 2015

Keywords:
Wireless sensor network
Coverage problem
NP-complete problem
Sensor deployment

ABSTRACT

Deploying minimum sensors to construct a wireless sensor network such that critical areas in a sensing field can be fully covered has received much attention recently. In previous studies, a sensing field is divided into square grids, and the sensors can be deployed only in the center of the grids. However, in reality, it is more practical to deploy sensors in any position in a sensing field. Moreover, the number of sensors may be limited due to a limited budget. This motivates us to study the problem of using limited sensors to construct a wireless sensor network such that the total weight of the covered critical square grids is maximized, termed the weighted-critical-square-grid coverage problem, where the critical grids are weighted by their importance. A reduction, which transforms our problem into a graph problem, termed the constrained node-weighted Steiner tree problem, is proposed and used to solve our problem. In addition, three heuristics, including the greedy algorithm (GA), the group-based algorithm (GBA), and the profit-based algorithm (PBA), are proposed for the constrained node-weighted Steiner tree problem. Simulation results show that the proposed reduction with the PBA provides better performance than the others.

1. Introduction

Due to the growth and advances in networking and electronic hardware techniques, wireless sensor networks have developed rapidly. In a wireless sensor network, many small sensors are deployed in a field to detect the environment and collect sensing data, such as temperature, humidity, or light data. Each sensor can process, compute, and transfer data to others in wireless sensor networks. Many applications based on the wireless sensor networks have been developed [1–6], such as medical safety protection, fire and explosion monitors, and environment monitors. Because the efficiency of the wireless sensor network is often related to the sensor deployment, the coverage problem has thus become a hot research topic, and is studied in this paper.

In the coverage problem, barrier coverage is a typical problem for applications for theft prevention and illegal intruder monitoring. For these applications, when an illegal intruder comes into a barrier coverage area, at least one sensor in the area will detect the event to ensure area security. In [7], methods are proposed to select and activate minimum sensors from sensors that are randomly deployed in a field to form barrier coverage. In [8], a sink-constructed barrier coverage method is proposed to construct virtual barrier coverage for optimizing the detection degree, detection quality, and transmission latency of a wireless sensor network. In [9,10], methods are proposed to schedule mobile sensors to construct barrier coverage in order to eliminate blind spots. In [11], the deployment for barrier coverage is studied when sensors are dropped from an aircraft along a given path. The study shows that the barrier coverage of line-based normal random offset distribution provides better performance than that of the Poisson model.

Full coverage is an important problem for applications that continuously monitor an entire area [12,13]. In [14], efficient methods are proposed to schedule sensors to be activated or inactivated to form a wireless sensor network that can cover the entire sensing field. In [15,16], a deployment-polygon-based method is proposed to achieve full coverage and k-connectivity. In addition, their proposed method has been proved to have optimal solutions for constructing wireless sensor networks under different ratios of the sensor transmission range to the sensor sensing range. In [17], the method that uses a combination of static sensors and a mobile-robot is proposed to deploy sensors such that the sensing field can be fully covered. In [18], methods are proposed to activate sensors whose total cost is minimized to fully cover the sensing field. In [19], sensor deployment

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http://dx.doi.org/10.1016/j.comcom.2015.07.027
0140-3664/

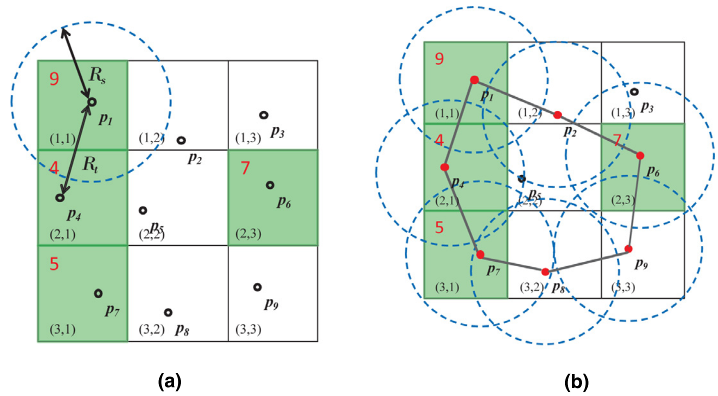

Fig. 1. Example of the weighted-critical-square-grid coverage problem. (a) A sensor field divided into 9 grids of squares with length ℓ, where $R_s = \frac{\sqrt{3}}{2}\ell$, $R_t = \ell$, every grid is labeled with a pair of numbers, four critical grids are labeled with (1, 1), (2, 1), (2, 3), and (3, 1) are shown in green, the weight of each critical grid is shown in red, and hollow circles are the points that are allowed to deploy sensors. (b) A wireless sensor network constructed by 7 sensors denoted by solid circles, where an edge between two sensors represents that the two sensors can communicate with each other. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

methods are proposed to fully cover an irregular sensing field by dividing the field into many sub-regions.

Recently, a new coverage problem that studies deploying minimum sensors to cover critical areas in a sensing field has received much attention. In [20], a critical-square-grid coverage problem is proposed and shown to be NP-complete. In the problem, a sensing field is divided into square grids. The problem is to deploy minimum sensors in the center of grids to cover all critical grids. In [21], an approximation algorithm, termed the Steiner-tree-based critical grid covering algorithm (STBCGCA), is proposed for the problem. In addition, in [22], improved methods based on STBCGCA are proposed to minimize the number of deployed sensors. Note that in [21,22], the sensors must be deployed in the center of square grids.

In reality, it is more practical to deploy sensors in any position in a sensing field. In addition, sensors are often characterized by various features, such as environmental detection, intruder detection, and nuclear, biological, chemical (NBC) attack detection [23–25], due to different monitoring objectives. The prices of the sensors may be costly such that only limited sensors can be used for deployment [26–28]. That is, the critical areas in the field may not be fully covered. Therefore, critical areas must be weighted by their importance. The more important a critical area, the higher the weight of the area. For example, in a wilderness ecological observation network [21,29], the nests of animals are more important than their foraging areas. This motivates us to study a coverage problem, termed the weighted-critical-square-grid coverage problem. In the problem, the sensing field is divided into weighted square grids. Although the number of sensors and the locations of points that are allowed to deploy sensors are given, the problem is to find a connected wireless sensor network such that the total weight of the covered critical grids is maximized. In the following sections, Section 2 illustrates the problem definition and its hardness. A reduction transformed from the weighted-critical-square-grid coverage problem into a general graph problem, termed the constrained node-weighted Steiner tree problem, is proposed in Section 3 to solve the coverage problem. In addition, three centralized heuristics, termed the greedy algorithm (GA), the group-based algorithm (GBA), and the profit-based algorithm (PBA), for the constrained node-weighted Steiner tree problem are proposed in Section 4. The simulations are discussed in Section 5 to show the performance of our proposed methods. Section 6 concludes the paper.

2. Problem definition and its hardness

We first introduce our problem, termed the weighted-critical-square-grid coverage problem, in Section 2.1. In Section 2.2, we discuss the hardness of the weighted-critical-square-grid coverage problem.

2.1. The weighted-critical-square-grid coverage problem

In this paper, the sensing model in the wireless sensor network is assumed to be a binary sensor model [18,22,30], in which the probability of detecting an event by a sensor u is 1 if the event is within u's sensing range R_s; otherwise, the probability is 0. In addition, the communication model is assumed to be a unit disk graph model [31], in which a sensor u can receive messages sent from sensor v if u is within the transmission range R_t of v. Let *Field* denote a sensing field, which is divided into grids of squares that have length ℓ. In *Field*, the set of points that are allowed to deploy sensors are denoted by *Location*. In addition, the set of grids that belong to critical areas are denoted by a weighted set *Critical*, where every grid $c \in$ *Critical* has a weight $w(c) \in Z^+$. Hereafter, grids in *Critical* are called critical grids. Here, a critical grid is said to be covered by a sensor v deployed on a point in *Location* if the grid is fully within v's sensing range [32]. Our problem, termed the weighted-critical-square-grid coverage problem, is the problem of finding a connected wireless sensor network W in *Field*, with at most n sensors, to cover critical grids in *Critical* of the maximum total weight, while the instance, containing R_s, R_t, n, *Field*, *Critical*, and *Location*, is given. The weighted-critical-square-grid coverage problem is illustrated as follows:

INSTANCE: R_s, R_t, n, *Field*, *Critical*, *Location*, and a positive integer k.

QUESTION: Does there exist a connected wireless sensor network W in *Field*, with at most n sensors deployed on the points in *Location*, such that W covers critical grids in *Critical* with total weight no less than k?

Take Fig. 1, for example. Fig. 1a shows an instance of the weighted-critical-square-grid coverage problem, containing R_s, R_t, *Field*, *Critical*, *Location*, where $R_s = \frac{\sqrt{3}}{2}\ell$, $R_t = \ell$, *Field* is the sensor field, *Critical* = $\{(1, 1), (2, 1), (2, 3), (3, 1)\}$, $w((1, 1)) = 9$, $w((2, 1)) = 4$, $w((2, 3)) = 7$, $w((3, 1)) = 5$, *Location* = $\{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9\}$. Here let $n =$ 7 in the instance. Fig. 1b shows a connected wireless sensor network W that has 7 sensors deployed on points p_1, p_2, p_4, p_6, p_7, p_8, and p_9, respectively. In addition, the total weight of the critical grids covered by W is 25.

2.2. The hardness of the weighted-critical-square-grid coverage problem

We show that the weighted-critical-square-grid coverage problem is NP-complete here. Because the problem of finding a minimum size connected wireless sensor network to fully cover all critical