Contents lists available at ScienceDirect

Discrete Applied Mathematics

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

Solving energy issues for sweep coverage in wireless sensor networks ☆

Barun Gorain, Partha Sarathi Mandal *

Indian Institute of Technology Guwahati, India

ARTICLE INFO

Article history:
Received 24 April 2015
Received in revised form 11 June 2016
Accepted 16 September 2016
Available online xxxx

Keywords:
Energy efficient
Energy restricted
Sweep coverage
Mobile sensor
Static sensor
k-TSP
k-MST
Approximation algorithms
Wireless sensor networks

ABSTRACT

Sweep coverage provides solutions for the applications in wireless sensor networks, where periodic monitoring is sufficient instead of continuous monitoring. The objective of the sweep coverage problem is to minimize the number of sensors required in order to guarantee sweep coverage for a given set of points of interest on a plane. Instead of using only mobile sensors for sweep coverage, use of both static and mobile sensors can be more effective in terms of energy utilization. In this paper, we introduce two variations in sweep coverage problem, where energy consumption by the sensors is taken into consideration. First, an energy efficient sweep coverage problem is proposed, where the objective is to minimize energy consumption by a set of sensors (mobile and/or static) with guaranteed sweep coverage. We prove that the problem is NP-hard and cannot be approximated within a factor of 2. An 8-approximation algorithm is proposed to solve the problem. A 2-approximation algorithm is also proposed for a special case. Second, an energy restricted sweep coverage problem is proposed, where the objective is to find the minimum number of mobile sensors to guarantee sweep coverage subject to the condition that the energy consumption by a mobile sensor in a given time period is bounded. We propose a $(5+\frac{2}{\alpha})$-approximation algorithm to solve this NP-hard problem.

1. Introduction

Coverage is one of the most important issues for environmental monitoring in wireless sensor networks (WSNs). In general, coverage is defined as the measurement of the quality of surveillance of sensing function of a WSN. Information from a target field are collected by deploying sensor nodes in different locations of the field. After deployment, sensor nodes in short sensors form a network through which the collected data are propagated to a sink. The quality of the collected information depends on how well the target field is covered by the set of sensors. Depending on the subject to be covered, coverage problems are broadly categorized into three types. The first one is point coverage [6,14,17], where a set of discrete points is continuously monitored, the second one is area coverage [2,18,21], where all points within a bounded region are continuously monitored, and the third one is barrier coverage [7,19], where specified path or boundary of a region is continuously monitored by sensors. For example, in forest monitoring [1], every location of the forest must be covered by at least one sensor in order to detect immediately any unusual activities like forest fire, activities of poachers, etc. Similarly, covering boundary of the forest allows controlling and elimination of the poaching activities and illegal entry through the boundary. A continuous monitoring with static sensors is required for the aforementioned types of coverage problems.

☆ A preliminary version of this paper appears in Proc. of International Conference on Algorithms and Discrete Applied Mathematics (CALDAM 2015).

* Corresponding author.
E-mail addresses: b.gorain@iitg.ernet.in (B. Gorain), psm@iitg.ernet.in (P.S. Mandal).

http://dx.doi.org/10.1016/j.dam.2016.09.028
0166-218X/

Please cite this article in press as: B. Gorain, P.S. Mandal, Solving energy issues for sweep coverage in wireless sensor networks, Discrete Applied Mathematics (2016), http://dx.doi.org/10.1016/j.dam.2016.09.028

But there are typical applications where only periodic patrol inspections are sufficient for a certain set of points of interest instead of continuous monitoring like traditional coverage. This type of coverage scenario is termed as *sweep coverage*. Sweep coverage concept in WSNs is introduced in the literature by Li et al. [15], where periodic patrol inspections are required for a given set of points of interest (PoIs) by a set of mobile sensors. As per the given definition, a point is said to be *t-sweep covered* if and only if at least one mobile sensor visits the point within every t time period, where t is called *sweep period* of the point. The objective of the sweep coverage problem is to find the minimum number of mobile sensors to guarantee sweep coverage for the set of PoIs.

Energy is a very important aspect which is needed to be considered while designing efficient algorithms for WSNs. Since the sensors have limited battery as the energy source, proper energy utilization can extend the lifetime of the sensors. In this paper, we consider an energy efficient sweep coverage problem with mobile and static sensors by minimizing the total energy utilization per unit time. The energy utilization by a sensor is restricted, that is why the activity is also restricted by the capacity of battery unless the battery is recharged or replaced. It is also recommendable to recharge or replace just before (at a limiting condition) exceeding the capacity of the battery for optimal resource utilization. So, with the restriction on maximum energy utilization, how to guarantee sweep coverage with the minimum number of mobile sensors is a challenging problem. In this paper, we consider an energy restricted sweep coverage problem where the maximum energy used by a mobile sensor in a given time period is bounded.

Contribution: In this paper, our contributions are as follows:

- We propose a variation of sweep coverage problem called energy efficient sweep coverage problem or ESweep coverage problem. The problem is NP-hard and cannot be approximated within a factor of 2 unless P = NP. We propose an 8-approximation algorithm to solve it.
- A 2-approximation algorithm is proposed for a special case of the above problem which is the best possible approximation factor.
- We introduce another variation of sweep coverage problem called energy restricted sweep coverage problem or ERSweep coverage problem and propose a $(5 + \frac{2}{\alpha})$-approximation algorithm to solve this NP-hard problem.

2. Related work

Several approaches are there in literature to overcome coverage problems in WSNs. Since, most of the coverage problems presented in [7,16,15] are NP-complete, several heuristics [4,18,21] and approximation algorithms [6,7] have been proposed to solve the problems. Point coverage problems are studied in [6,14,17]. In [6], the authors considered a geometric version of the point coverage problem called unit disk cover problem. The authors discussed the computational complexity of the problem which is NP-hard. A constant factor approximation algorithm was provided to solve the problem. Area coverage problems are studied in [3,4,18,22]. In [4], the authors proposed a fully distributed coverage preserving algorithm for WSNs with a set of static sensors. The algorithm extends network lifetime by the sleep and wake-up scheduling of the sensors. It guarantees network coverage without any off-duty conflict. Wang et al. [22] proposed three movement assisted algorithms for area coverage, which are vector based algorithm (VEC), Voronoi based algorithm (VOR) and Minimax. In the paper, Voronoi diagram is used to identify coverage holes. These movement strategies provide efficient improvements of the coverage with mobile sensors. Ma et al. [18] proposed a distributed heuristic, where in each iteration sensors move in such a way that the overall topology becomes closer to an equilateral triangulation of the plane and that is the optimal layout for area coverage.

The concept of sweep coverage initially comes from the context of robotics [3]. Recently there have been several works [5,8,15,23] found in the area of sweep coverage problem. Du et al. [8] proposed two different heuristics for different movement constraints on the mobile sensors. In the first heuristic *MinExpand*, mobile sensors move in the same path in every time period and in the second heuristic *OSweep*, the mobile sensors move in different paths in different time periods. Theoretical aspects of the sweep coverage problem is studied by Li et al. [15]. The authors proved that finding the minimum number of mobile sensors to sweep cover a set of discrete points is NP-complete. It is showed that this problem is equivalent to solve the Traveling Salesman Problem (TSP) and proved that the sweep coverage problem cannot be approximated within a factor less than 2. A $(2 + \epsilon)$-approximation and a 3-approximation algorithms are proposed. The authors remarked on the impossibility to design distributed local algorithm which can guarantee sweep coverage, i.e., a mobile sensor cannot locally determine whether all PoIs are sweep covered without global information. To extend the lifetime of sweep coverage, Yang et al. [24] utilized base station as a power source for refueling or replacing the battery of the mobile sensors periodically. The authors proposed two heuristics for sweep coverage with one base station and multiple base stations, respectively. Gorain et al. [10] proposed a 2-approximation algorithm to sweep cover a set of PoIs when all mobile sensors visit all PoIs. The authors discussed a distributed version of the proposed algorithm where a set of static sensors are considered as PoIs. Static sensors compute the number of mobile sensors and their movement schedule with initial locations for deployment by exchange of messages. The authors introduced area sweep coverage problem in this paper and proposed a 2-approximation algorithm for rectangular bounded regions. In [12], sweep coverage for a set of line segments called line sweep coverage problem is introduced and a 2-approximation algorithm is proposed in order to solve the problem. As an application of the line sweep coverage problem, a data gathering problem is formulated and solved with an approximation factor 3. In [13],