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Sensor deployment optimization methods to achieve both coverage and connectivity in wireless sensor networks

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A B S T R A C T

In this study, we aim to cover a sensing area by deploying a minimum number of wireless sensors while maintaining the connectivity between the deployed sensors. The problem may be reduced to a two-dimensional critical coverage problem which is an *NP-Complete* problem. We develop an integer linear programming model to solve the problem optimally. We also propose a local search (LS) algorithm and a genetic algorithm (GA) as approximate methods. We verify by computational experiments that the integer linear model, using Cplex, is able to provide an optimal solution of all our small and medium size problems. We also show that the proposed methods outperform some regular sensor deployment patterns.

1. Introduction

Nowadays, wireless sensor networks (WSNs) are considered among most effective tools in monitoring and tracking applications such as seismic monitoring, health care monitoring, and crop monitoring. A wireless sensor network is a set of connected sensors where each sensor node is capable of collecting some information, processing it, storing the information if necessary and communicating it via other sensors until the collected data reaches a base station (*called also the sink*) where necessary decisions have to be taken.

In most wireless sensor networks, the deployment of sensors is achieved either in a pre-planned manner or in an ad-hoc manner. The latter requires a large number of sensor nodes that have to be deployed randomly in the monitoring region. This method is generally used when the monitoring region's access is either impossible or costly to deploy (like in underwater sensing fields). The pre-planned deployment method is used when the sensing field access is easy and the sensors' deployment cost is not expensive.

In most pre-planned deployment cases, a good sensor deployment may bring great benefits such as better network management, energy and cost savings. In fact, covering an area with a minimum number of sensors minimizes the overall network cost, particularly when the sensor cost is high. Moreover, knowledge of an optimal sensor configuration will help to avoid improvised deployment, and will offer guidelines for later extensions in sensitive deployment situations.

In WSN literature, two types of sensor coverage problem are investigated: area coverage and target or point coverage. In the area coverage problem, the deployed sensors have to monitor a given area; whereas in the targets coverage problem, only a set of specific points (or targets) are monitored.

The sensor coverage problem can be further divided into either a *1-coverage* problem or a *k-coverage* problem. In the *1-coverage* problem, each target or point in the sensing field has to be covered by at least one active sensor. However, in the *k-coverage* problem, each target or point in the area needs to be covered by at least k different working sensors. Sometimes, the network coverage issue is closely related to the network energy consumption [1,3,6,7,10,13]. In our proposal, we do not consider the energy constraint; since we assume that each sensor can be powered by an energy source (this is true in many cases, like in fire detection sensors deployed in a large building).

In the last few years, the area coverage problem has been thoroughly studied. Ke et al. [11,12] proved that the problem of fully covering critical grids using a minimum number of sensors (known also as critical grid coverage problem) is *NP-Complete*. Charkrabarty et al. [8] propose a linear model for minimizing the cost of sensor deployment in a three-dimensional sensing field, while keeping a complete coverage area. In their study, the authors consider two types of sensors where each one has a specific cost. They also assume that each point in the grid has to be covered by at least k sensors. The developed linear formulation may be generalized to multiple sensor types. The authors also propose an approach based on the concept of identifying codes to determine sensor placement for unique target

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location. Anderson and Tirthapura [4] consider the same problem. However, instead of keeping a complete coverage area, they focus on partial coverage. The authors consider this problem as a set-cover problem with multiplicity k and they determine a lower bound based on a linear model. The obtained results show that the proposed approach minimizes the number of sensors while providing a high degree of coverage.

In the context of three-dimensional coverage, Alam and Haas [2] propose an approach based on the copy of a regular polyhedron with a small volumetric coefficient. Wang and Zhong [14] treat the problem of minimizing the cost of sensor placement in a three-dimensional sensing field. They develop a polynomial approximation algorithm with a proven approximation ratio. Zhou et al. [17] treat the k-coverage problem by minimizing the number of sensors in such a way that each point in the sensing field is covered by at least k distinct sensors while maintaining sensor connectivity. They propose a greedy algorithm that is a generalization of their centralized approximation algorithm designed for the 1-*coverage* problem.

Regarding the problem of achieving both total coverage and connectivity without considering the energy constraint, only a few studies have been proposed in the literature. Xing et al. [18] have proved that when the communication range R_{com} is at least twice the sensing range R_{cov}, the connectivity is automatically achieved when the total coverage is reached. In the case where the communication range $R_{com} \geq \sqrt{3}R_{cov}$, the triangular lattice pattern provides both coverage and connectivity. When $R_{com} = R_{cov}$, a strip deployment pattern is near optimal [9]. Bai et al. [5] propose an optimal deployment pattern to achieve both total coverage and 2-*connectivity* for each value of R_{com}/R_{cov} ratio. The simulation results show that their method is more efficient than some regular deployment patterns in terms of the number of sensors needed to provide coverage and connectivity. To the best of our knowledge, no results are known for general values of R_{com}/R_{cov} ratio. This contribution is the first to consider the connectivity constraint between the deployed sensors without imposing restrictions on the R_{com}/R_{cov} ratio, as in [18], or on the number of sensor connections, as in [5].

The developed methods are based on an integer linear formulation, a local search (LS) algorithm and a genetic algorithm (GA). The results of our methods are compared to the results of some regular deployment patterns such as hexagon pattern, square grid pattern, triangular lattice and rhombus-based pattern [5].

A review of other existing works on the area coverage problem may be found in [15,16,19].

The remainder of this paper is organized as follows. In Section 2, the problem description and necessary notations are given. In Section 3, an integer linear model is proposed. In Section 4, the approximate methods are presented. Section 5 illustrates the simulation results. Finally, we conclude the paper by summarizing our main contributions and giving an idea about our future works.

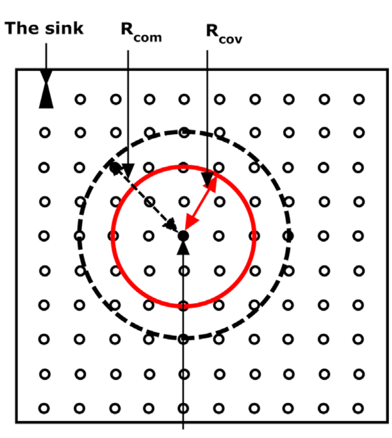

Fig. 1. The problem characteristics.

2. Problem description and assumptions

In this study, we aim to cover a two-dimensional sensing area fully using a minimum number of sensors. The deployed sensors have to be connected in an efficient way such that each deployed sensor can find a connection path (i.e., a set of connected sensors) to reach the base station. We assume that the sensing area may be represented by a grid $M \times N$ ($width \times length$) which is digitized into $M \times N$ points. The distance separating each two adjacent points is equal to 1 measurement unit. A sensor device, placed at the (i,j) grid position, has a sensing range R_{cov} and a communication range R_{com}. Using R_{cov}, the sensor covers each position (k,t) in the grid which verifies $(i-k)^2+(j-t)^2 \leq R_{cov}^2$. Using R_{com}, the sensor communicates the collected information to a next sensor in the (p,q) grid position such that $(i-p)^2+(j-q)^2 \leq R_{com}^2$, and so on until the information reaches the base station located at the grid position (l, w). Fig. 1 summarizes the problem characteristics of a grid of 10×10, $R_{cov}=2$ and $R_{com}=3$.

We assume in this work that the communication range R_{Com} is greater or equal than the coverage range R_{Cov}.

3. Integer linear programming model

In this section, we first propose some definitions. After that, we present the integer linear model. Then, we propose an improved form of the developed integer linear model which contains a minimum number of decision variables.

3.1. Definitions

Definition 1. Let (l,w) be the coordinates of the pre-fixed base station (i.e., *the sink position*) in the grid.

Definition 2. Let $F_{k,t} = \{(i,j)/(k-i)^2+(t-j)^2 \leq R_{cov}^2;\ i \neq l, j \neq w;\ i=1\ldots M; j=1\ldots N\}$ be the set of sensor positions that may cover the grid point (k,t).

Definition 3. Let $C_{p,q} = \{(i,j)/(p-i)^2+\ (q-j)^2 \leq R_{com}^2;\ i \neq l, j \neq w;\ i=1\ldots M;\ j=1\ldots N\}$ be the set of sensor positions that may communicate with the (p,q) sensor position.

3.2. Integer linear programming formulation

The integer linear model is based on the idea of selecting the required sensor positions in the grid which are connected to the sink via p sensors ($p=0\cdots\lceil(M\cdot N)/R\rceil$). Let us consider as decision variables:

$$z_{ij}^p \begin{cases} 1 & \text{if a sensor in } (i,j) \text{ position is connected to the sink via } p \text{ sensors} \\ 0 & \text{otherwise} \end{cases}$$

The linear model may be written as follows using the above decision variables:

$$min \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{p=0}^{\lceil(M\cdot N)/R\rceil} z_{ij}^p$$

subject to

$$\sum_{(i,j)\in F_{kt}}\ \sum_{p=0}^{\lceil(M\cdot N)/R\rceil} z_{ij}^p \geq 1 \quad \forall k=1\cdots M,\ \ \forall t=1\ldots N \tag{1}$$