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A genetic algorithm based exact approach for lifetime maximization of directional sensor networks

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ABSTRACT

This paper addresses the problem of maximizing lifetime of directional wireless sensor networks, i.e., where sensors can monitor targets in an angular sector only and not all the targets around them. These sectors usually do not overlap, and each sensor can monitor at most one sector at a time. An exact method is proposed using a column generation scheme where a two level strategy, consisting of a genetic algorithm and an integer linear programming approach, is used to solve the auxiliary problem. The role of integer linear programming (ILP) approach is limited to either escaping from local optima or proving the optimality of the current solution. Computational results clearly show the advantage of the proposed approach over a column generation approach based on solving the auxiliary problem through ILP approach alone as the proposed approach is several times faster.

1. Introduction

Rapid advancements in embedded systems and wireless communication technologies have facilitated the wide spread use of Wireless Sensor Networks (WSNs) for data gathering in remote or inhospitable environments such as battlefield surveillance, fire monitoring in forests, ecological and tsunami monitoring in deep sea. Under such environments, sensors are usually deployed in an *ad hoc* or *random* manner as their accurate placement is ruled out owing to risks and/or cost considerations. To cope with this random deployment, more sensors are deployed than actually required. This over deployment also makes WSNs more resilient to faults as some targets are redundantly covered by multiple sensors. Each sensor operates on a battery that has a limited lifetime. Moreover, replacement of batteries is not possible in remote or inhospitable environments. Therefore, prolonging the network lifetime by making best use of available resources is of prime concern in the design of WSNs for such environments. Most of the existing techniques for prolonging the network lifetime make use of redundancy in sensor deployment. These techniques divide the set of sensors into a number of *subsets* or *covers* (not necessarily disjoint), such that sensors in each subset covers all the targets. Amount of time during which each cover is used is also determined. Then, these covers are activated one-by-one for their determined time duration, i.e., at any instant of time only sensors belonging to a single cover are active, whereas all other sensors are inactive. This leads to a significant increase in lifetime because of the following two reasons. First, energy consumption of sensors in inactive state is negligible in comparison to active state [1,2], and, therefore, only keeping a required minimum subset of sensors active at any particular instant of time saves a lot of energy. Second, a sensor's battery lasts for longer duration, if it oscillates frequently between active and inactive states. In fact, if a battery is discharged in many short bursts with considerable off time then its lifetime may double in comparison to a situation where it is discharged continuously [3,4].

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This paper is concerned with the lifetime maximization problem mentioned above in the Directional Sensor Networks (DSNs), i.e., wireless sensor networks consisting of directional sensors only. Directional sensors can monitor targets in an angular sector only and not all targets around them. Video sensors [5,6], ultrasonic sensors [7] and infrared sensors [8] are common examples of directional sensors. In this paper, directional characteristics of sensors are assumed to be limited to sensing only and not to their communication ability. The sensing ability of directional sensors can be extended in several ways [9,10]. We can place several directional sensors of the same type on one sensor node in such a way that each sensor covers a different angular sector. A practical example of this kind of arrangement can be found in [8], where four ultrasonic sensors are placed on a single node to detect ultrasonic signals from any direction. Alternatively, each sensor node can be fitted with a mobile device so that nodes can move around. Another possibility is to equip each sensor node with a device that can switch the direction of the sensor over a range of directions in such a way that it can sense in all the directions though not at the same time. The direction of an active sensor at any instant of time is called its work direction at that instant of time. Like several previous approaches [9–13], in this paper we have considered the last model and assumed that several possible directions in which a sensor can work do not overlap and a base station is located within the communication range of each sensor, i.e., we have not discussed the connectivity issue of the active sensors.

The lifetime maximization problem in directional sensor networks, which we denote by LM-DS (Lifetime Maximization with Directional Sensors), can be formally stated as follows. Given m targets with known locations and n directional sensors randomly deployed in the vicinity of the targets, each sensor, when active, can monitor targets in one of σ non-overlapping directions at any instant of time and the sensor i has battery life b_i. The LM-DS problem consists in scheduling the sensor's activity in such a way that the network lifetime is maximized under the restriction that during the entire lifetime, each target is covered by the work direction of at least one active sensor. It has been shown in [14] that the problem is $\mathcal{NP}$-Hard in the strong sense even when there is no restriction due to the work direction (i.e., all sensors have a 360° sensing ability), then so is LM-DS, which is a generalization of this problem. Figs. 1 and 2 illustrate LM-DS with the help of a simple example. Fig. 1 shows a simple directional sensor network with $n = 9$, $m = 4$ and $\sigma = 4$. For the sake of simplicity, all sensors are assumed to have the same orientation and same battery life time of one time unit. Fig. 2 shows an optimal solution to LM-DS problem in directional sensor network of Fig. 1 with nine covers and total lifetime of 2.25 units. Fig. 2 shows for each cover, the work direction of each active sensor in that cover as a shaded sector centered at that active sensor. The time duration of each cover is also mentioned in this figure.

All the approaches available in the literature for LM-DS are heuristic in nature, i.e., there is no guarantee of the optimality of the obtained solution. In contrast to the existing approaches, this paper describes an exact approach based on column generation for the LM-DS. Column generation based approaches have already been used successfully for addressing lifetime maximization problems in wireless sensor networks [15–18]. However, so far no one has addressed lifetime maximization problems in directional sensor networks using column generation based approaches. This has motivated us to develop the approach described in this paper.

When a linear program consists of a very large number of variables and a reasonably low number of constraints, it can be decomposed through Dantzig–Wolfe decomposition algorithm into two subproblems which are referred to as the master problem, and the auxiliary problem. A column generation approach [19–21] alternately solves the master problem and the auxiliary problem until an optimal solution is found. The master problem is a version of the original problem with reduced number of variables, and the auxiliary problem generates one or more variables (a variable is represented by a column in the constraint matrix of the master problem) for adding into the master problem provided that these variables can aid in further improving the objective function value. The variables, which can aid in further improving the objective function value, have a strictly positive reduced cost ([22]), and are termed attractive. Indeed, by the linear programming theory, any non-basic variable with a positive reduced cost has a potential for increasing the objective function value in a maximization problem, whereas the variables that have a non-positive reduced cost cannot help in improving the current basic solution. If it can be proved that no attractive variables exist, then the current solution to the master problem is also proved optimal, and the column generation approach stops. Otherwise, the auxiliary problem returns one or more attractive variables which are added to the master problem and the whole process is repeated.

Clearly, in the context of LM-DS problem, covers are the variables. Therefore, to use column generation approach, LM-DS problem is decomposed as follows:

1. A master problem that schedules existing covers with the objective of maximizing the network lifetime.
2. An auxiliary problem that builds attractive covers for the master problem, so that it can maximize the network lifetime even further.

To solve the auxiliary problem, a two level procedure consisting of a genetic algorithm and an integer linear programming approach is used. First, the genetic algorithm (GA) is used to solve the auxiliary problem. If it fails to find even one attractive cover then another run of the GA is made. If this also fails, then the integer linear programming approach (ILP) is used as a last resort. If ILP also fails to find an attractive cover then that means that the current solution to the master problem is optimal and the column generation process stops. Therefore, the ILP is used only for escaping from local optima or proving the optimality of the current solution. As ILP, in general, consumes much more time than GA and produces a single cover, whereas GA can generate multiple covers, restricting the use of ILP can lead to significant savings in execution time. Our