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Wireless sensor network lifetime maximization by optimal sensor deployment, activity scheduling, data routing and sink mobility

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ABSTRACT

The longevity of Wireless Sensor Networks (WSNs) is a crucial concern that significantly influences their applicability in a specific context. Most of the related literature focuses on communication protocols aiming to reduce the energy consumption which would eventually lead to longer network lifetimes. On the other hand, a limited number of studies concentrate on providing a unifying frame to investigate the integrated effect of the important WSN design decisions such as sensor places, activity schedules, data routes, trajectory of the mobile sink(s), along with the tactical level decisions including the data propagation protocols. However, a monolithic mathematical optimization model with a practically applicable, efficient, and accurate solution method is still missing. In this study, we first provide a mathematical model which integrates WSN design decisions on sensor places, activity schedules, data routes, trajectory of the mobile sink(s) and then present two heuristic methods for the solution of the model. We demonstrate the efficiency and accuracy of the heuristics on several randomly generated problem instances on the basis of extensive numerical experiments.

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1. Introduction

Wireless sensor networks (WSNs) are formed by the collaborative effort of a large number of low-power, low-cost, multi-functional electronic devices called sensors. Sensors are deployed over a region of interest called the sensor field. They are capable of observing the area within their sensing range and sending the collected data to neighboring sensors within their communication range. All the data are finally sent to the central devices called sinks in a one-hop or multi-hop fashion. Distributed monitoring of the environment including inaccessible areas by the collaboration of multiple sensors is the very essence of WSNs, which explains their broad application range [1].

WSNs can be categorized according to sensor types they include. The type of the sensor depends on the technical characteristics such as the unit cost, sensing and transmission ranges. Homogeneous WSNs include only one type of sensor while heterogeneous WSNs consist of more than one sensor type. Another kind of WSN categorization is with respect to the characteristics of the coverage requirements of the field. Coverage requirements can be the same throughout the sensor field or some part of it may be more critical than others, and require a higher level of surveillance. In the former the WSN is said to be uniform, which becomes differentiated in the latter. Besides, the coverage requirements of the sensor field can approximately be represented by means of a finite set of points. Sensors may also have different working status such as standby and active. A standby sensor does not sense, transmit or receive any data throughout the standby period and the energy it uses is negligible. It should be noted that standby mode

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is different than sleep mode since a sensor in sleep mode continues to sense and uses energy. On the other hand, an active sensor senses, transmits and receives data and consumes energy for these operations.

The design of a WSN involves in four main decisions. First, sensor locations satisfying the budget restrictions and coverage requirements with a certain flexibility for individual sensor failures should be determined. Locations are also influential on the energy consumption of the sensors as the energy used during a transmission depends on the distance between the transmitter and the receiver. Thus, network designers should not only meet budget and coverage requirements but also take into account the energy consumption distribution among the sensors while determining sensor locations. The second decision to be considered in WSN design is the activity schedule of the sensors, which is a fundamental issue concerning energy consumption. A proper activity schedule results in an even distribution of the energy load among the sensors, since it enables resting relatively tired sensors for a while by putting them into standby mode. It should be noted that there must be enough active sensors at any time so that the WSN is fully operational throughout the network lifetime in the sense that the coverage requirements over the network field are satisfied. On the other hand, the network lifetime is defined as the time elapses until any active sensor set fails to satisfy the coverage requirements over the network field. Moreover, active sensors must form a connected network so that each can transmit its data to one of the sinks directly or indirectly through other sensors. It should also be underlined that the number and locations of the sensors significantly affect the quality of the sensor activity schedules. Therefore, these two design issues should be integrated. The third important decision involved in the design of a WSN follows from a phenomenon called as “the crowded center effect” [2], or “energy hole problem” [3,4], or “sink neighborhood problem” [5]. It is a well known fact that the sensors connected directly to a sink deplete their energy much faster than the rest of the network since they carry all the data collected by the sensors. A remedy for this problem suggests altering the neighboring sensor subsets by letting the sinks move over the sensor field in a controlled manner. Finally, the fourth main WSN design decision is the determination of the most efficient sensor-to-sink message flows. For the given sink and active sensor locations, it is relatively easy to find the most efficient data routes between sensors and sinks extending the network lifetime. However, the quality of the routes solely depends on the locations of the sensors and the sinks. A final note is that although it is easier to implement an a priori data propagation method such as the shortest path data routing protocol for the determination of data routes, it is possible to enhance the network lifetime significantly at the expense of a tolerable amount of extra computation time for the determination of the optimal sensor-to-sink data routes.

Although a rich literature on the optimal WSN design for maximizing lifetime exists, all but one of the mathematical optimization models from the literature takes only a subset of the aforementioned design issues into consideration. In other words, most of the mathematical models do not attempt to handle all the design criteria optimally at once but concentrate on a subset of the decisions while assuming that the rest of the decisions have been already made. Therefore, resulting WSN designs are suboptimal in terms of the network lifetime independent of the considered design issues. On the other hand, the mixed integer linear programming (MILP) model given in Keskin et al. [6] is the only one which takes all the above mentioned WSN design criteria into account. However, a unified framework which aggregates the aforementioned theoretical approach with practically applicable, efficient, and accurate solution methods is still missing. To be more precise, at the level of integration employed in the MILP of Keskin et al. [6], there exists a huge number of binary decision variables which make it impossible to obtain near optimal WSN designs especially for realistic sized instances. This obliges designers to resort to heuristic solution approaches. Therefore, in this study, we first provide a mathematical model which integrates WSN design decisions of sensor places, activity schedules, data routes, trajectory of the mobile sink(s) and then present two practical heuristic methods for the solution of the model. We demonstrate the efficiency and accuracy of the heuristics by extensive numerical experiments.

The rest of the paper is organized as follows. In the next section, a brief review of the mathematical optimization literature on the WSNs with mobile sinks is provided. Section 3 includes the mathematical model which integrates sensor location, activity schedule, data routes and sink mobility issues. Section 4 introduces heuristics that compute a feasible solution of the mathematical model given in Section 3. The efficiency and the accuracy of the developed heuristics are demonstrated using test problems in Section 5. Section 6 concludes the paper and points out possible future research directions.

2. Literature review

WSN studies with mobile sinks can roughly be grouped in two main classes: the ones concentrating on the coordination of the network so that the extra overhead due to the mobile sink(s) is compensated and those that focus on the determination of efficient mobile sink locations.

Studies belonging to the first class consider a given (constant or random) trajectory of the sink and propose data communication and propagation protocols aiming to improve some performance metrics of the network such as the energy, throughput, accuracy, message latency and message loss rate. We direct the interested reader to Hamida and Chelius [7], which analyzes the existing state-of-the-art data dissemination protocols with mobile sinks. Studies in the second class pay attention to the explicit decisions about sink moves. Furthermore, most of them provide mathematical models that optimize some WSN performance criterion such as the network lifetime, total energy spent and total cost for given data propagation protocols.

Our study belongs to the second group according to this rough classification. Therefore, we review in particular all the important studies that provide mathematical models

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