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Integrated topology control and routing in wireless sensor networks for prolonged network lifetime

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This study considers an integrated topology control and routing problem in wireless sensor networks (WSNs), which are employed to gather data via use of sensors with limited energy resources. We employ a hierarchical topology and routing structure with multiple sinks and devise a topology control scheme via usable energy fraction at the sensors. We develop and examine three different mathematical models whose solutions prescribe clusterhead and sink locations and data routing from sensors to sinks in a period of a deployment cycle. We develop a heuristic solution algorithm which provides very small optimality gaps for the models. The approach utilizes two types of solution representations, a combination of multiple neighborhoods, and objective value-based cut inequalities for improving the evaluation of candidate solutions. We present extensive numerical test results and analysis of the models and the solution approach. We determine that our proposed model, which minimizes average energy usage and the range of remaining energy distribution at the sensors, captures important characteristics of topology control and routing integration in WSN design and exhibits significantly better performance than our benchmark models and a well-known protocol HEED in extending network lifetime.

1. Introduction

Wireless sensors are used to sense a wide range of natural or artificial phenomena including temperature, pressure, humidity, light, motion, weight, noise, etc. Wireless sensor networks (WSNs) can be employed for data gathering purposes in inhospitable environments and difficult-to-reach terrains, such as forests, urban or rural battlefields, and borderlines; in wild habitats and oceans to monitor and observe natural phenomena; in disaster prevention and relief; in urban environments to monitor and control traffic; and in industrial settings to track inventories and the state of other resources [37]. Recently, data-gathering WSNs find increasingly widespread applications in ecological and environmental monitoring [13,14,29].

Two fundamental and related problems for effective and efficient design and operation of WSNs are *topology control*, which refers to the determination of an underlying network topology and *routing*, which refers to the determination data transfer paths over this network. The relationship between these problems is emphasized by WSN-specific attributes – *energy efficiency* and *computation-communication trade-off*. Energy efficiency is important because each sensor is equipped with an on-board nonrenewable power unit. The communication-computation trade-off refers to the fact that communication consumes more energy than performing computations on-board in a sensor [36].

In general, the lifetime of a sensor network can be defined as the time frame between two successive sensor deployments, i.e., a deployment cycle. A deployment cycle consists of successive *periods* of fixed time length for which topology and/or routing decisions are made. Thus, prolonging the network lifetime corresponds to obtaining the maximum number of successive periods that the data

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generated at the sensors can reach the user. In our case, the end of a deployment cycle is reached when it is not possible to obtain a feasible solution to the problem of transmitting data generated at the sensors to the user.

In this paper, we develop power-aware mathematical models and solution approaches for the *integrated topology control and data routing problems* to prolong the lifetime of a WSN. To this end, we consider three models that differ mainly in terms of their objective functions. The objectives include minimization of (1) *total or average energy usage in the system*, (2) *maximum energy used at a sensor node*, and (3) *a weighted sum of the range of end-of-period remaining energy distribution at the sensors and the average energy used in the system*.

We adopt a hierarchical data flow structure in which data generated at the sensors are first routed to the sensors designated as clusterheads (CHs). Each sensor is assigned to at least one CH which reduces the total data size that it receives from sensors via aggregation. Each CH routes data to a sink either through other CHs, which act only as relays without aggregation, or directly. Such a structure is beneficial in terms of energy efficiency in three ways: (1) Since the sensors in close proximity of each other are likely to be in the same cluster and may generate very similar data, data aggregation at CHs helps to reduce redundancy and energy consumption in communication. (2) Hierarchical structure distributes the energy usage to multiple sensors on multi-hop paths, thus eliminating the quick expiration of the sensors away from the sinks. (3) Since energy dissipation in communication is proportional to the square of the distance, compared to direct communication, the total energy dissipation due to communication is less on a multi-hop route [31].

Our contributions in this paper can be summarized as follows.

1. We devise three mathematical models for integrated topology and routing decisions for data-gathering WSNs. The objectives, minimization of total (or average) energy usage in the network and minimization of the maximum energy usage at a sensor, are commonly considered in devising communication protocols (e.g., [15,16,25,27,28,38]). However, this has not been done from an integrated mathematical modelling perspective as in our case. We consider these two models as benchmark models for our third proposed model, which minimizes the total energy and the range of remaining energy distribution in the network.
2. In devising our models, we consider the use of multiple sinks. This is helpful for energy efficiency since multiple sinks create an opportunity for better proximity to sensors, thus saving energy in communication. It is possible to route the data so that the energy drainage in the network is more evenly distributed to the sensors by changing the locations of the sinks and the CHs in each period. Xue et al. [39] also consider multiple sinks, however, with known locations as opposed to our case where the locations are also determined.
3. We suggest a new approach to achieve topology control via limiting the usable energy at a sensor as a fraction of its total available energy. We show that how this usable energy determined is important and difficult in our two benchmark models. On the other hand, the solution in the proposed third model is insensitive to this characteristic as the control of energy distribution is implicitly accounted in the objective.
4. We consider cases where an overall view of a measure, such as spatial and temporal temperature/humidiy/pressure gradients in a large sensor field deployed for environmental monitoring, is of interest. To this end, we employ a general data aggregation approach at the CHs that represents the elimination of data redundancy mentioned above. We assume that the aggregation ratio increases with increasing sensor deployment density. In previous studies with data aggregation (e.g., [15,16,19,42]), we observe that aggregation of data into a single signal at each CH, i.e., regardless of the amount of data received, is common which is applicable in such cases as monitoring maximum temperature in the sensor field.
5. Since the models dictate large discrete optimization formulations, obtaining exact solutions are highly impractical using exact optimization methods such as a branch-and-cut algorithm. Thus, we develop a heuristic solution algorithm which provides very small optimality gaps for the models. The approach utilizes two types of solution representations, a combination of multiple neighborhoods, and objective value-based cut inequalities for improving the evaluation of candidate solutions. Computational evidence demonstrates that our proposed third model performs significantly better than both benchmark models. Furthermore, we compare the performance of the proposed model to a well-known protocol HEED [42] and show that our proposed model performs significantly better in terms of network lifetime.

The rest of this paper is organized as follows. After a literature review in Section 2, we introduce the notation, problem definition and the optimization models in Section 3. In Section 4, we develop algorithmic approaches for solving our mathematical models. In Section 5, we provide computational results illustrating the performance of our algorithms, impact of usable energy fraction on network lifetime, and a comparison of the models in single-and multi-period settings as well as a detailed analysis based on energy characteristics and network lifetimes. Finally, in Section 6, we present a summary and conclusions.

2. Related literature

In the WSN literature, extensive effort has been invested in developing energy efficient protocols and routing paradigms to maintain a requested WSN topology. In this section, we provide an overview of the topology control and routing studies, and point out most relevant studies to our work.

Topology control is mainly achieved by the adjustment of sensors' transmission ranges, which is related to the power level settings at the sensors [30,31]. Topology