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Energy-efficient topology control algorithm for maximizing network lifetime in wireless sensor networks with mobile sink

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ABSTRACT

Uneven energy consumption is an inherent problem in wireless sensor networks characterized by multi-hop routing and many-to-one traffic pattern. Such unbalanced energy dissipation can significantly reduce network lifetime. In this paper, we study the problem of prolonging network lifetime in large-scale wireless sensor networks where a mobile sink gathers data periodically along the predefined path and each sensor node uploads its data to the mobile sink over a multi-hop communication path. By using greedy policy and dynamic programming, we propose a heuristic topology control algorithm with time complexity $O(n(m+n\log n))$, where n and m are the number of nodes and edges in the network, respectively, and further discuss how to refine our algorithm to satisfy practical requirements such as distributed computing and transmission timeliness. Theoretical analysis and experimental results show that our algorithm is superior to several earlier algorithms for extending network lifetime.

1. Introduction

In recent years, mobile data gathering by deploying a mobile sink in wireless sensor networks (WSNs) has attracted much interests from researchers [1]. A WSN is a multi-hop wireless ad hoc network with hundreds or thousands of unattended sensors. Since most sensor nodes are powered by limited disposable batteries, the energy consumption becomes one critical constraint in WSNs. The mobile sink could be a mobile robot or a vehicle equipped with powerful transceiver, battery, and large memory. The purpose of deploying the mobile sink is to reduce the communication expense among sensor nodes. In large-scale WSNs, to ensure that the sensed data are delivered to the base station in time, the mobile sink could not move nearby every sensor node and collect data one by one, thus only sensors that are deployed near the mobile sink's trajectory can directly send data to the mobile sink and other nodes should transmit their data to the mobile sink in a multi-hop manner, as shown in Fig. 1. This results in highly nonuniform energy usage among sensors. The energy of the sensors near the trajectory is depleted much faster than that of others since these sensors need to relay much more packets for the sensors far away from the trajectory. As a result, after these sensors fail, the network becomes disconnected even though most sensors still have plenty of energy.

Based on those observations, we focus on how to prolong network lifetime in large-scale WSNs with mobile sink. We adopt the definition of network lifetime as the time until the first node exhausts its energy, which has been widely used. We assume that the trajectory is pre-determined by the algorithms [2,3] or it is fixed due to environmental restriction. Comparing with prolonging network lifetime in WSNs with static sinks, the problem of maximizing network lifetime in WSNs with mobile sink has its particular difficulties:

(1) The trajectory may be irregular and the nodes which take charge of forwarding data to the mobile sink may be far away from each other, thus the corona-based algorithms such as EBDG [4] are infeasible.
(2) Lack of central node increases the difficulty of coordination among sensor nodes, especially for the design of distributed algorithms.

In this paper, we consider taking advantage of topology control to select forwarding path and transmission power for each sensor node. The key idea of topology control is that, instead of transmitting with the maximal power, the nodes in a wireless multi-hop network collaboratively determine their transmission powers and define the network topology by forming the proper

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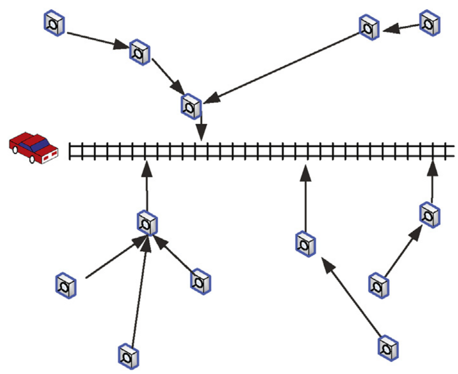

Fig. 1. Sensors transmit data to mobile sink by relaying in a multi-hop manner.

neighbor relation under certain criteria. In our algorithm, we try to reduce transmission powers of the nodes that have less residual energy. For such nodes have heavier loads, we consider reducing the amount of their relayed data so that the lifetime of all these nodes is maximized. Compared with existing algorithms such as MNL [5] and LOCAL-OPT [6], experimental results show that the network lifetime can be prolonged more than 15% by our proposed algorithm. Another advantage of our algorithm is having a lower computation complexity by getting rid of the redundant computations to the greatest extent.

In addition, we show that our algorithm can be implemented in a distributed manner where only using local information can mitigate the imbalance of the loads and prolong network lifetime to a certain extent. Furthermore, we improve our algorithm by considering the forwarding delay because it exists in real data gathering environments.

The rest of this paper is organized as follows: Section 2 gives an overview of the related work. We then define the problem in Section 3 and present algorithms in Section 4 and 5. Section 6 shows experimental results. The last section concludes this paper and discusses possible directions for future research.

2. Related work

2.1. WSNs with mobile sinks

In recent years, a number of approaches considering sink mobility in WSNs have been proposed [1,7]. The mobile sink may visit each sensor node and gather its data (single-hop communication) [8–15] or may visit only a small portion of sensor nodes and gather data by multi-hop communication [16–18,3,19–21]. In single-hop communication solution, since each node need not relay data for other nodes, energy consumption is minimized. However, this solution results in high data delivery delay, so it may be infeasible in large-scale WSNs. For multi-hop communication solution, one main problem is how to select a path for each sensor node to forward data to mobile sink. The forwarding path selection deeply depends on sink mobility, which can be classified into three categories: random trajectory, controllable trajectory, and constrained trajectory.

In sensor networks with random trajectories [10,22], mobile sinks are often mounted on some animals moving randomly to collect interested information sensed by sensor nodes. In this case, it is possible to guarantee the data delivery efficiency with the help of efficient communication protocols and data collection schemes while the trajectory of the mobile sink is constrained or controllable. Due to random mobility, however, it is difficult to bound the data transfer latency and the data delivery ratio.

For WSNs with controllable trajectories, most existing approaches focus on how to design the optimal trajectory of the mobile sink to improve the network performance [23,9,12,24,3]. In [25], Zhao et al. consider mobility control and develop the algorithms that generate ferry routes that meet traffic demand and minimize weighted packet delay. In [26], the mobile base station starts the cluster organization by broadcasting a beacon message while traversing the network. In [27], Ma et al. introduce a mobile data observer and present a heuristic algorithm for planning the trajectory of the mobile data observer and balancing the traffic load in the network. Rao et al. [24] propose a distributed and network assisted sink navigation framework to balance energy consumption and collection delay by choosing the appropriate number of multiple hops. Xing et al. [3] propose a rendezvous design to minimize the distance in multi-hop routing paths for local data aggregation under the constraint that the tour length of the mobile collector is no more than a threshold.

Trajectory constrained sensor networks also attract interests from researchers. In [28], a communication protocol and a speed control algorithm of the mobile sink are proposed to improve the energy performance and the amount of data collected by the sink. In this protocol, a shortest path tree (SPT) is used to choose the cluster heads and route data. In [29], a routing protocol, called MobiRoute, is proposed for WSNs with path predictable mobile sink to prolong the network lifetime and improve the packet delivery ratio. In [30], the Maximum Amount Shortest Path algorithm (MASP) is proposed for mobile sink traveling along a restricted path. The neighbors of the mobile sink are chosen as subsinks. The reference [21] provide a protocol, MobiCluster, that uses urban buses to carry mobile sinks that retrieve information from isolated parts of WSNs.

Our work belongs to the third category, where the trajectory is constrained. The main deference between our algorithm and most existing works is that power adjustment is used to save energy, which is proved to be effective in WSNs. We also take into account the residual energy of each sensor node, which means that any node in the network can be the bottleneck for prolonging network lifetime.

2.2. Algorithms for maximizing network lifetime

Although the average lifetime of nodes can be taken as the lifetime of the whole network, most works [6,5,31–34] refer to maximizing network lifetime as maximizing the minimum lifetime of nodes in the network because the network may be disconnected even if only a small number of sensor nodes deplete their energy. The problem of maximizing network lifetime is proved to be NP-complete [6,5], and many heuristic algorithms are proposed for this kind of problem.

In [32], two power efficient data gathering and aggregation protocols, PEDAP and PEDAP-PA, are presented based on the minimum spanning tree routing scheme. In [4], the energy balancing problem is formulated as the problem of optimal allocation of transmitting data by combining the ideas of corona-based network division and mixed-routing strategy together with data aggregation. Yet the research can only be applied to small networks as it assumes that the sink can communicate with all nodes in the network. In [35], the network lifetime is maximized by jointly optimizing data aggregation and routing. This algorithm integrates data aggregation with the underlying routing scheme and presents a smoothing approximation function for the optimization problem. However, it requires nodes to know their positions as well as their neighbors' positions, which are hard to be obtained in practical environments.

In addition, similar algorithms are proposed by [5,6]. In [5], an algorithm called MNL is used to find a routing tree such that the minimum residual energy of all nodes is maximized. Using a greedy policy, MNL adds nodes to the tree one by one. Each time a node is