J. Parallel Distrib. Comput. 83 (2015) 133–142

Contents lists available at ScienceDirect

J. Parallel Distrib. Comput.

journal homepage: www.elsevier.com/locate/jpdc

Dellat: Delivery Latency Minimization in Wireless Sensor Networks with Mobile Sink

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HIGHLIGHTS

- Formulate delivery latency minimization problem (DLMP) as an integer programming.
- Prove the NP completeness of DLMP.
- Propose a substitution heuristic algorithm to plan the travel route of the mobile sink by point.
- Minimize delivery latency by a relaxed linear programming.
- Extensive simulations validate the effectiveness of the proposed heuristic algorithm.

ARTICLE INFO

Article history:
Received 20 November 2014
Received in revised form
12 April 2015
Accepted 24 May 2015
Available online 3 June 2015

Keywords:
Wireless sensor networks
Mobile sink
Delivery latency minimization
Substitution heuristic algorithm

ABSTRACT

Adopting mobile data gathering in wireless sensor networks (WSNs) can reduce the energy consumption on data forwarding thus achieve more uniform energy consumption among sensor nodes. However, the data delivery latency inevitably increases in mobile data gathering due to the travel of the mobile sink. In this paper, we consider a delivery latency minimization problem (DLMP) in a randomly deployed WSN. Our goal is to minimize the travel latency of the mobile sink. We formulate the DLMP as an integer programming problem which subjects to the direct access constraint, the data transmission constraint and the route traverse constraint. We prove that the DLMP is an NP-Complete (NPC) problem, and then propose a substitution heuristic algorithm to solve it by shortening the travel route and having the mobile sink move and collect data at the same time. We compare the proposed algorithm with other two algorithms, a traveling salesman problem (TSP) heuristic algorithm and a random heuristic algorithm through simulations. Our extensive simulation results show that although all the three algorithms can shorten the data delivery latency in mobile data gathering, the proposed substitution heuristic algorithm is the most effective one.

1. Introduction

A wireless sensor network with mobile sink (WSN-MS) provides an effective method to collect data than the wireless sensor networks (WSNs) with static sink. In the traditional WSNs with static sink, the relaying forward often causes hot spot problem [18,23], that is, sensor nodes close to the sinks deplete their energy quickly. On the contrary, in a WSN-MS, although sensor nodes are still stationary, mobile sinks can access sensor nodes by moving around them thus data from sensor nodes can be transmitted to the sinks directly or through less relaying to save more energy and achieve longer lifetime. Moreover, mobile sinks can also access the disconnected WSNs. However, WSNs-MS still have a crucial problem that the delivery latency may be long due to the traveling of mobile sinks [13].

In a WSN-MS, the delivery latency is defined as the time mobile sinks take to traverse the sensing range of sensor nodes once to collect data and deliver the collected data to the base station [18,25,12]. The main reason which causes long delivery latency is the long moving time of mobile sinks. There are many challenges to minimize the delivery latency in WSNs-MS. First, the number of candidate turning positions for mobile sinks is infinite, and it is difficult to determine which one is the best. In [25], the selection of

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http://dx.doi.org/10.1016/j.jpdc.2015.05.005
0743-7315/

polling points is proved to be an NP-hard problem, and the polling points are selected by achieving the maximum compatible pairs among sensor nodes. For simplicity, most of other works [10,15,6,22,24] make assumption that the candidate positions are given. Second, the travel route is hard to plan for the circular travel route of the mobile sink which is formulated as a traveling salesman problem (TSP). This problem is also an NP-Complete (NPC) problem. For simplicity, some works treat the movement of mobile sinks as random walk, such as [17]. Other works use predefined trajectory, such as [1,3,19], and even some works simply ignore the moving time and moving path planning, such as [15,20].

In this paper, we aim to minimize the data delivery latency in a WSN-MS composed of a mobile sink and some stationary sensor nodes which are randomly deployed on a plane. We assume that the positions of both the mobile sink and sensor nodes are known in advance through the equipped global positioning system (GPS) [21] on the mobile sink, location service [7], or special guiding mechanisms [4,5]. The mobile sink visits sensor nodes directly, in other words, the mobile sink must lie in the communication range of sensor nodes to collect data. Our main idea is that the mobile sink traverses sensor nodes in the network and simultaneously collects their data to minimize the delivery latency. One data collection cycle is defined as that the mobile sink departs from the origin position, traverses every sensor node and gets back to the origin position.

The contribution of this work can be summarized as follows. First, we formulate the delivery latency minimization problem (DLMP) as an integer programming. Second, we further prove that the DLMP is an NPC problem, show that the anchor points should be located at the border of communication range of sensor nodes such that the length of travel route would be short, and prove that the lower bound of delivery latency is the sum of transmission time of sensor nodes. Third, we propose a substitution heuristic algorithm to plan the travel route of the mobile sink by point substitution and line substitution and minimize the delivery latency by a relaxed linear programming. Finally, our extensive simulations validate the effectiveness of the proposed heuristic algorithm in terms of shortening route length and reducing delivery latency by comparing with a TSP heuristic algorithm and a random heuristic algorithm. In the simulation, we further study the effects of moving speed of the mobile sink, transmission time and communication radius of sensor nodes on algorithm performance.

The rest of the paper is organized as follows. Section 2 summarizes the related works. Section 3 introduces the system model and formulates the DLMP. Section 4 proposes the substitution heuristic algorithm. Section 5 presents the simulation results and some discussions. Finally, Section 6 concludes the paper.

2. Related works

In recent years, several implementation techniques and network architectures of WSNs-MS have been proposed, which show that WSNs-MS are an effective approach for data gathering. In [9], Kansal et al. implemented a prototype system of WSNs-MS which is composed of a mobile router and several static motes. In [26], Zhao and Yang proposed a three-layer framework to achieve good scalability, long network lifetime and low data collection latency. In [19], Vlajic and Stevanovic simulated that the idealistic (zero-overhead) WSNs-MS can distribute routing load and prolong network lifetime. In [16], Pazzi et al. proposed a data dissemination protocol for a WSN with mobile sinks which combines cluster formation, sleep-wake mechanism, trail generation and path recovery. The above works provide the foundation for WSN-MS.

In addition, several studies show that the travel tour of mobile sinks greatly affects the network efficiency. In [21], Xu et al. locate the sensor nodes by equipping GPS. In [4,7,5], the authors propose approaches to locate the sensor nodes and mobile sink. In [17], Shah et al. utilize Data MULEs to collect data generated by randomly distributed wireless sensor nodes, and transfer it to access points. In this scheme, Data MULEs is a type of serendipitous mobile agents whose movements cannot be predicted in advance. In [3], Chakrabarti et al. propose a predictable observer mobility model and an observer-driven communication protocol in reducing energy consumption for data collection, which could be regarded as the second type of mobility. In [13,25,26,14], the moving tour of mobile sink is controllable, so that the metrics such as the network time and the energy consumption of sensor nodes which rely on the moving tour can be optimized. In [13], Ma and Yang utilize a mobile data collector, SenCar, to periodically traverse sensor nodes and collect data by clustering sensor nodes via multi-hop routing, and find that the moving path of SenCar greatly affects network lifetime. In [14], they further propose a data gathering algorithm to minimize the length of each data gathering tour with multiple collectors.

In the meanwhile, minimizing data gathering time in WSNs-MS has also been studied. Zhao et al. [25] adopt the mobility and space-division multiple access technique to minimize the total data gathering time in a WSN with a single or multiple mobile sinks, which is mostly related to our work in this paper. In [25], multiple antennas are equipped on each mobile sink so that distinct compatible sensor nodes may upload data concurrently, and the data gathering time problem is formulated as a problem of finding compatible pairs among sensor nodes, determining sensor association pattern and finding locations of selected polling points and the order for the mobile sink to visit. In contrast, in this paper we consider the scenario that the mobile sink traverses sensor nodes and at the same time gathers their data in a ubiquitous WSN-MS in which the mobile sink is only equipped with one antenna. We further define the data gathering time as the delivery latency, and study the effects of moving speed, data transmission time and communication radius of sensor nodes.

3. System model and problem statement

3.1. System model

In this paper, we consider a WSN with a single mobile sink. We assume that (1) sensor nodes are deployed on a plane randomly, and their positions can be measured by location technology [21,7]; (2) the communication ranges of sensor nodes are disks with the same communication radius [2]; (3) the communication is stable within communication radius [11], and the bandwidth of the links between the mobile sink and all sensor nodes are identical; (4) in a data collection cycle, every sensor node produces the same amount of data, and the mobile sink would spend the same amount of time to collect them; (5) the travel route of the mobile sink is made up of several line segments. Fig. 1 gives an example of the WSN-MS we consider. The notations that are used in the rest of the paper are summarized in Table 1.

Based on these assumptions, we will propose an approach to solve the DLMP whose main idea is to let the mobile sink move and collect data at the same time. The process of data collection is divided into two phases. In the first phase, the mobile sink traverses the whole deployed range of sensor nodes and detects their positions based on the localization method proposed in [21]. In the second phase, the mobile sink performs data collection periodically. To elaborate, the process of data collection includes three steps: the first step is to select some candidate points other than sensor nodes on the deployed plane as anchor points, the second step is to connect all the anchor points as a travel route, and the third step is to create a visiting schedule and assign visiting time to every sensor node. It is worth mentioning that S is the set of cluster heads