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Minimizing the number of mobile chargers for large-scale wireless rechargeable sensor networks ☆

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A B S T R A C T

Traditional wireless sensor networks (WSNs) are constrained by limited battery energy that powers the sensor nodes, which impedes the large-scale deployment of WSNs. Wireless power transfer technology provides a promising way to solve this problem. With such novel technology, recent works propose to use a single mobile charger (MC) traveling through the network fields to replenish energy to every sensor node so that none of the nodes will run out of energy. These algorithms work well in small-scale networks. In large-scale networks, these algorithms, however, do not work efficiently, especially when the amount of energy the MC can provide is limited. To address this issue, multiple MCs can be used. In this paper, we investigate the minimum MCs problem (MinMCP) for two-dimensional (2D) wireless rechargeable sensor networks (WRSNs), i.e., how to find the minimum number of energy-constrained MCs and design their recharging routes in a 2D WRSN such that each sensor node in the network maintains continuous work, assuming that the energy consumption rate for all sensor nodes are identical. By reduction from the Distance Constrained Vehicle Routing Problem (DVRP), we prove that MinMCP is NP-hard. Then we propose approximation algorithms for this problem. Finally, we conduct extensive simulations to validate the effectiveness of our algorithms.

1. Introduction

Wireless sensor networks (WSNs) have been widely used for structural health monitoring, scientific exploration, environmental monitoring, target tracking, etc. As sensor nodes in traditional WSNs are powered by batteries, the limited battery energy is considered as a major deployment barrier for large-scale WSNs. To elongate the lifetime of WSNs, many approaches have been proposed to harvest ambient energy from their surroundings such as solar energy [2], vibration energy [3], and wind energy [4]. However, due to the time-varying nature of renewable energy resources, the success of these methods remains very limited in practice.

The recent breakthroughs in wireless power transfer technology [5], which allow energy to be transferred from one storage device to another via wireless with reasonable efficiency, has provided a promising way to solve this problem. Since wireless recharging can guarantee the continuous power supply and is insensitive to the neighboring environment, it has found many applications including RFIDs [6], sensors [7], cell phones [8], laptops [9], vehicles [10], smart grids [11] and civil structures monitoring [12]. With the novel technology, recent studies [12–18,1] propose to employ a mobile charger (MC) to replenish energy to sensor nodes in wireless rechargeable sensor networks (WRSNs) [19–21] so that none of them in the network will run out of energy. Typically, the MC periodically traverses every node in the network and stays near every node for a short period to recharge it. Research results demonstrate that this approach works well for small-scale networks. For large-scale wireless sensor networks, a single mobile charger may not be enough. This is because the MC may not carry sufficient energy to recharge every node in a large-scale network on a single tour. Therefore, the MC needs to return to the base station after recharging a part of the network. As a result, single MC recharging algorithms become invalid and continuous working of sensor nodes can no longer be guaranteed.

To recharge a large-scale sensor network, it is necessary to use multiple energy constrained mobile chargers. In this work, we investigate the minimum mobile charger problem for wireless sensor networks. That is, how to find the minimum number of energy-constrained MCs as well as their routes to recharge a given WRSN such that each sensor node in the WRSN can work continuously. In our problem settings, the energy consumption rate for all sensor nodes are identical, which is a practical assumption for many

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applications as will be elaborated. This problem is highly challenging as we should jointly consider the energy constraints of MCs and the time-sensitive charging requirements of sensor nodes when determining the routes of MCs. We prove the NP-hardness of this problem and propose efficient approximation algorithms to solve it. Zhang et al. [22] also employed multiple energy-constrained MCs. However, their work focuses on only one-dimensional (1D) sensor networks, and their goal is to maximize the ratio of the amount of payload energy to the overhead energy. Our solution is designed for two-dimensional (2D) sensor networks, and concentrates on an entirely different problem compared with [22].

The contributions of this work are as follows.

- We are the first to consider the minimum mobile chargers problem (MinMCP) in general 2D WRSNs, i.e., how to find the minimum number of energy-constrained MCs and their recharging routes given a 2D WRSN, so as to keep the network running forever.
- We prove that MinMCP is NP-hard, and propose approximation algorithms to address MinMCP. Particularly, we first consider the relaxed version of MinMCP, which is named MinMCP-R, and propose an approximation algorithm to address it. Furthermore, we present approximation algorithms to MinMCP based on the results obtained for MinMCP-R.
- We conduct extensive simulations to verify our analytical findings. The simulation results demonstrate the effectiveness of our schemes.

The remainder of the paper is organized as follows. In Section 2, we investigate some related works. We present preliminaries and background in Section 3. In Section 4, we first formulate the problem and investigate its hardness. Then we propose approximation algorithms and conduct performance analysis respectively. Section 5 discusses how to extend our work to general cases. Experimental results are presented in Section 6 before we conclude the paper in Section 7.

2. Related work

In this section, we review some related works in terms of mobile charging problems where a single or multiple MCs are used.

There has emerged a considerable amount of work studying how to use one single MC to enhance the performances of WRSNs. In terms of data routing performance, Tong et al. [13] investigated the impact of wireless charging technology on data routing and deployment of sensor networks where a single MC is applied. A more practical scheme jointly considering routing and charging was reported in [15]. It aimed to maximize the network lifetime under practical constraints such as dynamic and unreliable communication environment, limited charging capability and heterogeneous node attributes. Other works were interested in the impact of mobile charging on the efficiency of data gathering. Shi et al. [14] employed an MC to periodically travel inside the sensor network to charge sensor nodes, and tried to minimize the aggregate charging time and travel time. By [23,24], a mobile charger was used to serve not only as an energy transporter that charges stationary sensors, but also as a data collector. In addition, Xie et al. [25] studied the problem of co-locating the mobile base station on the wireless charging vehicle to minimize energy consumption of the entire system while guaranteeing that none of the sensor nodes will run out of energy. Still others concentrated on stochastic event capture issues. Dai et al. [18] considered two closely related subproblems of mobile charging for stochastic event capture. One is how to choose the nodes for charging and decide the charging time for each of them, and the other is how to best schedule the nodes' activation schedules according to their received energy. Their goal is to maximize the overall quality of monitoring.

Besides the above concerns on traditional performances of sensor networks, some literature paid attention to practical issues related to the MC. Fu et al. [26] focused on minimizing the charging delay of the MC, an RFID-reader, by planning its optimal movement and charging strategy. While most existing works on the mobile charging problem mainly concentrated on the optimal offline path planning for the MC, He et al. [27] considered the on-demand mobile charging problem, i.e., how to dynamically plan the path for the MC where the charging requests from sensor nodes come randomly. Li et al. [16] tried to maximize the number of sensor nodes to be charged by using a single MC with limited energy, which is different from the above schemes that assume the employed MC has unbounded energy.

In order to charge a large-scale WRSN, multiple MCs are needed considering their energy constraint. Zhang et al. [22] proposed the only scheme employed multiple energy-constrained MCs to collaboratively charge a linear WSN. MCs are allowed to charge each other. Their goal is to maximize the energy efficiency of charging, which is totally different from ours.

3. Problem statement

3.1. Network model

We assume that there is a collection of rechargeable sensor nodes distributed over a 2D region. A base station (BS) serves not only as a data sink, but also as an energy source of the network by periodically dispatching MCs to charge the sensor nodes, as illustrated in Fig. 1. Let $G = (V, E)$ represent the topology of sensor nodes and the BS. Let $v_{BS} \in V$ denote the BS, and $J = V \setminus v_{BS}$ $(|J| = n)$ be the set of sensor nodes. Denote by $w(i,j)$ the time cost for MCs traveling from a sensor node v_i to another sensor node v_j, which we call the edge weight. Notice that $w(i,j)$ includes neither the charging time of MCs at the sensor node v_i nor that at the sensor node v_j. We assume that G is complete, and the edge weights form a metric space $\mathcal{W}$, namely, they are symmetric and satisfy the triangle inequality. To be specific, we have $w(i,j) = w(j,i)$ and $w(i,j) \leqslant w(i,k) + w(k,j)$ for arbitrary sensor nodes v_i, v_j and v_k. We emphasize that this assumption is without loss of generality because an MC can always travel along the shortest path between any two sensor nodes (e.g., if $w(i,j) > w(i,k) + w(k,j)$, an MC will prefer to travel from i to j by passing by k, which results in an

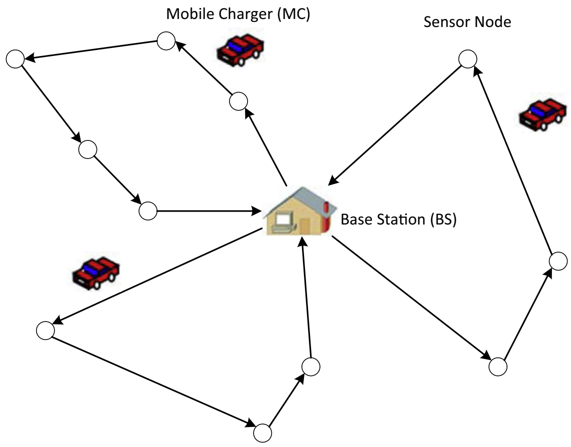

Fig. 1. Illustration of the network model.