Ad Hoc Networks 63 (2017) 79–90

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Improving charging capacity for wireless sensor networks by deploying one mobile vehicle with multiple removable chargers☆

Tao Zou[a], Wenzheng Xu[a,*], Weifa Liang[b], Jian Peng[a], Yiqiao Cai[c], Tian Wang[c]

[a] College of Computer Science, Sichuan University, Chengdu, 610065, PR China
[b] Research School of Computer Science, The Australian National University, ACT 2601, Australia
[c] Department of Computer Science and Technology, Huaqiao University, Xiamen, 361021, PR China

ARTICLE INFO

Article history:
Received 26 December 2016
Revised 25 May 2017
Accepted 29 May 2017
Available online 7 June 2017

Keywords:
Rechargeable sensor networks
One charging vehicle with multiple removable chargers
Charging vehicle scheduling
Approximation algorithms
Combinatorial optimization problems

ABSTRACT

Wireless energy transfer is a promising technology to prolong the lifetime of wireless sensor networks (WSNs), by employing charging vehicles to replenish energy to lifetime-critical sensors. Existing studies on sensor charging assumed that one or multiple charging vehicles being deployed. Such an assumption may have its limitation for a real sensor network. On one hand, it usually is insufficient to employ just one vehicle to charge many sensors in a large-scale sensor network due to the limited charging capacity of the vehicle or energy expirations of some sensors prior to the arrival of the charging vehicle. On the other hand, although the employment of multiple vehicles can significantly improve the charging capability, it is too costly in terms of the initial investment and maintenance costs on these vehicles. In this paper, we propose a novel charging model that a charging vehicle can carry multiple low-cost removable chargers and each charger is powered by a portable high-volume battery. When there are energy-critical sensors to be charged, the vehicle can carry the chargers to charge multiple sensors simultaneously, by placing one portable charger in the vicinity of one sensor. Under this novel charging model, we study the scheduling problem of the charging vehicle so that both the dead duration of sensors and the total travel distance of the mobile vehicle per tour are minimized. Since this problem is NP-hard, we instead propose a $(3+\epsilon)$-approximation algorithm if the residual lifetime of each sensor can be ignored; otherwise, we devise a novel heuristic algorithm, where ϵ is a given constant with $0 < \epsilon \leq 1$. Finally, we evaluate the performance of the proposed algorithms through experimental simulations. Experimental results show that the performance of the proposed algorithms are very promising.

1. Introduction

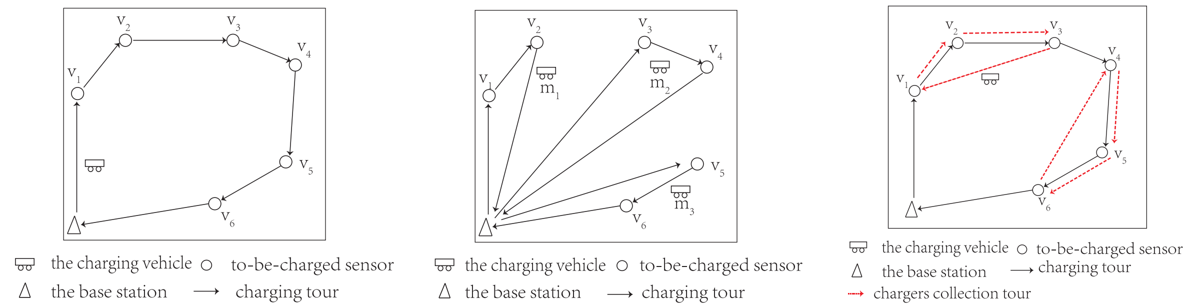
Wireless sensor networks (WSNs) are widely used in many applications, including ecological monitoring, structural health monitoring, traffic control, etc [9,17,19,29,35]. As sensors in traditional WSNs are mainly powered by energy-limited batteries, the lifetime of sensor networks is very limited. Sensors will not be functioning when their battery energy is run out. To prolong the lifetime of WSNs, extensive studies have been conducted in past years, and most of them focused on a fundamental problem–energy replenishments of sensors. In general, there are two different sensor charging categories. One is to enable sensors to harvest energy from their surrounding environments including vibration energy, solar energy and wind energy [7,21,23]. The main drawback of this method is that the energy harvesting rate is extremely unstable due to the time-varying environment. For example, the amount of energy harvested from a solar panel is very low in a cloudy or rainy day. The instability poses great challenges in the efficient usage of harvested energy. Another is to employ mobile charging vehicles to travel to the vicinity of sensors and charge them, using wireless energy transfer [8,10,28]. Thus, sensors can be charged via the wireless energy transfer with highly stable charging rates.

Existing studies of sensor energy replenishment via wireless charging vehicles assumed that either just one charging vehicle is employed [15,20,22,24,31,34,37] or multiple vehicles are deployed [5,6,13,16,18,25,26,33,36]. However, such an assumption may have its limitation for a real sensor network. On one hand,

☆ This document is a collaborative effort.

* Corresponding author.
E-mail addresses: scuzoutao@qq.com (T. Zou), wenzheng.xu3@gmail.com, wenzheng.xu@scu.edu.cn (W. Xu), wliang@cs.anu.edu.au (W. Liang), jianpeng@scu.edu.cn (J. Peng), caiyq@hqu.edu.cn (Y. Cai), cs_tianwang@163.com (T. Wang).

http://dx.doi.org/10.1016/j.adhoc.2017.05.006



(a) employ just one charging vehicle to charge sensors

(b) dispatch multiple charging vehicles to charge sensors

(c) deploy one charging vehicle carrying multiple low-cost removable chargers to replenish sensors

Fig. 1. An illustration of the charging model, which deploys one charging vehicle with multiple low-cost removable chargers.

when there is just one charging vehicle for charging sensors, some sensors may have already depleted their energy before the vehicle approaches them, because the charging capacity of the vehicle is very limited and it takes some time (e.g., 30–80 minutes) to fully charge a commercial sensor battery [26]. For example, assume that there are six energy-critical sensors $v_1, v_2, \ldots, v_6$ in the network, which is illustrated in Fig. 1(a). Before charging sensor v_2, the charging vehicle has to stay in the vicinity of sensor v_1 and fully charge v_1. Similarly, before charging sensor v_6, the vehicle has to fully charge the first five sensors $v_1, v_2, \ldots, v_5$. It can be seen that it is very likely that sensor v_6 has run out of its energy for a long time before the vehicle can visit it.

On the other hand, the employment of multiple charging vehicles can significantly reduce the dead durations of sensors. As shown in Fig. 1(b), the six sensors $v_1, v_2, \ldots, v_6$ will be charged by three charging vehicles m_1, m_2, and m_3, assuming that sensors v_1 and v_2 will be charged by vehicle m_1, sensors v_3 and v_4 will be replenished by m_2, and the residual two sensors v_5 and v_6 will be recharged by m_3. Each charging vehicle starts from the base station to charge sensors and returns to the base station after completing its charging task. It can be easily seen that the waiting time of each sensor before its charging in this multiple charging vehicles model is much shorter than that in the single charging vehicle model. However, it is usually too costly to invest and maintain many charging vehicles for sensor charging, since the investment cost of each charging vehicle is not cheap at all, its cost is usually from several hundred dollars to quite a few thousand dollars [2,3,11].

We can see that the existing studies either use just one charging vehicle but some sensors may deplete their energy for quite a while, or deploy multiple expensive charging vehicles to shorten sensor dead durations. A fundamental problem then is that, is it possible to improve the charging capacity with a low-cost of purchasing charging devices? We note that the existing works assumed that each charging vehicle can carry only one charger. In this paper, we propose a novel charging model. That is, we assume that one charging vehicle can carry multiple low-cost removable chargers with each charger being equipped with a wireless charging device and a portable high-volume battery. When there are energy-critical sensors to be charged, the charging vehicle can carry the multiple chargers and place one charger in the vicinity of one sensor to charge the sensor. Thus, multiple sensors, instead of a single one, can be charged simultaneously.

We here use an example to illustrate this novel charging model as follows, see Fig. 1(c). There are six to-be-charged sensors $v_1, v_2, \ldots, v_6$ in the network. A charging vehicle can carry three removable chargers mc_1, mc_2, and mc_3 for sensor charging. The charging vehicle first places the three chargers in the vicinities of sensors v_1, v_2, v_3, one charger for one sensor. That is, the vehicle visits sensor v_1 and places charger mc_1 in the vicinity of v_1 to charge v_1, then leaves and visits sensor v_2, and drops charger mc_2 at v_2, finally places charger mc_3 in the vicinity of sensor v_3. After the three chargers fully charge the three sensors, the charging vehicle revisits the three sensors for collecting the chargers. Then, the charging vehicle carries the three chargers for replenishing energy to the rest of the three sensors v_4, v_5, and v_6 in a similar way. It can be seen that under the simultaneous charging model via one charging vehicle carrying multiple removable chargers, the charging capacity is much larger than that with only one charging vehicle. Furthermore, the cost of buying one portable charger usually is much cheaper than that of one charging vehicle, e.g., tens of dollars [30] vs. hundreds of dollars [2,3,11].

In this paper, we propose the novel simultaneous charging model, in which one charging vehicle can carry multiple low-cost, removable chargers to provide energy supply to sensors in a large-scale sensor network. Under this novel charging model, we study the charging scheduling of the charging vehicle so as to minimize not only the dead duration of sensors but also the travel distance of the charging vehicle. There are however two essential differences between the vehicle scheduling under this new charging model and that under the traditional model, in which one vehicle carries only one charger. One is that multiple sensors, instead of only one, will be replenished by the chargers simultaneously. The other difference is that the travel trajectory of the vehicle under the new charging model is more complicated, because the vehicle needs both placing chargers at sensors and revisiting sensors for collecting chargers. It is thus very challenging to devise efficient algorithms to schedule the charging vehicle under the new charging model. Therefore, existing scheduling algorithms are not applicable to this new sensor charging problem, and new algorithms are desperately needed. Specifically, in this paper we consider two vehicle scheduling problems under this novel charging model. We first investigate the problem of finding a shortest charging trajectory for the charging vehicle to charge a set of lifetime-critical sensors, assuming that residual lifetimes of sensors are not considered. We then study the problem of finding a charging trajectory for the vehicle so that both the longest dead duration of sensors and the total travel distance of the vehicle are minimized if the residual lifetime of each sensor must be taken into account.

The main contributions of this paper are highlighted as follows.

- Unlike existing studies assumed that one charging vehicle can carry just one charger, we are the first to propose a novel si-