Computer Networks 97 (2016) 98–112

Contents lists available at ScienceDirect

Computer Networks

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

Hierarchical, collaborative wireless energy transfer in sensor networks with multiple Mobile Chargers[☆]

Adelina Madhja[a,b,*], Sotiris Nikoletseas[a,b], Theofanis P. Raptis[a,b]

[a] Department of Computer Engineering and Informatics, University of Patras, Greece
[b] Computer Technology Institute and Press "Diophantus" (CTI), Greece

ARTICLE INFO

Article history:
Received 10 July 2015
Revised 1 November 2015
Accepted 11 January 2016
Available online 18 January 2016

Keywords:
Sensor networks
Energy efficiency
Mobility
Distributed algorithms
Wireless energy transfer
Collaborative charging

ABSTRACT

Wireless energy transfer is used to fundamentally address energy management problems in Wireless Rechargeable Sensor Networks (WRSNs). In such networks mobile entities traverse the network and wirelessly replenish the energy of sensor nodes. In recent research on collaborative wireless charging, the mobile entities are also allowed to charge each other.

In this work, we enhance the collaborative feature by forming a hierarchical charging structure. We distinguish the Chargers in two groups, the hierarchically lower Mobile Chargers which charge sensor nodes and the hierarchically higher Special Chargers which charge Mobile Chargers. We define the Coordination Decision Problem and prove that it is NP-complete. Also, we propose a new protocol for 1-D networks which we compare with a state of the art protocol. Motivated by the improvement in 1-D networks, we propose and implement four new collaborative charging protocols for 2-D networks, in order to achieve efficient charging and improve important network properties. Our protocols are either centralized or distributed, and assume different levels of network knowledge.

Extensive simulation findings demonstrate significant performance gains, with respect to non-collaborative state of the art charging methods. In particular, our protocols improve several network properties and metrics, such as the network lifetime, routing robustness, coverage and connectivity. A useful feature of our methods is that they can be suitably added on top of non-collaborative protocols to further enhance their performance.

1. Introduction and contribution

In Wireless Sensors Networks (WSNs) the sensor nodes are equipped with small batteries and thus, the lifetime of the network is limited. Although there are several approaches that try to address this fundamental problem, the proposed solutions are still limited since the energy that is replenished is either uncontrollable (such as environmental harvesting approaches) or require the nodes to be accessible by people or robots in a very accurate way (such as battery replacement approaches).

However, the breakthrough of wireless energy transfer technology (see e.g. [2]) combined with rechargeable batteries with high energy density and high charge/discharge capabilities [3], has managed to directly address energy management and led to the paradigm of Wireless Rechargeable Sensor Networks (WRSNs). In such networks, special entities (called Chargers) are able to charge sensor nodes wirelessly. This procedure is called wireless charging. Thus, the limited available energy can be managed in a controllable and more efficient manner. This option introduced some new aspects that need investigation such as how Chargers should be deployed, how much energy

☆ A preliminary version of this paper appeared in [1].

* Corresponding author at: Department of Computer Engineering and Informatics, University of Patras, Greece. Tel.: +30 2610996964.
E-mail address: madia@ceid.upatras.gr (A. Madhja).

http://dx.doi.org/10.1016/j.comnet.2016.01.007
1389-1286/

each Charger should transfer to each sensor node or what is the minimum number of required Chargers in order to improve network properties such as lifetime, connectivity and coverage.

Another critical aspect that needs investigation is the effect of the exposure on the electromagnetic radiation, occurred by wireless energy transfer, in human health. Wireless charging may address more efficiently the problem of limited energy with respect to network properties if we use Mobile Chargers instead of simple Chargers. Mobile Chargers are called the devices which are able to both charge sensor nodes wirelessly and move throughout the network. This new capability introduced some additional options that need investigation such as how Mobile Chargers can coordinate or which is the trajectory that each Mobile Charger should follow.

The collaborative mobile charging approach proposed in [4] offers even more useful options. In this new charging method, Mobile Chargers are allowed to charge not only sensor nodes but also other Mobile Chargers. This new capability has been proven very important, since it provides better exploitation of the potentially limited available energy supplies.

The problem. Let a WRSN comprised of stationary sensor nodes and Mobile Chargers that can either charge the nodes or charge each other (collaborative charging). The transformation of the flat collaborative charging scheme to a hierarchical one (hierarchical, collaborative charging) imports new challenges for the network energy management. We aim at designing efficient protocols for the Mobile Chargers' coordination and charging procedure, in order to efficiently distribute and manage the available finite energy, prolong the network lifetime and improve key network properties such as coverage, routing robustness and network connectivity.

Our contribution. Since collaboration provides an efficient energy management potential, we envision collaboration in a hierarchical structure. More specifically, we propose a partition of Chargers into two groups, the hierarchically lower Mobile Chargers, that are responsible for transferring energy only to sensor nodes and the hierarchically higher Special Chargers that are responsible for transferring energy to Mobile Chargers. Using our hierarchical charging model, we first propose a protocol for 1-D networks that achieves a better performance ratio than known state of the art protocols, when the available energy supplies are limited.

Motivated by the improvement in 1-D networks we propose four protocols for 2-D networks as well. Our protocols differ on the available network's knowledge level (2-level knowledge, 1-level knowledge and no knowledge) as well as on their coordination procedure (distributed or centralized). Our No Knowledge No Coordination (NKNC) protocol actually serves as a performance lower bound since it assumes no network knowledge and does not perform any coordination. In contrast, our 2-Level Knowledge Centralized Coordination (2KCC) protocol assumes 2-level knowledge and performs centralized coordination. In between, our 2-Level Knowledge Distributed Coordination (2KDC) and 1-Level Knowledge Distributed Coordination (1KDC) protocols both perform distributed coordination but, since they assume different knowledge level, their coordination and charging procedures differ.

Moreover, the hierarchical solution that we provide can be easily added on top of non-collaborative protocols to further improve their performance (by applying the necessary transformations which depends on the existing charging model). In particular, we enhance a known state of the art protocol that does not use any collaboration, by adding a hierarchical collaborative charging structure and we show the added value of hierarchy.

2. Related work and comparison

Wireless energy transfer technology inspired a lot of researchers to investigate how to exploit it in WSNs efficiently. In [5], the authors used a realistic scenario where the sensor nodes are mobile and the Chargers are stationary. They proposed two protocols to address the problem of how to schedule the Chargers activity so as to maximize either the charging efficiency or the energy balance. Also, they conducted real experiments to evaluate the protocols' performance. In [6], the objective was to find a Charger placement and a corresponding power allocation to maximize the charging quality. They proved that their problem (called P^3) is NP-hard and proposed two approximation algorithms for P^3 (with and without fixed power levels) and an approximation algorithm for an extended version of P^3.

However, the exposure on the electromagnetic radiation that is caused by wireless energy transfer may lead to undesired phenomena for human health. That is why there are a lot of works that investigate this aspect and try to control the electromagnetic radiation. More specifically, in [7] the authors studied the Low Radiation Efficient Charging Problem in which they optimized the amount of "useful" energy that is transferred to nodes with respect to the maximum level of imposed radiation. In [8], the authors investigated the charging efficiency problem under electromagnetic radiation safety concern. More specifically, they formulated the Safe Charging Problem (SCP) of how to schedule the Chargers in order to increase the received power while there is no location in the field where the electromagnetic radiation exceeds a threshold value. They proved the hardness of SCP and proposed a solution which outperforms the optimal one with a relaxed threshold. Also, to evaluate the effectiveness of their solution, they conducted both simulations and real experiments.

The same research group in [9] studied the Safe Charging with Adjustable PowEr (SCAPE) problem which refers on how to adjust the power of the Chargers in order to maximize the charging utility of the devices while assuring that electromagnetic radiation intensity at any location on the field does not exceed a threshold value. They also proposed an $(1-\epsilon)$-approximation algorithm for the problem and conducted simulations and real experiments to evaluate the algorithm's performance.

Although all above works have studied a variety of problems caused by wireless energy transfer and try to maximize the received power by the sensor nodes under various constraints, the usage of stationary Chargers does not exploit all the capabilities of the technology. The hard-