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Distributed wireless power transfer in sensor networks with multiple Mobile Chargers ☆

Adelina Madhja, Sotiris Nikoletseas, Theofanis P. Raptis *

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

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ABSTRACT

We investigate the problem of efficient wireless power transfer in wireless sensor networks. In our approach, special mobile entities (called the Mobile Chargers) traverse the network and wirelessly replenish the energy of sensor nodes. In contrast to most current approaches, we envision methods that are distributed and use limited network information. We propose four new protocols for efficient charging, addressing key issues which we identify, most notably (i) what are good coordination procedures for the Mobile Chargers and (ii) what are good trajectories for the Mobile Chargers. Two of our protocols (DC, DCLK) perform distributed, limited network knowledge coordination and charging, while two others (CC, CCGK) perform centralized, global network knowledge coordination and charging. As detailed simulations demonstrate, one of our distributed protocols outperforms a known state of the art method, while its performance gets quite close to the performance of the powerful centralized global knowledge method.

1. Introduction and contribution

As wireless and portable mobile devices become pervasive, charging batteries for these devices has become a critical problem. Current battery charging technologies are dominated by wired technology, which requires a wired power plug to be connected to an electrical wall outlet. Existing wireless sensor networks are constrained by limited battery energy at a sensor node and can only remain operational for a limited amount of time. To prolong network lifetime, there have been many research efforts at all layers, from topology control, physical, MAC, and all the way up to the application layer. Despite these intensive efforts, the energy/lifetime of a wireless sensor network remains a performance bottleneck and is perhaps the key factor that hinders its wide-scale deployment.

Efficient wireless power transfer has been achieved through academic and industrial research by using technologies such as inductive coupling, electromagnetic radiation and magnetic resonant coupling [2]. Together with the research efforts on wireless power transfer, several international organizations, such as the *Wireless Power Consortium* (WPC, [3]) and the *Alliance for Wireless Power* (A4WP, [4]), aim at maximizing the use of these technologies. WPC, an open-membership cooperation of Asian, European, and American companies in diverse industries, including electronics manufacturers and original equipment manufacturers, is working towards the global standardization of wireless charging technology. A4WP, an independently operated organization composed of global wireless power and technology industry leaders, focuses on a new wireless power transfer technology that provides spatial freedom for charging of electrical devices

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* Corresponding author at: Department of Computer Engineering and Informatics, University of Patras, Greece. Tel.: +30 2610996964.

E-mail address: traptis@ceid.upatras.gr (T.P. Raptis).

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in cars, on table tops and for multiple devices simultaneously. Commercial products utilizing wireless power transfer are already available on the market such as those in [5,6].

These technologies and organizations lead the way towards *a new paradigm* for wireless sensor networks; the Wireless Rechargeable Sensor Networks. Such networks consist of sensor nodes that may be either stationary or mobile, as well as few mobile nodes with high energy supplies. The latter, by using wireless power transfer technologies are capable of charging sensor nodes. This way, the highly constrained resource of energy can be managed in great detail and more efficiently. Another important aspect is the fact that energy management in Wireless Rechargeable Sensor Networks can be performed passively from the perspective of sensor nodes and without the computational and communicational overhead introduced by complex energy management algorithms. Finally, Wireless Rechargeable Sensor Networks allow energy management to be studied and designed independently of the underlying routing protocol used for data propagation.

1.1. The problem

Let a Wireless Rechargeable Sensor Network comprised of *stationary* sensor nodes and *special mobile entities called the Mobile Chargers*. The Mobile Chargers have significant (yet finite) energy supplies, that are much larger than those of each sensor node, and are thus capable of charging the sensors in the network. We aim at designing and evaluating efficient protocols for the chargers' coordination and charging procedures in order to improve energy efficiency, prolong the lifetime of the network and also improve important network properties (such as the quality of network coverage and the robustness of data propagation).

In particular, we view the chargers' coordination as a distinct procedure, on top of the sensor nodes charging mechanism. Unlike other methods in the state of the art, we do not couple the chargers' coordination neither with the sensor nodes charging process nor with the underlying network energy information data propagation; actually, we wish to perform efficient coordinated wireless power transfer in a way which is agnostic of the network energy status, via adaptive techniques that *implicitly (based on the chargers' status) adapt to the network's energy evolution*.

Remark. We note that, although the wireless charging problem might look similar to other related research problems (such as aggressive data collection via mobile sinks), it admits special features that necessitate a direct approach, while the optimization of concrete trade-offs and the fine-tuning of design alternatives that arise in wireless charging necessitate the distinct investigation of special protocol design parameters.

Finally, we note that Mobile Charger optimization problems are (inherently) computationally hard e.g. in [7] we have formulated the wireless charging problem as the Charger Dispatch Decision Problem – CDDP, and showed that it is $\mathcal{NP}$-complete (via reduction from the Geometric Traveling Salesman Problem, G-TSP; see e.g. [8], p. 212).

1.2. Our contribution

While interesting research has been lately contributed to the wireless charging problem and particularly to the scheduling of a single Mobile Charger, most methods so far necessitate significant (in many cases even global) network knowledge (e.g. it is assumed that the charger knows the energy levels of all sensors in the network) and the solutions are centralized. On the contrary, our methods are *distributed, and use (at most) local network information*. Also, unlike other multiple chargers state of the art approaches that opt for integration and coupling of the coordination and charging procedures, our methods distinguish the network operations in three separate levels: *the coordination procedure*, *the charging process* and *the routing mechanism*. We identify the necessity of this demarcation as an efficient approach to the design of more detailed and better fine-tuned charger protocols.

In particular, we propose and evaluate selected *alternative strategies for efficient charging* in stationary Wireless Rechargeable Sensor Networks via multiple Mobile Chargers. Our design provides concrete, different solutions to some *key issues (and the associated trade-offs)* of wireless charging which we identify, most notably

i. assuming a number of Mobile Chargers in the network, *in what way should they coordinate*,
ii. given that the Mobile Chargers have coordinated, *what are good trajectories for the chargers to follow*.

More specifically, (a) we first distinguish two fundamental network operations, *charger coordination* and *node charging*, (b) taking into account the capability of *both centralized and distributed processing* we design selected charger coordination alternatives that efficiently split the network area and assign subregions to the Mobile Chargers and (c) assuming *different levels of network knowledge* we design different charging traversal strategies employed by the chargers in their region of interest.

We provide four new coordination and charging protocols based on their network knowledge (from global to local and to absence of knowledge) and their processing ability (from distributed to centralized). The CC and DC protocols perform centralized and distributed coordination respectively with no network knowledge, the DCLK protocol performs distributed coordination with local knowledge and the CCGK protocol performs centralized coordination with global knowledge. Actually, we view the centralized coordination with global knowledge CCGK protocol as a kind of performance upper bound to which the two distributed, partial knowledge protocols are compared with.

2. Related work and comparison

Recently there has been much research effort in the field of Wireless Rechargeable Sensor Networks using *a single Mobile Charger*. In [9], the authors build a proof-of-concept prototype by using a wireless power charger installed on a robot and sensor nodes equipped with