Computer Networks 70 (2014) 113–141

Contents lists available at ScienceDirect

Computer Networks

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

Wireless energy transfer in sensor networks with adaptive, limited knowledge protocols

Constantinos Marios Angelopoulos [c], 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), Patras, Greece
[c] Centre Universitaire d' Informatique, Université de Genève, Switzerland

A R T I C L E I N F O

Article history:
Received 21 September 2013
Received in revised form 14 March 2014
Accepted 28 April 2014
Available online 16 May 2014

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

A B S T R A C T

We investigate the problem of efficient wireless energy transfer in Wireless Rechargeable Sensor Networks (WRSNs). In such networks a special mobile entity (called the Mobile Charger) traverses the network and wirelessly replenishes the energy of sensor nodes. In contrast to most current approaches, we envision methods that are distributed, adaptive and use limited network information. We propose three new, alternative protocols for efficient charging, addressing key issues which we identify, most notably (i) to what extent each sensor should be charged, (ii) what is the best split of the total energy between the charger and the sensors and (iii) what are good trajectories the Mobile Charger should follow. One of our protocols (LRP) performs some distributed, limited sampling of the network status, while another one (RTP) reactively adapts to energy shortage alerts judiciously spread in the network. We conduct detailed simulations in uniform and non-uniform network deployments, using three different underlying routing protocol families. In most cases, both our charging protocols significantly outperform known state of the art methods, while their performance gets quite close to the performance of the global knowledge method (GKP) we also provide.

1. Introduction

The last decade energy harvesting technologies have been effectively integrated into wireless sensor networks. A variety of ambient energy, such as mechanical, thermal, photovoltaic and electromagnetic energy, can be converted into electrical energy to charge sensor batteries. However, as all these energy sources come from the external environment and their spatial–temporal profiles exhibit great variations, the strength of harvested energy is typically low, and especially sensitive to the environment dynamics. As there is generally a lack of a priori knowledge of energy profiles, such dynamics imposes much difficulty on the design of protocols that must keep sensors from running out of energy.

The technology of highly-efficient wireless energy transfer was proposed for efficient, non-radiative energy transmission over mid-range. The work in [1] has shown that through strongly coupled magnetic resonances, the efficiency of transferring 60 W of power over a distance in excess of 2 m is as high as 40%. Industry research also demonstrated that it is possible to improve transferring 60 W of power over a distance of up to 1 m with efficiency of 75% [2]. At present, commercial products utilizing wireless energy transfer have been available on the market such as those in [3–5].

These technologies offer new possibilities for managing the available energy in wireless sensor networks and lead

---

[*] 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).

http://dx.doi.org/10.1016/j.comnet.2014.04.022
1389-1286/

the way towards *a new class* of wireless sensor networks, the *Wireless Rechargeable Sensor Networks (WRSNs)*. WRSNs 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 energy transfer technologies are capable of fast charging [6] 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 WRSNs can be performed passively from the perspective of the sensor nodes and without the computational and communicational overhead introduced by complex energy management algorithms. Finally, WRSNs allow energy management to be studied and designed independently of the underlying routing protocol used for data propagation.

There are numerous application scenaria in which wireless charging is preferable to a normal wired charging procedure. Use cases that necessitate a network deployment over rough areas, where wired infrastructure is difficult to be maintained (e.g. oil rigs), maximize the profit gained from this technology. Also, in cases where unpredictable events may occur (e.g. natural disasters, industrial component failures), wireless charging serves as an efficient network maintenance alternative. In general, wireless charging fits realistically in scenaria where there is no backbone wired infrastructure, no capability of frequent mote battery replacement and a need for mass over the air charging.

1.1. The problem

Let a Wireless Rechargeable Sensor Network comprised of *stationary* sensor nodes and *a single, special mobile entity called the Mobile Charger*. The Mobile Charger has significant (yet finite) energy supplies, that are much larger than those of each sensor node, and is thus capable of charging the sensors in the network.

We aim at designing and evaluating efficient strategies for several critical aspects of the Mobile Charger's configuration 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, the robustness of data propagation).

We focus on the cases of both *randomly heterogeneous* and *homogeneous* sensor nodes deployment. An underlying routing protocol is taking care of the data propagation from sensors to the Sink. Unlike other methods in the state of the art, *we do not "couple" the charging process and the data propagation*. Actually, we wish to perform efficient wireless energy transfer in a way which is agnostic to the routing protocol, via adaptive techniques that (without knowing the routing protocol) *implicitly adapt to any routing protocol*.

Remarks. 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. 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 (like the extent of wireless charging at each node and the energy split between the charger and the nodes) mentioned above.

Finally, we note that such 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 *NP*-complete (via reduction form Geometric Travelling Salesman Problem, G-TSP; see e.g. [8], p. 212).

1.2. Our contribution

While interesting research has been contributed to the wireless charging problem and particularly to the scheduling of the 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 adaptive, and use only local (or limited) network information*. Also, unlike many state of the art approaches that opt for integration and coupling of the charging and routing problems, our methods can be used together with *any underlying routing protocol* (since they adapt on it implicitly). Furthermore, our protocols dynamically and distributively *adapt to network diversities, e.g. they cope well with heterogeneous node placement* (while still behaving very well in the homogeneous case too).

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

(i) given that the energy the Mobile Charger is finite, *to what extent each sensor should be charged*,
(ii) what should be the *split of the total available energy* between the charger and the sensors and
(iii) what are *good trajectories the Mobile Charger should follow* in order to charge the sensor nodes.

More specifically, (a) we first introduce a *network attribute*, which we call *energy/flow criticality*, capturing both the energy consumption at the node over time and the traffic flow served by the node, (b) taking the energy/flow criticality of each sensor node into account, we suggest *a particular amount of energy the sensor node should be charged* to when visited by the mobile charger and (c) for the trajectory followed by the mobile charger, we design *three alternative strategies* (GKP, LRP, RTP) assuming different levels of network knowledge (from global to limited and reactive); actually, we view the global knowledge protocol as a performance upper bound to which the two distributed, partial knowledge protocols are compared with.

One of our protocols (LRP) performs some distributed, limited sampling of the network status, while another one (RTP) reactively adapts to energy shortage alerts judiciously spread in the network. As detailed simulations demonstrate, both protocols significantly outperform known state of the art methods, while their performance