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Wireless charging for weighted energy balance in populations of mobile peers☆

Sotiris Nikoletseas[b,c], Theofanis P. Raptis[a,*], Christoforos Raptopoulos[b,c]

[a] Institute of Informatics and Telematics, National Research Council, Pisa, Italy
[b] Department of Computer Engineering and Informatics, University of Patras, Patras, Greece
[c] Computer Technology Institute and Press "Diophantus", Patras, Greece

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ABSTRACT

Wireless energy transfer is an emerging technology that is used in networks of battery-powered devices in order to deliver energy and keep the network functional. Existing state-of-the-art studies have mainly focused on applying this technology on networks of relatively strong computational and communicational capabilities (wireless sensor networks, ad-hoc networks); also they assume energy transfer from special chargers to regular network nodes. Different from these works, we study how to efficiently transfer energy wirelessly in populations of battery-limited devices, towards prolonging their lifetime. In contrast to the state-of-the-art, we assume a much weaker population of distributed devices which are exchanging energy in a "peer to peer" manner with each other, without any special charger nodes. We address a quite general case of diverse energy levels and priorities in the network and study the problem of how the system can efficiently reach a weighted energy balance state distributively, under both loss-less and lossy power transfer assumptions. Three protocols are designed, analyzed and evaluated, achieving different performance trade-offs between energy balance quality, convergence time and energy efficiency.

1. Introduction

Next generation wirelessly networked populations are expected to consist of very large numbers of distributed portable devices carried by mobile agents that follow unpredictable and uncontrollable mobility patterns. Recently, there has been an increasing interest to combine near-field communication capabilities and wireless energy transfer in the same portable device, allowing mobile agents carrying the devices to wirelessly exchange energy. For example, the same antenna, designed to exploit its far-field properties for communication purposes, can be suitably configured for simultaneously realizing wireless energy transfer via its near-field properties. The near-field behavior of a pair of closely coupled transmitting and receiving dual-band printed monopole antennas (suitable for mobile phone applications) can make it possible to achieve both far-field performance and near-field power transfer efficiency (from 35% to 10%) for mobile phones located few centimeters apart [1]. Further developments on the circuit design can render a device capable of achieving bi-directional, highly efficient wireless energy transfer and be used both as a transmitter and as a receiver [2,3]. In this context, energy harvesting and wireless energy transfer capabilities are integrated, enabling each device to act on demand either as a wireless energy provider or as an energy harvester.

Populations of such devices have to operate under severe limitations in their computational power, data storage, the quality of communication and most crucially, their available amount of energy. For this reason, the efficient distributed co-operation of the agents towards achieving large computational and communication goals is a challenging task. An important goal in the design and efficient implementation of large networked systems is to save energy and keep the network functional for as long as possible [4,5]. This can be achieved by using wireless energy transfer as an energy exchange enabling technology and applying interaction protocols among the agents which guarantee that the available energy in the network can be eventually distributed in a balanced way.

Inspired by the Population Protocol model of Angluin et al. [6] and Angluin et al. [7], we present a new model for configuring the wireless energy transfer process in networked systems of mobile agents. In contrast with the Population Protocol approach, our model assumes significantly stronger devices with complex wireless energy transfer hardware, not abstracted by computationally restricted finite-state automata.

☆ A preliminary version of this paper appeared in [8].

* Corresponding author.
E-mail address: theofanis.raptis@iit.cnr.it (T.P. Raptis).

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Our contribution. The contribution of this paper is three-fold:

- We continue and extend the model of interactive wireless charging, presented in [8]. We present a problem statement regarding population weighted energy balance.
- We consider the (quite different) cases of loss-less and lossy wireless energy transfer. We provide an upper bound on the time that is needed to reach weighted energy balance in the population at the loss-less case, and we experimentally investigate via simulations the complex impact of the energy levels diversity in the lossy case; also, we highlight several key elements of the charging procedure.
- We provide and evaluate three interaction protocols which take into account different aspects of the charging procedure and achieve different performance trade-offs; one that is quite fast in achieving weighted energy balance in the loss-less case, another one that achieves weighted energy balance without wasting too much energy in the lossy case and a third one which gradually builds and maintains some knowledge of the energy levels in the network in an on-line manner.

2. Related work

Wireless energy transfer applications in networked environments have been lately investigated, especially in sensor and ad hoc networks. Numerous works suggest the employment of mobile wireless energy chargers in networks of sensor nodes, by combining energy transfer with data transmission and routing [9–11], providing distributed and centralized solutions [12–14] and collaborative charging schemes [15,16]. Other works focus on multi-hop energy transfer in stationary networks [17,18], as well as UAV-assisted charging of ground sensors [19,20]. Most of those wireless energy transfer applications have also been verified experimentally, using real device prototypes [21–23]. Although all those works provide nice solutions on the efficient charging of networks comprised of next generation devices, none of them investigates the peer-to-peer charging procedure in populations of mobile agents.

3. The model

We consider a population of m mobile agents $\mathcal{M} = \{u_1, u_2, \dots, u_m\}$, each one equipped with a *battery cell*, a *wireless energy transmitter* and a *wireless energy receiver*. Every agent $u \in \mathcal{M}$ is assigned to a *weight* w_u that characterizes the importance or criticality of the agent. Whenever two agents meet (e.g. whenever their trajectory paths intersect), they can interact by exchanging energy between their respective battery cells, according to an *interaction protocol* $\mathcal{P}$. We assume that agents are identical, that is they do not have IDs, they have the same hardware and run the same protocol $\mathcal{P}$. As a consequence, the *state* of any agent $u \in \mathcal{M}$, at any time t, can be fully described by the *energy* $E_t(u)$ available in its battery.

More formally, we assume that time is discrete, and, at every time step $t \in \mathbb{N}$, a single pair of agents $u, u' \in \mathcal{M}$ is chosen for interaction. In the most general setting, interactions are planned by a *scheduler* (that satisfies certain fairness conditions ensuring that all possible interactions will eventually occur), which can be used to abstract the movement of the agents. To allow for non-trivial efficiency analysis of our algorithmic solutions, in this paper, we consider a special case of fair scheduler, namely the *probabilistic scheduler*, that, independently for every time step, selects a single interacting pair uniformly at random among all $\binom{m}{2}$ pairs of agents in the population.

Whenever a pair of agents u, u' interact, they are able to exchange energy, by using their wireless energy equipment. Any transfer of energy ε induces *energy loss* $L(\varepsilon)$, due to the nature of wireless energy technology (e.g. RF-to-DC conversion, materials and wiring used in the system, objects near the devices, etc.). For simplicity, we do not take into account energy loss due to movement or other activities of the agents, as this is besides the focus of the current paper (see also Section 3.1). In fact, we assume that most devices can be carried by individuals or other moving entities that have their own agenda, and thus devices interact when the latter happen to come in close proximity. We will assume that the energy loss function satisfies a linear law:

$$L(\varepsilon) = \beta \cdot \varepsilon, \tag{1}$$

where $\beta \in [0, 1)$ is a constant depending on the equipment. Therefore, if agents u, u' interact at time t and, according to the interaction protocol $\mathcal{P}$, agent u should transfer energy ε to u', then the new energy levels of u, u' at time t become

$$E_t(u) = E_{t-1}(u) - \varepsilon \quad \text{and} \quad E_t(u') = E_{t-1}(u') + \varepsilon - L(\varepsilon).$$

Furthermore, the energy levels of all other (i.e. non-interacting at time t) agents remain unchanged. Slightly abusing notation, we will write

$$\begin{aligned}(E_t(u), E_t(u')) &= \mathcal{P}(E_{t-1}(u), E_{t-1}(u'), w_u, w_{u'}) \\ &= (E_{t-1}(u) - \varepsilon, E_{t-1}(u') + \varepsilon - L(\varepsilon)).\end{aligned}$$

3.1. Problem definition and metrics

We will say that a set of agents $\mathcal{M}$ is in *weighted energy balance* if

$$\frac{E_t(u)}{\sum_{x\in\mathcal{M}} E_x} = \frac{w_u}{\sum_{x\in\mathcal{M}} w_x}, \forall u \in \mathcal{M}.$$

In this paper, we study the following problem:

Definition 1 (Population weighted energy balance problem)**.** Find an interaction protocol $\mathcal{P}$ for weighted energy balance at the minimum energy loss across agents in $\mathcal{M}$.

In the present paper, we measure weighted energy balance by using the notion of *total variation distance* from probability theory [24] and stochastic processes [25].

Definition 2 (Total variation distance)**.** Let P, Q be two probability distributions defined on sample space $\mathcal{M}$. The total variation distance $\delta(P, Q)$ between P and Q is

$$\delta(P, Q) \stackrel{def}{=} \frac{1}{2} \sum_{x\in\mathcal{M}} |P(x) - Q(x)|. \tag{2}$$

By standard results on total variation distance (see for example [24]), we have the following equivalent expressions, which will be useful in our analysis.

$$\delta(P, Q) = \sum_{x\in\mathcal{M}:P(x)>Q(x)} (P(x) - Q(x)) \tag{3}$$

$$= \sum_{x\in\mathcal{M}:P(x)<Q(x)} (Q(x) - P(x)). \tag{4}$$

For any time $t \in \mathbb{N}$, we define the *energy distribution* $\mathcal{E}_t$ on sample space $\mathcal{M}$ (i.e. the population of agents) given by

$$\mathcal{E}_t(u) \stackrel{def}{=} \frac{E_t(u)}{E_t(\mathcal{M})}, \tag{5}$$

for any $u \in \mathcal{M}$, where $E_t(\mathcal{M}) = \sum_{x\in\mathcal{M}} E_t(x)$. Furthermore, we denote by $\mathcal{W}$ the *weight distribution*, given by

$$\mathcal{W}(u) = \frac{w_u}{\sum_{x\in\mathcal{M}} w_x}. \tag{6}$$