Ad Hoc Networks 78 (2018) 42–53

Contents lists available at ScienceDirect

Ad Hoc Networks

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

# The charger positioning problem in clustered RF-power harvesting wireless sensor networks

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ARTICLE INFO

*Article history:*
Received 18 July 2017
Revised 24 April 2018
Accepted 21 May 2018
Available online 28 May 2018

*Keywords:*
Wireless power transfer
Energy harvesting
Wireless sensor networks
Clustering

ABSTRACT

Wireless charging brings forward several new challenges in designing energy efficient wireless sensor networks. In a wireless charging scenario, a number of chargers with high energy resources are placed in the network to recharge power constrained nodes. Nevertheless, due to the fading effect of the signals, a few only nodes can remarkably benefit from the charger power emission. For this reason we examine whether the organization of the nodes in clusters may extend the network lifetime. In this paper, we compute the maximum size of the cluster and we propose an efficient localized algorithm as well as a centralized one to compute the charger position so as to maximize the cluster lifetime. We compare to other solutions in the literature and we present both theoretical and simulation results to show the effectiveness of our approach. The results show an up to 360% increase in lifetime in comparison with the traditional 1-hop communication method between the nodes and the sink.



## 1. Introduction

Wireless sensor networks are capable of periodically monitoring their vicinity and reporting important information about the integrity and security of their environment. The sensor nodes are powered by batteries and depending on how often they take measurements, communicate or interfere with other devices, their energy may be depleted fast. The node battery replacement may be a difficult task since sensors networks are often deployed in inaccessible places or the cost of the replacement may be high.

A technology that has been recently developed takes advantage of the transmitted neighboring RF signals to harvest a small portion of energy. More specifically, an RF-power harvesting antenna is used which can convert part of the received signal power to electricity. Depending on the transmitted power and the distance between the transmitting source and the receiver, a node can harvest power from some uW to some mW [1]. However, this technology presents some major limitations mainly due to the strong signal attenuation and the low efficiency of the conversion unit [2]. The harvested power rapidly decreases when the receiver is moving more than a few meters away from the source; the conversion efficiency is substantial only for a short range, and there is a minimum received signal power corresponding to a maximum distance below which no conversion is possible. These weaknesses substantially limit the effective range around the transmitting source, making this solution advantageous only for a few neighboring nodes. On the other hand, a possible use of multiple chargers to cover big parts of the network could considerably increase the expenditure and operating costs [3].

In this paper, we consider networks consisting of nodes which can acquire energy from energy transmitters (chargers). We assume that a charger periodically and omni-directionally transmits data to the network.[1] Due to the restrictions described before, we organize the network in clusters so that the majority of the nodes use short communication links and the most of the communication burden falls onto the shoulders of the cluster heads. By using chargers close to these nodes, we alleviate their communication cost and, thus, extend the network lifetime. An example of the proposed model is depicted in Fig. 1.

The RF-power harvesting paradigm using dedicated chargers can meet several industrial applications such as the use of wire-free or battery-free sensors. Moreover, modern Internet of Things protocols, like Zigbee, are designed to operate at 2.4 GHz whereas some known RF-power harvesting manufacturers propose equipment that uses the sub-gigahertz spectrum. This permits collision-

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[1] For the rest of the paper we refer to the term "fake data" for the charger's transmissions.

https://doi.org/10.1016/j.adhoc.2018.05.013
1570-8705/

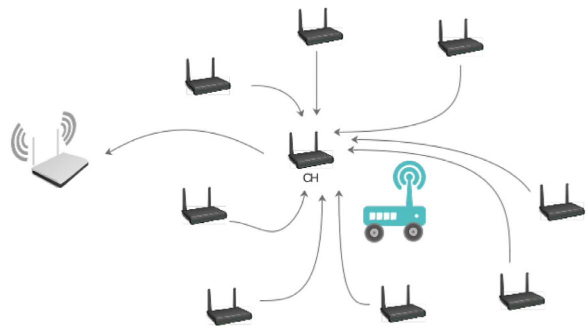


**Fig. 1.** Example of the proposed network model with a cluster consisting of 9 nodes, a sink, and a charger.

free communications between the nodes and the chargers, and facilitates the nodes deployment.

However, the question that arises is where to place a charger so that the network lifetime is prolonged as much as possible. In this paper we choose a charger placement strategy that (a) does not allow the cluster head to run out of energy throughout the whole monitoring process and (b) it provides the rest of the nodes (especially the most distant ones) with as much energy as possible. We explain that the placement problem is a special case of the Weber problem and we propose a local search algorithm that finds a solution very close to the optimal. The algorithm can operate in both centralized or distributed manner since it uses localized information and a number of successive steps to gradually move the charger towards more efficient positions. We, also, present an exhaustive search algorithm that examines a very large range of possible solutions exhibiting, however, higher computation costs.

The contribution of this paper is threefold; (a) we model a network that takes advantage of the very short efficient harvesting range and we organize the nodes in clusters so that by placing a charger close to the cluster head, it will have enough energy to forward the data of the rest of the nodes. (b) We analyze whether clustering is energy efficient and we compute the maximum possible cluster size. (c) We introduce the optimal charger positioning problem and we propose efficient algorithms to find solutions very close to the optimal. Finally, (d) we simulate our approach using realistic harvesting values and we compare to other approaches.

The present paper extends our previous work [4] by (a) presenting the theoretical background behind clustering in RF-power harvesting networks, (b) distinguishing two flavors of the optimal charger placement problem based on two network lifetime definitions, and (c) extending the theoretical and simulation results with comparison with other approaches in the literature.

The rest of the work is organized as follows. In Section 2, we make a discussion about previous works related to RF-power harvesting, routing, and placement problems. In Section 3 we describe the considered consumption, harvesting, communication, and network lifetime models. Section 4 presents a theoretical analysis on energy efficient clustering with RF-power harvesting nodes and Section 5 introduces the optimal charger positioning problem. Section 6 describes the proposed solutions and Section 7 presents the theoretical and simulation results. Finally, Section 8 concludes the paper and presents ideas for future work.

## 2. Related work

RF-energy harvesting networks have been extensively studied from different research aspects. Lu et al. [2] gives a general review of RF-power harvesting networks including a system architecture, RF energy harvesting techniques, and existing applications. Then, it surveys the state-of-the-art circuitry implementations, and reviews the communication protocols specially designed for this type of networks. Soyata et al. [5] focus on design tradeoffs to represent the diversity in the applications requiring wireless RF harvesting units. They analyze system combinations and how to wake up units, active storage, and duty cycling role in the consumption and harvesting of RF energy. Recent research studies on static charger scheduling strategies, mobile charger dispatch strategies, and wireless charger deployment strategies are reviewed in [6]. New research challenges and opportunities on RF-power harvesting networks focusing on their practical implementations are presented in [7]. A broad based perspective on the present RF-power harvesting state-of-the-art to the researchers and application engineers dealing with wireless transfer of power is given in [8]. Naderi et al. provide an experimental study to quantify the rate of charging, suitable ranges for charging, and how the placement and relative distances of multiple chargers affect the charging process, demonstrating constructive and destructive energy aggregation at the sensor nodes [9].

A fundamental issue in wireless sensor networks is routing. Unlike routing algorithms in conventional wireless sensor networks, in RF-powered networks more parameters need to be taken into account due to the fact that the available RF energy is not the same for all the nodes as well as due to the lower availability of the communication channel which is, also, in charge of transmitting fake data (acting as charger). Routing-based issues related to channel management and relay selection are handled by Doost et al. [10–13]. Finally, the node deployment problem taking into account the routing cost is examined in [14].

Clustering with RF-power harvesting nodes has been studied from different perspectives. In [15], the cluster heads get recharged by the data transmissions of the cluster members. The authors formulate a power resource allocation problem to maximize the energy efficiency among the cluster members. The reverse problem is tackled in [16], where it is assumed that the cluster heads are equipped with solar panels and they use the solar energy to recharge the cluster members. A cluster head placement problem is examined and it is proved that it is NP-hard. We must note here that our clustering problem differs to the previous two papers since we consider dedicated only chargers.

The dedicated charger positioning problem has been recently studied as a problem of maximizing an objective function subject to a power budget [17]. The objective function depends on the maximum consumption of the nodes and the power they harvest for a given deployment. The authors formulate an optimization problem and show that it is NP-Complete. They present approximation algorithms as well as greedy heuristics to find close to the optimal charger positions and their corresponding power transmission levels. The simulation results are close to the optimal and they outperform a random placement strategy. Overall, the work gives some useful insights of the charger placement problem, however, only centralized solutions are presented and non-realistic harvesting values are used for the simulation.

A similar problem is studied in [18]. The authors propose a wireless charger placement problem definition that takes into account the electromagnetic radiation. The solution they propose guarantees that the electromagnetic radiation levels are safe for every location on the plane. The performance of the proposed approximation algorithm is validated through both simulation and experimentation.

Pang et al. examined the problem of finding the optimal number of chargers to replenish the energy of a set of sensors [19]. They propose a partition algorithm to divide the network in different segments. They prove that their approach has a 50% probability to achieve the optimal solution. However, the authors consider a binary non-realistic harvesting model.