



Assessing the cost of deploying and maintaining indoor wireless sensor networks with RF-power harvesting properties

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ABSTRACT

Since Wireless Sensor Networks (WSNs) consist of nodes with limited power resources, methods that extend their energy lifespan are always in the spotlight. A potential method is the use of RF-power harvesting antennas which can absorb energy from radio frequency (RF) signals and transform a part of it into electricity. Dedicated energy transmitters (ETs) are used to emit power to the nodes. In this paper, we model the amount of harvesting energy as a function of several parameters such as the received power, the efficiency of the harvesting module and the transmission time. We consider a simple communication model that separates the ETs' transmissions with the node data transmissions to avoid interference whilst we allow multi-hop energy transfer between the nodes when it is achievable. However, the ultimate purpose of this paper is to examine whether the cost of the investment of using energy harvesting nodes can be covered by achieving a lower operation cost; that is longer and cheaper operation times and, thus, less frequent maintenance. We consider several scenarios with different node densities and transmitter populations. Simulation results show that the use of RF-energy harvesting nodes can save a significant amount of energy, while the cost of the investment can be (theoretically) covered in less than 7 years for dense networks.

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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 usually powered by batteries and depending on how often they take measurements and communicate with other devices, their energy may be depleted fast. To tackle this problem, a new technology has been recently developed by harvesting energy from wireless transmitted signals. This technology uses a new type of antenna which can convert part of the received signal power to electricity. RF-power harvesting has been recently attracted a lot of attention due to its several energy-critical applications in the broad area of Internet of Things [1]. Some examples are healthcare applications [2], structural monitoring [3], and industrial applications [4]. All these applications take advantage of the ability of this technology to charge batteries by distance while the battery replacement may be a hard task since the nodes are often placed in inaccessible places or the cost of the replacement may be high.

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Depending on the transmitted power and the distance between the transmitting source and the receiver, a node can harvest from some μW to some mW of power [5]. However, this technology is still new and presents some major limitations [6]. First, the harvested power dramatically decreases when the receiver is moving more than few meters away from the source. Second, the conversion efficiency is substantial only for a small range of distances. Third, there is a minimum received signal power, below which no conversion is possible, shortening the actual harvesting range. Finally, there are power losses due to leakage or discharging properties of the storage mediums.

Despite its weaknesses, wireless charging with dedicated ETs is a reliable way to charge low power consumption devices like WSN nodes, mainly due to the predictable and uninterrupted power supply. Other harvesting methods, like solar panels, exhibit higher energy gains (during sunlight), but the amount of energy depends on time, weather and seasonal conditions. Moreover, the solar radiation is in general case unpredictable and disappears at night. Another disadvantage is that panels take much space and require extra equipment like inverters and huge batteries to store the spare energy and present high installation costs as well. Due to these disadvantages the use of solar panels is considered impractical for indoor applications.

The energy transfer in RF-power harvesting is achieved either by taking advantage of the ambient RF signals transmitted by nearby primary devices or by dedicated chargers that continuously transmit energy beacons. Ambient harvesting has the advantage that does not require any additional equipment other than the harvesting module, however, the amount of harvesting power varies over time and it is much lower compared to dedicated chargers [7]. In this paper we consider dedicated and stationary ETs whose purpose is the periodic emission of RF signals. We model a network consisting of nodes and ETs taking into account the harvesting, communication and storage limitations described above. Unlike nodes whose power capacity is limited, the ETs are plugged into the power outlet and, thus, they have unlimited power resources. For simplicity reasons, we divide the time in rounds and every round includes two phases. The first phase allows the transmission of sensing data while the second phase is used for ET data transmissions. From now on we call the ET transmissions as “fake data” to distinguish them from node data transmissions.

Due to the fact that nodes that are closely to the ETs present high energy gains, we enhance our model by investigating whether these nodes could spend a spare part of their energy by transmitting some extra fake messages to their neighborhood. This action, known as *multi-hop energy transfer*, can extend the energy transfer range beyond the borders of the harvesting range of the ETs. We show that due to the current hardware limitations the performance gain is very limited for average or high distances.

In this paper, we consider the critical parameter of the *cost* in deploying and maintaining a network of nodes with RF-power harvesting capabilities. More specifically, we compute the capital and the operating expenditures focusing on indoor deployments. Taking into consideration the extra cost of the harvesting units, the cost of ETs, the cost of electricity, as well as the labor cost of maintaining a WSN (battery replacement), we introduce the *Minimum Reimbursement Time* problem. We particularly assess the time needed to cover the investment cost by an eventual reduced maintenance cost using a harvesting network. Since the maintenance cost is strongly connected with the network density, we examine a number of scenarios with different node and ET populations and we present extended simulation results. We extend the “Minimum Reimbursement Time” problem by introducing the problem of maximizing the coverage area whilst achieving the minimum possible reimbursement time.

The present paper extends our previous work [8] but it differentiates in the following ways: (a) the energy harvesting model is now more accurate, (b) a condition for networks consisting of nodes without batteries has been added, (c) the “Maximum Area Coverage” problem is introduced, (d) the position of the ETs is not fixed but it is computed based on the position of the nodes, (e) the simulation results derive by evaluating all the possible combinations between fake packet rate and number of ETs, and (f) the maximum number of ETs is increased from 8 to 16.

The contribution of this paper is threefold. First, we present the theoretical harvesting and communication background for RF-power harvesting networks and we provide conditions whether multi-hop energy transfer and node deployment without batteries are feasible. Second, we introduce the “Minimum Reimbursement Time” and the “Maximum Area Coverage” problems, to give some insights about (a) the scalability of the cost of a deployment consisting of RF-power harvesting devices, (b) how much of this cost can be covered by an eventual lower operating cost, and (c) finding upper bounds in terms of number of years for different node density deployments. Finally, extensive simulation results are conducted to evaluate the effectiveness of RF-power harvesting in terms of energy and cost savings.

The rest of the paper is organized as follows; Section 2 surveys the related work in the area of RF-energy harvesting WSNs. In Section 3 we present the energy harvesting and communication model while in Section 4 we give conditions to achieve multi-hop energy transfer and node deployment without batteries. In Section 5 we formulate the “Minimum Reimbursement Time” problem and we extend it by introducing the “Maximum Area Coverage” problem. Section 6 presents the theoretical and simulation results for different network scenarios, while Section 7 assesses the capital and operating costs. Finally, Section 8 concludes the paper and presents ideas for future work.

2. Related work

In the last few years there is an increased research effort for energy harvesting technologies due to the increased demand of power resources. The work of Basagni et al. [9] surveys all these technologies presenting their advantages and disadvantages. In the current paper we focus on RF-power harvesting which is frequently met in an indoor or outdoor environment since, nowadays, plenty of devices operate wirelessly, like television broadcasting, cell phones, Internet equipment etc.

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