Journal of
Sensor and Actuator Networks

MDPI

Article

Wireless Power Transfer Protocols in Sensor Networks: Experiments and Simulations †

Sotiris Nikoletseas [1,2], Theofanis P. Raptis [3,*], Alexandros Souroulagkas [2] and Dimitrios Tsolovos [1,2]

1 Computer Engineering and Informatics Department, University of Patras, 26504 Patras, Greece; nikole@cti.gr (S.N.); tsolobos@ceid.upatras.gr (D.T.)
2 Computer Technology Institute and Press "Diophantus", 26504 Patras, Greece; souroulagkas@gmail.com
3 Institute of Informatics and Telematics, National Research Council, 56124 Pisa, Italy
* Correspondence: theofanis.raptis@iit.cnr.it; Tel.: +39-050-315-8282

† A preliminary version of this article, entitled "An Experimental Evaluation of Wireless Power Transfer Protocols in Mobile Ad hoc Networks", was presented in IEEE Wireless Power Transfer Conference 2015.

Academic Editor: Dharma P. Agrawal
Received: 18 January 2017; Accepted: 24 March 2017; Published: 1 April 2017

Abstract: Rapid technological advances in the domain of Wireless Power Transfer pave the way for novel methods for power management in systems of wireless devices, and recent research works have already started considering algorithmic solutions for tackling emerging problems. In this paper, we investigate the problem of efficient and balanced Wireless Power Transfer in Wireless Sensor Networks. We employ wireless chargers that replenish the energy of network nodes. We propose two protocols that configure the activity of the chargers. One protocol performs wireless charging focused on the charging efficiency, while the other aims at proper balance of the chargers' residual energy. We conduct detailed experiments using real devices and we validate the experimental results via larger scale simulations. We observe that, in both the experimental evaluation and the evaluation through detailed simulations, both protocols achieve their main goals. The `Charging Oriented` protocol achieves good charging efficiency throughout the experiment, while the `Energy Balancing` protocol achieves a uniform distribution of energy within the chargers.

Keywords: wireless power transfer; wireless sensor networks; energy management

---

1. Introduction

Wireless sensor networks (WSNs) are limited by the lack of continuous energy supply. Typical commercial batteries are used to power the network nodes, and, usually, they are not being recharged or replaced. In such scenaria, the network is considered disposable. Efficient power consumption is essential in any protocol developed for this type of networks. Energy efficient design techniques have been studied for WSNs at all levels from hardware design to protocols for medium access control, routing, data gathering, topology control, etc. [1]. However, it is possible to sustain the nodes by recharging or replacing batteries when needed. Energy harvesting directly from the deployment environment can be used to recharge the wireless nodes. These harvesting techniques power network nodes via solar power, kinetic energy, floor vibration, acoustic noise, etc. [2]. However, due to the dynamic nature of such power sources and because there is generally a lack of a priori knowledge of energy profiles, such dynamics impose much difficulty on the design of protocols that keep network nodes from running out of energy. Wireless Power Transfer can be a key solution for overcoming these barriers.

Wireless Power Transfer, i.e., the ability to transfer electric energy from one storage device to another without any plugs or wires, has been proposed as an alternative method to traditional energy harvesting methods. Wireless Power Transfer technologies can be broadly classified into non-radiative coupling-based charging and radiative radio frequency (RF) based charging [3]. The former consists of three techniques: inductive coupling [4], magnetic resonance coupling [5] and capacitive coupling [6], while the latter can be further sorted into directive RF power beamforming and non-directive RF power transfer [7]. In capacitive coupling, the achievable amount of coupling capacitance is dependent on the available area of the device [8]. However, for a typical-size portable electronic device, it is hard to generate sufficient power density for charging, which imposes a challenging design limitation. As for directive RF power beam-forming, the limitation lies in the charger needing to know an exact location of the energy receiver.

The design of algorithms and protocols for coping with various aspects of the wireless charging procedure in WSNs has recently evolved as a very active research subject, as well as a topic of rapid technological progress, emerging practical development and application activities. In this paper, we focus on RF based wireless charging. The energy is transferred through the use of the electric field of an electromagnetic wave in a form of radiation. For safety issues, these types of wireless chargers operate in a low power region, which makes them suitable for use in WSNs.

Our Contribution. Current research in the field of WPT in Wireless Sensor Networks is, for the most part, focused on providing evaluations through the use of computer simulations. In this paper, we offer experimental evaluations for our proposed methods, using real devices. More specifically, we provide two protocols which consider several energy-related network properties. One of the proposed protocols takes into account the charging efficiency property. The second one performs wireless power transfer while keeping the energy level of the chargers balanced throughout the experiment. To evaluate our protocols, in addition to the experimental test-bed, we provide simulation results as well, in order to test the scalability of our solutions.

This paper is an expanded version of the conference paper [9]. We extend the real device experimental results of that work by evaluating the proposed protocols in a simulation environment. This way, we can test the protocol scalability and investigate some aspects that are difficult to be evaluated in small scale real device experiments. More specifically, we conduct simulations in order to identify and fine-tune some aspects of the proposed protocols: (1) the power threshold value for the `Charging Oriented` protocol and (2) the energy balancing parameter value for the `Energy Balancing` protocol. We provide figures that present the effect the power threshold has on charging efficiency and the charger inactivity percentage. We also provide a figure that presents the effect of the maximum allowed number of active chargers per round on the Energy balance property of the `Energy Balancing` protocol , and we compare the performance of the two protocols for a variable number of chargers. Finally, we fine-tuned the Abstract, Introduction and Related Work sections and added additional references.

2. Related Work

In [3], the reader can find an extensive overview of wireless charging techniques, the developments in technical standards, and their recent advances in network applications. In particular, with regard to network applications, the authors review the static charger scheduling strategies, mobile charger dispatch strategies and wireless charger deployment strategies. Additionally, they discuss open issues and challenges in implementing wireless charging technologies. Finally, they envision some practical future network applications of wireless charging.

In [10], the authors present an extensive literature review on the research progress in wireless networks with RF energy harvesting capability, referred to as RF energy harvesting networks. First, they present an overview including system architecture, RF energy harvesting techniques and existing applications. Then, they present the background in circuit design as well as the state-of-the-art circuitry implementations, and review the communication protocols specially designed for RF energy harvesting networks. The authors also explore various key design issues in the development of RF energy harvesting networks according to the network types, i.e., single-hop networks, multi-antenna networks, relay networks, and cognitive radio networks. Finally, they envision some open research directions.

The case of algorithmic design in sensor networks under the presence of one or more mobile wireless chargers has nicely been demonstrated in [11–13]. In these works, several distributed and centralized protocols using one or more mobile chargers are presented. In [14–16], some methods regarding joint Wireless Power Transfer and data gathering/routing have been presented. However, these works are restricted to theoretical design and evaluation in simulation environments, without conducting any experimentation with real devices.

Evaluation results using hardware equipment are provided in [17,18]. Although the authors use Wireless Power Transfer technology in order to evaluate their algorithms, the focus of the papers is mainly on the algorithmic design part and not on the real world application. Another novelty of our research is the focus on limited energy and on how to prolong the operation availability of the charging system, via energy balance methodologies.

Network lifetime can be enhanced without the use of wireless chargers as well. By designing protocols which take advantage of mobile components, the lifetime of a sensor network can be extended. More specifically, in [19], the authors exploit the mobility of the network nodes in their network in order to develop an intelligent fluid infrastructure. They have shown that their study has resulted in significant advantages on energy constrained systems. In [20], the authors propose a network in which the base station is mobile. Static base stations lead to high energy consumption by the neighbouring nodes. By using a mobile base station, the authors show that they can improve the network life time on the order of 500%.

Additionally, the authors in [21–23] explore the the ability of sensor nodes to exchange energy in a peer-to-peer manner. By using such techniques, the authors aim at creating specific energy distributions between the network nodes depending on the network topology.

3. The Model

Let $\mathcal{P} = \{v_1, v_2, \dots, v_n\}$ be a set of n rechargeable sensor *nodes* and $\mathcal{M} = \{u_1, u_2, \dots, u_m\}$ a set of m wireless power transfer devices (called *chargers*). Each charger has a charging angle ϕ_u and they are deployed inside an area $\mathcal{A}$ (say inside $\mathbb{R}^2$). The sensor nodes are mobile and they consume their available energy for typical networking tasks (such as routing, communicating and sensing, etc.). The wireless chargers are stationary throughout the course of the experiment and they have finite energy reserves. The available energy on each charger $u \in \mathcal{M}$ at time t, which can be used to charge the network notes, is denoted by $E_u^{(t)}$. We note that the existence of an energy (upper) bound for each charger greatly differentiates our model from other works in the literature.

Time is divided into "rounds" which are denoted by r and have length l. The rounds do not overlap each other. The first round begins at $t = 0$ and ends at $t = l - 1$. The mobile nodes change their positions at the beginning of each round, while the chargers decide their operational parameters according to the charging protocol. The protocol gives as output a set $\mathcal{S}$ of chargers which will be active during this round. The rest of the chargers will remain inactive.

We consider the following well established *charging model* (Friis equation): a node $v \in \mathcal{P}$ harvests energy from a charger $u \in \mathcal{M}$ with *charging rate* given by

$$P_{v,u}(t) = \frac{\alpha}{(\mathrm{dist}(v,u) + \beta)^2} P_u(t),$$

where

$$\alpha = G_u G_v \left(\frac{\lambda}{4\pi}\right)^2$$

and β are known constants which are dependent on the environment and the hardware of the devices. $P_u(t)$ is the power in Watts of the transmitter at time t, G_u and G_v are the antenna gains of the transmitter and receiver, respectively, λ is the wavelength of the transmitter's signal and $\mathrm{dist}(v,u)$ denotes the physical distance between node v and charger u. In this paper, we focus on two important network properties.

Definition 1 (Charging efficiency)**.** *The ratio of useful power fuelled in the network over power transmitted by the chargers, that is*

$$\eta = \frac{\sum_{v \in \mathcal{P}, u \in \mathcal{M}} P_{v,u}(t)}{\sum_{u \in \mathcal{M}} P_u(t)}.$$

Definition 2 (Energy balance)**.** *The additive variation of the energy dissipation of the chargers at time t, that is*

$$\iota = \sum_{u_i, u_j \in \mathcal{M}} |E_{u_i}^{(t)} - E_{u_j}^{(t)}|.$$

The problem. How can we schedule the charger operational activity so as to maximize important properties, such as the charging efficiency and the energy balance? We propose two protocols to address the problem. The first is designed taking into account the charging efficiency property and the second to ensure that every charger has similar energy reserves, so as to increase the sustainability of the system as a whole.

4. The Protocols

In many current application domains, including WSNs, the need for battery-free ultralow-power devices, possibly mobile, is increasing dramatically. Ambient monitoring based on the use of a large number of distributed battery-less devices with sensing capabilities is one of the main application areas toward the paradigm of efficient energy harvesting systems [24]. Such devices are normally being interrogated so as to provide wirelessly the information about their monitoring activity [25]. Energy harvesting systems exploit energy sources already present in the environment (e.g., electromagnetic, sunlight, mechanical, and thermal). The case of electromagnetic sources, where the energy to sustain device operations is provided by RF transmitters, is today commonly present in any humanized environment [26]. Based on this scenario, we provide two protocols which take into account different energy-related network properties, changing efficiency and energy balance.

`Charging Oriented` protocol. During the charging procedure, energy can be lost due to various parameters such as the distance between the transmitter and the receivers. The main goal of the `Charging Oriented` protocol (Protocol 1) is to maximize the amount of energy that reaches the network devices. In order to achieve this goal, the protocol introduces a threshold for the minimum acceptable received power ($P_{threshold}$). If there are no devices in the charging area of a charger $u \in \mathcal{M}$ for which $P_{v,u}(t) < P_{threshold}, \forall v \in \mathcal{P}$, then that charger will remain inactive for the current round. If at least one node is found which satisfies the above inequality, then the charger will be activated. To do this, the protocol activates each charger one by one and it measures the received power for each node. By using this threshold, the protocol aims at keeping the overall charging efficiency of the network above a certain level (which depends on the selected threshold value). In order to increase the charging efficiency, it is preferable for each charger to charge multiple mobile nodes simultaneously.

Protocol 1: `Charging Oriented`

Input : $\mathcal{P}, \mathcal{M}, P_{threshold}$
$\mathcal{S} = \emptyset$
foreach $v \in \mathcal{P}$ **do**
    foreach $u \in \mathcal{M}$ **do**
        if $P_{v,u}(t) \geq P_{threshold}$ **then**
            $\mathcal{S} = \mathcal{S} \cup \{u\}$
Output: $\mathcal{S}$

`Energy Balancing` protocol. When wireless power transfer is employed in Wireless Sensor Networks, it is preferable that all areas of the network will be covered for the whole duration of the experiment. The energy balance property ensures that the energy reserves of the chargers will remain the same during the experiment, which leads to the chargers being active for almost the same amount of rounds. This means that no areas will remain without coverage for long periods of time because the charger which covered this area depleted its energy faster than the other chargers. The `Energy Balancing` protocol (Protocol 2) aims at maintaining balance among the residual energy reserves of the chargers. In order to achieve this, at the beginning of each round, the protocol will select the μ number of chargers with the highest energy reserves and those chargers will be active for this round. Selecting chargers this way ensures that the average energy dissipation for each charger will be similar throughout time, but it leads to the selection of chargers which might be further away from the network nodes. This could lead to lower charging efficiency.

Protocol 2: `Energy Balancing`

Input : $\mathcal{P}$, $\mathcal{M}$, $E^{(t)}$, μ
$\mathcal{S} = \emptyset$
while $|\mathcal{S}| < \mu$ **do**
  $u_1 = \max_u E_u^{(t)}$
  $\mathcal{S} = \mathcal{S} \cup \{u_1\}$
  $\mathcal{M} = \mathcal{M} - \{u_1\}$
Output: $\mathcal{S}$

5. Performance Evaluation

To evaluate the performance of the protocols presented in the previous section, we conduct experiments using real devices, as well as simulations in order to test the performance of the protocols in a larger scale.

5.1. Experiments

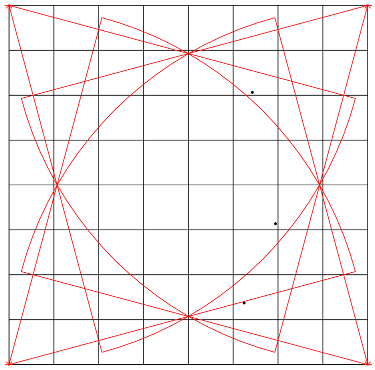
Deployment, parameter settings and adaptations. In Figure 1, the layout of the deployed equipment is depicted. The set of wireless chargers consists of $m = 4$ devices (TX91501 produced by Powercast (Pittsburgh, PA, USA) [27]), which are deployed on the vertices of a 2 m × 2 m square area $\mathcal{A}$. The set of the network nodes consists of $n = 3$ wireless sensor motes (TelosB TPR2420 produced by MEMSIC (Andover, MA, USA) [28]). Each node is powered by two 2400 mAh AA rechargeable batteries adjusted on three powerharvester receivers (P2110 produced by Powercast [27]). The chargers are directional. Their charging area is modelled as a sector with angle $\phi_u = 60^\circ$ and radius 2 m $\forall u \in \mathcal{M}$, whose bisector is perpendicular to the charger. The TelosB motes are programmed to perform sensing activities and transmit messages to other sensors in the network every 50 ms with 1 mW of power. For their programming, we used TinyOS (version 2.1.2, TinyOS Alliance) [29].

The two constant values of the Friis equation are set to $\alpha = 0.005$ according to the manufacturers omni-directional antenna specifications and $\beta = 0.23$ after applying the least square technique for fitting experimental data [30]. We set the length of each round to $l = 30$ min. The charger initial energy is set to $E_u^{(0)} = 22.5$ Wh, $\forall u \in \mathcal{M}$, the `Charging Oriented` threshold to $P_{threshold} = 1000$ µW and the `Energy Balancing` parameter to $\mu = 2$. The network area $\mathcal{A}$ is partitioned in an 8×8 grid and the nodes move in the beginning of each round to a new position, using a random walk strategy.

For the experimental evaluation of our protocols, we made some adaptations to our settings. We assume that each charger dissipates energy in a steady manner. More specifically, we assume that each active charger, transmits 3 W EIRP (Equivalent Isotropically Radiated Power), so, for each round, it provides the network with 1.5 Wh. In order to evaluate the state of charge in the batteries of the network nodes, we need to utilize techniques as described in [31] since modern batteries provide a steady voltage throughout their lifetime. For this reason, using a spectrum analyzer (Spectran HF-2025 mounted with an Omnilog 90200 omni-directional antenna, both manufactured by Aaronia

(Strickscheid, Germany) [32]), we measure the power received by each node. In our measurements, we also consider the RF-to-DC conversion efficiency, according to the manufacturer's specifications.

(a)



(b)

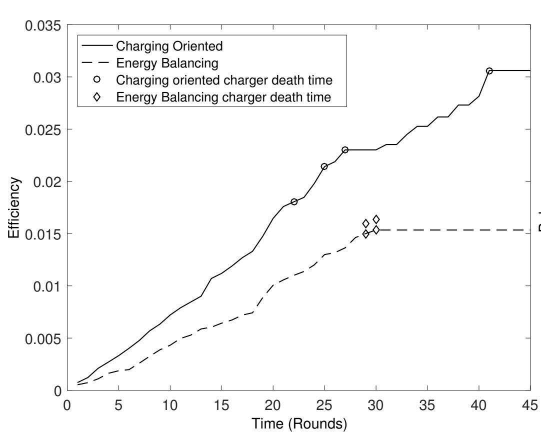
Figure 1. The testbed. **(a)** presents a snapshot of the testbed. **(b)** presents a graphical overview of the testbed.

Results. *Charging efficiency.* Figure 2a depicts the charging efficiency metric throughout the experiment. Additionally, it depicts the exact points in time when each charger depleted its available energy reserves and remained inactive during each protocol (point marks on the corresponding line plots). We observe that the `Charging Oriented` protocol achieves better performance on this metric than the `Energy Balancing` protocol, by fueling the network with energy over time in a higher rate, as the experiment progresses. When the third charger depletes all its available energy and only one is left in the network, the charging rate is significantly decreased. The `Energy Balancing` protocol delivers the available energy to the network sooner, since it frequently favours long distance transmissions.

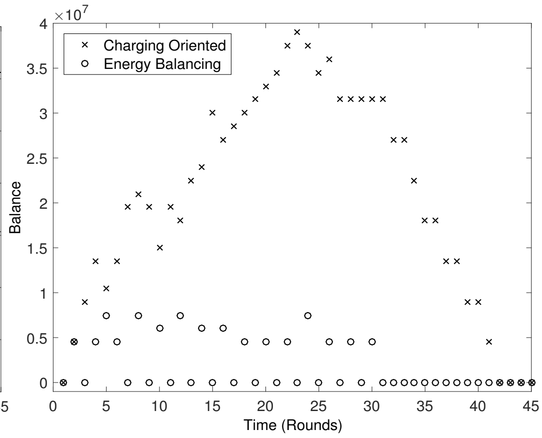
Energy Balance. Figure 2b depicts the performance of each protocol on the energy balance property. According to Definition 2, the optimal value at time t is 0. We observe that the `Energy Balancing` protocol outperforms the `Charging Oriented` protocol, since the points that represent the property's value are concentrated very close to 0. On the contrary, the performance of the `Charging Oriented` protocol is not ideal. We observe that the energy balance property keeps increasing until enough chargers deplete their energy reserves (this is evident from the first two points in Figure 2a). This happens at round 23 when the energy balance property starts decreasing again. This is explained by the fact that two specific chargers have been overused up until that time, thus increasing the difference in the available energy reserves between the chargers. When the energy of those two nodes was depleted, the value started to gradually return to normal levels.

Lifetime. In the `Energy Balancing` protocol, the chargers deplete their available energy uniformly. This can be observed in Figure 2c, which presents the lifetime of the chargers in each protocol, which is the number of rounds that each charger was able to fuel the network with energy. We observe that the `Charging Oriented` protocol achieves a longer overall charger lifetime, but this is performed by keeping just one charger alive.

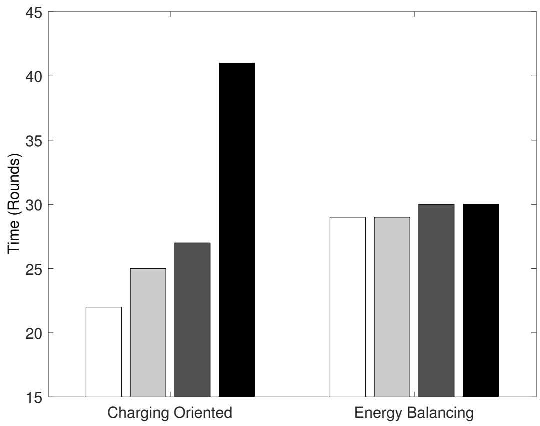
Operation time. Operation time is the percentage of (even a single) charger operation throughout the experiment. A useful outcome of the energy balance achieved by the `Energy Balancing` protocol is that the network was perpetually fuelled with energy until all chargers died. On the contrary, when using the `Charging Oriented` protocol, for almost 21% of the running time, there was not even one charger active in order to support the network needs. This can be observed in Figure 2a, where the `Energy Balancing` line plot is smoother and with no plateaus than the `Charging Oriented` one and in Figure 2c, where the number of `Charging Oriented` chargers is gradually diminishing. This increases the likelihood that the nodes will not fall within some charger's $P_{threshold}$.



(**a**)



(**b**)



(**c**)

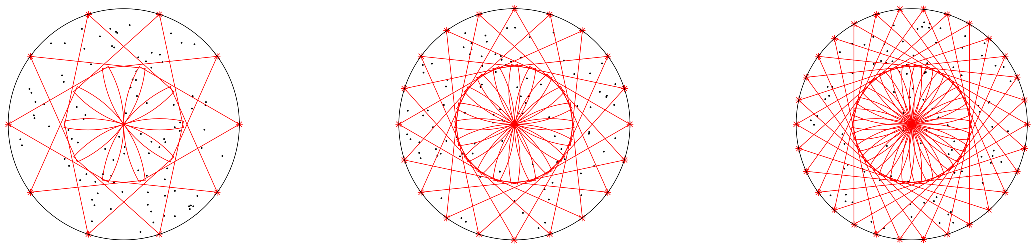
Figure 2. Experimental evaluation of the various metrics. (**a**) Cumulative charging efficiency over time. (**b**) Energy balance over time. (**c**) Lifetime of the chargers.

5.2. Simulations

Parameter settings. The simulation environment for conducting the experiments is Matlab (version: R2015a, MathWorks, Natick, MA, USA). A variable number of chargers is used (10, 20 and 30). The chargers are placed on the perimeter of a circle area $\mathcal{A}$ of radius equal to the transmission range of the chargers. The network nodes are placed uniformly at random in $\mathcal{A}$. Let $\mathcal{M}$ be the set of chargers and $\mathcal{P}$ the set of network nodes. We provide the chargers a total initial energy of $\sum_{u \in \mathcal{M}} E_u^{(0)} = 450$ Wh divided equally to each charger, their transmission range is set to $r_u = 6$ m, their transmission beam pattern is $\phi_u = 60^\circ$ and their transmission frequency is 915 Mhz. Finally, their output power is set to 3 Watts. The nodes have an initial energy of 5.3 Wh, and the RF to DC conversion efficiency is set to 50%. Round time is set to $l = 30$ min. At the end of each round, the network nodes are redistributed uniformly at random in $\mathcal{A}$. Figure 3 presents the simulation deployment. We repeat the simulations for $|\mathcal{M}| = 10$, $|\mathcal{M}| = 20$ and $|\mathcal{M}| = 30$. Note that, for every experiment instance, the total initial energy is the same, regardless of the number of chargers.

Results. *Charging oriented threshold value.* We first conduct simulations to fine-tune the threshold value for the `Charging Oriented` protocol. According to the Friis equation, the received power at a certain point is inversely proportional to the distance from the charger squared. We adapt our protocol and set a maximum distance threshold ($d_{threshold}$) instead of a minimum power threshold ($P_{threshold}$). In Figure 4a, the overall efficiency of our protocol for different values of $d_{threshold}$ is presented.

We observe that, for $d_{threshold} > 1$ m, the charging efficiency reaches a lower bound. This is due to the fact that the probability that $d_{v,u}(t) \leq d_{threshold},\ for\ v \in \mathcal{P},\ u \in \mathcal{M}$, is close to 1.



(**a**) (**b**) (**c**)

Figure 3. The simulation deployment for (**a**) 10, (**b**) 20 and (**c**) 30 chargers respectively.

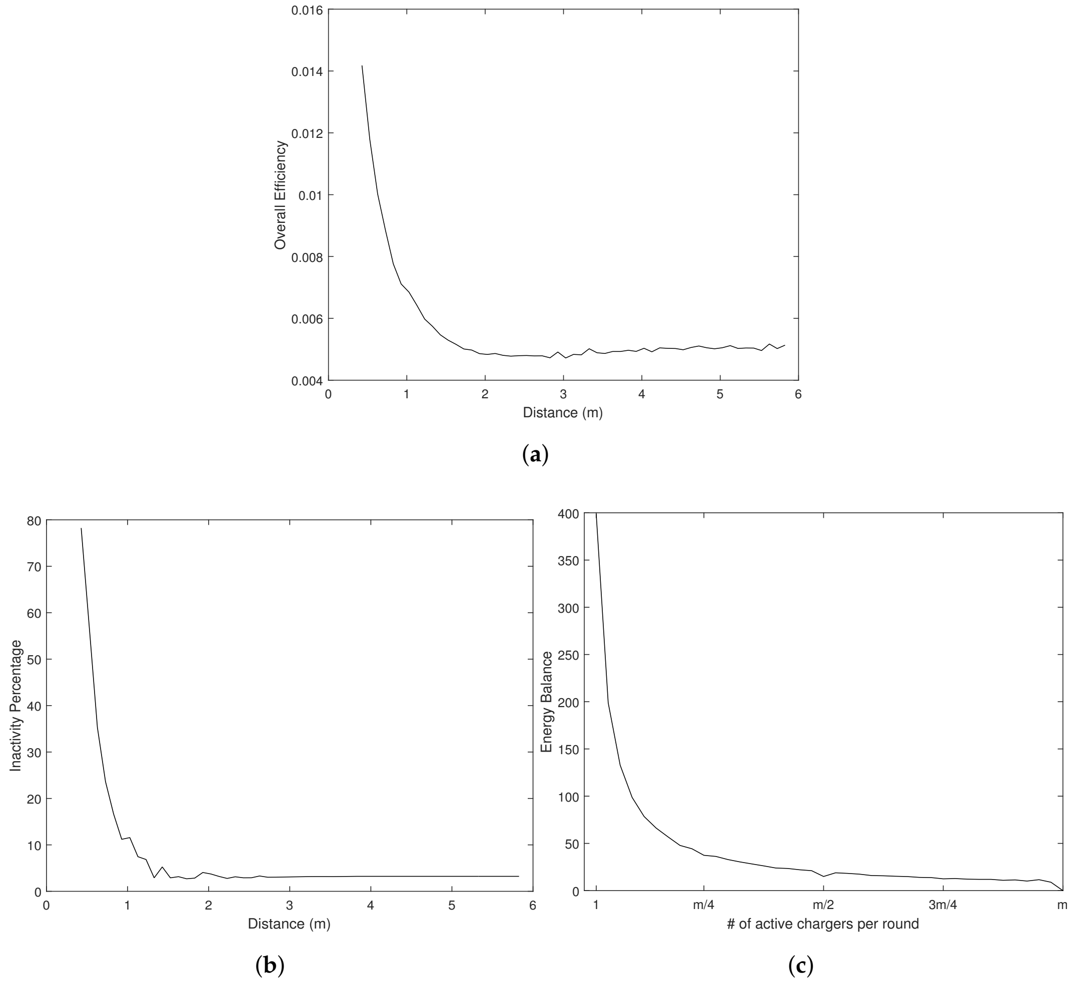


Figure 4. (**a**) Overall charging efficiency. (**b**) Percentage of inactivity. (**c**) Average energy balance.

Percentage of inactivity. Choosing the right value for $d_{threshold}$ is essential for the performance of the `Charging Oriented` protocol. A low value will result in a very low probability for a network node to be within this distance from a charger and the protocol will spend several rounds without any active chargers. This can be observed in Figure 4b. We see that for lower values of the distance threshold, all the chargers remain inactive most of the time.

Energy balancing parameter. We conduct simulations in order to calculate the optimal energy balancing parameter μ in the `Energy Balancing` protocol. We run the protocol several times, each time allowing a different number of active chargers per round. Figure 4c presents the average energy balance with respect to the number of active chargers per round. We observe that, if all the chargers are active in each round, the protocol achieves perfect energy balance, as expected. The protocol achieves good energy balance with $\mu \geq m/4$.

Taking into consideration the results of the above simulations, we choose $d_{threshold} = 0.8$ m, which, when converted to power, gives $P_{threshold} \simeq 2$ mW for the `Charging Oriented` protocol. This threshold should allow the protocol to have good charging efficiency without many periods of inactivity. For the `Energy Balancing` protocol, we choose $\mu = m/4$. This value should allow the protocol to achieve good energy balance and good lifetime for the chargers. We then run simulations for the network deployments discussed above.

Charging efficiency. Figure 5 depicts the performance of the two protocols in the charging efficiency throughout the simulations and the exact points in time when each charger ran out of energy and remained inactive for each protocol (cross marks on the corresponding line plots). We observe that, in all cases, the `Charging Oriented` protocol achieves a higher charging efficiency than the `Energy Balancing` protocol. This means that the `Charging Oriented` protocol is fueling the network with energy in a higher rate over time as the experiment progresses. When enough of the chargers die, this rate is significantly decreased. On the other hand, the `Energy Balancing` protocol transfers its available energy to the network faster, since it frequently favours long distance transmissions. We observe that the simulation results agree with the experimental results.

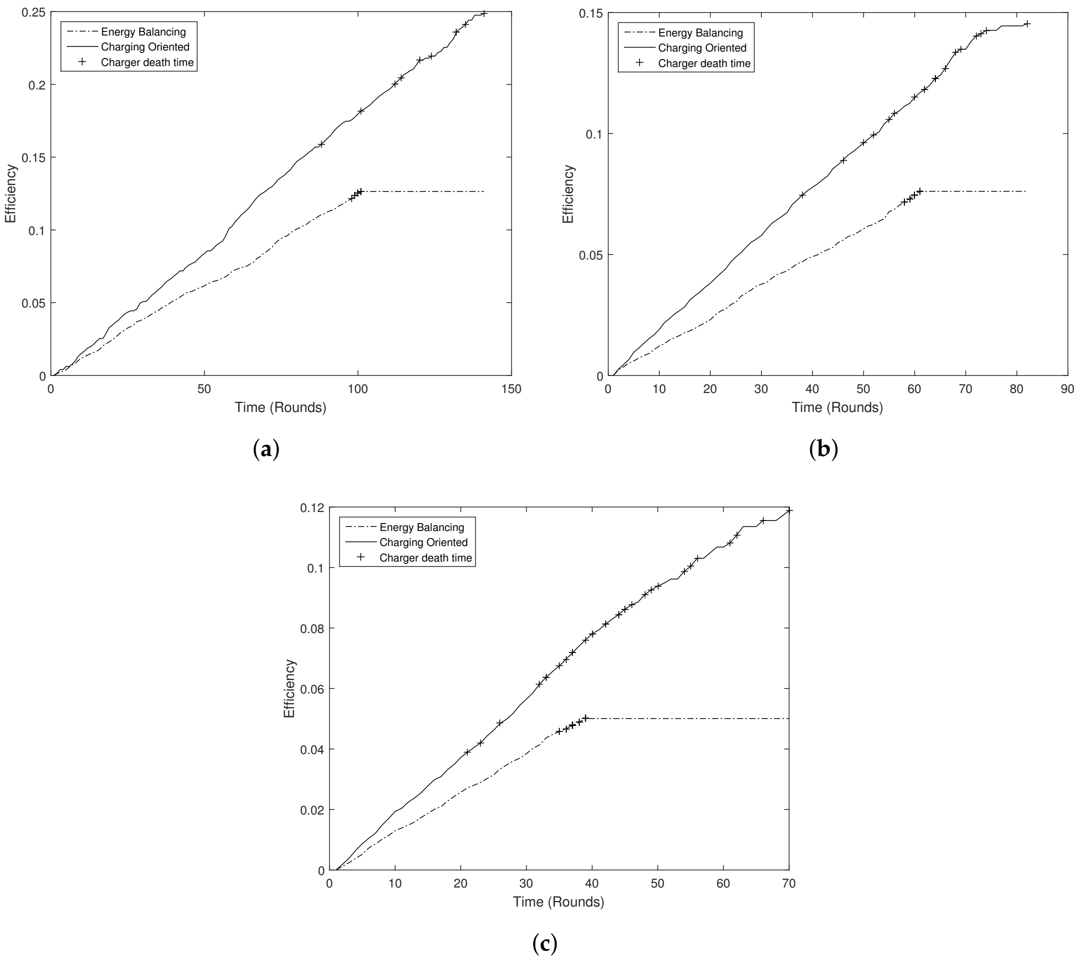


Figure 5. Cumulative charging efficiency over time for (**a**) 10, (**b**) 20 and (**c**) 30 chargers respectively.

Energy Balance. Figure 6 depicts the performance of both protocols on the energy balance metric. In the simulations, we observe similar results as in the real world experiments. More specifically, the `Energy Balancing` protocol outperforms the `Charging Oriented` protocol since its points that represent the property's value in the figure are highly concentrated close to zero. On the contrary, the points of the `Charging Oriented` protocol keep stretching far from zero. This means that the energy balance property keeps increasing up to the round when enough chargers have depleted their available energy (this is evident from the cross points in Figure 5). After this round, the energy balance starts decreasing again. This is explained by the fact that specific chargers are overused, resulting in an increase of the energy balance property value. When the energy of those chargers was depleted, the value started to gradually return to normal levels.

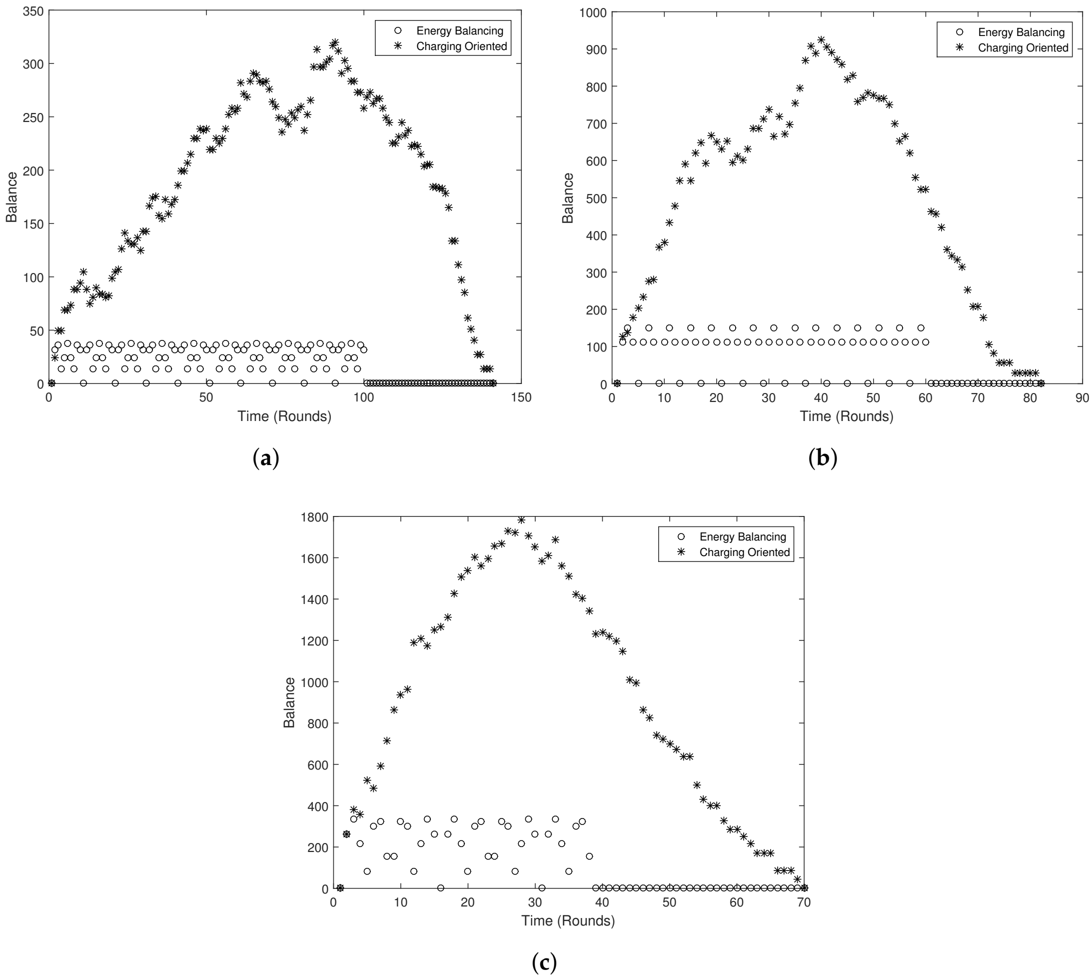


Figure 6. Energy balance over time for (**a**) 10, (**b**) 20 and (**c**) 30 chargers respectively.

Lifetime. Figure 7 represents the lifetime of the chargers for each protocol. The results are consistent with the experimental results in this metric as well. We observe that when using the `Energy Balancing` protocol, the chargers die in a uniform fashion. We also observe that the `Charging Oriented` protocol achieves longer overall charger lifetime. The reason for this behaviour is that the chargers remain inactive for several rounds as there are no nodes within their $P_{threshold}$.

Operation time. Operation time is the percentage of (even a single) charger operation throughout the experiment. A useful outcome of the energy balance achieved by the `Energy Balancing` protocol is that the network was perpetually fuelled with energy until all chargers died. On the contrary, when using the `Charging Oriented` protocol, for 20% of the running time on average, there was not even one charger active in order to support the network needs. This can be observed in Figure 5, where the

`Energy Balancing` line plot is smoother and with no plateaus than the `Charging Oriented` one and in Figure 7, where the number of `Charging Oriented` chargers is gradually diminishing. This increases the likelihood that the nodes will not fall within some charger's $P_{threshold}$.

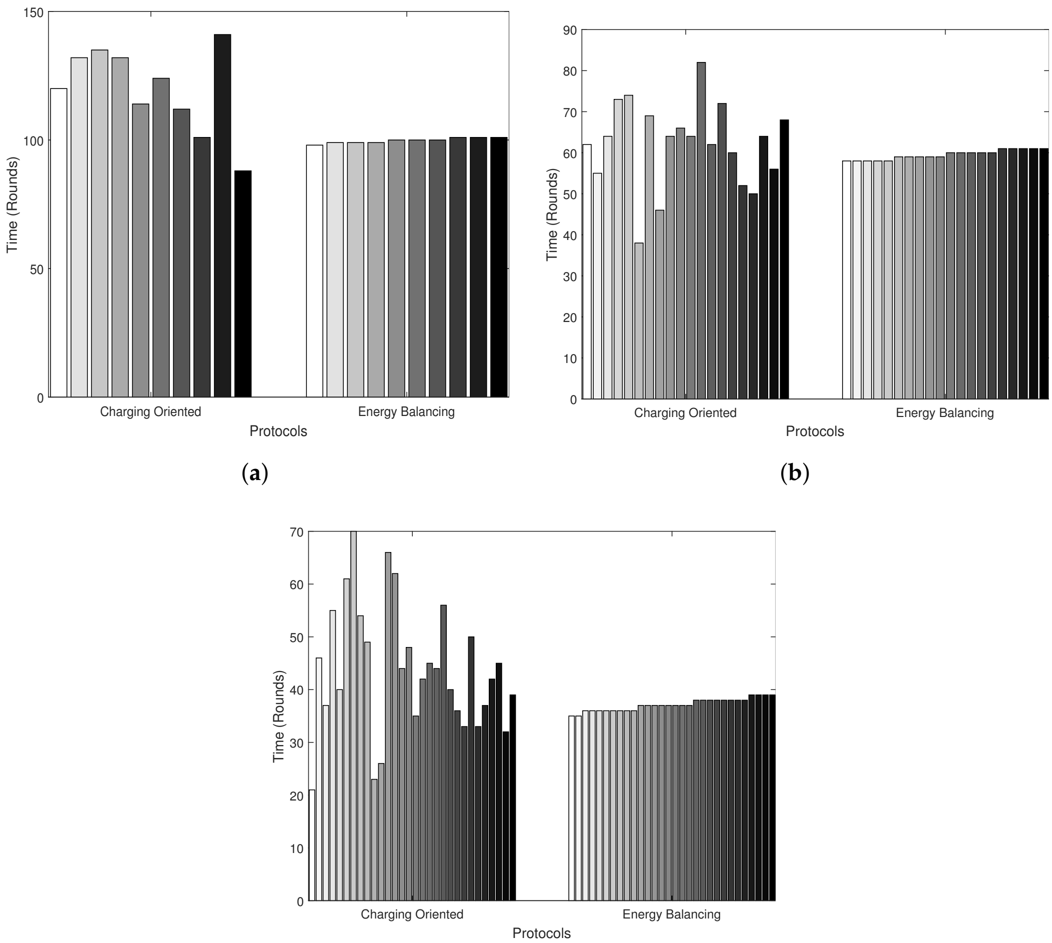


Figure 7. Lifetime of the chargers for (**a**) 10, (**b**) 20 and (**c**) 30 chargers respectively.

6. Conclusions

In this work, we have studied the problem of efficient and energy balanced Wireless Power Transfer in Wireless Sensor Networks. We designed two protocols that take into account either the charging efficiency or the energy balance of the chargers. After fine-tuning some key elements of these protocols, we investigate the performance of these protocols in a real test-bed and in a simulation environment.

We observe that the performance of the `Charging Oriented` protocol is highly dependent on the value of $P_{threshold}$ since allowing energy transmissions when the distance of the charger from the network nodes is high leads to very high energy loss (since all of the energy exchanges follow the Friis equation). The energy balance between the chargers is not taken into account in this protocol, which leads to some chargers being used much more than others. This, in turn, leads to some network areas not being charged for large periods of time, after the over-used chargers deplete their energy reserves.

On the other hand, the `Energy Balancing` protocol provides energy to the network more consistently since it ensures that a certain amount of chargers μ will be active at all times. In this protocol, the chargers "take turns" in fueling the network with energy, which leads to a uniform distribution of energy within the chargers. In order to achieve this, the protocol does not take into account the distance of the network devices. It allows energy transfers even if the distance between a network node and the charger is very large. This leads to higher amounts of energy loss.

Additionally, we observe that, in both the experimental evaluation and the evaluation through detailed simulations, both protocols achieve their main goals when compared to each other. The `Charging Oriented` protocol achieves good charging efficiency throughout the experiment, while the `Energy Balancing` protocol achieves a uniform distribution of energy within the chargers.

In this work, we proposed two protocols which achieve two specific goals. For future work, we plan to design a hybrid protocol that achieves a tunable trade-off between efficient charging and satisfactory energy balance, implement and validate protocols that use mobile chargers, and study the radiation patterns in the network area as well as design radiation-aware protocols.

Acknowledgments: This research was partially supported by the EU/FIRE IoT Lab project – STREP ICT-610477. This paper is an expanded version from the IEEE MTT-S Wireless Power Transfer Conference, Boulder, Colorado, USA, May 13-15, 2015.

Author Contributions: D.T., T.P.R. and S.N. conceived and designed the protocols and the experimental settings; D.T. performed the experiments and the simulations; D.T., T.P.R., S.N. and A.S. analyzed the data; D.T. and T.P.R. wrote the paper; and S.N. supervised the overall work. All authors contributed in discussing and revising the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yao, W.; Li, M.; Wu, M.Y. Inductive Charging with Multiple Charger Nodes in Wireless Sensor Networks. In *Advanced Web and Network Technologies, and Applications*; Lecture Notes in Computer Science; Springer: Berlin, Germany, 2006; Volume 3842, pp. 262–270.
2. Kansal, A.; Hsu, J.; Zahedi, S.; Srivastava, M.B. Power Management in Energy Harvesting Sensor Networks. *ACM Trans. Embed. Comput. Syst.* **2007**, *6*, 32.
3. Lu, X.; Wang, P.; Niyato, D.; Kim, D.I.; Han, Z. Wireless Charging Technologies: Fundamentals, Standards, and Network Applications. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 1413–1452.
4. Ho, S.L.; Wang, J.; Fu, W.N.; Sun, M. A Comparative Study Between Novel Witricity and Traditional Inductive Magnetic Coupling in Wireless Charging. *IEEE Trans. Magn.* **2011**, *47*, 1522–1525.
5. Kurs, A.; Karalis, A.; Moffatt, R.; Joannopoulos, J.D.; Fisher, P.; Soljačić, M. Wireless Power Transfer via Strongly Coupled Magnetic Resonances. *Science* **2007**, *317*, 83–86.
6. Kline, M.; Izyumin, I.; Boser, B.; Sanders, S. Capacitive power transfer for contactless charging. In Proceedings of the 2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Fort Worth, TX, USA, 6–11 March 2011; pp. 1398–1404.
7. Popovic, Z. Cut the Cord: Low-Power Far-Field Wireless Powering. *IEEE Microw. Mag.* **2013**, *14*, 55–62.
8. Hui, S.Y. Planar Wireless Charging Technology for Portable Electronic Products and Qi. *Proc. IEEE* **2013**, *101*, 1290–1301.
9. Nikoletseas, S.; Raptis, T.P.; Souroulagkas, A.; Tsolovos, D. An experimental evaluation of wireless power transfer protocols in mobile ad hoc networks. In Proceedings of the 2015 IEEE Wireless Power Transfer Conference (WPTC), Boulder, CO, USA, 13–15 May 2015; pp. 1–3.
10. Lu, X.; Wang, P.; Niyato, D.; Kim, D.I.; Han, Z. Wireless Networks With RF Energy Harvesting: A Contemporary Survey. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 757–789.
11. Angelopoulos, C.M.; Nikoletseas, S.; Raptis, T.P. Wireless energy transfer in sensor networks with adaptive, limited knowledge protocols. *Comput. Netw.* **2014**, *70*, 113–141.
12. Madhja, A.; Nikoletseas, S.; Raptis, T.P. Distributed wireless power transfer in sensor networks with multiple Mobile Chargers. *Comput. Netw.* **2015**, *80*, 89–108.
13. Wang, C.; Li, J.; Ye, F.; Yang, Y. NETWRAP: An NDN Based Real-Time Wireless Recharging Framework for Wireless Sensor Networks. *IEEE Trans. Mob. Comput.* **2014**, *13*, 1283–1297.
14. Guo, S.; Wang, C.; Yang, Y. Joint Mobile Data Gathering and Energy Provisioning in Wireless Rechargeable Sensor Networks. *IEEE Trans. Mob. Comput.* **2014**, *13*, 2836–2852.

15. Li, Z.; Peng, Y.; Zhang, W.; Qiao, D. J-RoC: A Joint Routing and Charging scheme to prolong sensor network lifetime. In Proceedings of the 2011 19th IEEE International Conference on Network Protocols (ICNP), Vancouver, AB, Canada, 17–20 October 2011; pp. 373–382.
16. Xie, L.; Shi, Y.; Hou, Y.; Lou, W.; Sherali, H.; Midkiff, S. Bundling mobile base station and wireless energy transfer: Modeling and optimization. In Proceedings of the 2013 IEEE INFOCOM, Turin, Italy, 14–19 April 2013; pp. 1636–1644.
17. Peng, Y.; Li, Z.; Zhang, W.; Qiao, D. Prolonging Sensor Network Lifetime Through Wireless Charging. In Proceedings of the IEEE 31st Real-Time Systems Symposium (RTSS), San Diego, CA, USA, 30 November–3 December 2010; pp. 129–139.
18. Dai, H.; Liu, Y.; Chen, G.; Wu, X.; He, T. Safe Charging for wireless power transfer. In Proceedings of the IEEE Conference on Computer Communications (INFOCOM), Toronto, ON, Canada, 27 April–2 May 2014; pp. 1105–1113.
19. Kansal, A.; Somasundara, A.A.; Jea, D.D.; Srivastava, M.B.; Estrin, D. Intelligent Fluid Infrastructure for Embedded Networks. In Proceedings of the 2nd International Conference on Mobile Systems, Applications, and Services (MobiSys '04), Boston, MA, USA, 6–9 June 2004; ACM: New York, NY, USA, 2004; pp. 111–124.
20. Luo, J.; Hubaux, J.P. Joint mobility and routing for lifetime elongation in wireless sensor networks. In Proceedings of the IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies, Miami, FL, USA, 13–17 March 2005; Volume 3, pp. 1735–1746.
21. Nikoletseas, S.; Raptis, T.P.; Raptopoulos, C. Interactive Wireless Charging for Energy Balance. In Proceedings of the 2016 IEEE 36th International Conference on Distributed Computing Systems (ICDCS), Nara, Japan, 27–30 June 2016; pp. 262–270.
22. Nikoletseas, S.; Raptis, T.P.; Raptopoulos, C. Energy Balance with Peer-to-Peer Wireless Charging. In Proceedings of the 2016 IEEE 13th International Conference on Mobile Ad Hoc and Sensor Systems (MASS), Brasilia, Brazil, 10–13 October 2016; pp. 101–108.
23. Madhja, A.; Nikoletseas, S.; Raptopoulos, C.; Tsolovos, D. Energy Aware Network Formation in Peer-to-Peer Wireless Power Transfer. In Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM '16), Malta, Malta, 13–17 November 2016 ; ACM: New York, NY, USA, 2016; pp. 43–50.
24. Costanzo, A.; Dionigi, M.; Masotti, D.; Mongiardo, M.; Monti, G.; Tarricone, L.; Sorrentino, R. Electromagnetic Energy Harvesting and Wireless Power Transmission: A Unified Approach. *Proc. IEEE* **2014**, *102*, 1692–1711.
25. Lui, K.W.; Murphy, O.H.; Toumazou, C. 32-μW Wirelessly-Powered Sensor Platform With a 2-m Range. *IEEE Sens. J.* **2012**, *12*, 1919–1924.
26. Piñuela, M.; Mitcheson, P.D.; Lucyszyn, S. Ambient RF Energy Harvesting in Urban and Semi-Urban Environments. *IEEE Trans. Microw. Theory Tech.* **2013**, *61*, 2715–2726.
27. Powercast. Available online: http://www.powercastco.com/ (accessed on 28 March 2017).
28. TelosB Platform. Available online: http://www.memsic.com/userfiles/files/Datasheets/WSN/telosb_datasheet.pdf (accessed on 28 March 2017).
29. The TinyOS Operating System. Available online: https://github.com/tinyos (accessed on 28 March 2017).
30. He, S.; Chen, J.; Jiang, F.; Yau, D.; Xing, G.; Sun, Y. Energy Provisioning in Wireless Rechargeable Sensor Networks. *IEEE Trans. Mob. Comput.* **2013**, *12*, 1931–1942.
31. Piller, S.; Perrin, M.; Jossen, A. Methods for state-of-charge determination and their applications. *J. Power Sources* **2001**, *96*, 113–120.
32. Aaronia. Available online: http://www.aaronia.com/ (accessed on 28 March 2017).