Journal of
Sensor and Actuator Networks

MDPI

Article

A Green Routing Protocol with Wireless Power Transfer for Internet of Things

Francesco Chiti, Romano Fantacci and Laura Pierucci *

Department of Information Engineering, Università di Firenze, Via di Santa Marta 3, 50139 Firenze, Italy; francesco.chiti@unifi.it (F.C.); romano.fantacci@unifi.it (R.F.)
* Correspondence: laura.pierucci@unifi.it; Tel.: +39-055-2758626

Abstract: The usually constrained resources and lossy links scenarios of Internet of Things (IoT) applications require specific protocol suite, as the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL). Due to its flexibility, RPL can support efficiently vertical applications such as environmental monitoring, smart city and Industry 4.0. In this paper, we propose a new Objective Function (OF) for RPL based on a composite metric considering jointly the residual energy of a node (parent) together with the energy that a neighbor node (child) can transfer to the parent according to the Wireless Power Transfer (WPT) concept. Specifically, we consider simultaneous wireless information and power transfer (SWIPT) technique, which enables both the energy harvesting and information decoding from the same radio frequency (RF) signal, in order to influence the selection of the best path according to the proposed energy efficient metric in RPL. Performance evaluation on a realistic scenario pointed out a remarkable energy saving to prolong the network lifetime, by selecting the best path toward the sink node, with respect to the OFs usually considered in the literature.

Keywords: Low-Power and Lossy networks; IPv6; Routing IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL); energy-harvesting; wireless power and information transfer

Citation: Chiti, F.; Fantacci, R.; Pierucci, L. A Green Routing Protocol with Wireless Power Transfer for Internet of Things. *J. Sens. Actuator Netw.* **2021**, *10*, 6. https://doi.org/10.3390/jsan10010006

Received: 29 December 2020
Accepted: 19 January 2021
Published: 24 January 2021

1. Introduction

Billions of "smart" objects are going to be connected to each other and in Internet according to the Internet of Things (IoT) paradigm. Emerging applications for smart city, smart building, industrial context, etc., increase the demand of IP-based networks to allow full interaction among heterogeneous devices with different features. Due to the constrained resources of IoT devices and the lossy links of IoT networks, new definitions of protocols suitable for Low-Power and Lossy Networks (LLNs) are needed, such as (i) IPv6 for Low-Power Wireless Personal Area Networks (6LoWPAN) [1], which allows to send IPv6 frames over IEEE 802.15.4 networks through a header compression mechanism proposed by the Internet Engineering Task Force (IETF) 6LoWPAN Working Group, and (ii) the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) [2], issued by the Internet Engineering Task Force (IETF) Routing over Low-Power and Lossy Networks (RoLL) Working Group.

RPL is an adaptive distance-vector routing protocol suitable for the requirements of different applications as it uses one or more Objective Function (OF) to find the best route from the leaf nodes to the destination (named sink node or root node, or gateway or border router). The routing topology created is a Destination Oriented Directed Acyclic Graph (DODAG) which is a logical topology formed over a physical network according to different metrics and constraints. Default routing metrics for RPL are objective function zero (OF0) and the Minimum Rank with the Hysteresis Objective Function (MRHOF) based on the expected transmission count (ETX) [3,4]. As new OFs can be designed, RPL can be adapted to a large variety of applications for different LLN networks by defining the most suitable OF. Indeed, recent studies focus on different OFs and hybrid metrics aimed at evaluating the performance of RPL based on packet loss rate, energy consumption and latency [5–9].

These OFs do not consider the node level congestion and can create unbalanced load and inefficient energy distribution in the network, especially for heterogeneous traffic load [10].

Saving power, together ensuring acceptable service quality, is an important challenge since in wireless sensor networks (WSN), sensors nodes are powered by limited time batteries and are usually distributed and not replaced in the case where they are energy depleted due to high costs. Therefore, energy-based OFs for RPL have been proposed in the literature to preserve the sensor nodes energy and prolong the network lifetime [7,8,11].

Energy harvesting (EH) overcomes the major drawback of battery, i.e., the reduction of stored energy due to the sensing, data processing, and communications. Compared to battery-operated nodes, energy harvesting can achieve almost unlimited lifetime, but at the same time, it raises the issue of operating a sensor node with intermittent energy supply and a limited capability of energy storing. Several solutions adopt the use of energy harvested from the photovoltaic cell which imposes in some cases very low duty cycles as shown in ref. [12].

Recently, Wireless Power Transfer (WPT) offers a promising solution for facilitating efficient and sustainable communication networks serving energy-limited communication devices. The existing WPT technologies can be categorized as: inductive coupling, magnetic resonant coupling, and RF-based WPT. RF-based energy-harvesting technology enables the possibility of simultaneous wireless information and power transfer (SWIPT), wireless-powered communication (WPC), and wireless-powered backscatter communication (WPBC) [13,14]. The SWIPT mechanism captures RF radiation from the environment and supports the harvesting of energy and decodes information from the same RF signal received in parallel by means of an energy and information division mechanism. In the literature, two practical approaches are proposed, namely "time switching" (TS) and "power splitting" (PS). In TS, two different time periods are used to switch from decode information to energy-harvesting while in PS the RF signal is divided into two parts with different power, one for information decoding and the other one for EH [15,16]. The first is simpler to implement then PS which, however, provides a better energy efficiency.

To the best of our knowledge, energy-harvesting mechanisms based on SWIPT have not been developed until now for RPL. Therefore, the paper proposes an optimal OF for the routing tree formation in order to preserve lifetime of the entire network. In the network a limited number of nodes with sufficient power to recharge the neighbor nodes (*child*) at the maximum level of battery are present and then, by using SWIPT, one intermediate node (*parent*) can recharge its own battery with a fraction of RF signal power received from its child node. As a consequence, the best route selection is influenced by choice of intermediate nodes forwarding data messages to the root node. For example, if an intermediate node has little residual energy (RE), a classical energy-based routing object function could specify a constraint such that any path with this node and other nodes with RE below a certain threshold should be avoided. By assuming that an intermediate node can be recharged with the power transferred by a child node, the route selection can instead include this node to recharge it for allowing an effective balance of the global energy in the network.

The main contribution of the paper is to address the use of SWIPT method applied to RPL. To achieve this goal, a novel OF for RPL is proposed, which is based on a composite metric combining (i) the energy consumption of intermediate nodes, due to sensing/data processing and to transmission/receiving modes, and (ii) the quantity of recharging available from the received power of a child node. This novel OF, called in the following OF2, can avoid that more loaded nodes spend their energy more intensively than other nodes, e.g., mainly the nodes closer to the root node. A performance comparison of the default and proposed OFs is also provided in terms of the Jain's Fairness Index [17], to better analyze the behavior of the OF2 for making the best decision for route selection jointly to maximize the lifetime of nodes.

The rest of the paper is organized as follows: Section 2 introduces a brief overview of RPL operations, while Section 3 reviews main papers related to RPL and SWIPT methods and outlines the differences of some related works with respect to this paper; Section 4 shows the proposed scenario; in Section 5, the proposed OF for energy-harvesting RPL is described; Section 6 validates the proposed OF by means of numerical results, and finally, in Section 7, the conclusions are drawn.

2. IPv6 Routing Protocol for Low-Power and Lossy Networks—RPL

RPL supports the point-to-point, multipoint-to-point, and multicast traffic with thousands of nodes. RPL is a dynamic routing protocol based on metrics, e.g., hop count, latency, throughput, expected transmission count (ETX), energy, etc. to minimize or maximize OFs for route discovery and data forwarding. Default routing metrics for RPL are objective function zero (OF0) and the Minimum Rank with the Hysteresis Objective Function (MRHOF) based on the expected transmission count (ETX).

OF0 uses rank value to decide upon the preferred next hop. The rank value indicates at what level nodes are in the directed acyclic graph. If the rank has a lower value then the node is closer (according to the hop numbers) to the sink node. The expected transmission count (ETX) is the metric considered for the target work when the quality of the connection is critical. The ETX metric is based on the number of transmission attempts for a successful transmission, thus it is a link metric [3]. In ref. [4], the Minimum Rank with the Hysteresis Objective Function (MRHOF) chooses paths that minimize a metric (ETX metric by default) while using "hysteresis", i.e., a threshold value, to avoid a restart of the route selection in response to small variations in the metric values.

In an RPL-based topology, the underlying nodes self-organize building one or several DODAGs, based on parent-to child- relationships optimized according to the considered OF. DODAG Information Object (DIO) messages are broadcasted by the sink node. The neighboring nodes receiving DIO messages select the best parent according the route metric and then joining to the route. Each node calculates a rank which determines its relative position in the DODAG to avoid routing loops. Then, the node sends DIO messages to the neighboring node usually selecting the one with the lowest rank and the process continues until all the network nodes are covered. During regular operations, the emission of DIO messages is periodic and regulated by the Trickle algorithm [18], which aims at reducing the power consumption of the nodes by minimizing the redundant messages and by adapting dynamically their transmission rate over time. Destination Advertisement Object (DAO) messages are sent by each node to maintain reverse route information, while DODAG Information Solicitations (DIS) packets solicit the DIO packet from neighboring nodes. The data messages flow in the network according to the routes selected in the route establishing phase. The data traffic can occur in an upward or downward manner. Due to interferences in the communication links or low battery level, the routes to the root can change. To repair the topology of the DODAG, the DODAG ROOT increments the DODAGVersionNumber to create a new DODAGVersion [19]. This operation is called global DAG repair. A local repair can also be done transferring the packets to nodes at the same level or switching to the parent node. However, any type of repair results in a longer delay and control overhead until many nodes fail where the network becomes inoperative. The typical DODAG management upon receiving a DIO message is represented as a flow chart in Figure 1, where the rank and parents list update are pointed out.

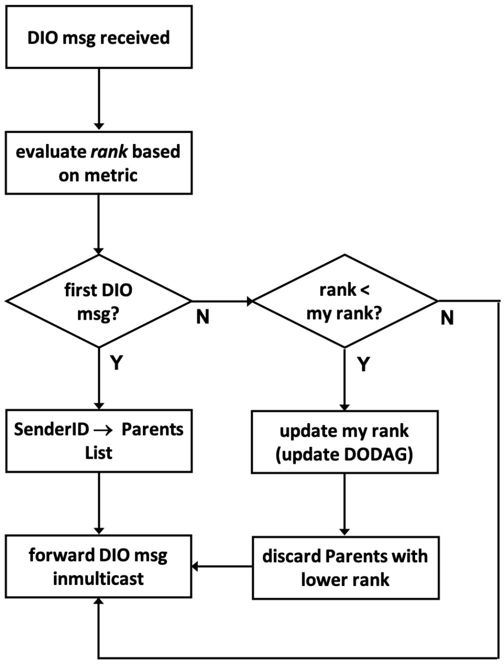

Figure 1. Routing Protocol for Low-Power and Lossy Networks (RPL) Destination Oriented Directed Acyclic Graph (DODAG) management flow chart upon receiving a DODAG Information Object (DIO) message.

3. Related Works

Several survey works summarized the RPL operations and other routing solutions for IoT/LLN networks as in refs. [20–23]. Recently, different papers have analyzed new RPL features mainly addressing security aspects, route maintenance and recovery mechanism, i.e., link failure detection and recovery mechanism, and various performance metrics such as packet reception rate, storing mode feature, average delay of paths, and energy usage.

In this brief review, we only consider the papers presenting composite metrics (in addition to the IETF proposed objective functions, i.e., OF0 and ETX) for RPL based on the residual energy of the nodes to improve the global lifetime of the network.

In ref. [24], the authors address energy efficiency and reliability issues when the network size and the location of the root node change in addition to considering storing mode and convergence time for local repair approaches. In ref. [5], an OF named EEQ is shown to preserve the node which has already sent sensed data towards the root node and has consumed too much of its energy. EEQ computes the rank of a node by using weighted combination of the following parameters: (i) expected number of transmissions, (ii) consumed energy, and (iii) active queue length. This composite metric under high intensity traffic loads presents less overhead of control messages resulting in energy conservation. In ref. [6], a variant of RPL is proposed for routing multimedia traffic which considers the remaining energy of nodes. Since multimedia traffic is extremely energy consuming, it is important to improve the network lifetime for multimedia content distribution.

The RPL protocol is analyzed under a heterogeneous traffic [10] by proposing an OF based on packet queue of the node to measure its congestion and on the link workload condition (QWL-RPL). This OF allows to distribute the load in a balanced way and to minimize the number of controls overhead when supporting heterogeneous traffic. In [9], the residual energy and the transmission delay are used as routing metric in the next hop selection process for RPL. The objective function named QoSRPL for this metric is based on ant colony optimization (ACO), i.e., on algorithms exploiting the ability of simple ants to solve complex problems through cooperation. The results of experiments show performance of QoSRPL in terms of energy consumption and delay better than ETX focused on the reliability of links. Energy Efficient and Path Reliability Aware Objective Function (ERAOF) for IoT applications is proposed in ref. [7] using an integration of energy consumption and link quality routing ETX metric. Results show that ERAOF improves the network performance in terms of packet delivery ratio and energy spent per delivered data packet. In ref. [8], the authors use both link and node metrics to define an index, called life cycle index (LCI), which includes also congestion detection to design the route selection. Riker et al. [25] proposed a solution (RAME) based on the lowest energy node to find an optimal path. Simulation results on 40 nodes showed the energy-harvesting efficiency in a multi-hop network. Another work [12] presents GreenNet, a wireless sensors network with photovoltaic energy-harvesting nodes. The GreenNet motes are manufactured by STMelectronics. The work also reports a novel mechanism to enhance the existing protocol stack, i.e., RPL.

Recently, SWIPT was introduced to harvest energy from the environment and simultaneously decode the desired information signal [15,16,26,27]. Sensor nodes and wireless devices in IoT are powered by limited time batteries and their replacement is costly, due to the extremely high number of sensors in a WSN, or hard, e.g., in environments where the sensors are difficult to reach. Indeed, the SWIPT has been introduced as a promising solution to prolong lifetime of the energy-constrained IoT devices. Usually, SWIPT receiver captures RF radiation mainly in cellular networks or WiFi environment and converts it into a direct current voltage through rectenna circuits [16]. In ref. [27], the tradeoff between information rate and harvested energy in a simultaneous wireless information and power transfer system under PS and TS schemes is evaluated providing the outer boundary of robust outage capacity-harvested power region. Several papers consider SWIPT technology integrated into IoT cognitive networks. For example, in ref. [28] the IoT devices harvest energy from the radio-frequency signals received from the primary users (PU) and act as decode-and-forward relays for a cooperative relaying communications to PUs. The same issue of sharing spectrum between PUs and IoT devices acting as relays to assist the transmission between the primary users is investigated in ref. [29], where two data-driven relay selection methods based on the neural network are proposed while in ref. [30] cooperative spectrum sharing and SWIPT are considered to improve the spectrum and energy efficiency for 6G Cognitive IoT Network. Current research on SWIPT generally address one hop and two-hops wireless networks and the interest is now extended to multi-hop wireless networks for balancing the remaining energy among nodes [31]. A main issue in SWIPT receiver design is that RF-EH is usually small and may not be sufficient for RF communications in multi-hop networks. Therefore, new SWIPT receiver has to be designed as proposed in refs. [32–34] to extend SWIPT in a multi-hop wireless network.

The authors in ref. [35] consider a hierarchical architecture using SWIPT to provide the so called energy neutral operation (ENO), where the nodes can perpetually work if the energy consumption is less than the harvested energy. In the proposed SWIPT structure, a Hybrid Access Point powers the wireless sensor nodes by the RF waves sent and the sensor nodes, organized in clusters, transmit the sensing data to the Cluster Head (CH). The CH is the node which requires more energy in the network due to more processing need to aggregate data and to transmit it to HAP. The nodes into the cluster transfer their remaining energy to the CH and, as a consequence, it allows to guarantee the ENO. In ref. [31] is the SWIPT method for energy-aware routing in a multi-hop energy-constrained wireless network. The energy-aware SWIPT routing algorithm allocates the information and energy of link with allocation algorithm during path finding process. An interference-aware SWIPT routing algorithm (ISWIPTR) is proposed in ref. [36] for multi-hop multi-flow wireless sensor networks. In a WSN network of N nodes, each node has PS energy harvester and information decoder and receives the desired signal plus interferences from other flows. ISWIPTR selects a node's next-hop before allocating information and energy for the node as receiver and with the complete use of the SWIPT technique and interference can improve the capacity information and energy allocation of a new flow.

The cited works [31,35,36] consider SWIPT method to manage the end-to-end routes selection in multi-hop energy constrained wireless network while our paper mainly addresses the use of SWIPT technique to create a new OF for the RPL protocol. This new OF based on SWIPT provides an optimized route selection to forward data towards the root node balancing the remaining energy among the nodes thanks to the recharge effect.

4. System Model

An LLN with N nodes is considered, as shown in Figure 2, while in Table 1 the definitions used in this paper are summarized. Each sensor node in the network is powered by the battery, it is equipped with one antenna and has homogeneous storage and computation capacity. Usually, in a WSN, the nodes are geographically distributed to periodically report measurements towards the sink node. This is the typical use case of the RPL routing protocol in which the predominant type of traffic is of the MP2P type. For this reason, a subset of nodes, particularly those ones closer to the root node, consume more energy of other ones and, therefore, are more vulnerable. Then, it is important to prevent these nodes from running out of energy too quickly, consequently allowing an extension of the whole network lifetime.

We assume that a limited number of nodes have sufficient power P, e.g., a CH which powers the nodes grouped in its cluster or a relay node or a cellular device in proximity, to recharge their neighbor nodes at the maximum level of battery. For example, in Figure 2, the node 3 has the power P necessary to recharge the nodes number 6 and number 1 in its surrounding. Moreover, we consider MP2P traffic pattern in RPL where the end-nodes send data messages to the root node, also known as a sink node or LLN Border Router (LBR) node in RPL, creating an upward flow as, e.g., in Figure 2.

Table 1. Notations and Definitions.

Notations	**Definitions**
E_i	Energy harvested by i-th node
P	Maximum Transmission power
T_r	Time to recharge nodes at power P
T_p	Duration time of a packet
G	average power attenuation
h_i	channel power gain from strong node and i-th node
h_{ij}	channel power gain from i-th node and $j - th$ node
d_i	distance from strong node to i-th node
α	path loss exponent
ζ_i	RF-EH efficiency of the node i (child)
η_j	RF-EH efficiency at node j (parent)
$P_c(t)$	Consumed power at time t at the parent
E_0	Initial energy level at the parent
E_r	Residual energy level at the parent
$P_h(t)$	Harvested power from the energy source
P_{rx}	Received power at the parent
P_{th}	RF-EH sensitivity level at the parent

The energy harvested by the i-th node in the surrounding of the node with power P, called hereinafter the strong node, is

$$E_i = \zeta_i h_i P T_r \tag{1}$$

where $0 < \zeta_i < 1$ is the RF-EH efficiency of the node$i$, h_i is channel power gain between the strong node and the node i, and T_r is the time necessary to charge at the maximum value the battery of node i. The channel power gain h_i is expressed as:

$$h_i = G d_i^{-\alpha} \tag{2}$$

Here, d_i is the distance between the strong node and i-th node, G refers to the average power attenuation at a reference distance of 1 m, and α is the path loss exponent.

The node i has a sufficient power to recharge the node j which has been selected as parent node according to the RPL path selection, during the SWIPT mode operation. For example, as shown in Figure 2, the node 3 recharges the node 1 which has a sufficient power to harvest energy to its parent, now. Then, node 1 can select as parent node 5 or node 7. It chooses node 7 with a lower level of battery than node 5 according to the OF of RPL, detailed in the next Section 5, to recharge it by SWIPT and, as a consequence, for achieving the goal of the global energy balance of the network.

In the SWIPT mode, the normal sensor functions, i.e., sensing, sending, and receiving, can work together for energy-harvesting. We consider the SWIPT PS receiver where the RF signal is divided into two parts with different power, one for information decoding and the other one for EH.

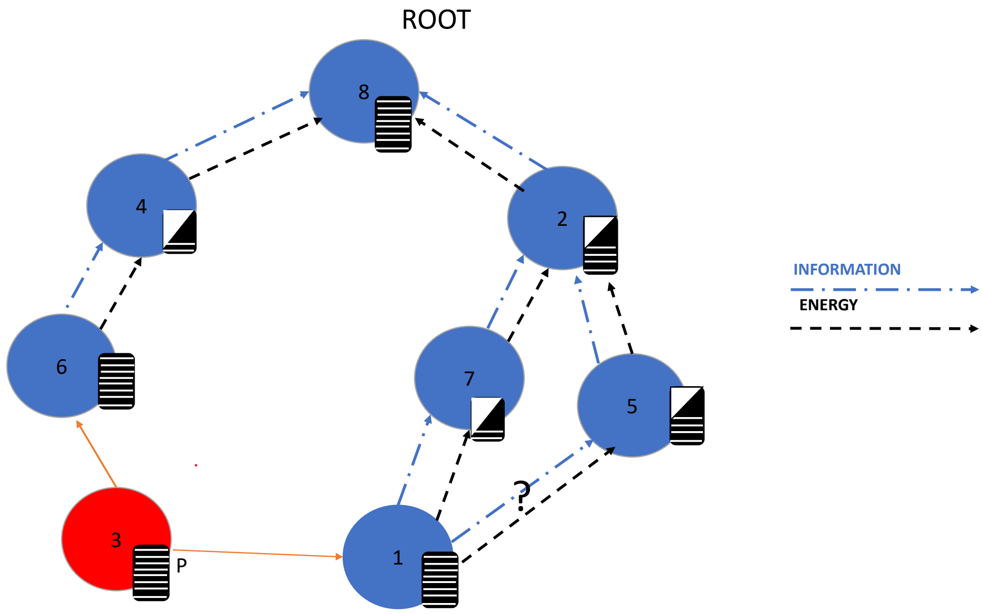

Figure 2. Low-Power and Lossy Network (LLN) network model.

5. Proposed OF for RPL

In this Section, we propose an efficient metric jointly based on the nodes battery level and the possibility to recharge a node by the SWIPT technique. In more details, the proposed approach is focused on dynamically adjusting the routing strategy based on the network state as represented by a proper metric for enhancing the network lifetime and, hence, minimizing its energetic footprint. It is equivalent to the solution of the following optimization problem:

$$\text{(OP)} \quad \underset{w_{i,j}}{\text{maximize}} \quad \theta(\pi_{s,R}) \qquad \text{subject to:} \quad s, R \in \mathcal{G}, \quad i, j \in \pi_{s,R} \tag{3}$$

where $\mathcal{G}$ represents the overall network graph, s a generic source node, R the unique destination (root node), $\pi_{s,R}$ a possible path connecting s to R, and i,j two generic adjacent nodes along $\pi_{s,R}$. Moreover, $\theta(\pi_{s,R})$ is the minimum time interval in which all the nodes along the path $\pi_{s,R}$ are jointly available.

It is worth recalling that in principle the solution of OP problem (3) can be easily obtained by applying the centralized Dijkstra algorithm, once a proper set of weights $\mathbf{w}$ is derived for every link. However, we adopted a distributed approach based on an enhanced RPL protocol to update the time varying weight set $\mathbf{w}(t) \doteq \{w_{i,j}(t)\}$, associated to the link connecting the i-th and j-th nodes.

The concept of RPL is extremely flexible as it allows to define new OF and also Routing Metric and Constraints. For this purpose, two RPL options are very important: "DODAG Configuration" and "DAG Metric Container". The OCP field in the RPL option "DODAG Configuration" identifies the OF. In the field OCP, the OF (e.g., the default OF0, MRHOF or a new OF) can be defined. The Type of "Routing Metric/Constraint" (the link-based or node-based metric or constraint) can be specified in the field "Routing-MC-Type" of the "DAG Metric Container" [2,3].

The energy consumption of sensors in the IoT network is mainly due to the sensing/data processing and communications. By assuming the sensing/data processing consumption constant for each node, in the proposed metric we only consider the consumption due to transmit/receive a packet. Moreover, the energy consumption and recharge capability are different according to the role of the node in the DODAG. Following the RPL topology, each node can be directly connected to the root node or connected to intermediate node(s), i.e., the parent nodes. In this second case, the node is called *child*. In our RF power transfer metric, we suppose that a fraction of the received power at the intermediate node from a child can recharge the parent's battery. In addition, in the network a limited number of child nodes have a sufficient battery level to recharge nodes in their surrounding, as explained in Section 4.

Therefore, assuming a data transmission flow in the network with destination to the root node, our model considers the following cases according to the nodes' role:

- Root node can receive and can recharge.
- Parent nodes can receive, transmit, and recharge.
- End-child nodes can only transmit.
- Some end-nodes have the maximum level of power equal to P.

The operation of energy-harvesting nodes relies on the concept of the energy balancing which for nodes with ideal storage and without any inefficiency in charging can be defined on a period T_p which is the transmission time of a packet, as ref. [37]

$$\int_0^{T_p} P_c(t)dt \leq \int_0^{T_p} P_h(t)dt + E_0 \;\; \forall T_p \in [0, \infty] \tag{4}$$

where E_0 is the initial energy level (which is related to the battery level B), $P_c(t)$ is the consumed power at time t to transmit or to receive and $P_h(t)$ denotes the harvested power from the energy source, that in our case, considering SWIPT operation, is a fraction of the received power from the child.

Summarizing, at the intermediate node j, over a time interval T_p, assuming the received power at the RF-EH circuit is P_{rx}, the amount of harvested energy can be represented as ref. [38]

$$EH_j = \eta_j T_p (P_{\text{rx}} - P_{\text{th}})^+ \tag{5}$$

where $0 \leq \eta_j \leq 1$ is the RF-EH process efficiency at node j, $(z)^+ \doteq \max(z, 0)$, P_{th} is the RF-EH sensitivity level, and P_{rx} can be expressed as function of Equation (1)

$$P_{rx} = \frac{\eta_j h_{ij} \zeta_i h_i P T_r}{T_p} \tag{6}$$

and h_{ij} is the channel power gain between the node i and the node j.

According to the existing studies [38], the RF-EH circuit can only harvest energy when its receive signal power, P_{rx}, is greater than the RF-EH sensitivity level, Pth, and the harvested energy is proportional to $(P_{\text{rx}} - P_{\text{th}})^+$. This additive metric is used for optimal route selection.

Therefore, the following OFs are considered to investigate the performance of RPL in terms of the network lifetime:

- default OF for RPL, i.e., OF0 considered for comparison in performance evaluation;
- energy-based OF, called OF1;

- energy-harvested OF, i.e., based on battery level and recharging capabilities aware, called OF2.

For OF1, the RE routing metric is calculated as follows

$$RE \doteq \frac{E_r}{E_0} \tag{7}$$

where E_0 is the node's initial energy and E_r is the node's remaining energy directly proportional to the battery level. It is worth pointing out that in deriving OF2 we refer to (4) and (6) for modeling both the battery level and the recharging capabilities awareness.

6. Results Analysis

In order to validate the proposed routing approach, we resorted to numerical simulations performed over the Cooja framework, which has been proven to be an accurate, flexible, and high fidelity tool for the simulation of RPL in WSNs [39]. In particular, we consider the parameters for the simulations as in ref. [36] and reported in Table 2. In addition, we focused on a worst case condition, where devices are not allowed to be in sleep mode, as it usually happens for emergency situation.

Table 2. Parameters adopted in performing numerical simulations.

Parameter	Value
Communication pattern	MP2P
L3 Protocol	RPL
L2 Protocol	IEEE 802.15.4
Transceiver	CC2420
E_0	25 (J)
Data message rate	1 (msg/min)
DIO	16 (bytes)
DAO	16 (bytes)
DAO-ACK	4 (bytes)
DIS	2 (bytes)
Data Packet	30 (bytes)
P	100 mW
P_h	10 mW
α	2.5
ζ	0.6
η	0.2
T_r	5 s
T_p	1 s

The scenario under investigation is comprised of 50 nodes randomly deployed over an area of 200 $\times$ 200 m^2, where a specific node acts as the sink, that is the device in charge of collecting data from the other sensors, as well as the DODAG Root. It has been supposed the presence of one node endowed with an additional power supply able to recharge its neighboring motes; in addition, it is located far enough from the sink node to enhance the benefits.

For the sake of simplicity, the initial energy level E_0 is the maximum value which is associated with the maximum battery level $B_{\max}$ for all the devices. Further, the energy-harvesting process has been modeled as a closed system, i.e, without any outer energy source, where the battery recharging is performed on the basis of the received RF signal. In particular, a fraction η of the received power is successfully convoyed to the battery, without any additional loss, according to (6). Considering the features of IEEE 802.15.4 standard and the specific network deployment, we assumed that $\eta = 0.2$.

In Figures 3–5, the residual normalized battery level as a function of the time normalized to the frame duration for the different *groups* of devices that are interconnected with RPL protocol with the OF0, OF1, or OF2 metric, is pointed out, respectively (The battery level of the DODAG Root A has not been depicted as its behavior is fairly trivial). In particular, each group has been associated with the corresponding rank, that is the minimum number of hops towards the root, so that the *i*-th set of nodes is *i*-hops far from its destination. It can be noticed that the proposed approach is able to prolong the network lifetime (i.e., the time interval within which all the network nodes are active) with a gain approximately equal to 54% and 14% w.r.t. the RPL endowed with OF0 or OF1 metric, respectively. This is due to the fact that OF0 metric does not take into account battery level, while OF1 metric relies only on the nodes' battery levels, without taking into account the opportunity of being recharged by neighboring nodes. In addition, the node with rank equal to 2 or 3 benefits from the proposed approach, thus lowering the DODAG disconnection probability.

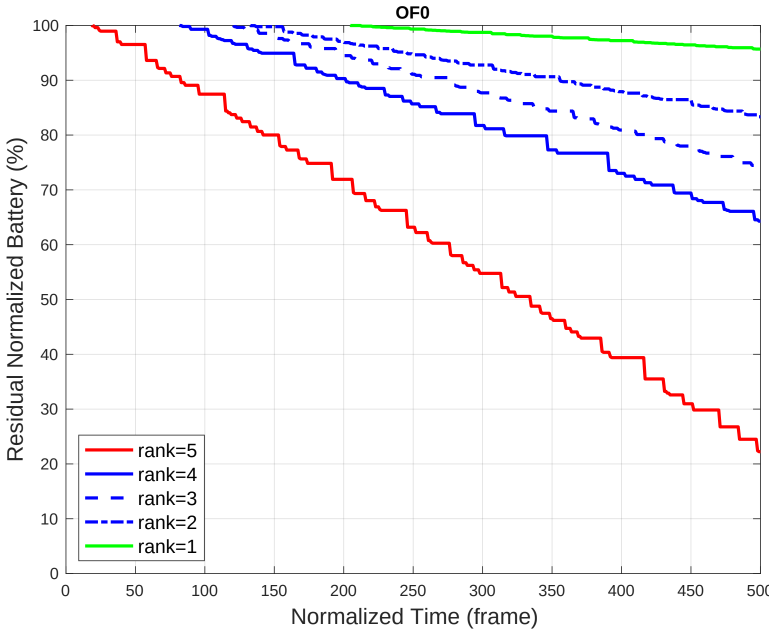

Figure 3. Residual normalized battery level time evolution of different groups of devices connected with RPL objective function zero (OF0).

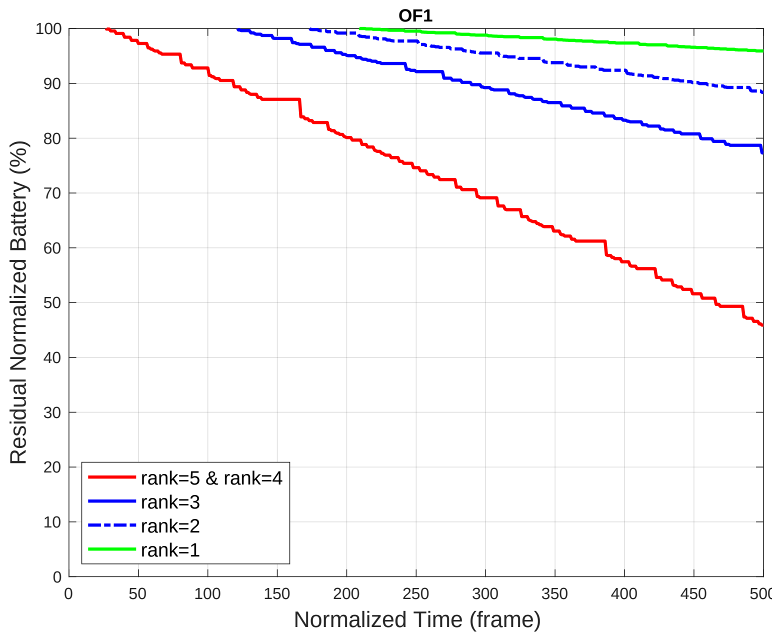

Figure 4. Residual normalized battery level time evolution of different groups of devices connected with RPL OF1.

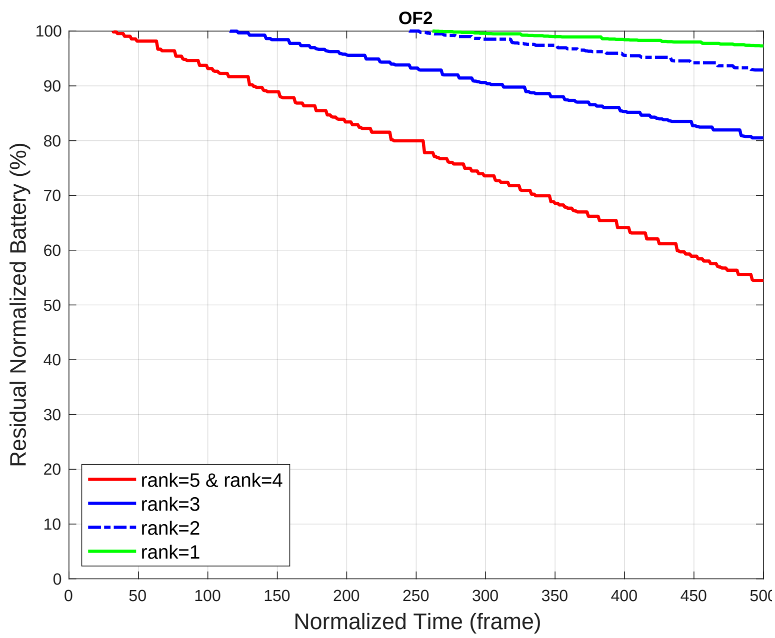

Figure 5. Residual normalized battery level time evolution of different groups of devices connected with RPL OF2.

Finally, in Figure 6, the Jain's Fairness Index for the WPAN nodes' battery level is depicted as a function of time for the RPL protocol based on OF0, OF1, and OF2 metrics.

Specifically, the raw data obtained from the Cooja simulator has been accurately post processed to derive this parameter, which is defined as ref. [17]:

$$J(b) \doteq \frac{\left(\sum_{i=1}^{N} b_i\right)^2}{N \sum_{i=1}^{N} b_i^2} \tag{8}$$

where N is the number of nodes and b_i denotes the battery level of node i. Jain's index approaches one when the battery level values of the nodes move closer to each other. The better behavior of the proposed approach is evident as the routing strategy balance the energy consumption, as already presented in Figure 5.

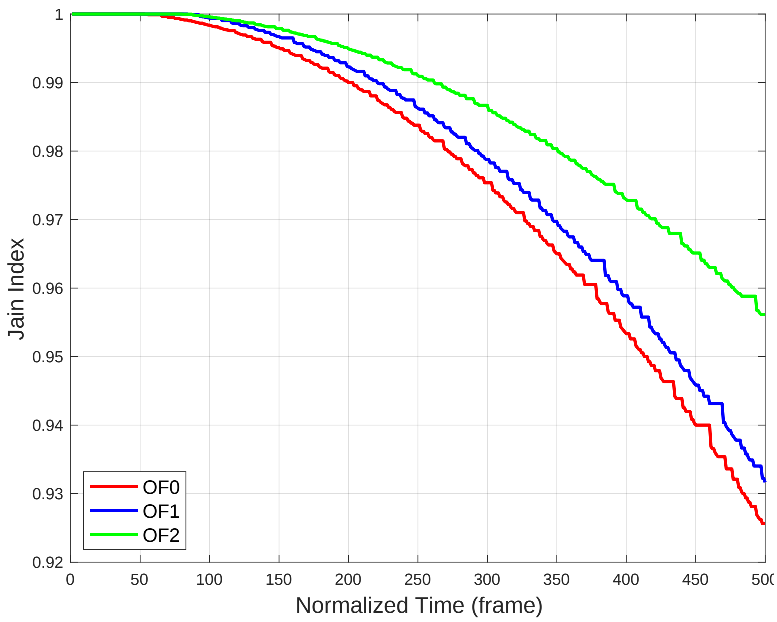

Figure 6. Jain' index of the residual normalized battery level as a function of time for the considered RPL Objective Functions.

7. Conclusions

This paper proposes a new Objective Function for RPL protocol, named OF2, aiming at improving the global IoT network lifetime. To this end, OF2 jointly considers, for deriving the routing metrics, the consumed and recharged energy in order to select the best path to forward a data message. Specifically, we consider SWIPT technology for the recharging. The proposed OF2 allows an effective balancing of the energy distribution among the nodes in a DODAG, allowing the selection of a node with low battery level, since it can be recharged by the signal power received from a child. Performance evaluation conducted on a realistic scenario has shown the proposed OF2 effectively minimizes the energy consumption and, consequently, the network lifetime by selecting the best paths toward the sink. In particular, when compared with OFs commonly adopted, it is possible to point out a lifetime increasing of about 54% with respect to basic RPL (OF0) and 14% with respect to RPL with metric based only on residual level (OF1). Thus, the main contribution of this work is a new objective function for RPL that can minimize the energy consumption for typical resource constrained IoT applications.

Author Contributions: All the authors contributed equally to the paper. R.F. coordinated the research activities, F.C. and L.P. mainly worked on the system model and on the development of results. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The Authors would like to sincerely thank Alessandro Maggi for his contribution to the discussion by providing fruitful comments.

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

References

1. Montenegro, G.; Kushalnagar, N.; Hui, J.; Culler, D. Transmission of IPv6 packets over IEEE 802.15.4 networks. *Internet Engineering Task Force IETF RFC 4944* , 2007, doi:10.17487/RFC4944.
2. Winter, T.; Thubert, P.; Brandt, A.; Hui, J.; Kelsey, R. RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. *IETF RFC 6550*, 2012
3. Vasseur, J.; Kim, M.; Pister, K.; Dejean, N.; Barthel, D. Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks. *IETF RFC 6551*; March 2012. doi:10.17487/RFC6551.
4. Levis, P.; Gnawali, O. The Minimum Rank with Hysteresis Objective Function. *IETF RFC 6719*, September 2012, doi:10.17487/RFC6719
5. Sarwar, S.; Rauf, S.; Rasheed, R.; Aslam, L. Energy-aware Routing in Internet of Things (IoT). In Proceedings of the 2019 2nd International Conference on Communication, Computing and Digital systems (C-CODE), Islamabad, Pakistan, 6–7 March 2019; pp. 81–86, doi:10.1109/C-CODE.2019.8680974.
6. Mortazavi, F.; Khansari, M. An Energy-Aware RPL Routing Protocol for Internet of Multimedia Things. In Proceedings of the International Conference on Smart Cities and Internet of Things, SCIOT '18, Mashad Iran September 2018; ACM: New York, NY, USA, 2018; pp. 11:1–11:6, doi:10.1145/3269961.3269965.
7. Sousa, N.; Sobral, J.V.V.; Rodrigues, J.J.P.C.; Rabêlo, R.A.L.; Solic, P. ERAOF: A new RPL protocol objective function for Internet of Things applications. In Proceedings of the 2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech), Split, Croatia, 12–14 July 2017; pp. 1–5.
8. Wang, Z.; Zhang, L.; Zheng, Z.; Wang, J. Energy balancing RPL protocol with multipath for wireless sensor networks. *Peer-to-Peer Netw. Appl.* **2018**, doi:10.1007/s12083-017-0585-1.
9. Mohamed, B.; Mohamed, F. QoS Routing RPL for Low Power and Lossy Networks. *Int. J. Distrib. Sens. Netw.* **2015**, *11*, 971545, doi:10.1155/2015/971545.
10. Musaddiq, A.; Zikria, Y.B.; Zulqarnain, K.; Won, S. Routing protocol for Low-Power and Lossy Networks for heterogeneous traffic network. *EURASIP J. Wirel. Commun. Netw.* **2020**, *2020*, doi:10.1186/s13638-020-1645-4.
11. Kamgueu, P.; Nataf, E.; Festor, T.D.N.O. *Energy-Based Routing Metric for RPL;* Research Report RR8208 National Institute for Research in Digital Science and Technology; INRIA: Paris, France, 2013.
12. Varga, L.; Romaniello, G.; Vučinić, M.; Favre, M.; Banciu, A.; Guizzetti, R.; Planat, C.; Urard, P.; Heusse, M.; Rousseau, F.; et al. GreenNet: An Energy-Harvesting IP-Enabled Wireless Sensor Network. *IEEE Internet Things J.* **2015**, *2*, 412–426, doi:10.1109/JIOT.2015.2425431.
13. Ng, D.W.K.; Duong, T.Q.; Zhong, C.; Schober, R. The Era of Wireless Information and Power Transfer. In *Wireless Information and Power Transfer: Theory and Practice*; Wiley: Hoboken, NJ, USA, 2019; doi:10.1002/9781119476863.ch1.
14. Liu, W.; Zhou, X.; Durrani, S.; Popovski, P. SWIPT with practical modulation and RF energy harvesting sensitivity. In Proceedings of the 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur, Malaysia, 22–27 May 2016; pp. 1–7, doi:10.1109/ICC.2016.7511404.
15. 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, doi:10.1109/COMST.2014.2368999.
16. Clerckx, B.; Zhang, R.; Schober, R.; Ng, D.W.K.; Kim, D.I.; Poor, H.V. Fundamentals of Wireless Information and Power Transfer: From RF Energy Harvester Models to Signal and System Designs. *IEEE J. Sel. Areas Commun.* **2019**, *37*, 4–33, doi:10.1109/JSAC.2018.2872615.
17. Jain, R.; Chiu, D.; Hawe, W. *A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems*; Technical Report DEC-TR-301; Eastern Research Laboratory, Digital Equipment Corporation: Hudson, MA, USA,1984.
18. Levis, P.; Clausen, T.; Hui, J.; Gnawali, O.; Ko, J. The Trickle Algorithm. *Internet Eng. Task Force IETF RFC 6206* 2011. doi:10.17487/RFC6206
19. Alvi, S.A.; Mian, A.N. On route maintenance and recovery mechanism of RPL. In Proceedings of the 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, Spain, 26–30 June 2017; pp. 1933–1938, doi:10.1109/IWCMC.2017.7986579.
20. Gaddour, O.; Koubâa, A. RPL in a nutshell: A survey. *Comput. Netw.* **2012**, *56*, 3163–3178, doi:10.1016/j.comnet.2012.06.016.
21. Sobral, J.; Rodrigues, J.; Rabêlo, R.; Al-Muhtadi, J.; Korotaev, V. Routing Protocols for Low Power and Lossy Networks in Internet of Things Applications. *ACM Trans. Embed. Comput. Syst.* **2019**, *19*, 2144, doi:10.3390/s19092144.
22. Witwit, A.J.H.; Idrees, A.K. A Comprehensive Review for RPL Routing Protocol in Low Power and Lossy Networks. In *New Trends in Information and Communications Technology Applications*; Al-mamory, S.O., Alwan, J.K., Hussein, A.D., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 50–66.

23. Iova, O.; Picco, P.; Istomin, T.; Kiraly, C. RPL: The Routing Standard for the Internet of Things... Or Is It? *IEEE Commun. Mag.* **2016**, *54*, 16–22, doi:10.1109/MCOM.2016.1600397CM.
24. Khelifi, N.; Kammoun, W.; Youssef, H. Efficiency of the RPL repair mechanisms for Low Power and Lossy Networks. In Proceedings of the 2014 International Wireless Communications and Mobile Computing Conference (IWCMC), Nicosia, Cyprus, 4–8 August 2014; pp. 98–103, doi:10.1109/IWCMC.2014.6906339.
25. Riker, A.; Curado, M.; Monteiro, E. Neutral Operation of the Minimum Energy Node in energy-harvesting environments. In Proceedings of the 2017 IEEE Symposium on Computers and Communications (ISCC), Heraklion, Greece, 3–6 July 2017; pp. 477–482, doi:10.1109/ISCC.2017.8024574.
26. Perera, T.D.P.; Jayakody, D.N.K.; Sharma, S.K.; Chatzinotas, S.; Li, J. Simultaneous Wireless Information and Power Transfer (SWIPT): Recent Advances and Future Challenges. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 264–302, doi:10.1109/COMST.2017.2783901.
27. Gu, Q.; Wang, G.; Fan, R.; Zhong, Z.; Yang, K.; Jiang, H. Rate-Energy Tradeoff in Simultaneous Wireless Information and Power Transfer Over Fading Channels With Uncertain Distribution. *IEEE Trans. Veh. Technol.* **2018**, *67*, 3663–3668, doi:10.1109/TVT.2017.2779457.
28. Gurjar, D.S.; Nguyen, H.H.; Tuan, H.D. Wireless Information and Power Transfer for IoT Applications in Overlay Cognitive Radio Networks. *IEEE Internet Things J.* **2019**, *6*, 3257–3270, doi:10.1109/JIOT.2018.2882207.
29. Zhang, Z.; Lu, Y.; Huang, Y.; Zhang, P. Neural Network-Based Relay Selection in Two-Way SWIPT-Enabled Cognitive Radio Networks. *IEEE Trans. Veh. Technol.* **2020**, *69*, 6264–6274, doi:10.1109/TVT.2020.2984327.
30. Lu, W.; Si, P.; Huang, G.; Han, H.; Qian, L.; Zhao, N.; Gong, Y. SWIPT Cooperative Spectrum Sharing for 6G-Enabled Cognitive IoT Network. *IEEE Internet Things J.* **2020**, 1, doi:10.1109/JIOT.2020.3026730.
31. He, S.; Xie, K.; Chen, W.; Zhang, D.; Wen, J. Energy-Aware Routing for SWIPT in Multi-Hop Energy-Constrained Wireless Network. *IEEE Access* **2018**, *6*, 17996–18008, doi:10.1109/ACCESS.2018.2820093.
32. Choi, K.W.; Hwang, S.I.; Aziz, A.A.; Jang, H.H.; Kim, J.S.; Kang, D.S.; Kim, D.I. Simultaneous Wireless Information and Power Transfer (SWIPT) for Internet of Things: Novel Receiver Design and Experimental Validation. *IEEE Internet Things J.* **2020**, *7*, 2996–3012, doi:10.1109/JIOT.2020.2964302.
33. Xu, P.; Flandre, D.; Bol, D. Analysis, Modeling, and Design of a 2.45-GHz RF Energy Harvester for SWIPT IoT Smart Sensors. *IEEE J. Solid-State Circuits* **2019**, *54*, 2717–2729, doi:10.1109/JSSC.2019.2914581.
34. Abbasizadeh, H.; Kim, S.Y.; Rikan, B.; Hejazi, A.; Khan, D.; Pu, Y.G.; Hwang, K.C.; Yang, Y.; Kim, D.; Lee, K. Design of a 900 MHz Dual-Mode SWIPT for Low-Power IoT Devices. *Sensors* **2019**, *21*, 4676, doi:10.3390/s19214676.
35. Choi, H.; Lee, J. Energy-Neutral Operation Based on Simultaneous Wireless Information and Power Transfer for Wireless Powered Sensor Networks. *Energies* **2019**, *12*, 3823.
36. He, S.; Tang, Y.; Li, Z.; Li, F.; Xie, K.; Kim, H.; Kim, G. Interference-Aware Routing for Difficult Wireless Sensor Network Environment with SWIPT. *Sensors* **2019**, *19*, 3978.
37. Kansal, A.; Hsu, J.; Zahedi, S.; Srivastava, M.B. Power Management in Energy Harvesting Sensor Networks. *ACM Trans. Embed. Comput. Syst.* **2007**, *6*, doi:10.1145/1274858.1274870.
38. Wu, T.; Yang, H. On the Performance of Overlaid Wireless Sensor Transmission With RF Energy Harvesting. *IEEE J. Sel. Areas Commun.* **2015**, *33*, 1693–1705, doi:10.1109/JSAC.2015.2391892.
39. Osterlind, F.; Dunkels, A.; Eriksson, J.; Finne, N.; Voigt, T. Cross-Level Sensor Network Simulation with COOJA. In Proceedings of the 2006 31st IEEE Conference on Local Computer Networks, Tampa, FL, USA, 14–16 November 2006; pp. 641–648, doi:10.1109/LCN.2006.322172.