

Energy Harvesting Framework for Network Simulator 3 (ns-3)

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Abstract

The problem of designing and simulating optimal communication protocols for energy harvesting wireless networks has recently received considerable attention, thus requiring an accurate modeling of the energy harvesting process and a consequent redesign of the simulation framework to include this. While the current ns-3 energy framework allows the definition of new energy sources that incorporate the contribution of an energy harvester, integrating an energy harvester component into an existing energy source is not straightforward using the existing energy framework. In this paper, we propose an extension of the ns-3.20 energy framework in order to explicitly introduce the concept of an energy harvester. Starting from the definition of a general energy harvester, we provide the implementation of two simple models for the energy harvester. In addition, we introduce the concept of an energy predictor, that gathers information from the energy source and harvester and uses this information to predict the amount of energy that will be available in the future. Finally, we extend the current energy framework to include a model for a supercapacitor energy source and a device energy model for the energy consumption of a sensor. Example simulation results show the benefit of our contributions to the ns-3 energy framework.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless communication; I.6.5 [Model Development]: Modeling methodologies.

General Terms

Design, Measurement, Performance

Keywords

ns-3, energy harvesting, energy-efficient design

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1 Introduction

In the last few years, the capability of Network Simulator 3 (ns-3) for simulating different aspects of wireless networks has increased rapidly, such that it now provides a wide range of models of real world objects, protocols and devices [1]. Simulation of communication systems and network protocols over realistic device operations is seen as a necessary task before implementation, because it allows for a flexible and fast, but still accurate, testing of the system evolution. Additionally, efficiently managing the energy consumptions of the different elements is a major requirement for an efficient design of wireless networks, since many wireless devices are battery operated.

In this regard, the authors in [2] presented an ns-3 energy framework that allows users to simulate the energy consumption at a node as well as to determine the overall network lifetime under specific conditions. This framework adds sufficient support to ns-3 to devise simulations that include the energy consumption of the communication network. In order to do this, this framework defines the concept of an *Energy Source*, which represents an abstraction of the way in which the node is powered, a *Device Energy Model*, that defines models for the energy consumption of the different elements that compose the node, and several methods that provide different types of energy information (e.g., residual energy, current load, etc.) to other ns-3 objects external to the framework. The framework is developed with the objective of allowing the interoperability of different energy sources and device energy consumption models, and it allows easy integration of new models. Moreover, some implementations of the energy source and device energy models are provided, so that an ns-3 user is able to incorporate them into their existing simulations.

The increasing demand for battery operated devices with longer lifetimes has required researchers to explore energy availability from a different perspective, starting from the hardware itself. While the battery technology keeps improving, with the recent advances in wireless devices, devices that are able to harvest energy from the environment, e.g., in the form of solar, thermal, vibrational or radio energy, are now commercially available.

Given the above, the problem of designing optimal communication protocols for energy harvesting wireless networks has recently received considerable attention [3, 4, 5]. When using an energy harvesting source, the objectives of

these protocols are fundamentally different than those of using a traditional energy source: rather than focusing on minimizing the maximum energy and adapting the operations according to the residual energy, algorithms need to shift the optimization to the maximum rate at which the energy can be used [6]. The need for an accurate modeling of the energy harvesting process, and a consequent redesign of the simulation framework to include it, is thus fundamental.

While the current ns-3 energy framework (version 3.20) allows the definition of new energy sources that incorporate the contribution of an energy harvester, the integration of an energy harvester component into an existing energy source, as well as the possibility of evaluating the interaction between different energy sources and harvester models, is not straightforward using the existing energy framework.

To this end, in this paper we propose an extension of the energy framework currently released with ns-3 in order to explicitly introduce the concept of an energy harvester¹. By doing so, different energy harvester models can be developed as independent ns-3 objects that can be connected to the current and future energy source implementations. Starting from the definition of the general interface, we provide the implementation of two simple models for the energy harvester: 1) a basic energy harvester, that provides a time-varying, uniformly distributed amount of energy, and 2) an energy harvester that recharges the energy source with an amount of energy gathered from a dataset of real solar panel measurements [7].

Our contribution to the energy framework extends beyond the introduction and example implementations of the energy harvester. In particular, we extend the set of implementations of the current energy framework to include a model for a supercapacitor energy source and a device energy model for the energy consumption of a sensor. Moreover, we introduce the concept of an *energy predictor*, and we provide an example implementation based on the energy prediction model described in [8]. As the name suggests, the idea behind the energy predictor is to gather information from the energy source and harvester and use this information to predict the amount of energy that will be available in the future. The information provided by this module can then be used to develop energy efficient protocols that can capitalize not only on the knowledge of the energy availability at a given time but also on a forecast of its future availability.

The rest of the paper is organized as follows. Section 2 provides motivation for the need for an accurate energy aware simulation framework and an overview of related work. In Section 3, we describe our contributions to the ns-3 energy framework, while in Section 4 we present some examples of simulation results that can be obtained with the new framework. Section 5 concludes the paper.

2 Motivation and Related Work

The need for a simulation framework for evaluating the performance of energy aware wireless networks has been widely recognized. Different generic network simulators are compared in [9], showing that no existing simulators natively provide models for the energy source and the energy harvester, nor for simulating the energy consumptions of the

different elements that compose the wireless node. To overcome these limitations, the authors in [9] propose WSNsim, one of the first simulators to include a set of flexible and extensible hardware and environment models to enhance the design of energy-aware sensor nodes. However, WSNsim is not available to the research community. Subsequently, an extension to ns-3 to support energy aware networks has been proposed [2]. The framework in [2] is designed and implemented with the objective of adding support for different energy sources and device energy consumption models on ns-3 simulations. A generic energy model for OMNeT++ has been presented in [10], which allows the accurate evaluation of the energy consumption and network lifetime of sensor networks, taking into account the energy consumption of both the radio transceiver and the CPU.

While these solutions provide viable simulation environments for energy-aware wireless networks, they do not include support for the simulation of wireless networks powered via energy harvesting. As a result, the increasing interest in evaluating the performance of energy harvesting wireless systems brought forth several contributions to fill this gap. In particular, GreenCastalia, an energy harvesting framework for the Castalia simulator [11] that allows the simulation of networks of embedded devices with heterogeneous harvesting and energy source capabilities, has been presented in [12]. The authors in [13] presented PASES, a standalone, flexible and extensible design space exploration framework that allows an accurate analysis of the performance and energy consumption of WSNs, from the application to the hardware level. This framework requires detailed power models of the node architecture to provide statistics about the power consumption and to determine the optimal hardware configuration. A complete ns-3 modeling of a practical Wireless Sensor Network architecture with energy harvesting capabilities has been described in [14]. However, the focus of [14] was to simulate the performance of the particular system under consideration, while our focus is to provide a generic framework to enhance the quality of simulations of energy-aware wireless networks. More recently, SensEH [15], a complete software framework for the simulation and emulation of wireless sensor networks with energy harvesting capabilities, has been proposed. The framework allows the reuse of the same code written for the simulations in real-world WSN deployments and, for this reason, relies heavily on the architecture of wireless sensor nodes, thus not being suitable for generic network simulations.

Given the above, it can be noticed that several contributions are available for simulating the energy requirements of wireless networks. Nevertheless, most of them are either standalone and proprietary solutions or target a specific network architecture, i.e., wireless sensor networks. We believe that there is still a need for a generic framework that provides an extensive and easy to use set of tools, available to the entire networking community. To this end, the design structure of the energy framework presented in [2], and the fact that it is based on the well-known open source simulator ns-3, represents a great starting point to achieve this goal.

¹The implementation of the energy harvester is included in ns-3.21.

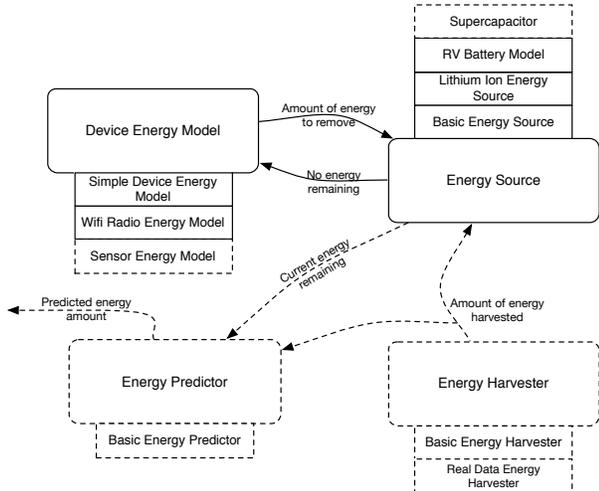


Figure 1: Energy Harvesting Framework. Our contributions are shown by the dashed lines.

3 Energy Harvesting Framework

The objective of our work is to extend the capability of ns-3 to support the simulation of different energy components, from the harvesting of the energy from the environment to the final consumption of the energy by the different elements that compose the simulation node. Moreover, our goal is to provide a way of comparing the impact of different energy storage devices (e.g., ideal energy buffer, lithium ion battery, nickel-metal hydride battery, supercapacitor, etc.) on the network performance, as well as to efficiently manage the residual energy at the different levels of the protocol stack, by additionally exploiting the knowledge about the energy harvesting process.

In what follows, we describe our extension to the energy framework described in [2] to include support for simulating wireless networks powered via energy harvesting, and the prediction of the future energy available at the node, while ensuring complete compatibility with the current implementation of the energy framework.

A diagram of the elements that compose the extended energy framework is presented in Figure 1, where our contributions are presented in the dashed lines. We follow the modular structure of the ns-3.20 energy framework to introduce two new modules, namely *Energy Harvester* and *Energy Predictor*. Moreover, we extend the set of implementations of the energy source and device energy models to include a model for the behavior of a supercapacitor energy source and for the energy consumption of a sensor.

3.1 Energy Harvester

The energy harvester represents the elements that harvest energy from the environment and recharge the energy source to which it is connected. In our design, the energy harvester includes the complete implementation of the actual energy harvesting device (e.g., a solar panel) and the environment (e.g., the solar radiation). This means that in implementing an energy harvester, the users need to jointly model the energy contribution of the environment and the additional en-

ergy requirements of the energy harvesting device such as the conversion efficiency and the internal power consumption of the device.

For the energy harvester, we defined a default interface that includes all the parameters required for the connection with the energy source and the functions required to install the energy harvester to an ns-3 node. Our implementation of *Energy Harvester* includes:

- *Basic Energy Harvester*: a simple model in which the amount of power provided by the harvester varies over time according to a uniformly distributed random variable with customizable bounds and time update intervals;
- *Real Data Energy Harvester*: an energy harvester that recharges the energy sources according to the power levels defined in a user customizable dataset of real measurements. As an example, we provide a dataset of real solar panel measurements [7].

Due to the modular structure inherited from the ns-3 energy framework and followed for the definition of the energy harvester, users are allowed to use any energy source, device energy model and energy harvester combination, while ensuring complete compatibility between the models. Moreover, defining new energy harvesters like, for example, an energy harvester that provides a time varying amount of power that follows a Markov process, is relatively easy by following the sample implementations provided with our contribution.

3.2 Energy Predictor

The energy predictor represents an additional element that can be used to improve the performance of energy harvesting systems. This is because when dealing with energy scavenging, the amount of energy available at the node dramatically changes over time, and some knowledge can be inferred from the past energy levels in order to devise smart energy allocation policies. The importance of energy predictions is widely recognized in the research community [8] [12].

Similarly to [12], we introduce the concept of an energy predictor to the energy framework. The standard interface of the energy predictor is connected to both the energy source and the energy harvester. It uses information about the current remaining energy available at the energy source and the amount of energy harvested at the energy harvester to estimate the energy that will be available in the future. The predicted value can be used at other layers of the protocol stack to better utilize the available energy.

Our implementation of *Energy Predictor* includes Pro-Energy [8], that improves over the approach presented in WCMA [16], for predicting the future energy intake. According to this model, the predicted energy \hat{E}_{t+1} is computed as $\hat{E}_{t+1} = \alpha C_t + (1 - \alpha) E_{t+1}^d$, where C_t represents the energy harvested during timeslot t of the current day, E_{t+1}^d is the energy harvested during timeslot $t + 1$ of a stored day d , and $0 \leq \alpha \leq 1$ is a weighting parameter. While WCMA selects as a reference for the energy prediction the previous day and adjusts the weighting factor α according to the similarity of the weather conditions of the two days, Pro-Energy stores a

set of harvesting profiles and selects as a reference the day with the weather conditions most similar to the current day.

3.3 Energy Source

The energy source represents the elements that store, and provide to the node, the energy required to perform the different operations. In real life, different types of energy sources with different characteristics are available. The characteristics of the energy sources include: maximum energy, voltage, charge-discharge patterns and lifetime. For this reason, having several implementations for the energy source allows for a more accurate simulation of the expected performance of the system under consideration. The current release of ns-3 includes three implementations of energy sources, namely *Basic Energy Source*, *Lithium Ion Energy Source* and *RV Battery Model* [17].

Our extension to the set of energy sources includes the implementation of a *Supercapacitor*. The supercapacitor implementation follows the simplified model presented in [18] and [19], that models the supercapacitor as an RC network, with an internal DC resistance and a linear voltage-dependent capacitance. According to this model, a supercapacitor can be characterized by its DC capacitance C_{DC} , rated DC voltage V_{DC} and voltage dependent capacitance k_V . Given these, the storage capacitance $C_V(v)$ is expressed as $C_V(v) = C_0 + k_V v$, where $C_0 = C_{DC} - k_V V_{DC}$ and v represents the voltage across the supercapacitor, which is derived from the standard differential equation of the RC circuit. Additionally, the energy stored in the supercapacitor is computed as $E_{sup} = \frac{1}{2} C_V(v) v^2$. While more accurate models for the supercapacitor short term response have recently been proposed (see, e.g., [19] and [20]), the associated computational complexity makes them unappealing for the simulation of long network operation time. Moreover, this simplified model is suitable for applications where the energy stored in the capacitor is of primary importance, as it is for network simulations, and the transient response can be neglected [18] [21].

It can be noticed that, in order to operate correctly, a node requires a fairly constant supply voltage. However, when dealing with a supercapacitor or, more generally, with a non-ideal energy source like, for example, the lithium ion battery, the supply voltage changes over time according to the intrinsic characteristics of the energy storage. Therefore, battery operated devices contain a Direct Current to Direct Current (DC-DC) converter to convert the DC voltage level of the battery to the DC voltage level required by the different elements that compose the node. To address this also in simulations, we modified the existing energy source interface to include the contribution of a DC-DC converter, with a user customizable efficiency, that is used to calculate the actual current consumption of the devices connected to the node. By defining I_{load} as the current required by the load, V_s as the supply voltage of the energy source and V_o as the operating voltage of the node, the actual current consumption of the device I_s is given by:

$$I_s = \frac{V_o I_{load}}{V_s \eta}, \quad (1)$$

where η represents the efficiency of the DC-DC converter.

Supercapacitor		Sensor Energy Model	
C_{DC}	50 F	$i_{reading}$	25 mA
V_{DC}	2.7 V	i_{idle}	7 μ A
k_V	0.5 F/V	$i_{shutdown}$	1 μ A

Table 1: Simulation parameters used for the supercapacitor and the sensor energy models [22] [23].

3.4 Device Energy Model

The device energy model describes the amount of energy required to power a certain device connected to the node. Each device energy model is connected on one side to the actual device, that determines the energy consumption according to a state-based model, and on the other side to the energy source that decreases its residual energy and notifies the device in case of energy depletion. The current release of ns-3 includes two example implementations, namely *Simple Device Energy Model* and *WiFi Radio Energy Model* [17], where the first allows the user to set a fixed current drain and is intended for testing purposes, while the latter is directly connected to the WiFi radio device implementation and updates the energy consumption of the device according to its state of operation (e.g., idle, transmission, reception, etc.).

Our extension to the set of device energy models includes the implementation of a *Sensor Energy Model*. The sensor energy model allows for the definition of three power consumption levels, associated with the states of a generic sensor that acquires some measurements. The states of a generic sensor are defined as shutdown, idle and reading, where we consider the shutdown state to be a low energy consumption state in which the sensor cannot be used directly, and thus represents a power saving state in which the sensor transitions when it is notified by the energy source of energy depletion.

4 Simulation Results

In this section we show some examples of the simulation results that can be obtained with our extension of the ns-3 energy framework. All the results of this section have been obtained by considering a node with operational voltage $V_o = 3.3V$, that integrates a DC-DC converter with efficiency $\eta = 0.9$ and cutoff voltage $V_{low} = 1.0V$. For the *Basic Energy Source* we fixed the supply voltage to V_o , while we used the default ns-3 settings for both the *Lithium Ion Battery* and the *RV Battery Model*. The supercapacitor and sensor energy model parameters are presented in Table 1.

We first evaluate the impact of the different implementations of the energy source on the lifetime of a node. To this end, in Figure 2 we present the residual energy as a function of time, for a simple node powered via different types of energy source and that performs periodic sensing of the environment through a basic *Sensor* implementation.

As expected, the best performance is attained by the *Basic Energy Source*, which represents an ideal energy buffer and thus does not include any energy leakage. The *Lithium Ion Battery*, the *RV Battery Model* and the *Supercapacitor*, instead, attain a lower system lifetime due to both the additional contribution of the leakage current and the energy dissipated by the DC-DC converter. It is important to note that

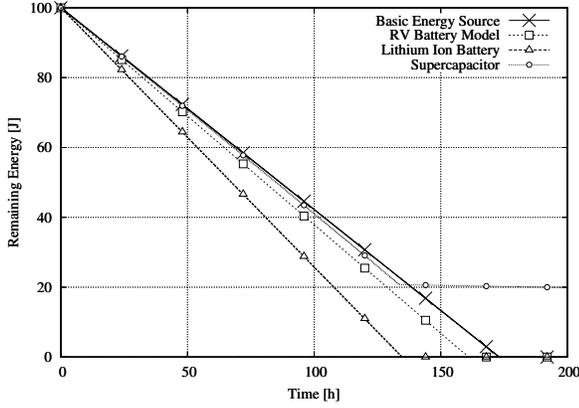


Figure 2: Remaining energy as a function of time for a simple node that senses the environment every 10 minutes, for different types of energy source.

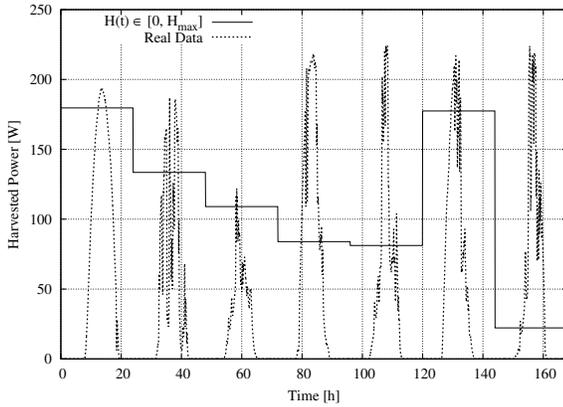


Figure 3: Harvested power as a function of time, for the basic energy harvester and the dataset of real solar panel measurements [7]. $H(t)$ is uniformly distributed in $[0, H_{max}]$, with $H_{max} = 220W$, and its value is updated every 24 hours.

the *RV Battery Model* included in the ns-3 energy framework represents an analytical model used to predict the lifetime of a battery based on the time-varying internal charge redistribution process, which depends on the particular current draw pattern of the load [24]. In Figure 2, the *RV Battery Model* represents the performance of a lithium ion battery with similar characteristic as the one modeled by the *Lithium Ion Battery*. Thus, the performance gain with respect to the *Lithium Ion Battery* represents the effect of modeling the internal charge redistribution process. Moreover, we note that all the energy sources follow an almost linear decrease of the remaining energy over time, and that the node stops functioning at 0 J for most of the battery models. However, the *Supercapacitor* shows two regions of operation because the DC-DC converter cannot operate below the voltage threshold V_{low} (which in turn translates to an energy level), causing the node to stop its operations, while the residual energy keeps decreasing due to the supercapacitor leakage current.

In Figure 3, we compare the power provided by the basic

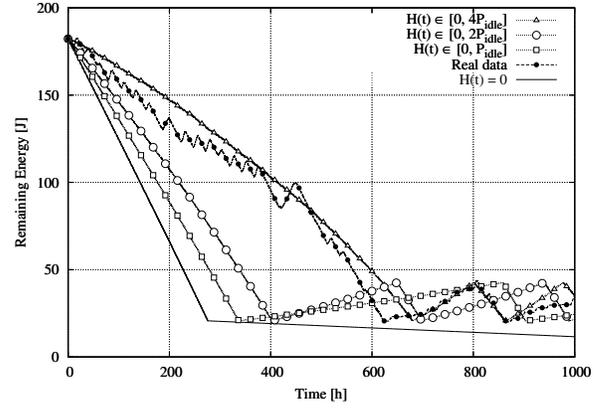


Figure 4: Remaining energy as a function of time for a simple node that senses the environment every 10 minutes, for different values of the energy harvested $H(t)$ and for real solar panel measurements [7]. $H(t)$ is uniformly distributed in the relative interval, and its value is updated every 5 minutes.

energy harvester with the harvester based on a real dataset for a period of 7 consecutive days (real data from [7], March 10-16, 2014). The *Real Data* plot clearly shows the night and day periodicity, as well as the variability between different days, for the power level provided by the harvester. For the basic energy harvester, instead, the power provided by the harvester is uniformly distributed in $[0, H_{max}]$, where H_{max} is the maximum value of the real data harvester (220W), and the harvested power is updated every 24 hours. While Figure 3 provides an example of the power levels that are provided by the different harvesters, it can also be used to infer some important considerations for the design of a real system. In fact, even if the two harvesters provide, on average, the same energy per day, the variation of the harvester process that they represent can result in completely different performance for the communication protocols.

To better evaluate the impact of the energy harvester, Figure 4 shows the remaining energy of a node that is powered by a supercapacitor, and that performs periodic sensing of the environment, as a function of time, for different values of harvested energy. As expected, the presence of the energy harvester increases the total operational time of the node for a time proportional to the amount of harvested energy. Moreover, while the non-harvesting case ($H(t) = 0$) follows a discharge pattern as in Figure 2, it can be observed that including the contribution of an energy harvester introduces an additional region of operation. In particular, the supercapacitor undergoes an initial discharge phase, that ends when the low energy threshold (V_{low}) is reached. At this point, the node stops its normal operations (i.e., the sensor stops the periodic readings and goes to the shutdown state) and it remains in this state until the harvester recharges the supercapacitor up to a second threshold (fixed here to 1.4V). After that, the node restarts the periodic reading operations until the low energy threshold is reached again.

Finally, in Figure 5 we compare the output of the energy predictor module with the actual energy provided by the *Real*

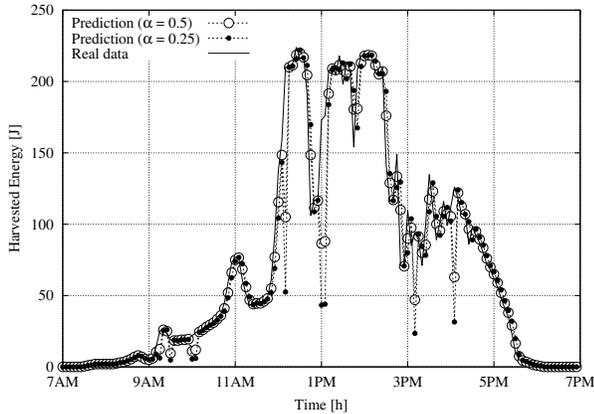


Figure 5: Energy predicted by the energy predictor module, for different values of α .

*Data Energy Harvester.*² According to Pro-Energy [8], for $\alpha = 0.5$, the energy E_{t+1}^d , harvested during timeslot $t + 1$ of a stored day d , and the actual energy C_t , harvested during the previous timeslot of the current day, are equally weighted, while for $\alpha = 0.25$ more weight is given to the stored day d harvested energy. We note that, when considering a small timeslot duration as in Figure 5, decreasing the value of α results in a predicted harvested energy less similar to the current harvested energy, due to the high correlation between subsequent updates of the actual harvested energy. However, a small value of α can be seen as a pragmatic way to capture the uncertainty in determining on-the-fly the actual amount of energy that will be harvested by the node.

5 Conclusions

In this paper we proposed an extension of the energy framework currently released with ns-3 to introduce the concept of an energy harvester and an energy predictor. Moreover, we extended the set of implementations of the current energy framework to include a model for a supercapacitor energy source and a device energy model for the energy consumption of a sensor. Additionally, we motivate the need for different models of the various elements that compose a simulation node and showed the impact on the system performance through some examples of simulation results. As future work, we plan to further extend the energy framework to include several implementations of the different elements that compose the framework, as well as to provide an application that links them together. As a result of these efforts, we believe that our contributions to the ns-3 energy framework will provide a useful tool to enhance the quality of simulations of energy-aware wireless networks that incorporate energy harvesting.

6 Acknowledgments

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²For simplicity, we fixed the slot duration of the energy predictor module to 1 second so that the amount of power provided by the harvester directly translates to an energy level.

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