Towards an Extensible and Scalable Energy Harvesting Wireless Sensor Network Simulation Framework

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ABSTRACT

Energy harvesting approaches are of increasing interest in the context of Wireless Sensor Networks. Energy harvesting as a source of intermittent power offers significant opportunities to extend the operating lifetime of sensors in a number of key application areas, including environmental monitoring and healthcare. This paper surveys existing simulation tool support, and highlights through experimentation the need for more expressive modelling approaches, and presents visions to enhance simulation support for EH-WSN.

Keywords

Wireless Sensor Networks; Energy Harvesting; IoT

1. INTRODUCTION

Wireless sensor networks (WSNs) have shown to be a valuable tool for gathering data in a wide range of applications. A key limiting factor to the use of wireless sensors is battery life, which limits their operational lifetime without incurring battery replacement costs. Consequently, a great deal of attention has been directed towards the use of energy harvesting (EH) as an alternative power source for WSNs (EH-WSNs). Energy harvesting involves the conversion of ambient energy sources such as solar, wind, kinetic, temperature gradient and radio emissions into electrical energy which is either used directly, or buffered temporarily for later use in rechargeable batteries or super-capacitors.

Since EH introduces significant unpredictability and variability in the energy yield available to the sensor node, a new generation of WSN simulators have emerged in the research community which are EH-aware. Such simulators are essential for the study of energy-neutral WSN theory with stochastic energy inputs, and the development of power management policies appropriate for different environmental conditions. Each EH-WSN simulator addresses particular areas and questions in this domain, by deploying models of varying degrees of detail, flexibility and generality.

ICPE '17 Companion, April 22 - 26, 2017, L'Aquila, Italy

ISBN 978-1-4503-4899-7/17/04...$15.00

DOI: http://dx.doi.org/10.1145/3053600.3053610

The ability to accurately predict the overall quality of service which will be provided by a large scale EH-WSN over time relies on having detailed, low-level models of all aspects of an EH-WSN system. Being able to accurately predict the overall quality of service of a proposed system before deploying it in the real world will reduce the risk in investing significant time and expense in deployment.

In this paper, we seek to identify the challenges and opportunities to develop accurate EH-WSN simulation. In Section 2 we further motivate the need for simulation support for EH-WSN systems, and present a system model in Section 3. In Section 5 we demonstrate experimentally the need for enhanced modelling and simulation approaches in the context of EH-WSN. Section 6 illustrates our ongoing work.

2. MOTIVATION

The attention to energy harvesting (EH) for wireless sensor networks has been driven by battery replacement costs such as material costs, labour involved in replacement of potentially hundreds or thousands of nodes in hazardous or remote environments, and recycling. These costs can make a proposed deployment of a WSN with a long lifespan infeasible. Where battery replacement is feasible, toxic substances used in battery technologies such as mercury, lead, zinc, cadmium, manganese and lithium make efficient and environmentally friendly battery recycling difficult to achieve [5].

The inherent unpredictability of energy harvesting yield has prompted a new generation of EH-aware WSN simulators, such as GreenCastalia [4], SensEH [9], HarvWSNet [11], WSNSim [18], extensions to NS-3 [8, 23] and other works [15, 14, 19]. Using EH-aware WSN simulators allow researchers to explore the design space of various EH-WSN policies and sub-systems within reasonable time, allowing experimental control and repeatability of environmental conditions of interest. As such, EH-WSN simulators typically model a subset of features of interest in detail, while simplifying others.

In contrast, in order to carry out an overall assessment of the long term predicted quality of service of a proposed EH-WSN system, it is important that a complete and accurate set of models are present for all processes important in energy harvesting and consumption. The need for enhanced accuracy and completeness of these models motivates the consideration of a scalable, extendible and open-source EH-WSN modelling framework which is proposed here.

	GreenCastalia [4]	SensEH [9]	WSNSim [18]	[8]	[16]	HarvWSNet [11]	[7]	[10]
Code available	✓		✓			✓		
Harvester model	✓	✓	✓	✓	✓	✓	✓	✓
Power regulation model				✓	✓	✓	✓	✓
Realistic storage model	✓	✓	✓	✓	✓	✓	✓	✓
Power consumption model	Detailed†a	Detailed†b	Detailed	Simple	Simple	Detailed†c	Simple	
Network stack model	✓†a	✓†b	✓	✓†d		✓†c		✓
Noise model	✓†a	✓†b	✓	✓†d		✓†c		✓
Emulation		✓						
Security model								

† Models extended from [a] Castalia[21], [b] Cooja[20], [c] WSNet / Worldsens[13], [d] NS-3[3]

Table 1: Feature comparison of existing energy-harvesting WSN simulators.

3. EH-WSN SYSTEM MODEL

The energy performance of an EH-WSN is dictated by a number of complex processes. These process models are summarised in Figure 1.a), which shows how these process models may feed into each other.

Figure 1.b) shows a component diagram of an example solar harvesting WSN system. In this system, the environment may be simulated using an astronomical model of the incidental angle of the sun to a particular location on earth over time, an obstruction model which takes into account occluding objects near a given mote, and a local weather model driven by solar irradiation data. The harvester model may simulate the effect of the solar panel's I-V efficiency curve given input from the environmental model. The power regulation model may simulate the efficiency, drop-out behaviour and maximum power point tracking behaviour of a voltage regulator system, which in turn feeds into the energy storage model. The energy storage model may simulate realistic charge-discharge characteristics of a super-capacitor, given the charge from the regulator and load from the mote. Finally, the power consumption model may simulate a complex power profile of a mote which is taking sensor readings, processing and storing data to a flash chip, and communicating with other motes using a given network stack. The performance of the communications may depend on the physical network topology, obstructing objects and background RF noise.

As this example illustrates, there are many complex and interacting sub-models which would constitute an ideal and complete simulation. It is not surprising that WSN simulators tend to implement a limited subset of these models in detail, while simplifying or omitting others. By simplifying or omitting sub-models, researchers can investigate one aspect in detail without having to develop an overly-complex and computationally intensive model.

4. STATE-OF-THE-ART

Complex interactions such as these exist between all levels of an EH-WSN system, as outlined in Section 3, highlighting how a complete set of sub-models is required for an accurate overall prediction of EH-WSN performance. In Table 1 we provide an overview of currently available EH-WSN simulator systems, which includes a survey of sub-model features. This table was constructed from a literature review of the papers referenced in the header row. Empty table cells denotes that a feature was not described in the referenced paper.

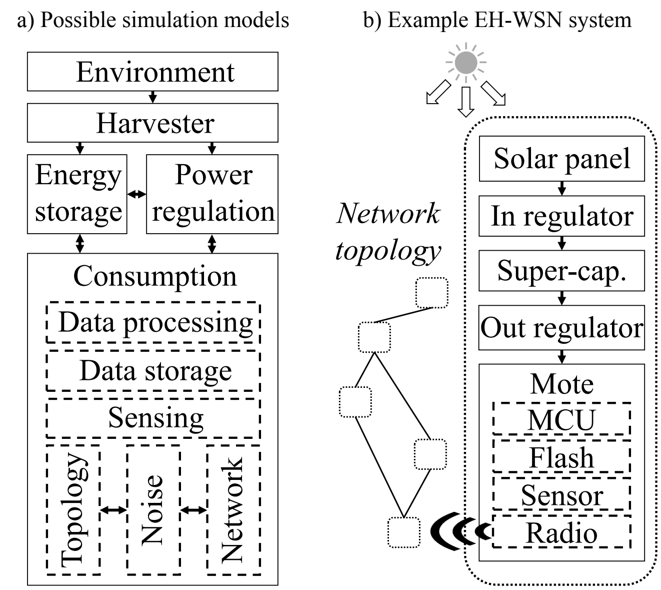

Figure 1: (a) Stack of simulation models (arrows denote possible model interactions) (b) An example EH-WSN setup (arrows denote energy flow)

As this survey illustrates, different simulators often implement a different selection of the possible sub-models. Where a sub-model is implemented, they vary greatly in the level of detail. This leads to varying levels of completeness.

Table 1 also shows that only GreenCastalia, WSNSim and HarvWSNet have made source code openly available, making it difficult for researchers to build a model stack using the models developed by other researchers.

The authors of Castalia [6] and GreenCastalia [4] (which is built upon Castalia) describe the benefits of open development [6], and have set out to address this by making Castalia an open-source extensible framework. Building on an open-source extensible framework will be essential if we are to realistically build a library of complex sub-models which can be integrated into each other, providing accurate simulations over a range of scenarios.

Other commonalities between the simulations considered here are present; namely different levels of environment monitoring, and a lack of EH-aware security models. These are considered in detail in the following section.

5. EXPERIMENTAL RESULTS

Having investigated the ability of state-of-the-art WSN simulators to model energy harvesting systems, we now seek to demonstrate experimentally the criticality of models currently absent from many simulation tools. In particular, we seek to quantify the impact of RF interference and security decisions on the energy consumption and performance of systems under test.

5.1 Environmental modelling

An example of complex sub-model interactions was investigated experimentally, and summarised in Figure 2 and Table 2. The energy consumption of a TelosB[22] mote was recorded while sending 150 separate 28 byte packets, with a short pause in between each send. Packets were sent via the on-board CC2420 radio chip, using the default CSMA/CA TinyOS 2.1.2 [17] MAC. All packets were transmitted over the IEEE 802.15.4 channel 26 (2.48 GHz), in the presence of varying levels of RF noise generated by nearby motes also operating in channel 26. These noise levels were created by placing 0-4 additional TelosB motes at 0.5m from the mote being analysed, and were programmed to continuously send packets. An RFExplorer 2.4G spectrum analyser [2] was used to measure the noise generated, and energy consumption was measured using a Monsoon power monitor [1].

Mean noise (dBm)	Mean energy (μJ)	SD
-65.6	564.9	192.9
-67.1	552.8	183.3
-71.1	511.1	172.1
-72.1	490.0	155.1
-76.7	457.55	147.0

Table 2: Energy used (μJ) by noise level

Figure 2 shows the background noise created by the additional motes had interactions on the energy expenditure of the mote under test. The energy required to send packets, even with no generated noise, is variable due to the random radio back-off periods created by the collision avoidance protocol (CSMA/CA). A back-off involves waiting for a random period of time, sensing the channel for transmissions, in order to minimise collisions. Detected transmissions during the back-off period will cause a further random 'congestion' back-off period. Increases in background noise clearly causes a shift in consumed energy, due to increasing back-off periods caused by CSMA/CA. Clearly, simulators which do not incorporate a sufficiently detailed noise and networking stack models and their interactions may not capture these complex interactions. This issue is exacerbated in the context of EH-WSN, where harvestable energy sources from the environment (e.g. RF) are of key interest.

5.2 Security modelling

A notable omission from the sub-models offered by EH-WSNs is a communications security model. Security is a feature which is becoming increasingly valuable, particularly in the face of rising exploitation of IoT security vulnerabilities. The adoption of 6loWPAN promises to enable energy efficient IPv6 networking capabilities for WSNs.

In Table 3 we investigate the impact of security using a TelosB mote programmed using TinyOS to send 150 64-byte packets under varying types of 128-bit AES encryption;

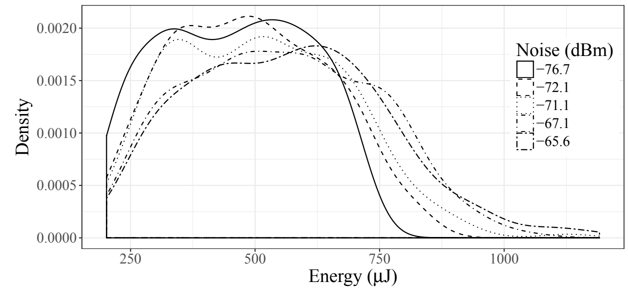

Figure 2: Energy (in micro-Joules) required to send a 28-byte radio packet in the presence of noise

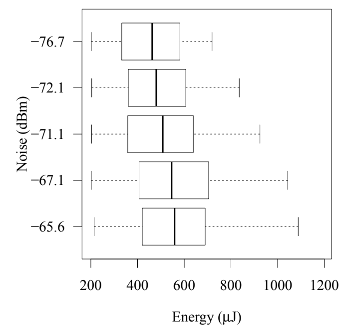

Figure 3: Energy (in micro-Joules) required to send a 28-byte radio packet in the presence of noise

Counter Mode Encryption (CTR), Cipher Block Chaining Message Authentication Code (CBC), and no encryption.

Encryption method	Mean energy (μJ)	SD
None	187.7	1.50
CTR	336.3	1.59
CBC	402.0	1.87

Table 3: Energy used (μJ) by encryption level

Example power traces of transmissions are shown in Figure 4. We can clearly see a significant impact on energy consumption, making security a critical element to incorporate into simulation models. We anticipate that adaptive security policies based on forecasts of the availability of energy (including that obtained through EH mechanisms) will increase in popularity, so efforts to understand the energy-performance-security trade-off are necessary.

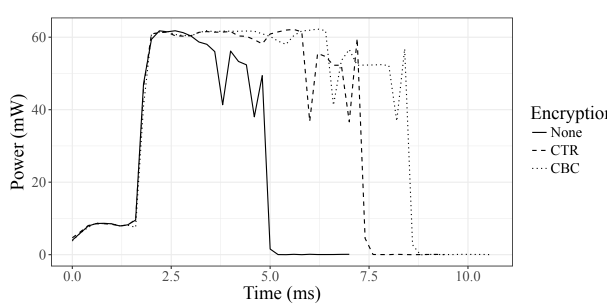

Figure 4: Example power traces of encrypted transmissions

6. TOWARDS AN OPEN, SCALABLE, CLOUD-BASED FRAMEWORK

In this paper we make the case for a framework for building a library of sub-models, allowing an overarching and accurate EH-WSN simulation framework. We demonstrate experimentally, the criticality of environmental and security modelling, areas which are currently lacking in state-of-the-art tooling in this area.

In our ongoing work, we seek to provide practitioners with usable simulation-based tooling support to address a number of common challenges inhibiting the use of simulation to reason over design and deployment decisions of EH-WSN systems. In particular, our work focuses on three key areas:

Uniform integration interfaces: There is the need to define common interfaces against which hardware models and protocol specifications may be defined. In doing so, we seek to alleviate the issue of model composability, reconciling models from disparate formalisms [12].

Scalability: As we evaluate WSNs as part of large-scale IoT deployments, computational intensity increases. We must design such a framework to allow distributed, parallel computation using scalable cloud resources, and usable tooling to allow practitioners to explore complex WSN hardware and software design spaces in reasonable time.

Democratisation of benchmarking and performance evaluation: The process of performance evaluation and benchmarking is often extremely costly. This is particularly critical in evaluation which considers modelling of energy consumption, with the required instrumentation prohibitively expensive for the majority of research groups. We seek to mitigate this benchmarking effort through a standardised performance and power model capable of modelling hardware and software used in EH-WSN/IoT.

Further issues are present in the choice of benchmarking methodology. Generalisable and repeatable results require mathematical rigour which is currently not well understood within all stakeholder communities. There is a need to bring together the performance evaluation and statistical communities in the design of a principled benchmarking framework to achieve generalisable performance models.

7. ACKNOWLEDGMENTS

This work was supported by the Engineering and Physical Sciences Research Council, Centre for Doctoral Training in Cloud Computing for Big Data [grant number EP/L015358/1].

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