Design Support for Energy Harvesting Driven IoT Devices

Lukas Sigrist
ETH Zurich
Computer Engineering and Networks Laboratory
Zurich, Switzerland
sigristl@ethz.ch

Lothar Thiele
ETH Zurich
Computer Engineering and Networks Laboratory
Zurich, Switzerland
thiele@ethz.ch

ABSTRACT

With the emerging Internet of Things, wireless sensor applications are increasingly being supplied from energy harvesting. While this shift away from batteries provides many advantages, it also increases the complexity of designing these highly energy constrained systems. Due to environmental dependencies, novel tools are necessary to support their design process. With the RocketLogger we introduce a measurement tool that addresses the specific needs of energy harvesting systems. It provides a highly increased dynamic range for current measurements, accommodating both ultra-low sleep currents of few nanoamperes as well as wireless communication currents in the range of hundreds of milliamperes. The portable design allows for in-situ measurements for characterizing and validating the system performance, while an extensible sensor bus provides flexible recording of the application specific environmental variables from which the energy is extracted. While the RocketLogger is an important first step, additional tools are still required to provide the necessary support for designing efficient and reliable harvesting-driven systems.

KEYWORDS

Energy Harvesting, Internet of Things, Wireless Sensor Networks.

1 INTRODUCTION

Energy harvesting is seen as a key long-term technology to power the billions of devices of the emerging Internet of Things (IoT). Advances in low power system design have enabled battery powered wireless sensor networks with increasing lifetimes that are today deployed in various application areas. However, with the vast amount of IoT devices and their deployment in hardly accessible locations, batteries are not a practical option, since their limited lifetimes would require expensive maintenance. Extracting energy from the surrounding environment is therefore seen as a key solution to the energy supply problem [1]. This lead to an increased integration of energy harvesting into new wireless sensor node designs and the new research of transiently powered computing systems, focusing on the design of highly energy constrained, batteryless systems that progress only as a function of their environment.

Unfortunately, the use of energy harvesting comes with additional complexity in the design process of these systems. Where previously a constant supply was guaranteed, the variable and application-specific environmental conditions have a direct impact on parameters like e.g. harvested energy and power conversion efficiencies [2]. To efficiently use the small amount of energy harvested by tiny IoT devices, these systems need to adapt to the ever changing supply conditions, which vary over a large range from nW to mW.

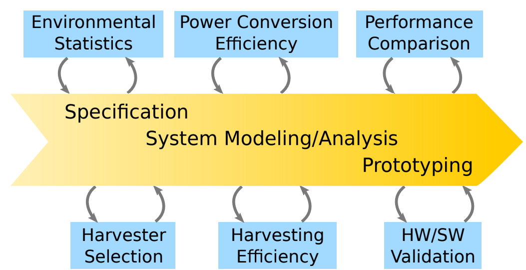

Figure 1: Sample design aspects of harvesting-based systems

Only application-specific solutions could provide the desired performance given the environmental, size and cost restrictions. While these solutions are highly specific, they all demand for a precise characterization of the environment-dependent energy budget, characterization and optimization of the application's active and sleep energy consumption during their design, as illustrated in Figure 1. The measurement of these metrics, however, include widely ranging currents: quiescent/sleep currents in the order nA-µA, and active currents of 100's mA. Because of the application and environment specific design, tools must be deployed with the energy harvesting system to record its behavior the production environment. Although measuring power and environmental properties are well known problems, portable tools that accurately and reliably measure harvesting-based systems do not exist.

Building these tools provides several challenges: they are required to measure a wide dynamic power range and environmental conditions in the field and for long periods of time. In addition, these tools must run independently from the system being measured, while minimizing the impact on them. Otherwise, the measured systems will not work in adverse power conditions or suffer a significantly degraded harvesting or power conversion efficiency.

While the RocketLogger presented in this work provides the required measurement capabilities, we also motivate the need for novel tools allowing to rapidly explore various system and harvester configurations under the same environmental conditions to further improve and accelerate the design of harvesting driven systems.

2 PORTABLE ACCURACY MEASUREMENTS

Currently available measurement equipment does not fulfill all the requirements of these different, but related design aspects outlined above. Portable or embedded solutions designed for battery operated devices lack ultra-low current measurement in the nanoampere range [3, 6], do not feature the desired dynamic range from below micro- up to hundreds of milliamperes [4, 5, 9], or do not

Table 1: RocketLogger performance overview

Characteristic	Performance
Voltage Range/Accuracy	±6 µV – 5.5 V / 0.02 % + 13 µV
Current Range/Accuracy	±1 nA – 500 mA / 0.09 % + 4 nA
Sampling Rate	up to 64 kSPS
Voltage Channel Impact	input impedance ~ 1 TΩ
Current Channel Impact	max. voltage drop ≤ 53 mV

target portable measurements with remote control [5, 6]. Benchtop devices with the desired performance exist, but focus on single measurement tasks with high accuracy and are bulky. They are therefore infeasible for mixed-signal in-situ measurements.

To address the specific measurement challenges in the designing and evaluation of energy harvesting systems we introduce the RocketLogger [7]. The novel mixed-signal data logger features high-accuracy power measurements and logging of environmental conditions like temperature or illuminance in a portable design of 103 mm × 68 mm. Two seamlessly switched current channels combined with up to four voltage channels, allow uninterrupted power measurements with a large dynamic range from 40 pW at 10 mV up to 2.75 W at 5.5 V with minimal impact on the device being measured. A remote web interface facilitates control and observation of long-term in-situ measurements. An brief summary of the loggers measurement performance is given in Table 1.

To show how the RocketLogger's unique features enhance the design process of harvesting driven systems, we consider a wearable multi-source harvesting circuit. The harvesting power and environmental conditions shown in Figure 2 were recorded in a scenario where the user walks outside during a warm, sunny day with high illuminance levels and then enters a colder, darker indoor space allowing for higher body to ambient temperature gradients. For the harvester measurements, it should be noted that the harvested TEG power is in the order of 100's µW, while solar power is in the mW range. This result shows that the solar harvesting power dominates outdoors, while the TEG generates more power indoor, although at a lower power level. This data is very valuable for subsequent iterations of system modeling and analysis to optimize important system parameters like harvesting efficiency.

3 CONCLUSION AND FUTURE WORK

In this work we motivated the need for novel tools to support the design process of energy harvesting driven applications. The presented RocketLogger device provides a combination of high-accuracy power measurements with large dynamic range, environmental logging, a mobile form factor, and an easy-to use remote interface. This unique set of features make it a versatile measurement instrument satisfying essential needs of the system design process for energy harvesting driven applications. While this solves important measurement needs in the design process of harvesting-driven systems, these measurements still require the deployment of the devices in the actual application environment.

We therefore see the need of emulating the physical environment in the lab to provide repeatable and consistent environmental conditions to accelerate the design process. State-of-the-art harvesting

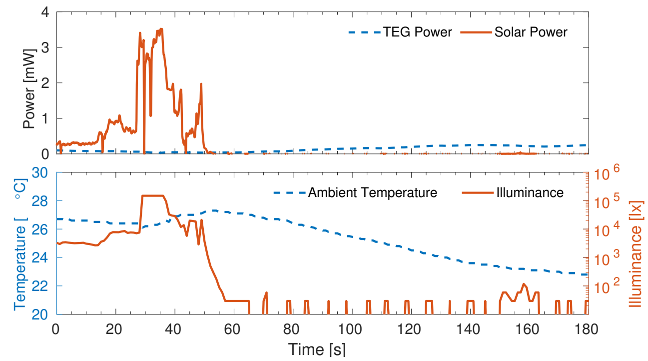

Figure 2: RocketLogger case study: in-situ measurement of a multi-source wearable harvesting system [7]

source emulators [3] allow recording and emulation of transducers like solar panels or TEGs in the application environment with reasonable accuracy. On other hand these solutions are limited to the emulation of the behavior of one specific transducer under specific environmental conditions. However, for the design of an optimized harvesting application, careful selection and precise characterization of the transducers is crucial to tune the harvesting circuitry and other system parameters [8]. For this reason we will focus on the emulation of the physical processes from which the energy is being extracted rather than the harvested power of a specific transducer. We are convinced that accurately reproducible environmental conditions are an important step that enables the comparison of different implementations of harvesting-driven applications and brings us closer to fully optimizing the design of purely energy harvesting-driven, transient computing systems.

ACKNOWLEDGMENTS

This research was funded by the Swiss National Science Foundation under grant 157048: Transient Computing Systems.

REFERENCES

[1] Naveed Anwar Bhatti, Muhammad Hamad Alizai, Affan A Syed, and Luca Mottola. 2016. Energy Harvesting and Wireless Transfer in Sensor Network Applications: Concepts and Experiences. *ACM Transactions on Sensor Networks* 12, 3 (2016).
[2] Andres Gomez, Lukas Sigrist, Thomas Schalch, Luca Benini, and Lothar Thiele. 2017. Efficient, Long-Term Logging of Rich Data Sensors using Transient Sensor Nodes. *ACM Transactions on Embedded Computing Systems* (2017).
[3] Josiah Hester, Timothy Scott, and Jacob Sorber. 2014. Ekho: Realistic and Repeatable Experimentation for Tiny Energy-harvesting Sensors. In *Proc.SenSys'14*.
[4] Xiaofan Jiang, Prabal Dutta, David Culler, and Ion Stoica. 2007. Micro Power Meter for Energy Monitoring of Wireless Sensor Networks at Scale. In *Proc. IPSN'07*.
[5] Saman Naderiparizi, Aaron N Parks, Farshid Salemi Parizi, and Joshua R Smith. 2016. µMonitor: In-situ Energy Monitoring with Microwatt Power Consumption. In *Proc. RFID'16*.
[6] A Pötsch, A Berger, C Leitner, and A Springer. 2014. A power measurement system for accurate energy profiling of embedded wireless systems. In *Proc. ETFA'14*.
[7] Lukas Sigrist, Andres Gomez, Roman Lim, Stefan Lippuner, Matthias Leubin, and Lothar Thiele. 2017. Measurement and Validation of Energy Harvesting IoT Devices. In *Proc. DATE'17*.
[8] Moritz Thielen, Lukas Sigrist, Michele Magno, Christofer Hierold, and Luca Benini. 2017. Human Body Heat for Powering Wearable Devices: From Thermal Energy to Application. *Energy Conversion and Management* 131 (2017), 44–54.
[9] R Zhou and G Xing. 2013. Nemo: A high-fidelity noninvasive power meter system for wireless sensor networks. In *Proc. IPSN'13*.