Energy Harvesting for the Internet-of-Things: Measurements and Probability Models

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***Abstract*—The success of future Internet-of-Things (IoT) based application deployments depends on the ability of wireless sensor platforms to sustain uninterrupted operation based on environmental energy harvesting. In this paper, we deploy a multi-transducer platform for photovoltaic and piezoelectric energy harvesting and collect raw data about the harvested power in commonly-encountered outdoor and indoor scenarios. We couple the generated power profiles with probability mixture models and make our data and processing code freely available to the research community for wireless sensors and IoT-oriented applications. Our aim is to provide data-driven probability models that characterize the energy production process, which will substantially facilitate the coupling of energy harvesting statistics with energy consumption models for processing and transceiver designs within upcoming IoT deployments.**

I. Introduction

Energy harvesting is now recognized as an important aspect of wireless sensor networks (WSNs) and Internet-of-Things (IoT) oriented technologies [1]. Indeed, a multitude of research efforts have studied energy management policies [2], theoretical aspects of coupling energy production with energy consumption [3], and practical applications [1], [4]–[10]. While most manufacturers of transducers provide specifications for the minimum, maximum and average energy harvesting characteristics of their devices, (photovoltaic, piezoelectric, thermoelectric, etc.), there is still a significant gap between the reality of practical energy harvesting testbeds and the assumptions made in the research literature. For example, within the recent literature on energy-harvesting based communications, there is a flurry of probability models about the harvesting process [11], but very limited experimental evidence is provided to support such models. This can be seen as a bottleneck in advancing the state-of-the-art in energy management frameworks for WSNs and IoT applications, as well as limiting the applicability and impact of theoretical studies in the field.

In this work, we attempt to provide an initial coverage of this gap by providing measurements and associated software tools to capture, parse and model photovoltaic and piezoelectric energy harvesting with a real-world multi-transducer platform. Our focus is on the “raw” power produced by each transducer after power conditioning, as measured by high-frequency analog-to-digital (ADC) conversion that causes no interference on the actual harvesting process. The selected application environments are an outdoor and two indoor environments that represent typical office and residential conditions where IoT-based applications and devices are expected to operate. The derived experimental datasets are matched with a variety of scaled probability distribution functions and results from the best-fit for each case are provided. Based on our results, we show that, for all our experiments, a mixture of two to four Normal and Half-Normal distributions turns out to provide for the best fit for all cases under consideration. It is hoped that future energy management frameworks will make use of our results in order to optimize the link between energy production and consumption in IoT-oriented deployments.

Section II provides a summary of related work. Section III presents the data collection process. Section IV presents the results and corresponding probability models. Finally, Section V provides some concluding remarks.

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II. Related Work

The literature on energy harvesting approaches for wireless sensors and IoT-oriented platforms can broadly be separated in three categories. The first category relates to physical properties and design of transducer technologies that scavenge energy from the environment. Essentially, the available sources of energy are: light, radio-frequency (RF), electromagnetic radiation, thermal gradients and motion (including fluid flow). The focus of research work in this category is on physical design of harvesters and transducing rates, rather than the statistical characterization of the manner energy is produced across time and within different environmental conditions. From the reported results for the transducer technologies available for the four sources of environmental energy, the most mature and commercially available ones are solar cells and piezoelectric energy harvesters [9], [12]–[16]. Ambient RF, electromagnetic radiation and thermal gradients have also received some attention (e.g., the Seiko thermic watch), but the availability of significant power levels is an issue, and, for the case of RF, efficient extraction using devices much smaller than the radiation wavelength is another key challenge [13]. Beyond these energy sources, fuel-based generation using ambient fluids, such as human bodily fluids, has also been

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