1 Introduction

1.1 Wireless Sensing Platforms

Energy harvesting technologies have spurred interest in the academic and industrial communities due to the emerging applications of miniature, low-power, wireless sensors. Concepts such as the Internet of Things (IoT) envision myriad networked devices used to integrate and automate homes, offices, factories – in other words, everything [1, 2]. One of the challenges for such devices is their ability to operate for long periods of time autonomously, i.e., without the need to be connected to a wired power supply or to substitute or recharge their batteries.

A notable milestone toward miniature wireless sensor nodes has been the smart dust project by University of California, Berkeley, researchers in the late 1990s [3]. The smart dust project introduced the concept of autonomous sensing and communication cubic-millimeter-sized motes (i.e., small particles) forming a massive distributed sensor network [3]. As a result, several wireless sensing platforms have been developed in an attempt to implement the smart dust concept. Widely popular implementations of such sensing platforms, albeit without achieving the ultimate cubic millimeter volume vision, have been the Mica mote [4] and subsequently the Telos mote [5] integrating a low-power microcontroller, sensor interface circuitry and a radio transceiver.

An alternative technology toward implementing ultralow-power wireless sensing platforms has been radio frequency identification (RFID) technology based on radar principles and backscatter communication [6]. In such systems, passive sensing and identification tags comprise ultralow-power radio transceivers that operate based on antenna load modulation that does not require an amplifier because the necessary power for both powering the tag and for communication is provided by an interrogator reader device [6].

Finally, the increased interest for ultralow-power, energy autonomous, wireless sensing platforms has been further fueled by the fifth generation (5G) communication systems that attempt to implement a massive number of interconnected devices communicating at low bit rates [7]. As the number of interconnected devices and potential for new applications keeps increasing, it is only natural to expect that the interest for energy autonomous, wireless sensing platforms will continue into the sixth generation (6G) systems and beyond.

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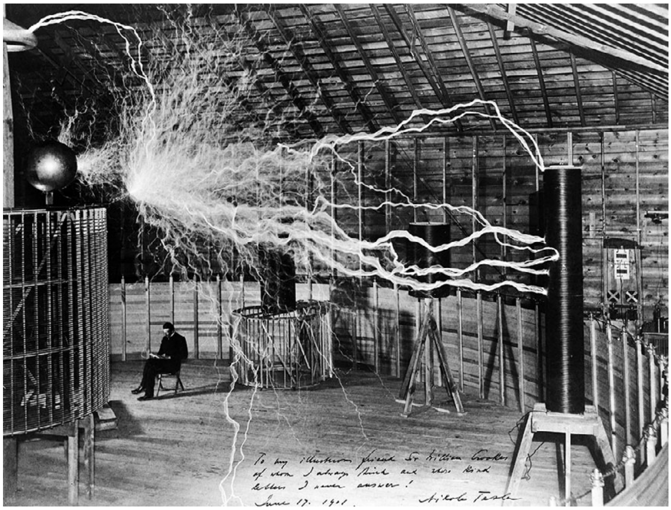

Figure 1.1 Nikola Tesla, with his equipment for producing high-frequency alternating currents. Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0)

1.2 Energy Harvesting Revolution

The physics behind the commonly employed energy harvesting technologies, solar, mechanical, thermal, and radio frequency, has been known for many years. For example, more than 100 years ago, Tesla envisioned the wireless transmission of power. Figure 1.1 shows a celebrated photo of Tesla in his laboratory in Colorado Springs. In another example, more than 100 years ago, Gulielmo Marconi began his experiments in wireless telegraphy in Vila Griffone, Bologna, Italy. The photo shown in Figure 1.2 is a setup of his laboratory in the Marconi Museum, where one can see on his desk a disc-shaped device that was a thermocouple, a thermoelectric generator that he used in his experiments.

One could probably come up with numerous other examples. Advances in materials and fabrication techniques have enabled the miniaturization and the performance improvement of such energy harvesting devices that make them suitable for low-power wireless sensors. Combined with advances in electronic design and integrated circuit technologies that have led to the reduction of operating power of electronic circuits, the vision of energy harvesting powered wireless sensor platforms becomes more and more possible.

1.3 This Book

The topic of energy harvesting technologies is very broad and diverse, given that each of the energy harvesting technologies represents a completely different field

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Figure 1.2 Marconi's laboratoy at Villa Griffone, Bologna, Italy.

of research. This book discusses the main energy harvesting technologies, namely solar, kinetic, thermal, and electromagnetic (EM), together with an introduction to power converters and energy storage. We try to provide an answer to questions such as how much power can be harvested and what are the main challenges in implementing these harvesting systems.

Table 1.1 presents indicative performance results from different types of energy harvesters with emphasis on low-profile transducers suitable for micropower generation. There exists a large variation among the size of the transducers and the amount of energy that can be generated. As a result, the final selection of the employed type of transducer depends greatly on the application requirements and scenario, which makes the presented results of Table 1.1 only indicative of the potential of the various harvesting methods.

Table 1.1 Indicative harvested power values from different transducer types [8].

Energy source	Harvested power	Conditions / available power
Light / solar	60 mW	6.3 cm $\times$ 3.8 cm flexible a-Si solar cell AM1.5 Sunlight (100 mW/cm^2) [9]
Kinetic	8.4 mW	Shoe-mounted piezoelectric [10]
Thermal	0.52 mW	Thermoelectric generator (TEG), $\Delta T = 5.6$ K [11]
Electromagnetic	1.5 μW	Ambient power density 0.15 μW/cm^2 [12]

Each transducer technology has distinct advantages and disadvantages. For example, solar energy is ubiquitous, whereas solar harvesting is challenging in indoor scenarios and during night or cloudy conditions. Thermal energy harvesters are typically hampered by a low transducer efficiency, especially when a

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low-temperature gradient is present, while kinetic energy harvesters are sensitive to the natural vibration frequencies of the harvester and application settings.

When it comes to ambient EM energy harvesting, the available energy density is usually orders of magnitude below the corresponding values of the other energy sources, although measurement campaigns in crowded urban settings have shown the possibility of harvesting a useful amount of EM energy from the ambient [13, 14, 15], especially using wideband or multiband harvesters. Nonetheless, EM energy harvesters are intimately related to systems exploring intentional EM radiation to power up electronic devices, wireless power transfer, with RFID technology being a notable application example that already enjoys commercial success.

The dc voltage output of the various energy harvesting transducers can vary significantly from the value that is necessary to operate the microcontroller, the transceiver, and sensor circuits of the wireless sensing platform. Consequently, it is necessary to use a dc-dc converter circuit in order to bring the voltage to a desired value and furthermore, regulating circuitry maybe necessary in order to minimize the variation of voltage. All these circuits penalize further the overall power conversion efficiency of the energy harvesting system and must be carefully selected and designed.

Finally, due to the time varying and many times random nature of the available ambient energy, the implementation of energy autonomous circuits for communication and sensing dictates the integration of multiple energy harvesters in order to ensure an average energy supply. In this case, combining the dc outputs of each energy harvesting device must also be done carefully because the efficiency of energy harvesting devices is also dependent on the load that is connected to them and the interconnection of different harvesters that present different and variable loads to each other will also affect efficiency.

These considerations demonstrate on one hand the great challenge for the designer in order to design an energy harvesting assisted wireless sensing platform, but on the other hand, they show the broad nature and the large amount of possibilities that arise by exploring the different disciplines related to the field of energy harvesting.