Preface

Wireless sensors and wireless sensor networks (WSNs) are nowadays becoming increasingly important due to their decisive advantages. They enable mobility and flexibility, and significantly reduce installation and maintenance costs. Different on-going trends towards the Internet of Things (IoT), Industry 4.0 and 5G Networks are based on WSNs. All these trends address massive sensing and admit to having wireless sensors deliver measurement data directly to the World Wide Web in a reliable and easy manner. They can only be supported, if sufficient energy efficiency and flexible solutions are developed for energy-aware wireless sensor nodes (WINO). Within system design of wireless sensors, several aspects related to technology, electronics and algorithms need to be considered to reach a high energy efficiency on the node and network level. In the last years, different possibilities for energy harvesting have been investigated and several works have been reported on theoretical and practical applications using these technologies. Generally, special aspects are treated and the overview of these methods remains on the level of personal effort.

Writing a book on energy harvesting is a huge work and can be only done in an aim-oriented way. In a previous book *Energy Harvesting*, we described different technologies and concepts more from the perspective of feasibility to introduce this technology to applications. At the time, the potential of ambient energy was not as clear and evident as it is today. This success is due to the developments towards low power consumption and also towards efficient and suitable converters based on manifold principles and able to generate enough energy. In this book, in addition to these topics, we focus on advanced and novel developments in vibration converters, wireless energy transfer and energy saving methods on the network level. This is no longer from the point of view of feasibility, but with the aim of giving an overview of novel developments that make technologies for using ambient energy and transferred energy to supply sensors realistic. These methods, systems and technologies are enabling technologies for the wide spread use of sensors in general and, especially, in the IoT era.

The specific motivation for writing this book is based on the convincement that an interlocked interaction between suitable methods and technologies is necessary to realize optimized solutions for energy aware WSNs. In the last years, this has become more visible with the increasing number of converters, hybrid solutions, energy transfer and energy management methods acting at node and network level.

The system design of an energy aware WINO begins with the choice of the suitable available ambient energy, such as solar radiation, vibration and electromagnetic fields and its characterization. Therefore, suitable converters need to be designed and improved in their performance to meet necessary requirements and to reach enough energy to guarantee the function of the WSNs. It is thereby not possible every time to supply a sensor node from just one ambient source. In order to enhance the energy income, a combination of similar or diverse converters can be envisaged. Energy

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transfer also plays an important role, as it supports wireless sensor nodes by additional energy in cases where ambient energy sources are not sufficient or the behavior of the converters is affected by environmental conditions or aging. Additionally, different techniques for enhancing the efficiency of energy converters and reducing energy consumption on node and network level are developed and need to be considered together to realize optimal solutions.

This book gives an overview on fundamentals and techniques for energy harvesting and energy transfer from different points of view. A distinct focus is dedicated to vibration converters as an often available ambient energy source where special optimization of the converter is needed. Different techniques and methods for energy transfer, management and energy saving on network level are reported together with interesting applications.

The first part of the book introduces essential fundamentals and methods. The first chapter describes techniques for finite element modeling of energy harvester at the example of vibrational devices. The focus is on the investigation of active materials, which have an intrinsic ability for coupling several branches of physics and, consequently, are commonly used for manufacturing harvesters. In particular, an investigation is carried out for the energy production from mechanical vibrations in high-speed railway bridges. The second chapter focuses on solar energy harvesting as one of the most predictable ambient energy sources with a good availability and energy level. The third chapter describes methods for the determination of incoming power and the most used methods for maximum power point tracking together with an efficiency analysis. The fourth chapter deals with energy management concepts, including maximum power point tracking, voltage and current conversion, energy income forecast and modeling and tuning the energy consumption profile.

The second part of the book also deals with vibration converters and hybridization. It begins with the fifth chapter, which deals with magnetoelectric vibration converters, which are based on promising conversion mechanisms for kinetic energy harvesting combining magnetostrictive and piezoelectric materials. The chapter begins with the basics of magnetoelectricity and an overview of the recent developments in the state of the art of magnetoelectric energy harvesting. After that, a model-based design method for magnetoelectric converters is presented.

In the sixth chapter, a nonlinear electromagnetic vibration converter based on the use of magnetic spring principle is discussed. It enables energy harvesting for a large bandwidth compared to the usual linear vibration converters. In order to improve efficiency, bistable random mechanical switching harvesting on inductors (RMSHI) is proposed to realize synchronization between mechanical movements and energy management. In the seventh chapter, an oscillating vertical piezoelectric cantilever with clearance is proposed for vibration energy harvesting. A mechanical resonator is realized as an inverted elastic pendulum excited by kinematic excitation and then characterized.

One of the most important possibilities to maximize the energy income from ambient vibration is to design a hybrid vibration converter. This is the subject of the eighth chapter that deals with hybridization of electromagnetic vibration converters dedicated to low vibration frequencies. Several macro hybrid vibration converters based on the combination with the electromagnetic principle are reviewed and compared. Thereby, electromagnetic and magnetoelectric energy harvesting techniques deliver energy with relative high efficiencies and are, therefore, very promising principles. The ninth chapter presents a combination of a piezoelectric and a magnetostrictive coil transducer. Thereby, the mechanical resonator moves in two degrees of freedom, which have been monitored in two channels to show the broadening of the total frequency transduction.

The third part of the book is dedicated to wireless energy transfer, including both RF and inductive energy transfer as an interesting solution to extend the lifetime of wireless nodes and to overcome the lack of ambient energy sources. Inductive energy transfer is contactless and reaches a high efficiency over short distances. Thereby, data can be transferred at radio frequencies concurrently to the energy transfer. This is the subject of the tenth chapter, where a secure simultaneous wireless information and power transfer (SWIPT) system is presented. The focus is on the use of multiple antennas to improve the efficiency of wireless power transfer (WPT) and secure information transmission. In particular, the objective is to maximize the secrecy rate via beamforming by a model-based approach to achieve a significant gain in the secrecy rate compared to conventional methods.

Over a relative high distance, radio frequency (RF) energy transmission and harvesting techniques enable proactive energy replenishment for wireless sensors. With RF power transfer, long distances can be overbridged. The eleventh chapter focuses on the use of RF energy harvesting into usable electrical form, providing a certain voltage or enabling delivery of a desired current to load.

The finite element method simulation of inductive wireless power transmission is the subject of the twelfth chapter, where a wireless power transfer system is analyzed, including important parts such as coil, core and driver, showing good agreement with experimental results.

Efficiency improvement of wireless power transmission via inductive links is the focus of the thirteenth chapter. It investigates the use of multi-coil inductive systems, in which the sending and/or the receiving sides have multiple coils in the case of misalignment, to provide energy to a movable receiver and to increase the system flexibility. Suitable energy management is also indispensable for wireless inductive power transmission via inductive links to reduce losses and compensate coil position perturbations. The fourteenth chapter examines energy management circuits applied to the sending and receiving sides of inductive power transmission systems.

The fourth part of the book treats energy saving and management strategies. It begins with Chapter 15, in which energy-saving concepts for WSNs based on scheduling, dynamic voltage, frequency scaling and dynamic power management are reported. Chapter 16 emphasizes the optimal energy allocation in WSNs by introducing a system engineering approach modeling and optimizing the system in order to derive policies on when and how to use the available energy in order to achieve the best possible performance. In Chapter 17, energy management concepts in WSNs are presented for large networks. The chapter presents a survey of energy conservation and energy optimization techniques for WSNs.

In the eighteenth chapter, the design of wake-up receivers for energy harvesting is discussed. The main idea thereby is that a wake-up receiver consumes much less power than the WINO. During non-active time, the WINO can, therefore, be turned off while only the wake-up receiver is switched on to detect possible signals and wake up the node. Hence, a high energy efficiency is realized.

Applications for energy harvesting and energy transmission are nowadays manifold. In the final part of the book, in the last part about system design and applications, a selection of specific solutions related to agriculture, structural health monitoring of bridges and power grids is given.

In total, the book reports about new advances and approaches in energy-aware wireless sensors and sensor networks including theory, methods and applications. The book is interesting for researchers, developers and students in the field of sensors, wireless sensors, WSNs, IoT and manifold application fields using related technologies.

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