Rechargeable Sensor Networks
Technology, Theory, and Application

Introducing Energy Harvesting to Sensor Networks

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Preface

With the rapidly growing applications of large-scale sensor networks, there is a need to provide unattended network operation and run sensor networks perpetually. Considerable effort has been devoted to the design of utilizing the constrained energy resources efficiently. However, most of the existing works tried to solve the problem from the viewpoint of algorithms, and thus cannot tackle the challenge of constrained energy fundamentally in sensor networks. More exciting and interesting methods should be to develop a device, which can make the sensor nodes self-powered by harvesting ambient energy from a variety of natural and man-made sources for sustained network operation.

Harvesting energy from ambient energy resources to power the electronic devices has been recognized as a promising solution to satisfy the long period requirement of unattended operation. The key technologies in the rapid growth of the energy-harvesting field are energy-harvesting devices, which are designed to capture the ambient energy surrounding the electronics and convert it into usable electrical energy to power the low-cost and small-size sensor nodes. Achieving sustainable network lifetime via battery-aware design brings forth a new frontier for energy optimization techniques, which experienced low-power hardware design at the early stage, evolved into power-aware design, and recently, battery-aware design. As a result, approaches of scavenging energy from sources of solar, vibration, temperature variations, wind, biochemical energy, and passive human power have been proposed as alternatives to replace the batteries on the electronic devices.

In practice, there is an increasing trend in integrating energy-harvesting technologies and wireless sensor networks, instead of optimizing hardware design of energy-harvesting and network protocols separately, in order to maximize the network performance. A variety of applications can be observed under development or in practical usage, e.g. surveillance system and personal healthcare. The advantages of different energy-harvesting approaches and their impacts on the overall performance of sensor networks should be systematically compared and analyzed, so as to make the rechargeable sensor networks more practical, efficient, and robust.

Rechargeable Sensor Networks: Technology, Theory, and Application is the book to provide a comprehensive technical guide on up-to-date new energy-harvesting technologies, novel design, and systematical understanding of protocol architecture and some practical applications of rechargeable sensor networks. Specifically, this book consists of 11 chapters, which can be further divided into three parts. The first part, consisting of Chapters 1 and 2, extensively introduces energy-harvesting technologies, providing a systematic presentation on the latest progress in energy-harvesting technologies. The second part, which is composed of six chapters, focuses on the design of architecture structure of the rechargeable sensor networks, showing its extraordinary difference from that of traditional sensor networks, and the promising approaches to system optimization. The third part with three chapters elaborates on the promising applications that rechargeable sensor networks can be applied to and its implications on advancing sensor networks.

This book has the following salient features:

- Provides an extensive introduction to state-of-the-art energy-harvesting technologies for sensor networks, and hardware design and optimization.
- Identifies the unique characteristics of rechargeable sensor networks and challenging research topics.
- Presents the systematic understanding of the architectural design and optimization when integrating energy-harvesting technologies into sensor networks.
- Offers vivid figures that enable easy understanding of hardware design and optimization of rechargeable sensor networks.
- Allows easy and comprehensive cross-referencing via the wide coverage on different aspects.
- Details the promising applications of rechargeable sensor networks and its implications.

This book provides detailed descriptions from node level of hardware design to network level of protocol optimization, covering most of the latest results on rechargeable sensor networks, with the expectation of offering a favorable handbook for those who are interested in energy-harvesting technologies.

We would like to thank all the contributors of each chapter for their expertise and cooperation, and effort invested, without which we could not

have such an excellent book. Specially, we highly appreciate the support, patience, and professionalism from Don Mak, Jing Zhang and Amanda Yun from the very beginning to the final publication of the book. Last but not least, we are grateful for our families and friends for their constant encouragement and understanding throughout this project.

Jiming Chen, Shibo He, and Youxian Sun

Contents

Chapter 1

Wind Energy Harvesting for Recharging Wireless Sensor Nodes: Brief Review and A Case Study

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1. Introduction

With the recent advances in wireless communication technologies, sensors and actuators, and highly integrated microelectronics technologies, wireless sensor networks (WSNs) have gained worldwide attention by facilitating the monitoring and control of physical environments from remote locations, which can be difficult or dangerous to reach. WSNs represent a significant improvement over wired sensor networks with the elimination of the hardwired communication cables and associated installation and maintenance costs. The possible uses of WSNs for real-time information in all aspects of engineering systems are virtually endless, from intelligent building control to health-care systems, environmental control systems, and more. As electronic hardware circuitries become cheaper and smaller, more and more of these WSN applications are likely to emerge, particularly as these miniaturized wireless sensor nodes offer the opportunity for electronic systems to be embedded unobtrusively into everyday objects to attain a "deploy-and-forget" scenario.[1]

The major hindrances of the "deploy-and-forget" nature of WSNs are their limited energy capacity and the unpredictable lifetime performance of the battery. To overcome these problems, energy harvesting (EH)/

scavenging, which harvests/scavenges energy from a variety of ambient energy sources and converts it into electrical energy to recharge the batteries, has emerged as a promising technology.[1] With the significant advancement in microelectronics, the energy and therefore the power requirement for sensor nodes continues to decrease from a few milliwatts to a few tens of microwatts. This paves the way for a paradigm shift from the battery-operated conventional WSN, which solely relies on batteries, toward a truly self-autonomous and sustainable energy-harvesting wireless sensor network (EH-WSN). EH for powering wireless sensor nodes from ambient environment has drawn more and more attention over the last decade. Some possible energy sources from ambient environment include photonic energy,[2] thermal energy,[3] vibration energy,[4] and flow energy.[5] For EH from the kinetic energy in flow of air (wind), existing methods include using turbines, harvesting energy from flow-induced vibration (FIV), and using Helmholtz resonators would be reviewed and elaborated with a case study.

2. Wind Energy Harvesting from Wind Turbines

2.1. *Description of technique*

A wind turbine is a device that converts wind energy into rotational mechanical energy. Electrical energy can be generated by employing transduction mechanism to exploit the mechanical energy. The first wind turbines for electricity generation had already been developed at the beginning of the 20th century and the technology improved incrementally since the early 1970s.

Wind turbines are classified into vertical and horizontal axis types. Horizontal axis wind turbines (HAWTs) have a horizontal shaft and blades (or sails) revolving in the vertical plane. The horizontal axis refers to the rotating shaft of the wind turbine, not the plane in which the blades rotate. The horizontal axis machine has its main shaft parallel to the ground. Figure 1 shows an example of the horizontal axis wind power generator.

Wind energy conversion systems can be divided into those which depend on aerodynamic drag and those which depend on aerodynamic lift. The early vertical axis windmills utilized the drag principle. Drag devices, however, have a very low maximum energy conversion efficiency of around 0.16.

The simplest vertical axis machine is a Savonious rotor, which consists of two oil-drum halves facing in opposite directions. They are extremely

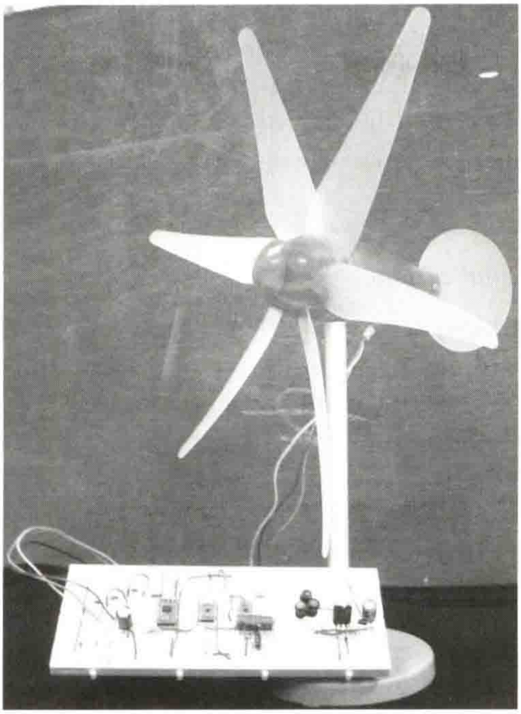

Fig. 1. A miniature wind power generator.

easy to construct and work by drag which makes them quite inefficient; a Savonious can manage to utilize only 10% of the wind energy. A more efficient vertical axis machine is the Darrieus rotor, which operates by lift forces. Its two blades are aerofoil in shape and so are more efficient than the Savonious, and the rotor can turn quite fast. The only problem with the Darrieus is that it is not self-starting and needs a small drag rotor on top. The advantage of all vertical axis machines is that they can turn on wind coming from any direction. So, unlike the horizontal axis machines, they do not have to face up or downwind in order to rotate. Since the end of the 1980s, however, the research and development of vertical axis wind turbines (VAWTs) has almost stopped worldwide. The horizontal axis approach currently dominates wind turbine applications.

Modern wind turbines are predominantly based on the aerodynamic lift. Lift devices use aerofoils to interact with the incoming wind. The force resulting from the aerofoils' body intercepting the air does not only consist of a drag force component in direction of the flow but also of a force component that is perpendicular to the drag — the lift forces. The lift force is a multiple of the drag force and therefore the relevant driving power of the rotor. By definition, it is perpendicular to the direction of the airflow that is intercepted by the rotor blade, and via the leverage of the rotor, it causes the necessary driving torque. More details are illustrated in Ref. 1.

2.1.1. *Savonius wind turbine*

Savonius wind turbines are a type of VAWT, used for converting the power of the wind into torque on a rotating shaft. They were invented by the Finnish engineer Sigurd Johannes Savonius in 1922. Savonius turbines are a relatively simple form of turbine. Aerodynamically, they are drag-type devices, consisting of two or three scoops as shown in Fig. 2.

Looking down on the rotor from above, a two-scoop machine has an "S"-shaped cross section. Because of the curvature, the scoops experience less drag when moving against the wind than when moving with the wind. The differential drag causes the Savonius turbine to spin. Savonius turbines extract much less of the wind's power than other similarly-sized lift-type turbines. The efficiency of a Savonius turbine is only around 10–20%.

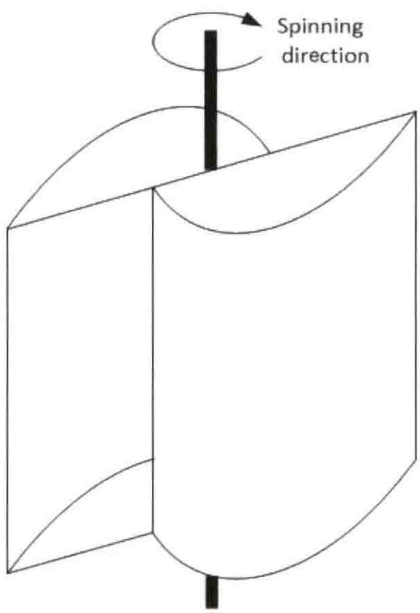

Fig. 2. Savonius turbine.