Preface

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1 Linking Bits and Atoms

Sensors are points of contact between the material world of atoms, mass, and energy and the seemingly immaterial world of information, computation, and cognition. Linking these two domains more tightly yields all sorts of practical benefits, such as improved input devices for computers, more effective medical devices (implanted or worn), more precise agricultural operations, better monitored buildings or bridges, more secure payment systems, and more reliable sensor–actuator control systems. There are many settings in which tighter coupling between digital and physical planes can enhance safety, security, performance, and reliability.

1.1 The Problem of Powering Sensors

In recent years, powering sensor systems has emerged as a key problem that is inhibiting their long-term, wide-scale adoption. Batteries need to be replaced or recharged, which can render impractical many large-scale systems that might otherwise be deployed. Batteries also increase the size, weight, and cost of sensor systems and must be disposed properly at the end of a system's life. Furthermore, rechargeable batteries can only sustain a finite number of charge–discharge cycles, which limits the lifetime of battery-powered systems even when it is feasible to recharge them.

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1.2 A Solution: Power Harvesting

Power harvesting promises to enable sensing and computing systems that can operate perpetually. Solar power is the most mature energy-harvesting technology, but it has drawbacks. For nighttime operation, systems require enough energy storage to operate for many hours without light, which typically means a battery. Solar cells require a direct optical line of sight from the energy-transducing element (a PN junction, typically on glass) to the sun, a significant constraint on the design of solar-powered devices. New forms of harvesting are needed to expand the design space of energy-harvesting systems.

1.2.1 RF Power Harvesting

RF harvesting has a number of desirable properties. Radio waves can propagate through materials such as plastic, wood, gypsum board, concrete, and (to some extent) animal tissue. This allows RF power-harvesting systems to be embedded more deeply and permanently than systems that rely on solar harvesting. For example, an RF harvesting system can be embedded in a wall or roof, in concrete, or implanted inside the human body; the energy-transducing element (the antenna, for RF harvesting) does not have to be on the host object's exterior surface. By eliminating the batteries needed for nighttime operation, the weight of RF harvesting systems can be made very low. One chapter in this book presents an RF-powered device that is light enough to be flown by a living moth.

2 Wirelessly Powered Sensor Networks and Computational RFID

The focus of this book is the design and application of systems that harvest energy from RF signals, either deliberately transmitted or ambient. RF harvesting is a rapidly emerging area of research, and this is the first book to survey wirelessly powered sensor systems. The book maps the space of RF-powered sensing, computing, and actuating systems, through a collection of specific research examples. Radio frequency identification (RFID) tags are the first widely deployed RF-powered sensor systems, and many of the papers build on RFID technology. The research in this book includes RF power harvesting and transmission, computational RFID, wireless networking, and sensing applications.

2.1 Structure of the Book

The chapters of this book fall into five clusters: introduction, hardware platforms, communication, wireless power transfer, systems and applications, and security.

2.1.1 Introduction

The introductory section includes two chapters. The first chapter, "Range Scaling of Wirelessly Powered Sensor Systems," is an examination of the macro-level scaling trends, in particular ongoing exponential improvements in the energy efficiency of computation, which have enabled the research in this book, and will determine its future as well. The second chapter, "History of the WISP Program," presents the history of what we believe to be the first far-field RF-powered computational RFID platform (i.e., the first computational RFID to operate at UHF frequencies). This chapter provides historical context and makes connections among many of the chapters in the book.

2.1.2 Hardware Platforms

The hardware section describes the design of three computational RFID platforms. The chapter entitled "The Wireless Identification and Sensing Platform" describes the design of the original WISP. The SOCWISP (for "System on Chip WISP," a single-chip implementation of every portion of the WISP functionality except for the general purpose computing capability) is described in the chapter "A 9 μA, Addressable Gen 2 Sensor Tag for BioSignal Acquisition" by Daniel Yeager, Fan Zhang, Azin Zarrasvand, Nicole George, Thomas Daniel, and Brian Otis. The next chapter describes a similar platform (with sensors that are powered and read by UHF signals) produced by Spanish start-up FARSENS; the paper by Roc Berenguer, Ivan Rebollo, Ibon Zalbide, and Inaki Fernandez is entitled "Battery-Less Wireless Sensors Based on Low Power UHF RFID Tags."

2.1.3 Communication and Tools

This section has four chapters covering a range of topics related to communication as well as tools. In the chapter "Passive RFID-Based Wake-Up Radios for Wireless Sensor Networks" He Ba, Ilker Demirkol, and Wendi Heinzelman show how to use computational RFID tags to wake up larger battery-powered sensor nodes, thereby saving power for the larger node. The chapter "BAT: Backscatter Anything-to-Tag Communication" is a very exciting example of overlaying a more sophisticated communication protocol on top of the base EPC Class 1 Generation 2 (C1G2) protocol. Molina-Markham, Shane Clark, Benjamin Ransford, and Kevin Fu present a protocol in which tags can relay messages to other tags, through the reader. These first two papers were both enabled by the WISP challenge, a program described in the chapter "History of the WISP Program". In the chapter "Implementing the Gen 2 MAC on the Intel-UW WISP" Michael Buettner and David Wetherall present an implementation for the WISP of the EPC Class 1 Generation 2 MAC (Medium Access Control scheme). The final chapter in this section is on debugging WISPs. Combining the lack of interface with power constraints, debugging code on RF-powered computers, can be tricky; the chapter “WISP Monitoring and Debugging” by Richa Prasad, Michael Buettner, Ben Greenstein, and David Wetherall presents tools that aim to simplify debugging of RF-powered computing systems.

2.1.4 Cryptography and Security for Computational RFID

One of the surprises when we began giving WISPs away was the degree of interest in the platform from the security community. Apparently there had been no way to implement security algorithms on a passive UHF RFID tag before WISP. The chapter “Maximalist Cryptography and Computation on the WISP UHF RFID Tag,” by Hee-Jin Chae, Mastooreh Salajegheh, Daniel J. Yeager, Joshua R. Smith, and Kevin Fu, presents what we believe was the first implementation of a strong cryptographic algorithm on a UHF-powered tag. The chapter “Security Enhanced WISPs: Implementation Challenges,” by Alexander Szekely, Michael Hofler, Robert Stogbuchner, and Manfred Aigner, presents an implementation of AES on the WISP. Both of these papers arose from the WISP challenge program.

2.1.5 Wireless Power Transfer Beyond RFID

This section covers alternate approaches to wireless power transfer, not the basic techniques used by the WISP. The section starts with the chapter “Power Optimized Waveforms that Enhance the Range of Energy Harvesting Sensors” by Matthew Trotter and Gregory Durgin. Power optimized waveforms are RF signals that are designed specifically to facilitate efficient harvesting (while not violating any regulations). This chapter was a result of the WISP challenge program. The next two chapters are projects that are described briefly in the “History of the WISP program” chapter as outgrowths of the WISP project, but not directly part of it. The chapter “Wireless Ambient Radio Power,” by Alanson Sample, Aaron Parks, Scott Southwood, and Joshua R. Smith, measures environmental sensing data and then transmits it short distances using a 2.4 GHz radio. The entire thing is powered by ambient RF power harvested from a TV tower. The chapter “Powering a VAD Using the Portable FREED System,” by Benjamin Waters, Kara Kagi, Jordan Reed, Alanson Sample, Pramod Bonde, and Joshua R. Smith, is an example of our high-power (tens of watts) medium-range wireless power transfer technology. The application to implanted heart pumps could improve quality and length of life for heart failure patients.

2.1.6 Systems and Applications

This section presents two very unusual applications of WISP. The first, in Chap. 13, describes the use of WISPs for oceanographic temperature sensing, as part of an undersea neutrino telescope. This project was another that was made possible by the WISP challenge. The key benefit of wirelessly powered sensing in this application is avoiding the need to penetrate a pressure vessel that must withstand high pressure. The benefit of using wireless power to avoid breeching a significant boundary with a cable in this undersea application is very similar in some respects to the biomedical application, in which wireless power allows us to eliminate a transcutaneous cable. The chapter "RFID-Vox: A Tribute to Leon Theremin," by Pavel Nikitin, Aaron Parks, and Joshua R. Smith, presents the life story of the inventor, and how he created an early version of RFID technology. The article also uses WISP to present an RFID implementation of another of his famous inventions, the theremin electronic musical instrument.

2.2 Intended Audience

The book should be useful to anyone with an interest in deepening the links between the physical world and information processing systems. Sensor networking researchers can explore perpetually operating battery-free sensor nodes. Researchers and practitioners in the area of RFID will gain an understanding of the opportunities that arise from adding sensing and computing to RFID tags. Security researchers and practitioners will be exposed to the security challenges and opportunities (both physical and digital) presented by sensor-enhanced, computational RFID tags. Power-harvesting researchers will find challenging questions and issues. Engineers interested in using or designing wireless power systems will find valuable material. Researchers in the areas of ubiquitous computing and human–computer interaction (HCI) can learn about the possibilities for wirelessly powering sensors and input devices. Researchers interested in communication protocols will encounter new research questions, for both backscatter communication protocols, and low overhead "burst networks" that harvest small amounts of power over long periods of time, communicate a very short data burst, and then return to power harvesting.

3 Outlook

The types of RF-powered systems described in this book today seem somewhat exotic and are still not always robust. Because wireless power is such a novel capability, it is exciting to be able to use RF power to operate even small workloads at short range. The chapter "Range Scaling of Wirelessly Powered Sensor Systems" of this book argues that the range at which any particular workload can be wirelessly powered is increasing exponentially. If this trend continues, then capabilities that barely work today will become robust and operate at long range tomorrow. Further research progress and continued energy efficiency scaling could transform RF-powered sensing and computing systems from the novelties they are today to mainstream, essential technologies that will be widely relied upon tomorrow.

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