Topology Control in Wireless Sensor Networks
Topology Control in Wireless Sensor Networks

– with a companion simulation tool for teaching and research –
Dedicado a mi esposa Mariela, y a mis hijos Miguel Andrés y Daniel Ignacio, mis más grandes tesoros.

Miguel A. Labrador

To my three girls: Astrid, Hillary and Sophia; my foundation, my support, my inspiration.

Pedro M. Wightman
Preface

The field of wireless sensor networks continues to evolve and grow in both practical and research domains. More and more wireless sensor networks are being used to gather information in real life applications. It is common to see how this technology is being applied in irrigation systems, intelligent buildings, bridges, security mechanisms, military operations, transportation-related applications, etc. At the same time, new developments in hardware, software, and communication technologies are expanding these possibilities. As in any other technology, research brings new developments and refinements and continuous improvements of current approaches that push the technology even further.

Looking toward the future, the technology seems even more promising in two directions. First, a few years from now more powerful wireless sensor devices will be available, and wireless sensor networks will have applicability in an endless number of scenarios, as they will be able to handle traffic loads not possible today, make more computations, store more data, and live longer because of better energy sources. Second, a few years from now, the opposite scenario might also be possible. The availability of very constrained, nanotechnology-made wireless sensor devices will bring a whole new world of applications, as they will be able to operate in environments and places unimaginable today. These two scenarios, at the same time, will both bring new research challenges that are always welcome to researchers.

Book Origin and Overview

This book is the result of more than six years of research in wireless sensor networks. This research involved investigating new techniques for localization and localization services, energy-efficient MAC, network, and transport layer protocols, and more recently, topology control, the main topic of the book. Not surprisingly, although the book emphasizes topology control, it also includes background information on communication protocols for wireless sensor networks.

The book is divided in three parts. Part I consists of six chapters containing general information about wireless sensor networks, communication protocols, and topology control. Chapter 1 is an introductory chapter that describes the architec-
ture of a generic wireless sensor device and network architectures. The chapter ends
with the motivation for these types of networks describing the possible application
domains and the challenges that still remain. Chapter 2 describes the most important
aspects of the physical layer as they relate to wireless sensor networks. This is not
a typical chapter on physical layer communication technologies; instead, it includes
needed information about signal propagation models, energy dissipation models,
error generation models in wireless networks, and sensing models, all of them of
utmost importance in the design and evaluation of wireless sensor networks. Chap-
ter 3 is about the Data Link Layer of the communication protocol stack, and as
such, includes the Medium Access Control protocols for energy efficient access of
the wireless media and Logical Link Control protocols for flow and error control.
The topic of routing for wireless sensor networks is included in Chapter 4 where the
most important routing protocols are surveyed and explained. Chapter 5 is devoted
to transport layer protocols for wireless sensor networks. Protocols for applications
with different reliability requirements are explained along with a discussion about
the need of congestion control and the use of TCP and UDP in wireless sensor net-
works. Finally, Chapter 6 introduces the reader to the topic of topology control and
provides the road map for the rest of the book. In this chapter, the reader is pre-
sent with the motivations for topology control, its challenges, and general design
guidelines. A formal definition of topology control is presented along with a dis-
cussion about where in the communication protocol stack this function should be
implemented. Lastly, a new taxonomy of topology control is presented that includes
the concept of topology construction (currently known as topology control), and for
the first time, the concept of topology maintenance.

Part II of the book is devoted to what we call Topology Construction, or tech-
niques that, given a set of nodes, build a reduced topology to save energy while
preserving important network characteristics, such as network coverage and con-
nectivity. Chapter 7 discusses those topology construction mechanisms that build
the reduced topology by controlling the transmission power of the nodes. Chapter 8
includes those techniques that build reduced hierarchical topologies. The last chap-
ter of Part II is Chapter 9, which includes hybrid topology construction techniques
for the first time.

The third and last part of the book, is about Topology Maintenance, a concept
that had never been formally defined as part of topology control. Chapter 10 in-
duces the topic and includes general information about topology maintenance
that applies to all three remaining chapters, such as design issues, topology mainte-
nance triggering criteria, and radio synchronization. Chapter 11 introduces topology
maintenance static techniques and includes a performance evaluation of global static
techniques in sparse and dense networks. Chapter 12 is about topology maintenance
dynamic techniques, and it also includes a performance evaluation of both global
and local dynamic techniques in sparse and dense networks. Finally, Chapter 13,
which ends Part III of the book, includes topology maintenance hybrid techniques
and their performance evaluation, and two sections where all topology maintenance
techniques described in this part of the book are further evaluated and compared.
Intended Audience

The book is intended for graduate students, professors, researchers, and industry professionals interested in wireless sensor networks. The book can be used as a reference book in a graduate class on wireless sensor networks, or as the main book in an advanced, research oriented course on the same topic with emphasis on topology control. The Atarraya simulator is an excellent teaching aid for explaining difficult concepts in a graphical way, and an invaluable tool for experimentation and the assignment of research-oriented projects for the class.

Resources

Appendix A is another important contribution of this book. It describes the structure of the Atarraya simulator in detail. Atarraya is a Java-based simulation tool developed for teaching and researching topology control topics in wireless sensor networks. We hope that you use the tool as much as we have in your classes and in your research. As a Java-based tool, it is easily understandable and expandable, so you can include new topology control mechanisms as well as other aspects of wireless sensor networks, such as new propagation models, error models, etc. Atarraya comes with a graphical user interface that can be used to visualize the effect of applying topology control algorithms in a class or demonstration. All experimental-based figures included in the book were generated with Atarraya.

Atarraya, which is copyrighted under the GNU license agreement, can be downloaded for free from http://www.csee.usf.edu/~labrador/Atarraya.

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Tampa, October 2008

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Part I

Introduction to Wireless Sensor Networks and Topology Control
Chapter 1

Wireless Sensor Networks

1.1 Introduction

Recent advances in sensor and wireless communication technologies in conjunction with developments in microelectronics have made available a new type of communication network made of battery-powered integrated wireless sensor devices. Wireless Sensor Networks (WSNs), as they are named, are self-configured and infrastructureless wireless networks made of small devices equipped with specialized sensors and wireless transceivers. The main goal of a WSN is to collect data from the environment and send it to a reporting site where the data can be observed and analyzed. Wireless sensor devices also respond to queries sent from a “control site” to perform specific instructions or provide sensing samples. Finally, wireless sensor devices can be equipped with actuators to “act” upon certain conditions. These networks are sometimes more specifically referred as Wireless Sensor and Actuator Networks.

At present time, due to economic and technological reasons, most available wireless sensor devices are very constrained in terms of computational, memory, power, and communication capabilities. This is the main reason why most of the research on WSNs has concentrated on the design of energy- and computationally-efficient algorithms and protocols, and the application domain has been restricted to simple data-oriented monitoring and reporting applications. However, all this is changing very rapidly, as WSNs capable of performing more advanced functions and handling multimedia data are being introduced. New network architectures with heterogeneous devices and expected advances in technology are eliminating current limitations and expanding the spectrum of possible applications for WSNs considerably.

This chapter provides a general view of wireless sensor networks describing the node and network architectures, examples of application domains, and the main challenges faced by WSNs with an emphasis on energy conservation.
1.2 Node and Network Architectures

1.2.1 Wireless Sensor Device Architecture

The architecture of a wireless sensor device is very simple. As shown in Figure 1.1, a wireless sensor device contains a processor, memory, a radio transceiver and antenna, a power source, and an input/output interface that allows the integration of external sensors into the wireless device. Wireless sensor devices are equipped with low-power and computationally constrained microcontrollers. Microprocessors are not usually included in WSNs because of the cost and because of the simple and specialized tasks that wireless sensor devices are supposed to perform. Also, microcontrollers consume less energy than more advanced CPUs, an important consideration in WSNs since wireless sensor devices are usually battery powered. Further, they are very well suited for WSNs because some parts of the microcontrollers can be set to sleep, if so needed. Normally, microcontrollers for WSNs are either 16- or 32-bit Reduced Instruction Set Computer (RISC) architectures running at low frequencies. Examples of well-known microcontrollers used in WSNs are the Intel StrongARM SA-1100 [57], a fairly high-end processor running at 206 MHz, and the Atmel ATmega 128L [4], an 8-bit microcontroller.

In wireless sensor devices there is also the need for Random Access Memory (RAM) to store application related data such as sensor readings, and Read-Only Memory (ROM) to store program code, which needs to be stored permanently, even if power supply is interrupted. RAM memory is usually included in the microcontroller and is restricted to a few hundreds of kilobytes. The advantage is that the energy needed to drive this memory is usually included in the power consumption figures of the microcontroller. Normally, wireless sensor devices include a few hundreds of Electrically Erasable Read-Only Memory (EEPROM) for configuration data and more memory in the form of FLASH memory, which not only preserves the data in the event of power interruptions but also can be used as RAM memory when needed. FLASH memory is available by external memory devices connected to the
node through USB interfaces. FLASH-based thumb drives and memory sticks provide the memory space needed at lower energy cost than off-chip RAM and ROM memory.

A wireless sensor node also contains a radio transceiver. Radio transceivers contain all necessary circuitry to send and receive data over the wireless media: modulator and demodulator modules, digital to analog and analog to digital converters, low noise and power amplifiers, filters, mixers and antenna are among the most important components. Radio transceivers usually work half-duplex as simultaneous transmission and reception of data over the wireless media is impractical.

Similar to microcontrollers, transceivers can operate in different modes. Normally, transmit, receive, idle and sleep operational modes are available. The sleep mode is a very important energy saving feature in WSNs. However, turning the transceiver on and off must be done carefully, as it may take the transceiver an appreciable amount of energy to turn the circuitry on again. Some transceivers offer additional capabilities, including several sleep modes that turn different parts of the hardware on and off.

Commercially available transceivers for WSNs have different characteristics and capabilities. Normally, they work on three different frequency ranges: 400 MHz, 800–900 MHz, and 2.4 GHz or the Industrial, Scientific, and Medical (ISM) frequency band. Transmission power, modulation schemes, and data transmission rates vary from vendor to vendor. For example, the TR1000 family from RF Monolithics [57] works in the 800–900 MHz range, can dynamically change its transmission power up to 1.4 mW, and transmit up to 115.2 Kbps. The popular Mica motes from Crossbow are equipped with the Chipcom family of transceivers [25]. MICA2 motes have the Chipcom CC100 chip which operates in the 800/900 MHz range, offers up to 50 programmable channels, uses FSK modulation, and has programmable output power. The Chipcom CC1000 draws 27 mA when transmitting at its maximal power, 10 mA when receiving, and less than 1 µA in the sleep mode. The Chipcom CC2420 is included in the MICAZ mote that was built to comply with the IEEE 802.15.4 standard for low data rate and low cost wireless personal area networks [53].

Wireless sensor devices are usually powered by two AA batteries externally attached to the node. Normally, AA batteries store 2.2 to 2.5 Ah at 1.5 V. However, these numbers vary depending on the technology utilized. For example, Zinc–air-based batteries have higher capacity in Joules/cm$^3$ than lithium batteries. Alkaline batteries have the smallest capacity, normally around 1200 J/cm$^3$.

Finally, wireless sensors devices are equipped with sensor boards, which contain application-specific sensors. The variety of sensors and sensor boards that can be directly interfaced with the wireless sensor device is very large. Temperature, air quality, pressure, magnetometers, light, acoustic, and accelerometers, are just a small sample of the types of commercially available sensors. This interfacing flexibility is the cause of the wide popularity of WSNs, as they serve as a general platform to solve practical problems in many application domains.
1.2.2 Network Architectures

Wireless sensor network architectures have evolved over time and continue to evolve as new devices and capabilities are available. Initially, WSNs consisted of a flat topology made of homogeneous wireless sensor devices measuring a single variable. Most of these networks consisted of several (not many) wireless sensor devices spread throughout the area of interest and one sink node that received all the data and interfaced the WSNs with other networks so that WSN data could be made available at the remote site of interest for monitoring and analysis.

Then, newer applications required a considerable larger number of nodes, hundreds, or even thousands of them. These applications required new architectures for the efficient transmission of wireless sensor data. As such, layered or clustered topologies were designed that included multiple sinks. Further, these large networks required different points of connectivity with the outside world, so the interconnection of WSNs with the Internet, private networks, cellular networks, wireless ad hoc networks, etc., was a necessity. Of course, this triggered large efforts in the design and implementation of communication protocols to include these new capabilities. Figure 1.2 shows two flat small wireless sensor networks with a single sink node connected to a wireless ad hoc network, cellular network and the Internet, which at the same time can serve as interconnecting networks between them.

The incorporation of several sinks evolved network architectures to include heterogeneous devices. WSNs are now capable of measuring different variables, and able to take advantage of the capabilities of more powerful devices to perform complex functions of interest or even save additional energy. For example, more powerful devices have been given clusterhead roles to aggregate and transmit data on behalf of other less powerful nodes.

Figure 1.2 General wireless sensor network architecture.
Finally, new advances in technology are producing and are expected to continue producing new devices that will soon reduce or eliminate most of the constraints that WSNs have today. Relaxing these constraints will expand the application domains of WSNs considerably. For example, research is being done today in what is called Wireless Multimedia Sensor Networks (WMSNs) assuming that several of these constraints no longer exist.

1.3 Application Domains and Examples

Wireless sensor networks have gained considerable popularity given their flexibility to solve problems in different application domains. Wireless sensor devices can be equipped with single or multiple sensors according to the application at hand. WSNs have been applied in a myriad of applications and have the potential to change our lives in many different ways. WSNs have been successfully applied in the following application domains:

- **Agriculture**: WSNs have been used to control irrigation systems according to the humidity of the terrain.
- **Military**: Intrusion detection systems based on WSNs have been used by the military.
- **Manufacturing**: WSNs have been used to monitor the presence of lethal gases in refineries.
- **Transportation**: Real-time traffic information is being collected by WSNs to later feed transportation models and alert drivers of congestion and traffic problems.
- **Environmental**: WSNs have been installed to monitor water deposits in mountains to detect mudslides. WSNs have been utilized in intelligent buildings to automatically control the temperature.
- **Engineering**: Civil engineers have used WSNs technology to monitor the condition of civil structures, such as bridges.

Additional advantages of WSNs are the possibility of monitoring these applications from remote places and having a system that can provide large amounts of data about those applications for longer periods of time. This large amount of data availability usually allows for new discoveries and further improvements.

1.4 Challenges and the Need for Energy Saving Mechanisms

Wireless sensor networks present a series of serious challenges that still need considerable research effort. While some of these challenges are a direct consequence of the constrained availability of resources in the wireless sensor nodes, and therefore very specific to WSNs, others are common challenges faced by most networking technologies. The following list briefly explains the most important challenges faced by WSNs today.
• **Network lifetime:** WSNs are battery powered, therefore the network lifetime depends on how wisely energy is used. In large scale wireless sensor networks or in dangerous applications it is important to minimize the number of times batteries need to be changed. It is desirable to have network lifetimes in the order of one or more years. In order to achieve such long network lifetimes it is imperative to operate the sensors in a very low duty cycle. For example, a typical energy consumption of a microcontroller is about 1 nJ per instruction. If the microcontroller is powered by a 1 J battery and the entire node is working continuously for one day, it needs to consume no more than 11 µW, which is not achievable by the microcontroller alone. Therefore, using the microcontroller and transceiver sleeping modes is crucial for the long operation of WSNs.

• **Scalability:** Some applications require hundreds or even thousands of wireless sensor devices. For example, imagine a WSNs to monitor the U.S.–Mexico border, or an application to monitor an oil pipeline. These large-scale WSNs present new challenges not seen in small-scale ones. Algorithms and protocols that work fine in small-scale networks don’t work necessarily well in large-scale ones. One typical example is the routing function. Small-scale networks can easily run well-known proactive or reactive routing protocols using Dijkstra’s shortest path algorithm. However, this approach will not be energy-efficient for large-scale wireless sensor networks. Location-based routing mechanisms using local information are better suited instead. Similar scalability problems arise in other areas.

• **Interconnectivity:** WSNs need to be interconnected so that data reaches the desired destination for storage, analysis, and possible action. WSNs are envisioned to be interconnected with many different networking technologies, as shown in Figure 1.2 before. However, this is easier said than done. New protocols and mechanisms need to be designed to achieve these interconnections and allow the transfer of data to and from WSNs. Normally, these interconnections are being handled by the use of gateway devices, such as the sinks, which require new capabilities for the appropriate discovery of networks and the translations of different communication protocols.

• **Reliability:** Wireless sensor devices are cheap devices with fairly high failure rates. Further, in many applications, these devices have to be thrown to the area of interest from a helicopter, or similar vehicle. As a result, several nodes break or partially break affecting their normal functionality. Node reliability is also effected by crucial levels of available energy.

• **Heterogeneity:** New WSNs are embedding wireless sensor devices with different capabilities and functionalities that require new algorithms and communication protocols. For example, cluster-based architectures may utilize more powerful devices to aggregate data and transmit information on behalf of resource constraint nodes. This heterogeneity includes the need of clustering and data aggregation algorithms that are not of trivial design.

• **Privacy and security:** Privacy and security are normal concerns in networking, and WSNs are not the exemption. However, security mechanisms are usually very resource demanding, which is not always in line with the resources avail-
able in wireless sensor devices. Therefore, new security algorithms with low computational complexity and low energy requirements are needed.

One constraint that somehow affects all these and other challenges is energy. Simply put, the lifetime of the network depends on the energy available in individual sensor nodes. Therefore, in WSNs, the design of energy-efficient algorithms and protocols is of utmost importance. It is not surprising that a large number of publications addressing energy concerns in Medium Access Control mechanisms, routing protocols, transport layer protocols, security, etc., exist.

Given this strong constraint, it is important to know which node components consume more energy to explore new design trade-offs. Normally, transceivers and microcontrollers are the most energy consuming components. However, one important aspect to consider is that both can be set to operate in less energy-operating modes whenever possible. However, given that they are working, which one consumes more energy? Typically, computing one instruction on a microcontroller consumes about 1 nJ. If we use the RFM TR1000 transceiver as an example, it needs 1 µJ to transmit a single bit and 0.5 µJ to receive one. Therefore, it is clear that communication is considerably more expensive than computing. In [98], the authors utilize example numbers from wireless sensor devices to reach the same conclusion pointing out that to reduce energy costs, it pays to process data locally to reduce the need of communication. This is the concept of in-network processing, or using computations to reduce communication costs. The authors also explain that if short-range communication is considered, as is usually the case in WSNs, the communication energy budget is dominated by the oscillators and mixers, which make transmitting as energy consuming as receiving.

Another interesting trade-off is found working with memory, FLASH memory in particular, since RAM memory consumption figures are usually included in the microcontroller figures. FLASH manufacturers data indicate that reading times and energy consumption figures for reading are similar regardless of the FLASH memory, however, writing times and writing energy consumption vary widely from memory to memory. Therefore, the difference in energy consumption between reading and writing operations can be considerable. In [80], the authors show that Crossbow’s MICA motes consume 1.11 nAh reading and 83.33 nAh writing, a substantial difference that immediately suggests that it is better to avoid writing as much as possible.
Chapter 2
The Physical Layer

2.1 Introduction

This chapter covers some of the most important aspects of the Physical Layer of the protocol stack related to the study of WSNs. The chapter is not meant to cover available communication technologies, such as modulation techniques, noise and interference issues, and the like. Rather the chapter provides the reader with basic understanding of some fundamental concepts that are useful for later sections and chapters, such as wireless channel propagation models, energy consumption models, and sensing and error models in WSNs.

2.2 Wireless Propagation Models

This section provides an introduction to wireless propagation models. In wireless communications, signals travel from sender to receiver through the radio channel. These signals, which are sent at a particular power by the transmitter, suffer attenuation in the radio channel. The receiver, at the other end, is only able to receive the sender’s transmission if the signal is received with a power level greater than the sensitivity of its transceiver. The attenuation, commonly known as the path loss of the channel, directly depends on the distance between sender and receiver, the frequency of operation and other factors. Path loss models exist to predict if there is a radio channel between two nodes. This section describes the three most commonly known path loss models available in the literature: the free space model, the two-ray ground model, and the log-distance path model [101].