PROTOCOLS AND ARCHITECTURES FOR WIRELESS SENSOR NETWORKS

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Contents

Preface

Integrating simple processing, storage, sensing, and communication capabilities into small-scale, low-cost devices and joining them into so-called wireless sensor networks opens the door to a plethora of new applications – or so it is commonly believed. It is a struggle to find a business model that can turn the bright visions into a prosperous and actually useful undertaking. But this struggle can be won by applying creative ideas to the underlying technology, assuming that this technology and its abilities as well as shortcomings and limitations are properly understood. We have written this book in the hope of fostering this understanding.

Understanding (and presenting) this new type of networks is a formidable challenge. A key characteristic is the need to understand issues from many diverse areas, ranging from low-level aspects of hardware and radio communication to high-level concepts like databases or middleware and to the very applications themselves. Then, a joint optimization can be attempted, carefully tuning all system components, drawing upon knowledge from disciplines like electrical engineering, computer science and computer engineering, and mathematics. Such a complex optimization is necessary owing to the stringent resource restrictions – in particular, energy – by which these networks are constrained. As a consequence, a simple explanation along the lines of the ISO/OSI model or a similar layering model for communication networks fails. Nonetheless, we have attempted to guide the reader along the lines of such a model and tried to point out the points of interaction and interdependence between such different "layers".

In structuring the material and in the writing process, our goal was to explain the main problems at hand and principles and essential ideas for their solution. We usually did not go into the details of each of (usually many) several solution options; however, we did provide the required references for the readers to embark on a journey to the sources on their own. Nor did we attempt to go into any detail regarding performance characteristics of any described solution. The difficulty here lies in presenting such results in a comparable way – it is next to impossible to find generally comparable performance results in scientific publications on the topic of wireless sensor networks. What is perhaps missing is a suite of benchmarking applications, with clearly delimited rules and assumptions (the use of a prevalent simulator is no substitute here). Tracking might be one such application, but it clearly is not the only important application class to which wireless sensor networks can be applied.

Often, a choice had to be made whether to include a given idea, paper, or concept. Given the limited space in such a textbook, we preferred originality or an unusual but promising approach over papers that present solid but more technical work, albeit this type of work can make the difference whether a particular scheme is practicable at all.

We also tried to avoid, and explicitly argue against, ossification but rather tried to keep and promote an open mind-set about what wireless sensor networks are and what their crucial research topics entail. We feel that this still relatively young and immature field is sometimes inappropriately narrowed down to a few catchwords – energy efficiency being the most prominent example – which, although indubitably important, might prevent interesting ideas from forming and becoming publicly known. Here, we tried to give the benefit of the doubt and at least tried to include pointers and references to some "unusual" or odd approaches.

Nonetheless, we had to omit a considerable amount of material; areas like middleware, security, management, deployment, or modeling suffered heavily or were, in the end, entirely excluded. We also had to stop including new material at some point in time – at the rate of new publications appearing on this topic, this book would otherwise never be completed (if you feel that we have overlooked important work or misrepresented some aspects, we encourage you to contact us). We still hope that it can serve the reader as a first orientation in this young, vigorous, and fascinating research area. Visit the website accompanying this book, `www.wiley.com/go/wsn`, for a growing repository of lecture slides on ad hoc and sensor networks.

Audience and Prerequisites

The book is mainly targeted at senior undergraduate or graduate-level students, at academic and industrial researchers working in the field, and also at engineers developing actual solutions for wireless sensor networks. We consider this book as a good basis to teach a class on wireless sensor networks (e.g. for a lecture corresponding to three European Credit Transfer System points).

This book is not intended as a first textbook on wireless networking. While we do try to introduce most of the required background, it will certainly be helpful for the reader to have some prior knowledge of wireless communication already; some first contact with mobile ad hoc networking can be beneficial to understand the differences but is not essential. We do, however, assume general networking knowledge as a given.

Moreover, in several parts of the book, some concepts and results from discrete mathematics are used. It will certainly be useful for the reader to have some prior idea regarding optimization problems, NP completeness, and similar topics.

Acknowledgments

We are indebted to numerous people who have helped us in understanding this research field and in writing this book. A prominent place and heartfelt thanks are owed to our colleagues at the Telecommunication Networks Group at the Technische Universität Berlin, especially Prof. Adam Wolisz, Vlado Handziski, Jan-Hinrich Hauer, Andreas Köpke, Martin Kubisch, and Günther Schäfer. Also, we are grateful to many colleagues with whom we had the pleasure and the privilege to discuss WSN research issues – colleagues from different research projects like the EU IST project EYES and the German federal funded project AVM deserve a special mention here. Robert Mitschke from the Hasso Plattner Institute did an excellent job in proofreading and criticizing an intermediate version of this book. The anonymous reviewers provided us with many useful comments. The help of our editors and the support team at Wiley – in particular, Birgit Gruber, Julie Ward and Joanna Tootill – was very valuable.

We also want to express our deep gratitude to all the researchers in the field who have made their results and publications easily available over the World Wide Web. Without this help, collecting the material discussed in the present book alone would have been too big a challenge to embark on.

And last, but most importantly, both of us are very deeply indebted to our families for bearing with us during the year of writing, grumbling, hoping, and working.

Berlin & Paderborn
April 2005

List of abbreviations

ABR Associativity-Based Routing

ACPI Advanced Configuration and Power Interface

ACQUIRE ACtive QUery forwarding In sensoR nEtworks

ADC Analog/Digital Converter

AIDA Application-Independent Data Aggregation

ANDA Ad hoc Network Design Algorithm

AODV Ad hoc On-demand Distance Vector

APIT Approximate Point in Triangle

API Application Programming Interface

ARQ Automatic Repeat Request

ASCENT Adaptive Self-Configuring sEnsor Networks Topologies

ASIC Application-Specific Integrated Circuit

ASK Amplitude Shift Keying

AVO Attribute Value Operation

AWGN Additive White Gaussian Noise

BCH Bose–Chaudhuri–Hocquenghem

BER Bit-Error Rate

BIP Broadcast Incremental Power

BPSK Binary Phase Shift Keying

BSC Binary Symmetric Channel

CADR Constrained Anisotropic Diffusion Routing

CAMP Core-Assisted Mesh Protocol

CAP Contention Access Period

CCA Clear Channel Assessment

CCK Complementary Code Keying

CDMA Code Division Multiple Access

CDS Connected Dominating Set

CGSR Clusterhead Gateway Switch Routing

CIR Carrier to Interference Ratio

CMMBCR Conditional Max–Min Battery Capacity Routing

CODA COngestion Detection and Avoidance

CPU Central Processing Unit

CRC Cyclic Redundancy Check

CSD Cumulative Sensing Degree

CSIP Collaborative Signal and Information Processing

CSMA Carrier Sense Multiple Access

CTS Clear To Send

DAC Digital/Analog Converter

DAD Duplicate Address Detection

DAG Directed Acyclic Graph

DAML DARPA Agent Markup Language

DBPSK Differential Binary Phase Shift Keying

DCF Distributed Coordination Function

DCS Data-Centric Storage

DCS Dynamic Code Scaling

DHT Distributed Hash Table

DISCUS Distributed Source Coding Using Syndromes

DLL Data Link Layer

DMCS Dynamic Modulation-Code Scaling

DMS Dynamic Modulation Scaling

DPM Dynamic Power Management

DQPSK Differential Quaternary Phase Shift Keying

DREAM Distance Routing Effect Algorithm for Mobility

DSDV Destination-Sequenced Distance Vector

DSP Digital Signal Processor

DSR Dynamic Source Routing

DSSS Direct Sequence Spread Spectrum

DVS Dynamic Voltage Scaling

EEPROM Electrically Erasable Programmable Read-Only Memory

EHF Extremely High Frequency

ESRT Event-to-Sink Reliable Transport

FDMA Frequency Division Multiple Access

FEC Forward Error Correction

FFD Full Function Device

FFT Fast Fourier Transform

FHSS Frequency Hopping Spread Spectrum

FIFO First In First Out

FPGA Field-Programmable Gate Array

FSK Frequency Shift Keying

GAF Geographic Adaptive Fidelity

GAMER Geocast Adaptive Mesh Environment for Routing

GEAR Geographic and Energy Aware Routing

GEM Graph EMbedding

GHT Geographic Hash Table

GOAFR Greedy and (Other Adaptive) Face Routing

GPSR Greedy Perimeter Stateless Routing

GPS Global Positioning System

GRAB GRAdient Broadcast

GTS Guaranteed Time Slot

HHBA Hop-by-Hop Broadcast with Acknowledgments

HHB Hop-by-Hop Broadcast

HHRA Hop-by-Hop Reliability with Acknowledgments

HHR Hop-by-Hop Reliability

HMM Hidden Markov Model

HVAC Humidity, Ventilation, Air Conditioning

IDSQ Information-Driven Sensor Querying

IEEE Institute of Electrical and Electronics Engineers

IFS InterFrame Space

IF Intermediate Frequency

ISI InterSymbol Interference

ISM Industrial, Scientific, and Medical

LAR Location-Aided Routing

LBM Location-Based Multicast

LEACH Low-Energy Adaptive Clustering Hierarchy

LED Light-Emitting Diode

LNA Low Noise Amplifier

LOS Line Of Sight

MAC Medium Access Control

MANET Mobile Ad Hoc Network

MBCR Minimum Battery Cost Routing

MCDS Minimum Connected Dominating Set

MDS Minimum Dominating Set

MDS MultiDimensional Scaling

MEMS MicroElectroMechanical System

MIP Multicast Incremental Power

MLE Maximum Likelihood Estimation

MMBCR Min–Max Battery Cost Routing

MPDU MAC-layer Protocol Data Unit

MSE Mean Squared Error

MST Minimum Spanning Tree

MTPR Minimum Total Transmission Power Routing

MULE Mobile Ubiquitous LAN extension

MWIS Maximum Weight Independent Set

NAT Network Address Translation

NAV Network Allocation Vector

NLOS Non Line Of Sight

OOK On-Off-Keying

PAN Personal Area Network

PA Power Amplifier

PCF Point Coordination Function

PDA Personal Digital Assistant

PEGASIS Power-Efficient GAthering in Sensor Information Systems

PHY Physical Layer

PPDU Physical-layer Protocol Data Unit

PPM Pulse Position Modulation

PSD Power Spectral Density

PSFQ Pump Slowly Fetch Quickly

PSK Phase Shift Keying

PTAS Polynomial Time Approximation Scheme

QAM Quadrature Amplitude Modulation

QPSK Quaternary Phase Shift Keying

QoS Quality of Service

RAM Random Access Memory

RFD Reduced Function Device

RF ID Radio Frequency Identifier

RF Radio Frequency

RISC Reduced Instruction Set Computer

RMST Reliable Multisegment Transport

RNG Relative Neighborhood Graph

ROHC RObust Header Compression

ROM Read-Only Memory

RSSI Received Signal Strength Indicator

RS Reed–Solomon

RTS Request To Send

SAR Sequential Assignment Routing

SDMA Space Division Multiple Access

SFD Start Frame Delimiter

SINR Signal to Interference and Noise Ratio

SMACS Self-Organizing Medium Access Control for Sensor Networks

SNR Signal-to-Noise Ratio

SPIN Sensor Protocol for Information via Negotiation

SPT Shortest Path Tree

SQL Standard Query Language

SRM Scalable Reliable Multicast

SSR Signal Stability Routing

STEM Sparse Topology and Energy Management

TAG Tiny Aggregation

TBF Trajectory-Based Forwarding

TCP Transmission Control Protocol

TDMA Time Division Multiple Access

TDoA Time Difference of Arrival

TORA Temporally Ordered Routing Algorithm

TRAMA Traffic-Adaptive Medium Access

TTDD Two-Tier Data Dissemination

TTL Time To Live

ToA Time of Arrival

UML Unified Modeling Language

UTM Universal Transverse Mercator

UWB UltraWideBand

VCO Voltage-Controlled Oscillator

VLF Very Low Frequency

VOR VHF Omnidirectional Ranging

VPCR Virtual Polar Coordinate Routing

VPCS Virtual Polar Coordinate Space

WLAN Wireless Local Area Network

WPAN Wireless Personal Area Network

WRP Wireless Routing Protocol

WSDL Web Service Description Language

WSN Wireless Sensor Network

A guide to the book

The design and optimization of a wireless sensor network draws on knowledge and understanding of many different areas: properties of the radio front end determine what type of MAC protocols can be used, the type of application limits the options for routing protocols, and battery self-recharge characteristics influence sleeping patterns of a node. A book, on the other hand, is a linear entity. We are therefore forced to find a consecutive form of presenting an inherently nonconsecutive, but densely interwoven, topic.

To overcome this problem, we structured the book in two parts (Figure 1). The three chapters of the first part give a high-level overview of applications and problems, of hardware properties, and of the essential networking architecture. These first three chapters build a foundation upon which we build a detailed treatment of individual communication protocols in the second part of the book.

This second part is loosely oriented along the lines of the standard ISO/OSI layering model but, of course, focuses on algorithms and protocols relevant to wireless sensor networks. We start out by looking at the protocols needed between two neighboring nodes in the physical, link, and medium access layers. Then, a discussion about names and addresses in a wireless sensor network follows. The next three chapters – time synchronization, localization and positioning, and topology control – describe functionality that is important for the correct or efficient operation of a sensor network but that is not directly involved in the exchange of packets between neighboring nodes. In a sense, these are "helper protocols".

On the basis of this understanding of communication between neighbors and on essential helper functionality, the following three chapters treat networking functionality regarding routing protocols in various forms, transport layer functionality, and an appropriate notion of quality of service. The book is complemented by a final chapter on advanced application support. For extra learning materials in the form of lecture slides, go to the accompanying website, `www.wiley.com/go/wsn`, which is gradually being populated.

A Full Course

Selecting the material for a full course from this book should be relatively easy. Essentially, all topics should be covered, more or less in depth, using a variable number of the example protocols discussed in the book.

A Reduced Course

If time does not permit covering of all the topics, a selection has to be made. We consider the following material rather important and recommend to cover it, if at all possible.

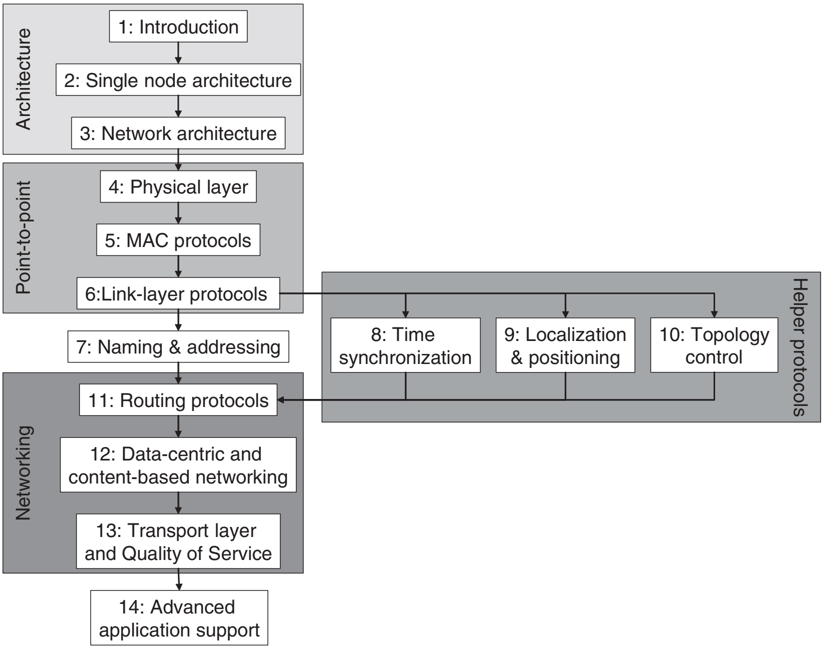

Figure 1 Structure of the book

Chapter 1: Introduction Completely.

Chapter 2: Single node architecture Treat at least Sections 2.1 and 2.2 to some level of detail. Section 2.3 on operating systems can be covered relatively briefly (depending on the focus of the course, this might not be very important material).

Chapter 3: Network architecture Cover Sections 3.1 to 3.3. The sections on service interface and gateways can be omitted for a first reading.

Chapter 4: Physical layer Depending on previous knowledge, this chapter can be skipped entirely. If possible, Section 4.3 should, however, be covered.

Chapter 5: MAC protocols An important chapter that should be covered, if possible, in its entirety. If time is short, some examples for each of different protocol classes can be curtailed.

Chapter 6: Link layer protocols Any of the three Sections 6.2, 6.3, or 6.4 can be selected for a more detailed treatment.

Chapter 7: Naming and addressing This chapter should be treated fairly extensively. Sections 7.3 and 7.4 can be omitted.

Chapter 8: Time synchronization This chapter can be skipped.

Chapter 9: Localization and positioning This chapter can be skipped.

Chapter 10: Topology control While this chapter can, in principle, be skipped as well, some of the basic ideas should be covered even in a condensed course. We would suggest to cover Section 10.1 and a single example from Sections 10.2 to 10.6 each.

Chapter 11: Routing protocols An important chapter. Sections 11.2 and 11.6 may be omitted.[1]

Chapter 12: Data-centric and content-based networking Quite important and characteristic for wireless sensor networks. Should receive extensive treatment in a lecture.

Chapter 13: Transport layer and Quality of Service This chapter also should be treated extensively.

Chapter 14: Advanced application support Much of this chapter can be skipped, but a few examples from Section 14.3 should make a nice conclusion for a lecture.

Evidently, the amount of detail and the focus of a lecture can be controlled by the number of examples discussed in class. It is probably infeasible to discuss the entire book in a lecture.

[1] We would like to make the reader aware of the Steiner tree problem described in Section 11.4.2. It did surprise us in preparing this book how often this problem has been "rediscovered" in the sensor network literature, often without recognizing it for what it is.

1

Introduction

Objectives of this Chapter

Applications should shape and form the technology for which they are intended. This holds true in particular for wireless sensor networks, which have, to some degree, been a technology-driven development. This chapter starts out by putting the idea of wireless sensor networks into a broader perspective and gives a number of application scenarios, which will later be used to motivate particular technical needs. It also generalizes from specific examples to types or classes of applications. Then, the specific challenges for these application types are discussed and why current technology is not up to meeting these challenges.

At the end of this chapter, the reader should have an appreciation for the types of applications for which wireless sensor networks are intended and a first intuition about the types of technical solutions that are required, both in hardware and in networking technologies.

Chapter Outline

1.1 The vision of Ambient Intelligence

The most common form of information processing has happened on large, general-purpose computational devices, ranging from old-fashioned mainframes to modern laptops or palmtops. In many applications, like office applications, these computational devices are mostly used to process information that is at its core centered around a human user of a system, but is at best indirectly related to the physical environment.

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In another class of applications, the physical environment is at the focus of attention. Computation is used to exert control over physical processes, for example, when controlling chemical processes in a factory for correct temperature and pressure. Here, the computation is integrated with the control; it is *embedded* into a physical system. Unlike the former class of systems, such **embedded systems** are usually not based on human interaction but are rather required to work without it; they are intimately tied to their control task in the context of a larger system.

Such embedded systems are a well-known and long-used concept in the engineering sciences (in fact, estimates say that up to 98 % of all computing devices are used in an embedded context [91]). Their impact on everyday life is also continuing to grow at a quick pace. Rare is the household where embedded computation is not present to control a washing machine, a video player, or a cell phone. In such applications, embedded systems meet human-interaction-based systems.

Technological progress is about to take this spreading of embedded control in our daily lives a step further. There is a tendency not only to equip larger objects like a washing machine with embedded computation and control, but also smaller, even dispensable goods like groceries; in addition, living and working spaces themselves can be endowed with such capabilities. Eventually, computation will surround us in our daily lives, realizing a vision of "**Ambient Intelligence**" where many different devices will gather and process information from many different sources to both control physical processes and to interact with human users. These technologies should be unobtrusive and be taken for granted – Marc Weiser, rightfully called the *father of ubiquitous computing*, called them *disappearing technologies* [867, 868]. By integrating computation and control in our physical environment, the well-known interaction paradigms of person-to-person, person-to-machine and machine-to-machine can be supplemented, in the end, by a notion of person-to-physical world [783]; the interaction with the physical world becomes more important than mere symbolic data manipulation [126].

To realize this vision, a crucial aspect is needed in addition to computation and control: communication. All these sources of information have to be able to transfer the information to the place where it is needed – an actuator or a user – and they should collaborate in providing as precise a picture of the real world as is required. For some application scenarios, such networks of sensors and actuators are easily built using existing, wired networking technologies. For many other application types, however, the need to wire together all these entities constitutes a considerable obstacle to success: Wiring is expensive (figures of up to US$200 per sensor can be found in the literature [667]), in particular, given the large number of devices that is imaginable in our environment; wires constitute a maintenance problem; wires prevent entities from being mobile; and wires can prevent sensors or actuators from being close to the phenomenon that they are supposed to control. Hence, *wireless communication* between such devices is, in many application scenarios, an inevitable requirement.

Therefore, a new class of networks has appeared in the last few years: the so-called Wireless Sensor Network (WSN) (see e.g. [17, 648]). These networks consist of individual nodes that are able to interact with their environment by sensing or controlling physical parameters; these nodes have to collaborate to fulfill their tasks as, usually, a single node is incapable of doing so; and they use wireless communication to enable this collaboration. In essence, the nodes without such a network contain at least some computation, wireless communication, and sensing or control functionalities. Despite the fact that these networks also often include actuators, the term wireless sensor network has become the commonly accepted name. Sometimes, other names like "wireless sensor and actuator networks" are also found.

These WSNs are powerful in that they are amenable to support a lot of very different real-world applications; they are also a challenging research and engineering problem because of this very flexibility. Accordingly, there is no single set of requirements that clearly classifies all WSNs, and there is also not a single technical solution that encompasses the entire design space. For example, in many WSN applications, individual nodes in the network cannot easily be connected to a wired power supply but rather have to rely on onboard batteries. In such an application, the energy