

PROTOCOLS AND ARCHITECTURES FOR WIRELESS SENSOR NETWORKS

Holger Karl

University of Paderborn, GERMANY

Andreas Willig

Hasso-Plattner-Institute at the University of Potsdam, GERMANY



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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

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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 GAttering 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.

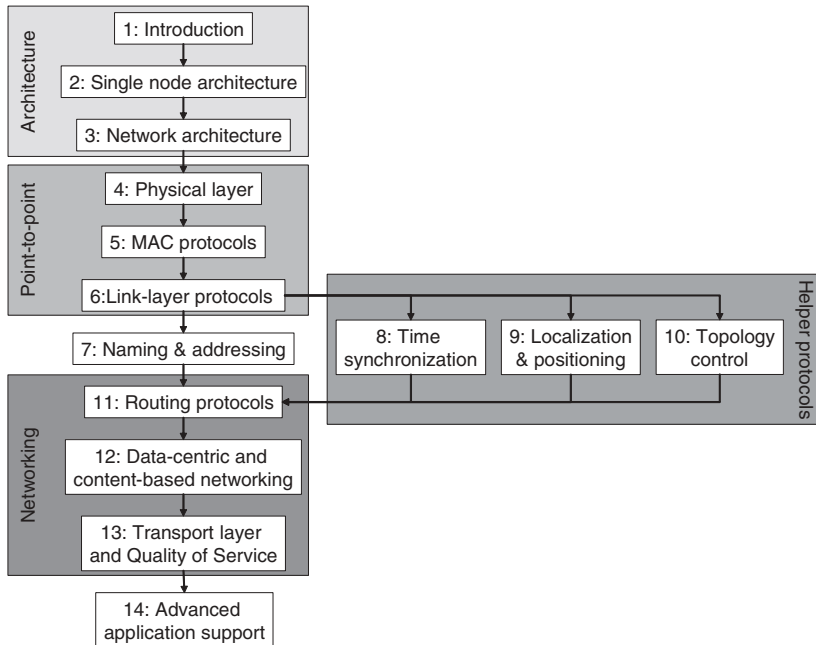


Figure 1 Structure of the book

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

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1.4	Challenges for WSNs	7
1.5	Why are sensor networks different?	10
1.6	Enabling technologies for wireless sensor networks	13

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.

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