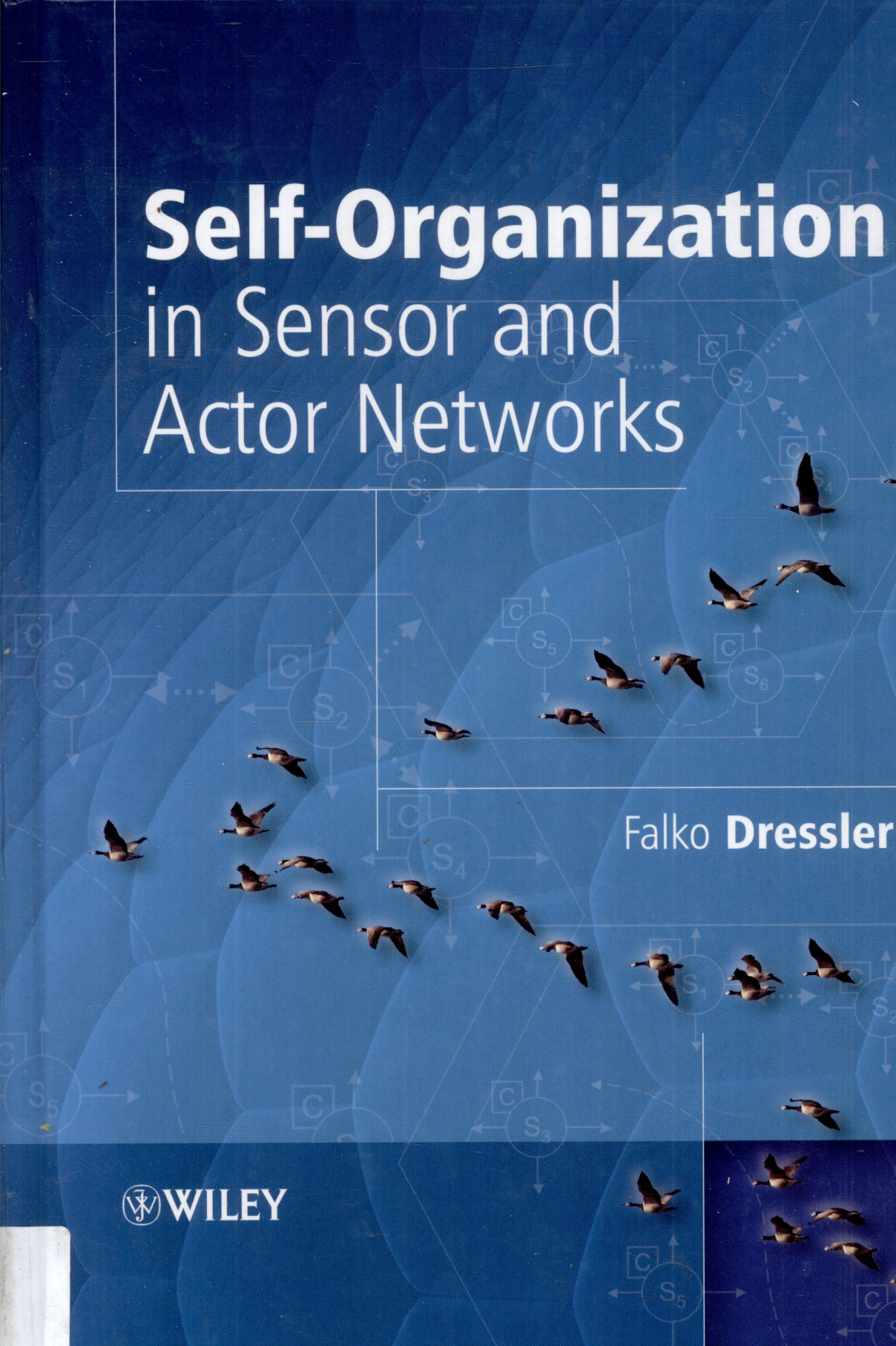
Self-Organization in Sensor and Actor Networks



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Library of Congress Cataloging-in-Publication Data

Dressler, Falko.
Self-Organization in sensor and actor networks / Falko Dressler.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-02820-9 (cloth)
1. Sensor networks. 2. Self-organizing systems. 3. Biologically-inspired computing 4. Computer networks–Management–Data processing. I. Title.
TK7872.D48D74 2007
681′2 – dc22

2007028888

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0-470-02820-9 (HB)

Typeset in 10/12pt Times by Laserwords Private Limited, Chennai, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

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Foreword

It seems likely that in the future there will be a strong degree of self-organization in many deployed networked systems. This is an intuitively appealing notion, and one that has fired up the imaginations of researchers who are now actively pursuing research in this area.

Self-organization is still very much an evolving subject – one of the reasons why a new book in the area is most welcome – but there are aspects that have been known for many years, and that derive from the study of Systems in the 1950s, 60s and 70s. General Systems Theory held out the promise of understanding any system, whether natural or man-made, and this was a strong theme in some Universities (indeed, in Systems Departments such as the one at Lancaster University). Much of this work later became embedded in Management Science and in Engineering Departments where 'soft' and 'hard' variants of Systems work have been respectively studied.

One can easily see that ad hoc wireless networks need to self-organize just to get communications under way; they also need to self-reorganize whenever changes occur to the infrastructure. Less clear is the extent to which fixed-line networks including the Internet will in future need to become more self-organizing than they are today. However, the Internet increasingly supports enterprises of many kinds that demand (or at least expect) a very high level of availability, while at the same time experiencing more and more attacks on its infrastructure and services. Therefore, there is a need to find approaches to providing resilience without human intervention and where the system, guided by appropriate policies, learns how to improve its strategies and mechanisms for detection and remediation of the many challenges.

In this book, Falko Dressler sets out to give a general introduction to self-organization and to specialize in sensor and actor networks, where a detailed description is given of the challenges and possibilities offered by self-organization in practice. His text, in five major parts, covers theory through network technologies to the application of self-organization in various types of network. Although it is an advanced text, I believe it is accessible to others who have a general interest in the subject.

This book provides a comprehensive coverage of the principles and practices of network self-organization. It is an excellent addition to the Wiley CNDS Series.

Additional material including lecture slides are available at http://selforg.org

David Hutchison
Lancaster University

Preface

Self-organization is a rather fascinating concept that enables systems consisting of huge numbers of autonomously acting subsystems to perform a collective task. Moreover, self-organizing systems show an overall behavior that cannot easily be predicted or even preprogrammed in a scalable way. It was in the early 1960s that people like Ashby and Eigen investigated self-organization properties in (natural) systems. Since then, a great number of (technical) solutions have been developed, which, either on purpose or unintentionally, inherently formed the basic concepts of self-organization.

The aim of this book is to investigate the concepts of self-organization in the context of autonomous sensor and actor networks. The primary objective is to categorize the basic self-organization methods and to survey techniques for communication and coordination in massively distributed systems according to the developed classification scheme. Basically, two possible approaches can be thought of for organizing this book. First, we could start analyzing sensor and actor network technology and figure out what basic mechanisms are employed and how these relate to self-organization. A second approach would be to introduce self-organization as a methodology, apparently used everywhere in our life (in nature and in technical systems), and afterwards to continue with technical issues in sensor and actor networks, searching for previously learned self-organization methods. I decided to follow the second approach in order to keep the focus on self-organization while studying the term in the world of sensor and actor networks. The term 'self-organization' is still often misunderstood and misinterpreted. Therefore, this textbook is intended to be a basis for a better understanding of the concepts of self-organization, especially in the domain of sensor and actor networks. It provides a stepwise introduction of definitions, methodologies and corresponding techniques relevant in the context of self-organization.

Recent advances in miniaturization and wireless communication enabled the development of low-cost sensor nodes. Additionally, new application domains of sensor and actor networks emerged that demand huge numbers of interacting devices. Thus, the relevance of self-organization methods is rapidly increasing, as it is considered the primary control paradigm for distributed and massively distributed systems. The reader will see that self-organization has a number of advantages compared with other control paradigms. So, it becomes possible to operate huge numbers of collaborating subsystems, even in cases of limited resources, unreliable communication and massive failures of single systems. Unfortunately, these advantages are accompanied by some rather annoying side effects, such as the increasing complexity and a nondeterministic behavior. By using optimal combinations of the basic methods of self-organization, these disadvantages can be minimized to some extent.

According to the objective of this textbook – to study sensor and actor networks – the most relevant domains of communication and coordination are deeply investigated based on well known algorithms and mechanisms and a number of case studies. This includes networking aspects of medium-access control, ad hoc routing, data-centric communication and clustering techniques. Additionally, control mechanisms for cooperation, task and resource allocation, and collaborative actuation are investigated. The book is concluded by a brief introduction to the domain of bio-inspired algorithms. This study is included for two reasons – first, to demystify the term bio-inspired networking, and, secondly, to show the capabilities of such bio-inspired approaches.

What is unique about this textbook?

This book represents the first comprehensive overview of self-organization techniques in the context of wireless sensor and actor networks. It also provides a detailed classification of the basic mechanisms of self-organization. There are many reasons to study self-organization, such as the fascinating effects, which, if correctly understood and employed, provide the possibility of envisioning new kinds of previous system limitations. Additionally, this book is the first comprehensive study of technical solutions focusing particularly on sensor and actor networks.

Audience

This textbook is intended for graduate students, researchers and practitioners who are interested in the broad field of self-organization techniques as well as in application domains in sensor and actor networks. The book is structured to accompany a graduate course in computer science. Thus, some basic knowledge of networking, communication protocols and distributed systems is required. As this textbook provides a global view of algorithms and protocols developed for building self-organizing networking architectures, it can also serve as a reference resource for researchers, engineers and developers working in the field of sensor and actor networks.

Structure and organization

The book is organized into five parts. We start with an introduction to self-organization as a control paradigm for massively distributed systems. Thus, Part I introduces the main ideas and concepts of self-organization. It can be seen as a reference for general studies in the field of self-organization. All relevant terms are introduced, based on examples of natural and technical self-organization. The primary intention is to become familiar with concepts of self-organization and to understand its opportunities and limitations.

Networking aspects relevant to ad hoc and sensor networks are investigated in Part II. This part can be regarded as a broad introduction to algorithms and protocols needed to develop and to maintain wireless sensor networks. Therefore, aspects of protocols for wireless communication, ad hoc routing, data-centric communication and clustering are discussed. The bridge to self-organization methods introduced in Part I is built in the form of permanent discussions of self-organizing aspects of investigated algorithms.

Coordination and control aspects are studied in Part III. This part starts with an introduction to the concepts, challenges and opportunities that emerged with the development

of sensor and actor networks. Besides the networking issues discussed in Part II, communication and coordination are relevant for sensor–actor control. Additionally, concepts of task and resource allocation are investigated that allow collaborative executions of complex tasks by autonomously self-organizing systems. Again, the basic self-organization methods are outlined in all analyzed techniques.

Part IV is intended as a conclusion and summary of the investigations in the previous parts of the book. The basic self-organization methods are revisited in the context of the algorithms, techniques and protocols investigated in the context of sensor and actor networks. Additionally, evaluation criteria are discussed that are relevant for estimating the quality and performance of self-organization techniques in sensor and actor networks.

Finally, Part V introduces a very special field that is strongly related to self-organization, namely bio-inspired networking. After a brief introduction to this research domain, the principles and concepts of three selected areas of bio-inspired research are investigated. In all three domains, case studies are depicted that provide solutions for the efficient operation of sensor and actor networks.

Acknowledgments

Since I began working on this textbook on self-organization in sensor and actor networks, many people have given me invaluable help and have been influential in shaping my thoughts on how to organize and teach a course on this topic. I want to thank all these people, including my students, colleagues, faculty members and helpful friends from around the world. Namely, I would like to mention Ian F. Akyildiz and Adam Wolisz, who encouraged me to stay with this topic, Imrich Chlamtac, who shared my visions in the bio-inspired networking domain, Özgür B. Akan, who helped me in various ways and with whom I co-edited a special issue on bio-inspired computing and communication for *Ad Hoc Networks*, Reinhard German, who encouraged me to initiate my studies on integrated robot-sensor networks, and to Bettina Krüger, Isabel Dietrich and Christoph Sommer for proofreading the manuscript. Last, but not least, I wish to thank Birgit Gruber from Wiley, who contacted me at an Infocom conference and convinced me of the idea to write a book on this topic, and all the staff at Wiley (Sarah Hinton, Wendy Hunter, Richard Davies and Joanna Tootill) for their assistance during the writing and the production phase of this book.

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About the Author

Falko Dressler is an assistant professor leading the Autonomic Networking Group at the Department of Computer Sciences, University of Erlangen-Nuremberg. He teaches on self-organizing sensor and actor networks, network security and communication systems. Dr Dressler received his M.Sc. and Ph.D. degree from the Dept of Computer Sciences, University of Erlangen in 1998 and 2003, respectively. From 1998 to 2003, he worked at the Regional Computing Center at the University of Erlangen as a research assistant. In 2003, he joined the Computer Networks and Internet group at the Wilhelm-Schickard-Institute for Computer Science, University of Tuebingen. Since 2004, he has been with the Computer Networks and Communication Systems group at the Department of Computer Sciences, University of Erlangen-Nuremberg.

Dr Dressler is an Editor for the *ACM/Springer Wireless Networks* (WINET) journal and Editor for the *Journal of Autonomic and Trusted Computing* (JoATC). He is a guest editor of a special issue on bio-inspired computing and communication in wireless ad hoc and sensor networks for the *Elsevier Ad Hoc Networks* journal. Dr Dressler is General Chair of the 2nd ICST/IEEE/ACM International Conference on Bio-Inspired Models of Network, Information, and Computing Systems (Bionetics 2007). He was co-chair and TPC member of a number of international conferences and workshops organized and sponsored by ACM, ICST, IEEE and IFIP.

Dr Dressler is a member of ACM, IEEE, IEEE Communications Society and IEEE Computer Society. He is actively participating in several working groups of the IETF. His research activities are focused on (but not limited to) Autonomic Networking addressing issues in Wireless Ad Hoc and Sensor Networks, Self-Organization, Bio-inspired Mechanisms, Network Security, Network Monitoring and Measurements and Robotics.

List of Abbreviations

ACK	Acknowledgment
ACO	Ant Colony Optimization
AI	Artificial Intelligence
AIS	Artificial Immune System
ANN	Artificial Neural Network
AODV	Ad Hoc on Demand Distance Vector
ASCENT	Adaptive Self-Configuring Sensor Network Topologies
BEB	Binary Exponential Back-off
CADR	Constrained Anisotropic Diffusion Routing
CBR	Constant Bit Rate
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
DAA	Dynamic Address Allocation
DAAP	Dynamic Address Allocation Protocol
DACP	Dynamic Address Configuration Protocol
DAD	Duplicate Address Detection
DBTMA	Dual Busy Tone Multiple Access
DEPR	Distributed Event-driven Partitioning and Routing
DHCP	Dynamic Host Configuration Protocol
DINTA	Distributed In-network Task Allocation
DNA	Deoxyribonucleic Acid
DSDV	Destination Sequenced Distance Vector

DSR Dynamic Source Routing

DYMO Dynamic MANET on Demand

EA Evolutionary Algorithm

FCM Fuzzy C-Means

FEC Forward Error Correction

FORP Flow Oriented Routing Protocol

GA Genetic Algorithm

GEAR Geographical end Energy-Aware Routing

GPS Global Positioning System

GPSR Greedy Perimeter Stateless Routing

HEED Hybrid Energy-Efficient Distributed Clustering Approach

HSR Hierarchical State Routing

IDSQ Information Driven Sensor Querying

IETF Internet Engineering Task Force

ILP Integer Linear Programming

IVC Inter-Vehicle Communication

LEACH Low-Energy Adaptive Clustering Hierarchy

MAC Medium Access Control

MACA Multiple Access with Collision Avoidance

MACA-BI MACA By Invitation

MACAW Multiple Access with Collision Avoidance for Wireless

MANET Mobile Ad Hoc Network

MINLP Mixed Non-Linear Programming

MILD Multiplicative Increase and Linear Decrease

MRTA Multi-Robot Task Allocation

NAV Network Allocation Vector

NHDP Neighborhood Discovery Protocol

NTP Network Time Protocol

OAA Open Agent Architecture

OAP Optimal Assignment Problem

OLSR Optimized Link State Routing

PACMAN Passive Auto-Configuration for Mobile Ad Hoc Networks

PCM Power-Control MAC

PDAD Passive Duplicate Address Detection

PEGASIS Power-Efficient Data-Gathering Protocol for Sensor Information Systems

PLL Phase-Locked Loop

QoS Quality of Service

RABR Route-Lifetime Assessment Based Routing

RBS Reference Broadcast Synchronization

RERR Route Error

RFID Radio Frequency ID

RIP Routing Information Protocol

RON Resilient Overlay Network

RREQ Route Request

RREP Route Reply

RPF Reverse Path Forwarding

RSN Rule-based Sensor Network

RTOS Real-Time Operating System

RTS Request To Send

RWP Random Way Point

S-MAC Sensor MAC

SANET Sensor and Actor Network

SI Swarm Intelligence

SOTIS Self-Organizing Traffic Information System

TBRPF Topology Broadcast based on Reverse Path Forwarding

TDM Time Division Multiplexing

TDMA	Time Division Multiple Access
ToF	Time of Flight
TPSN	Timing-sync Protocol for Sensor Networks
TTL	Time To Live
VANET	Vehicular Ad Hoc Network
WLAN	Wireless LAN
WMN	Wireless Mesh Network
WPDD	Weighted Probabilistic Data Dissemination
WSN	Wireless Sensor Network
ZRP	Zone Routing Protocol

Contents