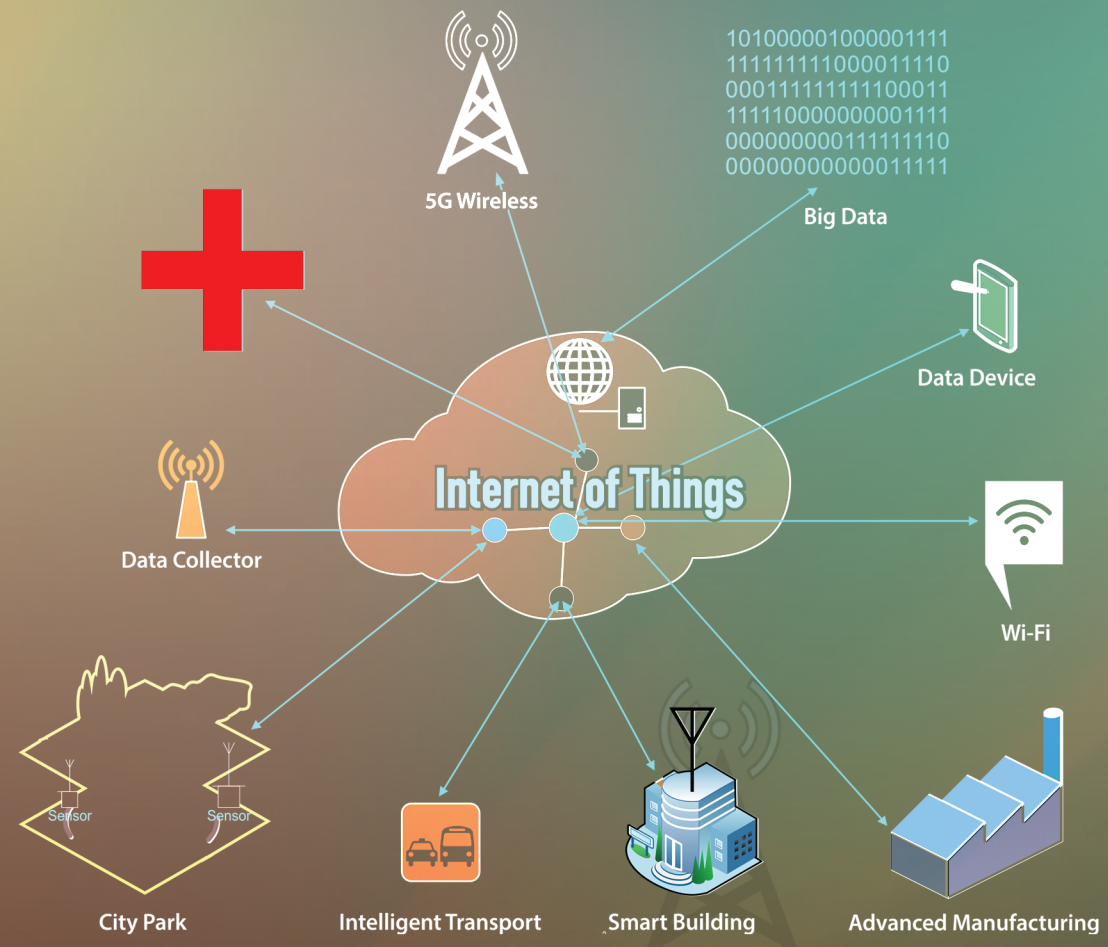
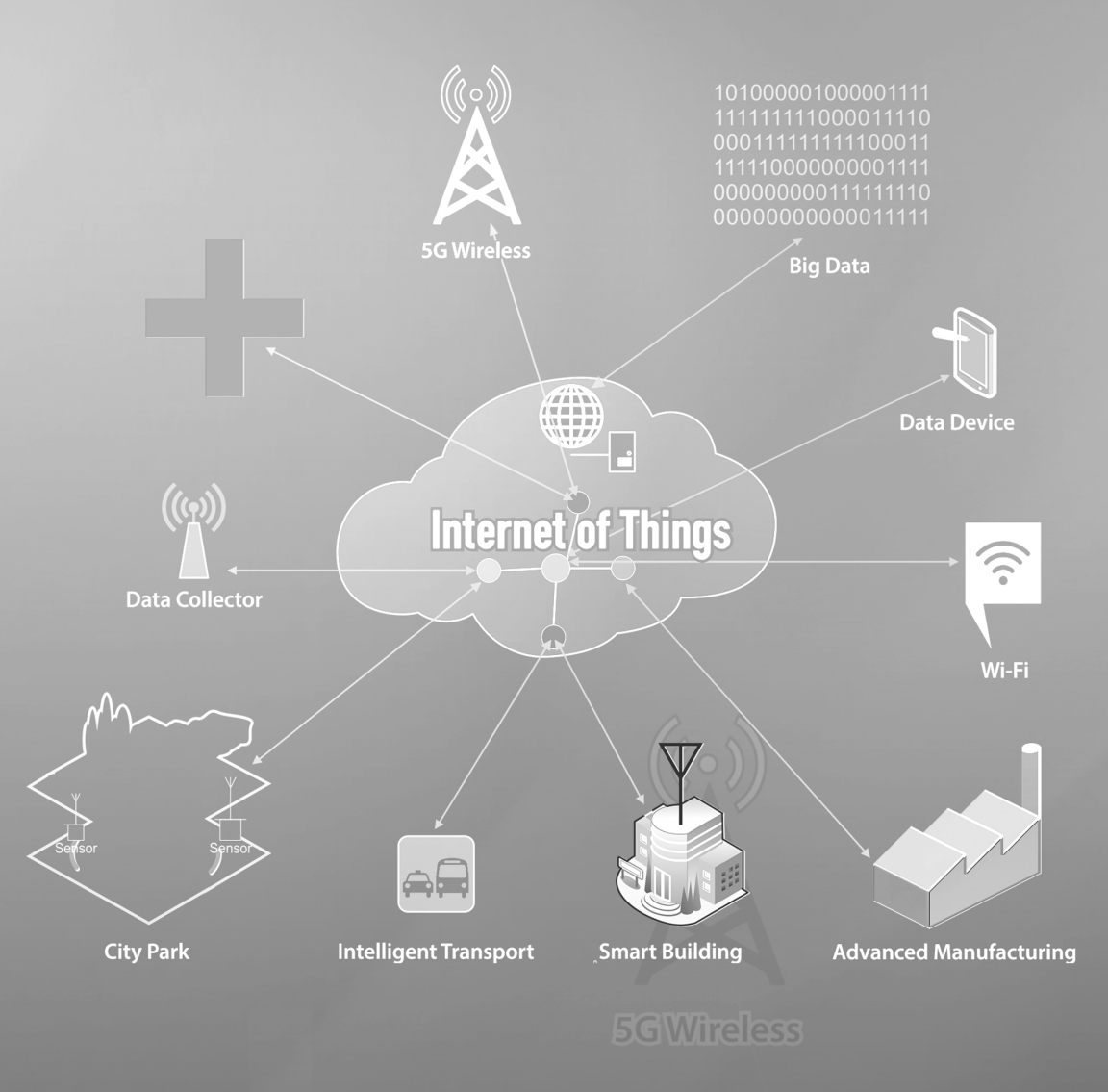


Internet of Things (IoT)

Systems and Applications

edited by **Jamil Y. Khan | Mehmet R. Yuce**



Internet of Things (IoT)

Internet of Things (IoT)

Systems and Applications

edited by

Jamil Y. Khan

Mehmet R. Yuce

JENNY STANFORD
PUBLISHING

Published by

Jenny Stanford Publishing Pte. Ltd.
Level 34, Centennial Tower
3 Temasek Avenue
Singapore 039190

Email: editorial@jennystanford.com
Web: www.jennystanford.com

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Internet of Things (IoT): Systems and Applications

Copyright © 2019 Jenny Stanford Publishing Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN 978-981-4800-29-7 (Hardcover)
ISBN 978-0-429-39908-4 (eBook)

Contents

Preface xiii

1 Introduction to IoT Systems **1**
Jamil Y. Khan
1.1 Introduction 2
1.2 Overview of IoT Applications 5
1.2.1 Healthcare 5
1.2.2 Utility Services 7
1.2.3 Automotive/Vehicular IoT 9
1.2.4 Smart Agriculture 10
1.2.5 Smart City 11
1.3 IoT System Architectures and Design Approaches 13
1.4 IoT Standards 17
1.5 Summary 21

2 Big Data in IoT Systems **25**
Fayeem Aziz, Stephan K. Chalup, and James Juniper
2.1 Introduction 25
2.1.1 The Digital Economy and Ubiquitous Computing Systems 25
2.1.2 The Internet of Things 28
2.2 Theoretical Approaches to UCS 31
2.2.1 Category Theory 31
2.2.2 Process Algebras 31
2.3 Core Digital Technologies for UCS 32
2.3.1 Semantic Technologies 32
2.3.2 Cognitive Computing and Deep Learning 34
2.4 Big Data and Its Sources 37
2.4.1 Radio Frequency Identification 38

2.4.2 Wireless Sensor Networks 39
2.4.3 Machine-to-Machine Communications 39
2.4.4 Cloud Computing 40
2.5 Big Data in IoT Application Areas 40
2.5.1 Healthcare Systems 40
2.5.2 Food Supply Chains 42
2.5.3 Smart Environment Domain 43
2.5.3.1 Smart power system 43
2.5.3.2 Smart home 43
2.5.3.3 Smart environment control 43
2.5.3.4 Safety and surveillance 44
2.5.3.5 Smart city 45
2.5.4 Safer Mining Production 45
2.5.5 Transportation and Logistics 45
2.5.6 Firefighting 46
2.6 Challenges of Big Data in IoT Systems 47
2.6.1 Big Data Mining 47
2.6.2 Proposed Big Data Management and Analysis Techniques 48
2.7 New Product Development and UCS 49
2.8 Organizational and Policy Implications 52

3 Basics of Communication Networks 65
Jamil Y. Khan
3.1 Introduction 66
3.2 Basic Networking Techniques 68
3.2.1 Network Architecture 69
3.2.1.1 Wide area network 72
3.2.1.2 Local area network 72
3.2.1.3 Personal area network 73
3.2.1.4 Infrastructure and ad hoc networks 73
3.3 Packet Communication Protocols 74
3.3.1 Communication Protocols/Software Models 74
3.3.2 Data Link Layer Protocols 77
3.3.2.1 LLC sublayer 78
3.3.2.2 Forward error correction techniques 81
3.3.2.3 MAC sublayer 84
3.3.2.4 Static channelization: TDMA 85

3.3.2.5 Dynamic medium access control techniques 86
3.3.2.6 Polling access technique 86
3.3.2.7 Random access technique 88
3.3.2.8 Network protocols 91
3.3.3 Transport Protocols 93
3.4 Wireless Networking Basics 95
3.4.1 Radio Propagation Environment 100
3.5 Traffic Modeling 101
3.6 Summary 103

4 Low-Power Wide-Area Networks 105
Jamil Y. Khan and Dong Chen
4.1 Introduction 106
4.1.1 IoT Communication Requirements 107
4.2 IoT Network Design Fundamentals 110
4.3 LPWAN Standards 112
4.3.1 Long-Range Wide-Area Network (LoRaWAN) 112
4.3.2 SigFox 115
4.4 Open Short-Range Networking Techniques 116
4.4.1 IEEE802.11 Standards 117
4.4.2 IEEE802.11ah Standard 118
4.4.3 IEEE802.15.4 Standard 124
4.4.4 Extension of the IEEE802.15.4 Standard 127
4.5 A Heterogeneous IoT Network Architecture 129
4.5.1 MFDRR Architecture 132
4.5.2 The Blank Burst Algorithm 133
4.6 Performance Evaluation of the Heterogeneous Network 135
4.7 Conclusions 143

5 Energy-Harvesting IoT Networks 147
Thien D. Nguyen, Jamil Y. Khan, and Duy T. Ngo
5.1 Review of Energy Harvesting Techniques 147
5.1.1 Solar-Based Energy Harvesting Technique 149
5.1.2 Thermal Energy Harvesting Technique 151
5.1.3 Vibration-Based Energy Harvesting Technique 151

5.1.4 Radio Frequency (RF) Energy Harvesting Technique 152
5.2 Energy-Harvested Sensor Network Architecture 153
5.2.1 Radio Frequency (RF) Energy Harvesting Technique 153
5.2.2 An Energy Consumption Model for the IEEE 802.15.4 EHWSN 155
5.3 A Proposed Algorithm for Kinetic Energy–Based Energy Harvesting 157
5.3.1 System Model 158
5.3.2 Vehicle Energy Generation Model 160
5.3.3 Piezoelectric Roadway Energy Harvester 162
5.3.4 An Adaptive Beacon Order, Superframe Order, and Duty Cycle (ABSD) Algorithm 164
5.3.4.1 Incoming traffic load estimation 165
5.3.4.2 Node's queue state estimation 165
5.3.4.3 Algorithm description 166
5.3.5 EH-ABSD Algorithm 168
5.3.5.1 Energy back-off process 169
5.3.5.2 Algorithm description 170
5.4 A Proposed Model for RF-Based Energy Harvesting 171
5.4.1 System Model 172
5.4.2 RF Energy Harvesting Process 174
5.4.3 RF-AASP Algorithm 175
5.4.3.1 Incoming harvested RF energy estimation 175
5.4.3.2 Algorithm description 175
5.5 A Proposed Model for Solar-Based Energy Harvesting 178
5.5.1 System Model 178
5.5.2 Energy Consumption Model 179
5.5.3 Energy Harvesting Prediction 180
5.5.4 Energy Harvesting Process 181
5.5.4.1 Case 1: $Level\ 3 \leq E_{\mathrm{r}}^{i} \leq Level\ 2$ 181
5.5.4.2 Case 2: $0 < E_{\mathrm{r}}^{i} < Level\ 3$ 181
5.5.5 Proposed Routing Algorithm 183
5.6 Performance Analysis of Energy-Harvested Wireless Sensor Network 183
5.6.1 EH-ABSD Algorithm 184

5.6.1.1 Vehicular traffic simulation 184
5.6.1.2 Harvested energy at sensor nodes 185
5.6.2 RF-AASP Algorithm 189
5.6.3 Solar-Based Routing Algorithm Performance 194
5.7 Conclusion 197

6 Wide-Area Wireless Networks for IoT Applications 203
Jason Brown
6.1 Introduction 203
6.2 Evolution of Wide-Area Wireless Standards 205
6.3 LTE, LTE Advanced, and LTE Advanced Pro Overview 207
6.3.1 Overall Roadmap 207
6.3.2 LTE 208
6.3.3 LTE Advanced 214
6.3.4 LTE Advanced Pro 215
6.4 M2M/IoT Challenges and Opportunities 215
6.5 Employing LTE Advanced and LTE Advanced Pro for M2M/IoT Applications 217
6.5.1 Random Access Overload 218
6.5.2 PDCCH Saturation 221
6.5.3 Exploiting Spatial and Temporal Correlation 224
6.5.4 LTE-M and Narrowband LTE-M 226
6.6 Summary 228

7 Low-Power Design Considerations for IoT Sensors 231
Fan Wu, Md Shamsul Arefin, Jean-Michel Redoute, and Mehmet R. Yuce
7.1 Introduction 232
7.2 Transmission Frequency of IoT Wireless Sensors 234
7.3 IoT Hardware Platform 237
7.4 IoT Wireless Sensor Network Platforms 241
7.4.1 Waspmote 241
7.4.2 MySignals 243
7.4.3 MEMSIC 243
7.4.4 WiSense 244
7.5 IoT Sensor Node with Energy Harvesting 246
7.6 A Self-Powered IoT Sensor Node Design (A Case Study) 249

7.6.1 Hardware Design 250
7.6.2 Software Design 251
7.6.3 Performance Analysis 254
7.7 Conclusions 257

8 Energy Harvesting Solutions for Internet of Things (IoT) Sensors 261
Mehmet R. Yuce and York Ying
8.1 Introduction 262
8.2 Solar Energy Harvesting 264
8.2.1 Photovoltaic Effect 265
8.2.2 *I–V* Characteristics 266
8.2.3 Maximum Power Point Tracking 269
8.2.4 Power Conditioning Topologies 272
8.2.5 Boost Converter with MPPT 273
8.2.6 Charge Pump 276
8.2.7 Transformer or Self-Starting Converter 279
8.3 Sensor Nodes with Solar Energy Harvesting 283
8.4 Vibration-Based Harvesting Techniques 286
8.5 RF Energy Harvesting 289
8.6 Commercial Conditioning Chips and Circuits 291
8.7 Conclusions 294

9 Network Security for IoT and M2M Communications 299
Jorge Granjal, André Riker, Edmundo Monteiro, and Marilia Curado
9.1 Introduction 300
9.2 Network Technologies for IoT and M2M 301
9.2.1 IETF IoT and M2M Communications 301
9.2.1.1 6LoWPAN (network-layer communications) 303
9.2.1.2 ROLL RPL (routing) 304
9.2.1.3 CoAP (application-layer communications) 305
9.2.2 ETSI IoT and M2M Communications 306
9.2.2.1 High-level ETSI M2M architecture 306
9.2.2.2 Service capabilities layers 308
9.2.2.3 Secure M2M device registration 310

9.3 Security for IoT and M2M Network Technologies 313
9.3.1 Attacks and Threats 313
9.3.2 Security Requirements 315
9.4 Security in IETF M2M Network Technologies 316
9.4.1 Security in 6LoWPAN 317
9.4.2 Security in RPL 318
9.4.3 Security in CoAP 319
9.4.4 Open Research Opportunities 321
9.4.4.1 Research challenges and proposals at the network-layer 321
9.4.4.2 Research challenges and proposals for routing security 323
9.4.4.3 Research challenges and proposals for application-layer security 324
9.5 Security in ETSI M2M Network Technologies 327
9.6 Other M2M Standard Efforts 329
9.7 Conclusions 330

Index 337

Preface

Internet of Things (IoT), also known as the Internet of Everything (IoE), is bringing in massive evolutionary changes in information and communication technology (ICT) by integrating wireless communications, sensors, and data collection and processing techniques. IoT will define new ICT dimensions in almost all segments of society and industry. It is predicted that billions of IoT devices will be connected through the internet and will be capable of interacting with each other, generating a huge amount of data (the so-called Big Data) that should be processed through cloud and/or fog computing techniques. IoT technologies are expected to improve the quality of life, create new business opportunities, and improve the productivity of factories, buildings, public infrastructure, and services.

The ultimate goal of IoT is to connect everything to the internet, generating new applications and services. eIoT technology will facilitate the development of creative ICT platforms that can connect factories, cities, workplaces, and homes, and will be aimed at providing support to the efficient and effective operation of infrastructure in our daily environment.

IoT applications will be deployed in different operating environments, ranging from small indoor areas to large, wide areas. To cater to such diverse needs of the IoT system, it is vital that the e-communications industry develops new networking standards.

The objective of this book is to provide existing and emerging solutions to design and develop IoT platforms, enable new applications, present regulatory implications, and address challenges in current IoT deployments and to offer guidelines for possible future applications. The rapid growth of IoT products raises several issues

such as standardization networking, security, and privacy, besides other regulations that are all discussed in this book.

IoT systems carry out various tasks, including sensing, actuation, communication, and control of the intended applications. They need to be reliable and capable of interoperability between networks. They must contain smart semantic middleware systems for the successful deployment of IoT-based platforms. IoT technology will shape our future technology and open a new landscape for enterprises and consumers.

This book covers a range of topics on IoT technology, introduced in a manner suitable to a broad range of readers. The book will be a key resource for ICT professionals, computer engineers, and graduate and senior undergraduate students in computers, electronics, sensors, wireless communication, and electrical engineering.

This book discusses the current state of the art by focusing on the latest research and new designs and developments related to IoT and wireless sensor network technologies. It introduces basic concepts of communication and network techniques, hardware, software and system design techniques, and various sensor network platforms for IoT applications. It also discusses some potential applications of IoT as case studies. Energy harvesting solutions with wireless sensors are introduced. These can be used to enable autonomous IoT sensor network platforms.

The book offers a comprehensive review of wireless sensor design, including development and deployment techniques. All chapters are written by leading experts in their fields. The contributions by the authors focus on applications of IoT, implementation, communication, network topologies, wireless standards, energy harvesting, and Big Data handling.

Chapter 1 starts with an introduction to IoT and systems design to help readers to understand the topic and the associated basic techniques.

Chapter 2 presents Big Data-processing techniques for IoT applications. Concepts such as fog and cloud computing and Industry 4.0 are discussed. Deep learning, machine learning, and pattern recognition are described to improve the performance of Big Data-computing algorithms.

Communication networks are the key elements of IoT systems that provide the necessary infrastructure to exchange information among a large number of connected devices. Chapter 3 introduces basic communication networking techniques with basic network architectures, protocols, wireless network solutions, and traffic characteristics.

Chapter 4 discusses networking standards for low-power wide-area network (LPWAN) technology. IoT applications are deployed in various operating environments supporting sensor nodes and devices over tens of kilometers of the network coverage area. To cater to such diverse needs, IoT systems with new networking standards are discussed in this chapter. Several major emerging LPWAN technologies for IoT and M2M applications are presented. In addition, this chapter presents the implementation of a unique heterogeneous LPWAN network standard and design techniques that can be used to develop effective and reliable IoT networks for various applications.

Chapter 5 focuses on wireless sensor networks with energy harvesting solutions for IoT applications. Energy harvesting is considered for the IEEE802.15.4 wireless sensor network (WSN) for IoT applications. Details of sensor networks with their power management techniques and network performance criteria using various energy harvesting methodologies are discussed.

The use of wide-area cellular wireless networks for IoT connectivity, including the 3GPP Long-Term Evolution (LTE), LTE Advanced, and LTE Advanced Pro cellular systems, is presented in Chapter 6. It also discusses the current state-of-the-art setup with respect to supporting M2M/IoT applications over wide-area wireless networks.

Chapter 7 examines low-power design considerations for IoT sensor node designs. Several design considerations such as sensor node, network, and transmission frequency for the development of low-power IoT WSNs are highlighted in this chapter. This part of the book also presents an implementation of self-powered wireless sensors for IoT-based environmental monitoring applications.

The sensor device in an IoT application requires an uninterrupted power source to operate for continuous data collection. Thus, energy harvesting methods, circuits, and systems as power supply

solutions are presented in Chapter 8. Several energy harvesting techniques have been discussed and compared with each other. In addition, this section explores power-conditioning circuits. Energy harvesting is a key component in the development and deployment of IoT devices in large-scale environments. Energy harvesting can eventually eliminate the need for batteries, establishing continuous operation and therefore continuous connectivity for years.

Chapter 9 discusses network security for IoT and M2M communications. It offers the readers a clear view of the main challenges currently faced by the industry and the research undergone in dealing with security in the context of such applications, as well as in identifying open research issues and opportunities in this context.

We hope that this book will be a key resource for network designers, ICT professionals, researchers, and students who work in this emerging area of Internet of Things technology. Considering the rapid progress in the area, we firmly believe that IoT technology will play an important role in future smart industry and smart city applications. Finally, we would like to thank all the authors for their excellent contributions, which enabled us to develop a key book on IoT technology. We also thank the publisher for delivering an important book in a timely manner on one of the most vital technologies of this century.

Jamil Y. Khan
Mehmet R. Yuce