Contents

Preface *xv*

1 Preliminaries, Motivation, and Related Work *1*
1.1 What is the Internet of Things? *1*
1.2 Wireless Ad-hoc and Sensor Networks: The Ancestors without IP *2*
1.3 IoT-enabled Applications *3*
1.3.1 Home and Building Automation *3*
1.3.2 Smart Cities *4*
1.3.3 Smart Grids *4*
1.3.4 Industrial IoT *5*
1.3.5 Smart Farming *7*

2 Standards *9*
2.1 "Traditional" Internet Review *9*
2.1.1 Physical/Link Layer *10*
2.1.1.1 IEEE 802.3 (Ethernet) *11*
2.1.1.2 IEEE 802.11 *12*
2.1.2 Network Layer *14*
2.1.2.1 IPv6 and IPv4 *14*
2.1.3 Transport Layer *17*
2.1.3.1 TCP and UDP *19*
2.1.4 Application Layer *21*
2.1.4.1 HTTP *21*
2.1.4.2 AMQP *22*
2.1.4.3 SIP *23*
2.2 The Internet of Things *25*

2.2.1 Designing the Architecture of an IP-based Internet of Things *26*
2.2.2 Physical/Link Layer *28*
2.2.2.1 IEEE 802.15.4 and ZigBee *28*
2.2.2.2 Low-power Wi-Fi *30*
2.2.2.3 Bluetooth and BLE *31*
2.2.2.4 Powerline Communications *32*
2.2.3 Network Layer *33*
2.2.3.1 The 6LoWPAN Adaptation Layer *34*
2.2.4 Transport Layer *34*
2.2.5 Application Layer *34*
2.2.5.1 CoAP *35*
2.2.5.2 CoSIP Protocol Specification *60*
2.3 The Industrial IoT *76*

3 Interoperability *79*
3.1 Applications in the IoT *79*
3.2 The Verticals: Cloud-based Solutions *80*
3.3 REST Architectures: The Web of Things *81*
3.3.1 REST: The Web as a Platform *82*
3.3.1.1 Resource-oriented Architectures *83*
3.3.1.2 REST Architectures *84*
3.3.1.3 Representation of Resources *84*
3.3.1.4 Resource Identifiers *85*
3.3.1.5 Statelessness *86*
3.3.1.6 Applications as Finite-state Machines *86*
3.3.1.7 Hypermedia as the Engine of Application State *86*
3.3.2 Richardson Maturity Model *88*
3.3.2.1 Level 0: the Swamp of POX *88*
3.3.2.2 Level 1: Resources *90*
3.3.2.3 Level 2: HTTP Verbs *90*
3.3.2.4 Level 3: Hypermedia *95*
3.3.2.5 The Meaning of the Levels *97*
3.4 The Web of Things *97*
3.5 Messaging Queues and Publish/Subscribe Communications *98*
3.5.1 Advantages of the Pub/Sub Model *99*
3.5.2 Disadvantages of the Pub/Sub Model *100*
3.5.3 Message Queue Telemetry Transport *100*
3.5.3.1 MQTT versus AMQP *101*

3.6 Session Initiation for the IoT *102*
3.6.1 Motivations *102*
3.6.2 Lightweight Sessions in the IoT *104*
3.6.2.1 A Protocol for Constrained Session Initiation *106*
3.6.2.2 Session Initiation *106*
3.6.2.3 Session Tear-down *108*
3.6.2.4 Session Modification *108*
3.7 Performance Evaluation *109*
3.7.1 Implementation *109*
3.7.2 Experimental Results *111*
3.7.3 Conclusions *114*
3.8 Optimized Communications: the Dual-network Management Protocol *115*
3.8.1 DNMP Motivations *115*
3.8.2 Related Work *117*
3.8.3 The DNMP Protocol *118*
3.8.4 Implementation with IEEE 802.15.4 and IEEE 802.11s *123*
3.8.4.1 LPLT Networking *123*
3.8.4.2 HPHT Networking *123*
3.8.4.3 Node Integration *124*
3.8.5 Performance Evaluation *125*
3.8.5.1 Experimental Setup *125*
3.8.5.2 Operational Limitations of IEEE 802.15.4 *126*
3.8.6 IEEE 802.15.4-controlled Selective Activation of the IEEE 802.11s Network *129*
3.8.7 Conclusions *130*
3.9 Discoverability in Constrained Environments *131*
3.9.1 CoRE Link Format *131*
3.9.1.1 CoRE Link Format: Discovery *132*
3.9.1.2 Link Format *133*
3.9.1.3 The Interface Description Attribute *135*
3.9.2 CoRE Interfaces *135*
3.9.2.1 Sensor *136*
3.9.2.2 Parameter *137*
3.9.2.3 Read-only Parameter *137*
3.9.2.4 Actuator *137*
3.10 Data Formats: Media Types for Sensor Markup Language *138*
3.10.1 JSON Representations *141*
3.10.1.1 Single Datapoint *141*

3.10.1.2 Multiple Datapoints *142*
3.10.1.3 Multiple Measurements *142*

4 Discoverability *145*
4.1 Service and Resource Discovery *145*
4.2 Local and Large-scale Service Discovery *146*
4.2.1 ZeroConf *151*
4.2.2 UPnP *152*
4.2.3 URI Beacons and the Physical Web *152*
4.3 Scalable and Self-configuring Architecture for Service Discovery in the IoT *154*
4.3.1 IoT Gateway *156*
4.3.1.1 Proxy Functionality *156*
4.3.1.2 Service and Resource Discovery *158*
4.3.2 A P2P-based Large-scale Service Discovery Architecture *159*
4.3.2.1 Distributed Location Service *160*
4.3.2.2 Distributed Geographic Table *161*
4.3.2.3 An Architecture for Large-scale Service Discovery based on Peer-to-peer Technologies *162*
4.3.3 Zeroconf-based Local Service Discovery for Constrained Environments *167*
4.3.3.1 Architecture *167*
4.3.3.2 Service Discovery Protocol *168*
4.3.4 Implementation Results *170*
4.3.4.1 Local Service Discovery *171*
4.3.4.2 Large-scale Service Discovery *175*
4.4 Lightweight Service Discovery in Low-power IoT Networks *178*
4.4.1 Efficient Forwarding Protocol for Service Discovery *180*
4.4.1.1 Multicast through Local Filtered Flooding *181*
4.4.2 Efficient Multiple Unicast Forwarding *183*
4.5 Implementation Results *185*

5 Security and Privacy in the IoT *191*
5.1 Security Issues in the IoT *192*
5.2 Security Mechanisms Overview *196*
5.2.1 Traditional vs Lightweight security *196*
5.2.1.1 Network Layer *197*
5.2.1.2 Transport Layer *199*

5.2.1.3 Application Layer *201*
5.2.2 Lightweight Cryptography *202*
5.2.2.1 Symmetric-key LWC Algorithms *203*
5.2.2.2 Public-key (Asymmetric) LWC Algorithms *206*
5.2.2.3 Lightweight Cryptographic Hash Functions *210*
5.2.2.4 Homomorphic Encryption Schemes *213*
5.2.3 Key Agreement, Distribution, and Security Bootstrapping *214*
5.2.3.1 Key Agreement Protocols *215*
5.2.3.2 Shared Group-key Distribution *215*
5.2.3.3 Security Bootstrapping *216*
5.2.4 Processing Data in the Encrypted Domain: Secure Data Aggregation *217*
5.2.5 Authorization Mechanisms for Secure IoT Services *219*
5.3 Privacy Issues in the IoT *222*
5.3.1 The Role of Authorization *222*
5.3.2 IoT-OAS: Delegation-based Authorization for the Internet of Things *227*
5.3.2.1 Architecture *227*
5.3.2.2 Granting Access Tokens *229*
5.3.2.3 Authorizing Requests *231*
5.3.2.4 SP-to-IoT-OAS Communication: Protocol Details *231*
5.3.2.5 Configuration *232*
5.3.3 IoT-OAS Application Scenarios *232*
5.3.3.1 Network Broker Communication *233*
5.3.3.2 Gateway-based Communication *235*
5.3.3.3 End-to-End CoAP Communication *235*
5.3.3.4 Hybrid Gateway-based Communication *235*

6 Cloud and Fog Computing for the IoT *237*
6.1 Cloud Computing *237*
6.2 Big Data Processing Pattern *238*
6.3 Big Stream *239*
6.3.1 Big-stream-oriented Architecture *243*
6.3.2 Graph-based Processing *247*
6.3.3 Implementation *251*
6.3.3.1 Acquisition Module *251*
6.3.3.2 Normalization Module *253*
6.3.3.3 Graph Framework *254*
6.3.3.4 Application Register Module *255*

6.3.4 Performance Evaluation *257*
6.3.5 Solutions and Security Considerations *262*
6.4 Big Stream and Security *263*
6.4.1 Graph-based Cloud System Security *266*
6.4.2 Normalization after a Secure Stream Acquisition with OFS Module *268*
6.4.3 Enhancing the Application Register with the IGS Module *269*
6.4.4 Securing Streams inside Graph Nodes *273*
6.4.5 Evaluation of a Secure Big Stream Architecture *277*
6.5 Fog Computing and the IoT *281*
6.6 The Role of the IoT Hub *283*
6.6.1 Virtualization and Replication *285*
6.6.1.1 The IoT Hub *285*
6.6.1.2 Operational Scenarios *287*
6.6.1.3 Synchronization Protocol *290*

7 The IoT in Practice *303*
7.1 Hardware for the IoT *303*
7.1.1 Classes of Constrained Devices *305*
7.1.2 Hardware Platforms *307*
7.1.2.1 TelosB *307*
7.1.2.2 Zolertia Z1 *307*
7.1.2.3 OpenMote *310*
7.1.2.4 Arduino *313*
7.1.2.5 Intel Galileo *315*
7.1.2.6 Raspberry Pi *318*
7.2 Software for the IoT *321*
7.2.1 OpenWSN *321*
7.2.2 TinyOS *322*
7.2.3 FreeRTOS *323*
7.2.4 TI-RTOS *323*
7.2.5 RIOT *324*
7.2.6 Contiki OS *325*
7.2.6.1 Networking *325*
7.2.6.2 Low-power Operation *326*
7.2.6.3 Simulation *326*
7.2.6.4 Programming Model *327*
7.2.6.5 Features *328*

7.3 Vision and Architecture of a Testbed for the Web of Things *328*
7.3.1 An All-IP-based Infrastructure for Smart Objects *330*
7.3.2 Enabling Interactions with Smart Objects through the IoT Hub *332*
7.3.2.1 Integration Challenges *334*
7.3.3 Testbed Access and Security *335*
7.3.3.1 The Role of Authorization *335*
7.3.4 Exploiting the Testbed: WoT Applications for Mobile and Wearable Devices *336*
7.3.5 Open Challenges and Future Vision *338*
7.4 Wearable Computing for the IoT: Interaction Patterns with Smart Objects in RESTful Environments *340*
7.4.1 Shaping the Internet of Things in a Mobile-Centric World *340*
7.4.2 Interaction Patterns with Smart Objects through Wearable Devices *342*
7.4.2.1 Smart Object Communication Principles *342*
7.4.2.2 Interaction Patterns *343*
7.4.3 Implementation in a Real-world IoT Testbed *345*
7.4.3.1 Future Vision: towards the Tactile Internet *348*
7.5 Effective Authorization for the Web of Things *349*
7.5.1 Authorization Framework Architecture *353*
7.5.1.1 System Operations *353*
7.5.2 Implementation and Validation *357*

Reference *359*

Index *381*