A Large-Scale Software-Defined Internet of Things Platform for Provisioning IoT Services on Demand

A thesis submitted in fulfillment of the requirements for
the degree of Doctor of Philosophy
in the Faculty of Engineering and Information Technology
at the University of Technology Sydney

by

Thi Minh Chau Nguyen

Supervised by

Professor Doan B. Hoang

2020

Certificate of Original Authorship

I, Thi Minh Chau Nguyen, declare that this thesis is submitted in fulfillment of the requirements for the award of the degree of Doctor of Philosophy in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in this thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Production Note: Signature removed prior to publication. Thi Minh Chau Nguyen

Date: 15/04/2020

Dedication

To my parents, aunty, and siblings

To my primary supervisor

Thank for your great support

Acknowledgment

During my doctoral candidature, I have received a myriad of lessons, support, and encouragement. First of all, I would like to express my sincere gratitude to my primary supervisor, Professor Doan B. Hoang, for his precious lessons and patient guidance. He has taught me significantly valuable lessons that cannot be found from books or any document. I have learned not only research and academic skills but also problem-solving skills from him. Starting from zero research background, I have gradually become an independent researcher. His understanding, enthusiasm, advice, and supervision have pushed me farther than I thought I could go. Without his critical comments, insightful feedback, encouragement, and motivation, none of my work would have been possible and successful, and I would still be in the marsh of the academic career.

I wish to acknowledge the support of my co-supervisor, Dr. Zenon Chaczko. I am thankful for SEDE staff always helping me with admin procedures.

I would extend my thanks to the Mekong 1000 project and CTU-UTS (Can Tho University – University of Technology Sydney) scholarship that has offered me an opportunity to pursue the Ph.D. course.

I will never forget the encouragement and assistance from my colleagues and friends, including Tham Nguyen, Sara Farahmandian, Ngoc Le, Vinh Ha, Dat Dang, Thai Nguyen, Cheng te Wang, Nhut Huynh, Firas AI Dughman, Jan Szymanski, Ashish Nanda, and Deepak Puthal.

Finally, I wish to show my appreciation to my parents, aunty, and siblings, who are always by my side to encourage me and keep me going.

Without all of you, this research would not have been possible.

Sydney, 2020.

The Author's Publications

International Conference Publications and Proceedings:

1. **Nguyen, T.M.C.**, D.B. Hoang, and Z. Chaczko. "Can SDN Technology Be Transported to Software-Defined WSN/IoT?" in *2016 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData)*. 2016.
2. **Nguyen, T.M.C.**, D.B. Hoang, and T.D. Dang. "Toward a programmable software-defined IoT architecture for sensor service provision on demand." in *2017 27th International Telecommunication Networks and Applications Conference (ITNAC)*. 2017.
3. **Nguyen, T.M.C.**, D.B. Hoang, and T.D. Dang. "A software-defined model for IoT clusters: Enabling applications on demand." in *2018 International Conference on Information Networking (ICOIN)*. 2018.
4. **Nguyen, T.M.C.,** and D.B. Hoang. "S-MANAGE Protocol for Software-Defined IoT." in *2018 28th International Telecommunication Networks and Applications Conference (ITNAC)*. 2018.
5. **Nguyen, T.M.C.,** and D.B. Hoang. "Software-Defined Virtual Sensors for Provisioning Services on Demand." in 2020 International Conference on Information Technology and Internet of Things (ITIOT) (accepted for publication).

Journal papers:

6. **Nguyen, C.** and D. Hoang, "S-MANAGE Protocol for Provisioning IoT Applications on Demand." *Journal of Telecommunications and the Digital Economy, 2019*. 7(3): p. 37-57.
7. **Nguyen, C.** and D. Hoang, "Large-scale Software-Defined Internet of Things Platform for Provisioning IoT Services on Demand," submitted to *International Journal of Smart Sensor Technologies and Applications (IJSSTA)*. (Under 2nd round review) (2020)

Table of Contents

Certificate of Original Authorship i
Dedication ii
Acknowledgment iii
The Author's Publications iv
List of Figures ix
List of Tables xii
List of Abbreviations and Acronyms xii
Abstract xv
Chapter 1 Introduction 1
1.1 Introduction 1
1.2 Brief Background 5
1.3 Research Questions 7
1.4 Research Aim and Objectives 10
1.5 Research Contributions and Significance 10
1.6 Research Methodology 12
1.7 Thesis Structure 13
Chapter 2 Background and Related Work 17
2.1 Introduction 17
2.2 IoT System 18
2.2.1 IoT Evolution Stages 18
2.2.2 Things, Services, and Resources in IoT 22
2.2.3 IoT System – Key Components 25
2.2.4 IoT Architecture 28
2.2.5 Requirements for an IoT System 32
2.3 IoT Deployment Models and Scenarios 34
2.3.1 IoT Deployment Models 34
2.3.2 Real IoT Scenarios 35
2.3.3 IoT Application Development - Challenges 36

2.4 Software-Defined Networking (SDN) Technique 38
2.4.1 SDN Architecture 39
2.4.2 SDN Paradigm's Implications to WSN/IoT 44
2.4.3 Challenges of Application of SDN to WSN/IoT 46
2.5 Network Function Virtualization (NFV) Technique 48
2.6 Solutions to a Programmable IoT Device 50
2.7 SDN-NFV-based Solutions to a Programmable IoT System 52
2.8 SDN-NFV-Based Solutions to a Large-Scale IoT System 54
2.9 Open-Sources for Developing LSSD-IoT Platform 55
2.10 Summary 56
Chapter 3 Large-Scale Software-Defined Internet of Things (LSSD-IoT) Model 57
3.1 Introduction 57
3.2 Why Large-Scale and Programmable Services on Demand? 58
3.3 LSSD-IoT Model 60
3.3.1 Software-Defined Cluster Layer 64
3.3.2 Software-Defined Device Layer 65
3.4 LSSD-IoT Features 67
3.5 Practical Realization of the Proposed LSSD-IoT Model 69
3.6 Thesis Roadmap 70
3.7 Summary 71
Chapter 4 Software-Defined Virtual Sensor (SDVS) 72
4.1 Introduction 72
4.2 Proposed SDVS 74
4.3 SDVS – Representation Types 77
4.4 SDVS Features 79
4.5 SDVS Architecture and Software Implementation 81
4.5.1 SDVS Architecture 81
4.5.2 Software Implementation 83
4.6 Use Case Scenario and Practical Implementation 91
4.7 Performance Evaluation 92
4.7.1 SDVS – Feasibility and Programmability 92

4.7.2 SDVS – Efficiency 95
4.8 Summary 97
Chapter 5 S-MANAGE Protocol 98
5.1 Introduction 98
5.2 S-MANAGE in Relation to SD-IoT Model 99
5.3 S-MANAGE Protocol 102
5.3.1 S-MANAGE Header 104
5.3.2 S-MANAGE Message types 105
5.3.3 Forwarding Table Specifications 108
5.3.4 Configuring Table Specifications 110
5.4 Software Implementation 111
5.5 Implementation and Performance Evaluation 115
5.5.1 Implementation Set up 115
5.5.2 Performance Evaluation 116
5.6 Summary 120
Chapter 6 Software-Defined Internet of Things (SD-IoT) Model 121
6.1 Introduction 121
6.2 SD-IoT Model 123
6.2.1 Software-Defined Virtual Sensor (SDVS) 124
6.2.2 S-MANAGE Protocol 124
6.3 SD-IoTD Controller 125
6.3.1 SD-IoTD Controller – Functional Components 125
6.3.2 SD-IoTD Controller – Operational Mechanism 126
6.4 SD-IoTD Controller - Software Implementation 129
6.5 SD-IoT Model – Software Implementation 131
6.5.1 Use Case Scenario 131
6.5.2 Implementation Scenario 132
6.5.3 Implementation Set up 133
6.6 Performance Evaluation 134
6.7 Summary 142
Chapter 7 Software-Defined Cluster Layer and LSSD-IoT Platform 143
7.1 Introduction 143

7.2 SD Cluster Layer 144
7.2.1 SD-IoTC Controller 145
7.2.2 SD-IoT Clusters and Communication with the SD-IoTC Controller 148
7.3LSSD-IoT Platform – Procedure of the Provision of IoT Services on Demand 149
7.4 LSSD-IoT Platform – Use cases 151
7.5 LSSD-IoT Platform Implementation 157
7.5.1 Implemented Platform 157
7.5.3 Implementation Scenario 160
7.5.3 Implementation Set up 161
7.5.4 SD-IoTC Controller – Software Implementation 163
7.6 Performance Evaluation 170
7.6.1 Implementation Platform Capability 170
7.6.2 Platform Performance 180
7.7 Summary 185
Chapter 8 Conclusion and Future Work 187
8.1 Research Remarks 187
8.2 Future Work 191
Appendices 193
Bibliography 202

List of Figures

Figure 1.1 Research phases **12**
Figure 1.2 Research Methodology **13**
Figure 1.3 Thesis Organization **14**
Figure 2.1 IoT Evolution **19**
Figure 2.2 Relationship between IoT applications, services, and resources [36] **25**
Figure 2.3 IoT building blocks and technologies **25**
Figure 2.4 IoT service types **27**
Figure 2.5 IoT architecture **29**
Figure 2.6 IoT reference model [32] **31**
Figure 2.7 Mapping of IoT requirements for enabling technologies **33**
Figure 2.8 Real IoT Scenarios **35**
Figure 2.9 SDN architecture **39**
Figure 2.10 Three main components of an SDN switch and OpenFlow switch **41**
Figure 2.11 NFV architecture **49**
Figure 2.12 Mapping SDN components for NFV architecture **50**
Figure 3.1 LSSD-IoT architecture **63**
Figure 3.2 SD Cluster layer architecture **64**
Figure 3.3 SD Device layer architecture **65**
Figure 4.1 SDVS in relation to LSSD-IoT model **73**
Figure 4.2 SDVS' s representation types **79**
Figure 4.3 Sensor node architecture **82**
Figure 4.4 SDVS architecture **83**
Figure 4.5 SDVS in software **84**
Figure 4.6 Class diagram of the SDVS **85**
Figure 4.7 SDVS's java class **86**
Figure 4.8 Basic parameters defining an SDVS and its represented entity **87**
Figure 4.9 Abstract methods defining fundamental functions of an SDVS and its represented entity **90**
Figure 4.10 Implementation prototype **92**
Figure 4.11 SDVS's programmable features **93**
Figure 4.12 Sensor tag's log file **94**
Figure 4.13 Configuration status of SDVS21 ..... **95**
Figure 4.14 SDVS's average response time for one request per multiple requests **96**
Figure 5.1 S-MANAGE protocol in relation to the LSSD-IoT model **99**
Figure 5.2 SD-IoT model **100**

Figure 5.3 Sequence diagram for Forwarding Statistics achievement 104
Figure 5.4 S-MANAGE header 104
Figure 5.5 S-MANAGE message types 106
Figure 5.6 Forwarding table structure 108
Figure 5.7 Configuring table structure 110
Figure 5.8 Class diagram of the configuring table 112
Figure 5.9 Details of a configuring entry 113
Figure 5.10 Class diagram of the forwarding table 114
Figure 5.11 Class diagram of S-MANAGE packets 115
Figure 5.12 Implementation prototype 116
Figure 5.13 Forwarding table status before configuration 117
Figure 5.14 Forwarding table status after configuration 118
Figure 5.15 Configuring table status before configuration 118
Figure 5.16 Configuring table status after configuration 119
Figure 5.17 Sensor service status before configuration 119
Figure 5.18 Sensor service status after configuration 119
Figure 6.1 SD-IoT model in relation to the LSSD-IoT model 122
Figure 6.2 SD-IoT model 123
Figure 6.3 SD-IoTD controller structure 125
Figure 6.4 Class diagram of SD-IoTD controller 130
Figure 6.5 Use case scenario 132
Figure 6.6 Implementation prototype 133
Figure 6.7 Status of the SDVS before its configuration 135
Figure 6.8 Status of the SDVS after its configuration 136
Figure 6.9 Dynamic response from the controller's resource orchestrator to an IoT request 137
Figure 6.10 Handling multiple application requests and solving conflicts among them 139
Figure 6.11 Status of ongoing application requests and corresponding results 140
Figure 6.12 SD-IoTD Controller – Processing time for one per multiple simultaneous requests ranging between 10-90 141
Figure 6.13 Number of exchanged control and data messages between SD-IoTD controller and SDVSs 142
Figure 7.1 SD cluster layer in relation to LSSD-IoT model 144
Figure 7.2 SD-IoTC controller architecture 145
Figure 7.3 Overall procedure of provisioning IoT services on demand via LSSD-IoT platform 150
Figure 7.4 Workflow of the SD-IoTC Controller 151
Figure 7.5 Workflow of the SD-IoTD Controller 151
Figure 7.6 Monitoring air pollution use case 153
Figure 7.7 IoT service provision scenario number 1 153
Figure 7.8 Smart traffic control use case 154

Figure 7.9 IoT service provision scenario number 2 155
Figure 7.10 IoT service provision scenario number 3 156
Figure 7.11 Detailed implementation of LSSD-IoT architecture 159
Figure 7.12 LSSD-IoT Model - Implementation scenario 161
Figure 7.13 Detailed implementation of the LSSD-IoT platform 162
Figure 7.14 Class diagram of the SD-IoTC controller 164
Figure 7.15 RequestAnalyser class 165
Figure 7.16 SdiotModule class 167
Figure 7.17 Class diagram for REST-API 168
Figure 7.18 Table 1 - Connections to SD-IoT clusters 169
Figure 7.19 Table 2 – Available IoT services 169
Figure 7.20 Table 3 – SD-IoTC clusters' capability 170
Figure 7.21 Level of programmability and orchestration of the LSSD-IoT platform 172
Figure 7.22 Control and management panel at the SD cluster and device level 173
Figure 7.23 Overview of the control and management at the cluster level 174
Figure 7.24 Overview of the control and management at the device level 174
Figure 7.25 Available SD-IoT resources 175
Figure 7.26 IoT Requests Status 176
Figure 7.27 IoT Application Announcements 176
Figure 7.28 SD-IoTC Controller – Resource Orchestration 177
Figure 7.29 SD-IoTD Controller – Resources Orchestration 178
Figure 7.30 SD-IoTD Controller – Device Configuration 180
Figure 7.31 Timing diagram 181
Figure 7.32 View of resource orchestration at the cluster level 182
Figure 7.33 Orchestration time with and without optimization 183
Figure 7.34 SD-IoTC Controller – Response Time 184
Figure 7.35 Orchestration and Response Time for optimization case with various input requests 185

List of Tables

Table 2.1 Requirements for an IoT system **32**
Table 2.2 Differences between proposals to network architecture [45] **37**
Table 7.1 Summary of IoT application requests and corresponding IoT services provided by IoT clusters (Ri represents a request from an IoT use case) **157**

List of Abbreviations and Acronyms

AODV	Ad hoc On-Demand Distance Vector
API	Application Programming Interface
CASAGRAS	Coordination and Support Action for Global RFID-Related Activities and Standardization
CERP-IoT	Cluster of European Research Projects-IoT
CoT	Chain of Things
DEEC	Distributed Energy-Efficient Clustering
EM	Element Management
EPC	Electronic Product Code
FPGA	Field-Programmable Gate Array
ICN	Information-Centric Networking
IEEE	Institute of Electrical and Electronics Engineers
IERC	IoT European Research Cluster
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPSO	Internet Protocol for Smart Objects
IPv4	Internet Protocol version 4

IPv6	Internet Protocol version 6
ITS	Intelligent Transport Systems
ITU	International Telegraph Union
ITU-T	ITU Telecommunication Standardization Sector
ITU-TY.	ITU-T for machine learning
LEACH	Low-energy adaptive clustering hierarchy
LLDP	Link Layer Discovery Protocol
M2M	Machine to machine
MAC	Media Access Control
MANO	Management and Orchestration
MIT	Massachusetts Institute of Technology
NBI	Northbound Interface
NFC	Near-Field Communication
NFV	Network Function Virtualization
NFVI	NFV Infrastructure
NOS	Network Operating System
OS	Operating System
OvS	OpenvSwitch
REST/ RESTful	Representational State Transfer
RFID	Radio Frequency Identification
SBI	Southbound Interface
SD	Software-Defined
SD-IoT	Software-Defined Internet of Things
SD-IoTC	Software-Defined Internet of Things Cluster
SD-IoTD	Software-Defined Internet of Things Device
SDN	Software-Defined Networking
SDN-NFV	Software-Defined Networking and Network Function Virtualization
SDVS	Software-Defined Virtual Sensor
SDWSN	Software-Defined Wireless Sensor Network

SDWSN-RL	SDWSN-Reinforcement Learning
SIoT	Social Internet of Things
SOA	Service-Oriented Architecture
SOC	System on Chip
TCP	Transmission Control Protocol
TWh	terawatt-hours
UDP	User Datagram Protocol
uIP/uIPv6	Micro Internet Protocol/Micro Internet Protocol version 6
UWB	Ultra-Wide Band
VNF	Virtual Network Function
VNF	Virtual Network Function
VNFM	Virtual Network Function Manager
WSN	Wireless Sensor Network
WSN/IoT	Wireless Sensor Network or Internet of Things

Abstract

Internet of Things (IoT) has developed into an interconnected platform infrastructure for providing essential services ranging from personal health care, smart homes and cities to the manufacturing industry. Relying on such an infrastructure, a multitude of emerging IoT services will no doubt be developed for not only local regions but also multiple separated regions spreading over a wide geographical area. However, existing IoT systems are mostly rigid and cannot be easily adapted or programmed to accommodate new services. The challenge is also in orchestrating a large number of sensors/IoT devices, many with limited capability, into intelligent, useful, and on-demand services. Many efforts have been made to address the issue, but very little has been attempted to consider an overall solution to a programmable IoT ecosystem that includes IoT service provision components, IoT devices, and transporting infrastructure. Moreover, there is no framework/platform that allows an end-to-end control, management, and orchestration of IoT resources in accordance with IoT demands.

We apply the benefits of the two promising technologies including software-defined networking and network function virtualization in provisioning IoT services on demand over a wide region, and overcome challenges in applying the technologies to constrained IoT devices/systems. We propose a large-scale software-defined IoT (LSSD-IoT) model and develop the LSSD-IoT platform. The model provides two levels of management and orchestration at the cluster and device level. At the cluster level, we develop a software-defined Internet of Things Cluster (SD-IoTC) controller that is capable of controlling and managing both IoT clusters and network infrastructure that accommodates the IoT systems. At the device level, each IoT cluster under the control and management of the SD-IoTC controller needs to be programmable and manageable for provisioning IoT services on demand. For that purpose, we propose a software-defined Internet of Things (SD-IoT) model (local platform) with three novel components, including the IoT device-constrained controller, the S-MANAGE protocol, and the software-defined virtual sensor.

The novelty of this research lies in the novel approach to programmable and re-usable devices in the provision of IoT services on demand over a wide area. It enables i) IoT service providers to control end-to-end quality of services of IoT services provision over

a large-scale IoT environment; ii) owners of IoT systems to be able to gain benefits from sharing their IoT resources; iii) IoT application developers to develop innovative and comprehensive IoT applications on demand with more options regarding QoS, security, mobility, or billing.