



THE UNIVERSITY  
*of* ADELAIDE

**Classifying and Clustering  
the  
Web of Things**

Thesis submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy in Computer Science

by

Sujith Samuel Mathew

Supervisors

A/Prof. Michael Sheng, A/Prof. Yacine Atif, and Prof. Zakaria Maamar

Faculty of Engineering, Computer, and Mathematical Sciences

The University of Adelaide, Australia

2013

© Copyright by  
Sujith Samuel Mathew  
2013

## ORIGINALITY STATEMENT

“I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis to be made available on the Web, via the University’s digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.”

*Sujith Samuel Mathew*

PhD Candidate

School of Computer Science

University of Adelaide

April, 2013

*To Jesus, my Lord and Saviour, who walked this walk with me.*

## ACKNOWLEDGMENTS

This work has been challenging and would not have been possible if it wasn't for several people. Their support and encouragement cannot be expressed in words, but I acknowledge them here.

I would like to thank my supervisors, who relentlessly inspired me to pursue excellence. Dr. Michael Sheng taught me to always aim high and to not give up. Dr. Yacine Atif believed in me, encouraged me to run this race, and critically reviewed my work. Dr. Zakaria Maamar keenly refined my efforts and promptly corrected my work. Their experience, guidance, and positive attitude were pivotal for my study. I am deeply indebted to them.

I would like to thank my colleagues at the College of IT, UAE University for their support. A special thanks to Dr. Mohamed Adel Serhani, who faithfully and patiently reviewed my work.

Finally, I am indebted to my parents, my wife, and my two boys, for their constant support and prayers. I express my heartfelt gratitude to them for all their sacrifices, their love, and for standing by me every single day. This would have been impossible without them.

## ABSTRACT

The *Web of Things* is emerging as a promising solution for realizing ubiquitous applications, where real-world things and people seamlessly connect and communicate. The challenges of integrating real-world things into the virtual environment of the Web have been the subject of much research recently. Such environments present a major challenge i.e. to retrieve combined environmental services and relevant information through prevalent means. Research in this direction is significantly challenging because of the growing number of heterogeneous things connected to the Web and the potential ubiquitous applications that would positively influence society, business, and industry. The substantial numbers of proprietary applications that integrate real-world things reveal the requirement for an open and scalable framework for including the plethora of things in a systematic and structured manner. Adequate solutions to manage the ever increasing number of things are paramount to induce flexibility, robustness, and usability in future ubiquitous applications.

In this dissertation, we propose a novel semantic structure to represent things on the Web. We classify things into an ontological structure based on required capabilities to participate in the Web. We introduce the *Ambient Space framework* to manage things in a scalable manner and use it to model the creation of *communities of things*. We describe the process of analyzing thing's semantic structure to cluster them into communities. We also discuss how things join these communities inherently to establish relationships with people on contemporary social networks. Finally, we present case-studies centered on environment sustainability which show applications where a number of things are managed using our framework in autonomous, heterogeneous, and dynamic environments. Our evaluations reveal the benefits of such applications, compared to conventional solutions, in support of sustainable environments.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Motivations . . . . .	2
1.2	Research Issues . . . . .	5
1.3	Contributions . . . . .	8
1.4	Dissertation Organization . . . . .	10
<b>2</b>	<b>Background and Related Work</b>	<b>13</b>
2.1	The Web – An Application Platform for Real-World Things . . . . .	14
2.2	Technologies Driving the Web of Things . . . . .	17
2.2.1	Web Services . . . . .	17
2.2.2	Embedded Web Servers . . . . .	22
2.2.3	Networking Real-world Things . . . . .	23
2.3	Building Web of Things Applications . . . . .	26
2.3.1	AJAX Approach . . . . .	26
2.3.2	Mashup Approach . . . . .	27
2.3.3	Event Driven Approach . . . . .	28
2.4	Research Directions . . . . .	29

---

2.4.1	Integrating Things on the Web . . . . .	29
2.4.2	SOCRADES Integration Architecture (SIA) . . . . .	30
2.4.3	The Web of Things Application Architecture . . . . .	32
2.5	Related Work . . . . .	34
2.6	Summary . . . . .	38
<b>3</b>	<b>A Classification of Things for the Web of Things</b>	<b>39</b>
3.1	Overview . . . . .	40
3.1.1	Design of an Ambient Learning Space . . . . .	41
3.1.2	Supporting Work Towards Classifying Things . . . . .	45
3.2	A Capability Based Classification of Things . . . . .	46
3.2.1	An Ontology of Things on the Web . . . . .	47
3.2.2	Prototype of Ambient Learning Space . . . . .	55
3.3	Social Attributes of Things on the Web . . . . .	57
3.4	Summary . . . . .	61
<b>4</b>	<b>Managing Things in Ambient Spaces</b>	<b>62</b>
4.1	Web Object Metadata (WOM) . . . . .	63
4.2	Actors Building the WOM . . . . .	65
4.3	Ambient Space Framework . . . . .	69
4.4	Creating Web Smart Things . . . . .	71
4.5	A Collection of Things . . . . .	75
4.6	Summary . . . . .	77
<b>5</b>	<b>Towards a Community of Things on the Web</b>	<b>78</b>



---

5.1	The Social Web of Things . . . . .	80
5.2	Building a Community of Things . . . . .	82
5.2.1	Grouping Similar Type of Web Smart Things . . . . .	84
5.2.2	Grouping Web Smart Things with Similar Social Relationships . . . . .	85
5.3	Modeling a Community of Things . . . . .	87
5.3.1	Grouping Things into Ambient Spaces . . . . .	87
5.3.2	Modeling the Similarity of Web Smart Things . . . . .	89
5.3.3	Clustering Algorithm . . . . .	95
5.3.4	Benefits of Clustering Things into Communities . . . . .	98
5.4	Handling Incomplete WOM-Profiles . . . . .	102
5.4.1	Assumptions to Address Sparse WOM-Profiles . . . . .	103
5.4.2	Adapting the K-Tree and Random Indexing Approach . . . . .	103
5.5	Summary . . . . .	105
<b>6</b>	<b>Case Studies and Implementation</b>	<b>106</b>
6.1	Case Study 1: Building Sustainable Parking Lots . . . . .	106
6.1.1	Motivational Scenario . . . . .	109
6.1.2	Survey of Automated Parking Solutions . . . . .	110
6.1.3	Ambient Parking Lot Application . . . . .	112
6.1.4	Design and Prototype Implementation . . . . .	115
6.1.5	Analysis and Evaluation . . . . .	121
6.1.6	Discussion and Conclusion . . . . .	126
6.2	Case Study 2: A Sustainable Campus with the WoT . . . . .	127
6.2.1	Survey of Ambient Infrastructure . . . . .	128

---

6.2.2	Ambient Classroom Framework . . . . .	129
6.2.3	Challenges of Building an Ambient Classroom . . . . .	131
6.2.4	Design and Prototype Implementation . . . . .	136
6.2.5	Preliminary Evaluation . . . . .	140
6.2.6	Discussion and Conclusion . . . . .	141
6.3	Summary . . . . .	141
<b>7</b>	<b>Conclusions</b>	<b>142</b>
7.1	Summary . . . . .	142
7.2	Future Directions . . . . .	146
	<b>Bibliography</b>	<b>149</b>

# List of Figures

2.1	Realizing Web-Enabled Things . . . . .	15
2.2	Internet Enabling Things with RFID . . . . .	24
2.3	Comparison between TCP/IP and 6LoWPAN protocol stacks . . . . .	26
2.4	Main layers of SOCRADES Integration Architecture (SIA) . . . . .	31
2.5	Application Architecture for the Web of Things . . . . .	32
3.1	Design of Immersive Learning Room . . . . .	43
3.2	Model of Web Object Metadata (WOM) . . . . .	48
3.3	WOM-Capability class and IPCS sub-classes . . . . .	51
3.4	UML Descriptors for the Class Relationships . . . . .	52
3.5	Experiential Learning Cycle . . . . .	56
3.6	Immersive Learning Room . . . . .	57
3.7	Lifespan of Things . . . . .	59
4.1	Extended Model of Web Object Metadata (WOM) . . . . .	64
4.2	The Ambient Space framework for classrooms on a campus . . . . .	70
4.3	Transforming things into Web Smart things . . . . .	73
4.4	Light transformed into Web Smart Light . . . . .	74

---

4.5	Social Web of Things created by mashup of Ambient Spaces . . . . .	76
5.1	Connecting People and Things through Ambient Spaces . . . . .	81
5.2	Two types of Ambient Spaces . . . . .	84
5.3	Clustering Web Smart things into Ambient Spaces . . . . .	88
5.4	Structure and Content Representation of four WOM-Profiles . . . . .	92
5.5	Comparing cost of communication: Community versus Individual Things . . . . .	101
6.1	Smart Parking Spots in an Ambient Parking Lot . . . . .	108
6.2	Layers of an Ambient Parking Lot Application . . . . .	113
6.3	Exposing information on a thing as RESTful Web services . . . . .	114
6.4	Design of Ambient Parking lot with three Smart Parking Spots . . . . .	115
6.5	Reservation page and online display of the parking spots . . . . .	116
6.6	Things in a Smart Parking Spot (SPS) . . . . .	118
6.7	Composition of parking services . . . . .	120
6.8	(a) Cruising time of Ben and Jon, and (b) Total time of Ben and Jon . . . . .	125
6.9	The emission rates for SPS and unreserved parking spots . . . . .	126
6.10	Classrooms abstracted using Ambient Space framework . . . . .	130
6.11	Comparison of the actual usage of lights <i>versus</i> the required usage in two classrooms	132
6.12	A Web Smart thing representing a real-world thing . . . . .	133
6.13	(a) Room signage fixed outside a classroom and connected to the campus Intranet. Insets show the operating system, the monthly view of the calendar service and the touch screen interface. (b) Things Control and Sensing (TCS) subsystem. . . . .	137
6.14	The Average use of lights in ambient classrooms . . . . .	140

# List of Tables

- 3.1 Classification of Primitive Things and Complex Things . . . . . 50
- 4.1 Example of WOM-Profile (Partial) . . . . . 66
- 5.1 Path Matrix for Structural Model . . . . . 93
- 5.2 Term Matrix for Content Model . . . . . 93
- 6.1 Traveling events to the parking lot for Ben and Jon . . . . . 122

# List of Publications

**Mathew S.S.**, Atif Y., Sheng Q. and Maamar Z., "The Web of Things - Challenges and Enabling Technologies", In Internet of Things and Inter-cooperative Computational Technologies for Collective Intelligence (N. Bessis, F. Xhafa, D. Varvarigou, R. Hill, and M. Li, eds.), Vol. 460 of Studies in Computational Intelligence, pp. 1-23. Springer Berlin Heidelberg. 2013.

**Mathew S.S.**, Atif Y., Sheng Q. and Maamar Z., "Building Sustainable Parking Lots with the Web of Things", Personal and Ubiquitous Computing (PUC) journal, pp. 1-13, Springer-Verlag. June 2013.

**Mathew S.S.**, Atif Y., Sheng Q. and Maamar Z., "A New Parking System based on the Web of Things", In Proceedings of the workshop on Computing and Networking for Internet of Things (ComNet-IoT), in conjunction with International Conference on Distributed Computing and Networking (ICDCN), Mumbai, India, January , 2013.

**Mathew S.S.**, Atif Y., Sheng Q. and Maamar Z., "Towards an efficient sales pitch with the Web of Things", In the Tenth IEEE International Conference on eBusiness Engineering (ICEBE). Coventry, United Kingdom, 2013.

**Mathew S.S.** , "Managing Things in an Ambient Space", In the Ninth International Confer-

ence on Service Oriented Computing (ICSOC), pp. 226-232. Cyprus, 2012.

Maamar Z., Sheng Q.Z., Atif Y., **Mathew S.S.** and Boukadi K, "Towards an Approach for Weaving Preferences into Web Services Operation", Journal of Software. Vol. 7(7), pp. 1429-1439. 2012.

Trabelsi Z., Hayawi K., Al Braiki A. and **Mathew S.S.**, "Network Attacks and Defenses: A Hands-On Approach", Auerbach Publications (Taylor and Francis). 2012.

**Mathew S.S.**, Atif Y., Sheng Q. and Maamar Z., "Web of Things: Description, Discovery and Integration", In International Conference on Internet of Things and Cyber, Physical and Social Computing (iThings/CPSCoM), pp. 9-15. Dalian, China, 2011.

*Citations: 6*

**Mathew S.S.**, Atif Y., Sheng Q. and Maamar Z., "Ambient things on the Web", Journal of Ubiquitous Systems and Pervasive Networks (JUSPN). Vol. 1(1), pp. 1-8. 2010.

*Citations: 2*

Atif Y., **Mathew S.S.**, "Ambient Learning Companion", in Proceedings of 2nd International Conference on Education and New Learning Technologies (EDULEARN10), pp. 4787-4791. Barcelona, Spain. 2010.

Atif Y., Serhani M.A., Campbell P. and **Mathew S.S.**, "Trusted Translation Services", In Collaborative Computing: Networking, Applications and Worksharing. Vol 10, pp. 778-791. Springer Berlin Heidelberg. 2009.