

University of Technology Sydney

Faculty of Engineering and IT

School of Electrical and Data Engineering

**Development and Optimisation
of Wireless Indoor localisation
for the IoT Solutions**

Doctoral Candidate: Yu, Zheng yu

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Zheng yu Yu declare that this thesis, is submitted in fulfilment of the requirements for the award of a degree of Doctor of Philosophy, in the Faculty of Engineering and IT 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 the 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.

Date:

19/07/2020

ACKNOWLEDGMENTS

I would first like to express thanks to my PhD supervisors, Dr Zenon Chaczko and Prof Robin Braun. I have collaborated with my supervisors on several projects for the past four years. Dr Chaczko, you have been more than a supervisor to me all these days, and you have been with me every step of the way throughout this research. Thank you for your kind support during, at times, very stressful moments that I have experienced. I really appreciated your clear guidance and feedback very much.

Also, I appreciate support and help received from the Faculty of Engineering and IT staff and academics, especially that of Prof David McGloin. Thank you so much for organising series of insightful research seminars and providing comments related to my research in those past years. I have learned so much and adopted many of the most up-to-date research information and technology from these presentations.

Lastly, to my family and friends those who always support and encourage me, thank you for being with me all the time. I could not have got this far today without you. I wish for everyone's dream to come true and that you will all lead a happy life.

Contents

ABSTRACT	XV
CHAPTER 1	1
INTRODUCTION	1
1.1 BACKGROUND	1
1.2 SCOPE.....	2
1.3 RESEARCH QUESTIONS	3
1.4 RESEARCH HYPOTHESIS	3
1.5 RESEARCH CONTRIBUTIONS.....	4
1.6 THESIS STRUCTURE	6
1.6.1 Introduction	7
1.6.2 Literature Review.....	7
1.6.3 Research Methodology.....	7
1.6.4 Research Implementation of iBeacon Localisation	8
1.6.5 Research Implementation of UWB Localisation	8
1.6.6 Conclusions and Future Work	9
1.6.7 Reference.....	9
CHAPTER 2	10
LITERATURE REVIEW.....	10
2.1 INDOOR LOCALISATION TECHNIQUES REVIEW	10
2.1.1 Ultrasonic Sensor-Based Indoor Localisation System ¹	10
2.1.2 RSSI-based Indoor Localisation with High Accuracy ¹	11
2.1.3 FM Signals-Based Indoor Localisation ¹	13
2.1.4 RSS Fingerprint-Based Indoor Multi-Resolution Localisation ¹	15
2.1.5 Fingerprint-Based 3D Indoor Localisation in Wireless Sensor Networks.....	17
2.1.6 RSS-based Fingerprinting in Indoor WLAN Localisation.....	19
2.1.7 Hybrid Techniques in Indoor Localisation Environment	20
2.1.8 Wireless Optical Indoor Localisation System	22
2.1.9 Bluetooth-Based Indoor Localisation System.....	23
2.1.10 Wi-Fi Fingerprint-Based and Trilateration Techniques in Indoor Localisation.....	24
2.2 iBEACON LOCALISATION TECHNIQUES REVIEW	25
2.2.1 Beacon Code Extension Structure	25

2.2.2	<i>iBeacon-based TV Companion Applications</i>	25
2.2.3	<i>A Bluetooth-based iBeacon Indoor Localisation Networks</i>	26
2.2.4	<i>Smart Building Managed by iBeacon</i>	28
2.2.5	<i>iBeacon Technology Implemented in Location-based Services</i>	29
2.2.6	<i>iBeacon Deployment for Mobile Devices in Indoor Positioning</i>	30
2.2.7	<i>iBeacon Interaction System in a Museum</i>	31
2.2.8	<i>iBeacon Implementation in Internet of Things Environment</i>	33
2.2.9	<i>An Extended iBeacon System Proposed in Indoor Localisation</i>	33
2.3	UWB LOCALISATION TECHNIQUES REVIEW.....	35
2.3.1	<i>Optimised UWB-Based Localisation in IoT</i>	35
2.3.2	<i>UWB Multi-User in Indoor Localisation System</i>	36
2.3.3	<i>3-Tier UWB Technology for Indoor Localisation System</i>	38
2.3.4	<i>Low-Cost UWB System using Linear Bayesian Filter for Mobile Device in Indoor Localisation Environment</i>	38
2.3.5	<i>Bluetooth/UWB using Weighted LSA for Indoor Localisation</i>	39
2.4	SUMMARY.....	40
CHAPTER 3		44
RESEARCH METHODOLOGY		44
3.1	INDOOR LOCALISATION METHOD.....	44
3.1.1	<i>Signal Strength Spatial Mapping</i>	44
3.1.2	<i>Time of Flight (ToF) Method</i>	45
3.1.3	<i>Kalman Filter Method in Position Measurement</i>	45
3.1.4	<i>Trilateration and Triangulation Techniques</i>	46
3.1.5	<i>Fingerprinting Signal Mapping</i>	47
3.2	BLUETOOTH LOW ENERGY (BLE) BEACONS.....	47
3.3	THE iBEACON PROTOCOL.....	48
3.3.1	<i>The Universal Unique Identifier (UUID)</i>	48
3.3.2	<i>Major Number in BLE</i>	49
3.3.3	<i>Minor Number in BLE</i>	49
3.3.4	<i>Advertising Interval</i>	49
3.4	RANGING.....	50
3.5	CALIBRATION AND RANGING ACCURACY.....	50
3.6	FUNCTIONAL BLOCK DIAGRAM.....	51

3.7	SUMMARY	56
CHAPTER 4		58
RESEARCH IMPLEMENTATION OF IBEACON LOCALISATION		58
4.1	TESTBED SETUP FOR IBEACON LOCALISATION SYSTEM	58
4.2	CALIBRATION PROCESS FOR DIFFERENT ANGLES	61
4.2.1	<i>System Calibration for Device 1</i>	<i>62</i>
4.2.2	<i>System Calibration for Device 2</i>	<i>63</i>
4.2.3	<i>System Calibration for Device 3</i>	<i>64</i>
4.2.4	<i>System Calibration for Device 4</i>	<i>66</i>
4.2.5	<i>System Calibration for Device 5</i>	<i>67</i>
4.2.6	<i>System Calibration for Device 6</i>	<i>68</i>
4.3	ERROR MODELLING CALIBRATION PROCESS FOR DISTANCE MEASUREMENT	70
4.3.1	<i>Error Modelling Calibration for Device 1</i>	<i>71</i>
4.3.2	<i>Error Modelling Calibration for Device 2</i>	<i>77</i>
4.3.3	<i>Error Modelling Calibration for Device 3</i>	<i>83</i>
4.3.4	<i>Error Modelling Calibration for Device 4</i>	<i>88</i>
4.3.5	<i>Error Modelling Calibration for Device 5</i>	<i>94</i>
4.3.6	<i>Error Modelling Calibration for Device 6</i>	<i>101</i>
4.4	ERROR MODELLING OPTIMISED CALIBRATION RESULTS	106
4.5	FIELD EXPERIMENT OF IBEACON LOCALISATION	111
4.6	SUMMARY	117
CHAPTER 5		120
RESEARCH IMPLEMENTATION OF UWB LOCALISATION		120
5.1	TESTBED SETUP FOR UWB LOCALISATION SYSTEM	120
5.2	UWB CALIBRATION PROCESS FOR ANGLES.....	122
5.2.1	<i>System Calibration for UWB Anchor 1</i>	<i>123</i>
5.2.2	<i>System Calibration for UWB Anchor 2</i>	<i>124</i>
5.2.3	<i>System Calibration for UWB Anchor 3</i>	<i>126</i>
5.3	UWB CALIBRATION PROCESS FOR DISTANCE.....	127
5.3.1	<i>Error Modelling Calibration for UWB Anchor 1</i>	<i>129</i>
5.3.2	<i>Error Modelling Calibration for UWB Anchor 2</i>	<i>132</i>
5.3.3	<i>Error Modelling Calibration for UWB Anchor 3</i>	<i>135</i>

5.4	ERROR MODELLING OPTIMISED CALIBRATION RESULTS	137
5.5	FIELD EXPERIMENT OF UWB LOCALISATION	140
5.6	SUMMARY	147
CHAPTER 6		149
CONCLUSIONS AND FUTURE WORK		149
6.1	SUMMARY	149
6.2	THESIS CONTRIBUTION	151
6.3	DISCUSSION AND LIMITATION	153
6.4	FUTURE WORK.....	154
CHAPTER 7		156
REFERENCE		156
APPENDIX		164
PUBLICATION.....		164

List of Figures

Figure 1 Thesis structure.....	6
Figure 2 Basic concept of localisation system.....	10
Figure 3 An example of localisation processes	11
Figure 4 Wireless Signal Fingerprint	14
Figure 5 The Next Generation of the Internet Access System.....	17
Figure 6 Illustration of the experiment system	18
Figure 7 Fingerprinting localisation system	19
Figure 8 Floor Map of Testbed.....	21
Figure 9 Architecture for both data transmission and user localisation	22
Figure 10 Tag within the Transmission Range of Multiple Gateways.....	24
Figure 11 A star topology of BLE network	27
Figure 12 Main aspects of the proposed solution	29
Figure 13 Distance calculations with iBeacon.....	30
Figure 14 Partitioning of space into locations	31
Figure 15 Working process of iBeacon technology.....	32
Figure 16 App communicates with iBeacon.....	33
Figure 17 Multiple beacon modules for indoor route guidance.....	34
Figure 18 A design of iBeacon.....	35
Figure 19 Double-sided two-way ranging between tag and an anchor.....	36
Figure 20 Pseudo-time synchronisation localisation scheme schematic.....	37
Figure 21 3-Tier UWB Technology for Indoor Localisation System	38
Figure 22 Flowchart of low-cost localisation system diagram.....	39
Figure 23 System calibration and error modelling estimation	51
Figure 24 Curve Fitted Kalman Filter Error Modelling	53
Figure 25 Kalman Filter Error Modelling.....	54
Figure 26 Testbed setup at 1-meter range for different angles from 10° to 170°.....	59
Figure 27 Testbed setup for iBeacon and mobile receiver (a) (b)	60
Figure 28 Six iBeacons used in the experiment	60
Figure 29 iBeacon set up horizontally.....	60
Figure 30 Polar diagram for iBeacon device 1 at different horizontal angles from 10° to 170°	62

Figure 31 Box-and-whisker diagram for iBeacon device 1 at different horizontal angles from 10° to 170°	63
Figure 32 Polar diagram for iBeacon device 2 at different horizontal angles from 10° to 170°	63
Figure 33 Box-and-whisker diagram for iBeacon device 2 at different horizontal angles from 10° to 170°	64
Figure 34 Polar diagram for iBeacon device 2 at different horizontal angles from 10° to 170°	65
Figure 35 Box-and-whisker diagram for iBeacon device 3 at different horizontal angles from 10° to 170°	65
Figure 36 Polar diagram for iBeacon device 4 at different horizontal angles from 10° to 170°	66
Figure 37 Box-and-whisker diagram for iBeacon device 4 at different horizontal angles from 10° to 170°	67
Figure 38 Polar diagram for iBeacon device 5 at different horizontal angles from 10° to 170°	67
Figure 39 Box-and-whisker diagram for iBeacon device 5 at different horizontal angles from 10° to 170°	68
Figure 40 Polar diagram for iBeacon device 6 at different horizontal angles from 10° to 170°	69
Figure 41 Box-and-whisker diagram for iBeacon device 6 at different horizontal angles from 10° to 170°	69
Figure 42 Testbed setup for 1-meter distance range (a)	70
Figure 43 Testbed setup for 1-meter distance range (b)	70
Figure 44 Diagram for Raw Data and CF Estimated Data (iBeacon device 1)	72
Figure 45 Diagram for Measured Distance and CF Estimated Distance (iBeacon device 1)	74
Figure 46 Diagram for Measured Distance and KF Estimated Distance (iBeacon device 1)	75
Figure 47 Diagram for KF Estimated Distance and KF Estimated Distance (iBeacon device 1)	75
Figure 48 Diagram for Raw Data and CF Estimated Data (iBeacon device 2)	78
Figure 49 Diagram for Measured Distance and CF Estimated Distance (iBeacon device 2)	80
Figure 50 Diagram for Measured Distance and KF Estimated Distance (iBeacon device 2)	81
Figure 51 Diagram for KF Estimated Distance and CFKF Estimated Distance (iBeacon device 2)	81
Figure 52 Diagram for Raw Data and CF Estimated Data (iBeacon device 3)	84
Figure 53 Diagram for Measured Distance and CF Estimated Distance (iBeacon device 3)	85
Figure 54 Diagram for Measured Distance and KF Estimated Distance (iBeacon device 3)	87
Figure 55 Diagram for KF Estimated Distance and CFKF Estimated Distance (iBeacon device 3)	87
Figure 56 Diagram for Raw Data and CF Estimated Data (iBeacon device 4)	90
Figure 57 Diagram for Measured Distance and CF Estimated Distance (iBeacon device 4)	91

Figure 58 Diagram for Measured Distance and KF Estimated Distance (iBeacon device 4)	92
Figure 59 Diagram for CF Estimated Distance and CFKF Estimated Distance (iBeacon device 4)	93
Figure 60 Diagram for Raw Data and CF Estimated Data (iBeacon device 5)	96
Figure 61 Diagram for Measured Distance and CF Estimated Distance (iBeacon device 5)	97
Figure 62 Diagram for Measured Distance and KF Estimated Distance (iBeacon device 5)	99
Figure 63 Diagram for KF Estimated Distance and CFKF Estimated Distance (iBeacon device 5)	99
Figure 64 Diagram for Raw Data and CF Estimated Data (iBeacon device 6)	102
Figure 65 Diagram for Measured Distance and CF Estimated Distance (iBeacon device 6)	103
Figure 66 Diagram for Measured Distance and KF Estimated Distance (iBeacon device 6)	105
Figure 67 Diagram for KF Estimated Distance and CFKF Estimated Distance (iBeacon device 6)	105
Figure 68 Diagram of Error Modelling Calibration Result (iBeacon device 1)	107
Figure 69 Diagram of Error Modelling Calibration Result (iBeacon device 2)	108
Figure 70 Diagram of Error Modelling Calibration Result (iBeacon device 3)	109
Figure 71 Diagram of Error Modelling Calibration Result (iBeacon device 4)	109
Figure 72 Diagram of Error Modelling Calibration Result (iBeacon device 5)	110
Figure 73 Diagram of Error Modelling Calibration Result (iBeacon device 6)	111
Figure 74 iBeacon set up vertically	111
Figure 75 Polar diagram for iBeacon device 1 at different vertical angles from 10° to 170°	112
Figure 76 Testbed for iBeacon localisation field experiment (a)	113
Figure 77 Testbed for iBeacon localisation field experiment (b) and (c)	113
Figure 78 Raw data of RSSI in the field experiment.....	114
Figure 79 Diagram of error modelling calibration result for field experiment	115
Figure 80 Three UWB Anchors and one UWB tag.....	121
Figure 81 Testbed setup for UWB anchor and tag (a) and (b)	121
Figure 82 Testbed setup for UWB anchor and tag (c) and testbed setup for UWB tag (d)	122
Figure 83 Polar diagram for UWB Anchor 1 at different horizontal angles from 10° to 170°	123
Figure 84 Box-and-whisker diagram for UWB Anchor 1 at different horizontal angles from 10° to 170°	124
Figure 85 Polar diagram for UWB Anchor 2 at different horizontal angles from 10° to 170°	124
Figure 86 Box-and-whisker diagram for UWB Anchor 2 at different horizontal angles from 10° to 170°	125
Figure 87 Polar diagram for UWB Anchor 3 at different horizontal angles from 10° to 170°	126

Figure 88 Box-and-whisker diagram for UWB Anchor 3 at different horizontal angles from 10° to 170°	127
Figure 89 Testbed setup for 1-meter distance range for UWB localisation (a)	127
Figure 90 Testbed setup for 1-meter distance range for UWB localisation (b) (c).....	128
Figure 91 Testbed setup for 1-meter distance range for UWB localisation (d).....	128
Figure 92 Diagram for Measured Distance and KF Estimated Distance (UWB anchor 1).....	130
Figure 93 Diagram for KF Estimated Distance and CFKF Estimated Distance (UWB anchor 1)	131
Figure 94 Diagram for Measured Distance and KF Estimated Distance (UWB anchor 2).....	133
Figure 95 Diagram for KF Estimated Distance and CFKF Estimated Distance (UWB anchor 2)	134
Figure 96 Diagram for Measured Distance and KF Estimated Distance (UWB anchor 3).....	136
Figure 97 Diagram for KF Estimated Distance and CFKF Estimated Distance (UWB anchor 3)	137
Figure 98 Diagram of Error Modelling Calibration Result (UWB anchor 1)	138
Figure 99 Diagram of Error Modelling Calibration Result (UWB anchor 2)	139
Figure 100 Diagram of Error Modelling Calibration Result (UWB anchor 3)	140
Figure 101 Floor plan for the testbed of UWB field experiment	141
Figure 102 Testbed for UWB field experiment (a).....	142
Figure 103 Testbed for UWB field experiment (b).....	142
Figure 104 Diagram of UWB field experiment results	145
Figure 105 Diagram of UWB field experiment zoomed results	145

List of Tables

Table 1 The advantages and disadvantages of the most popular localisation techniques	40
Table 2 Specification of iBeacon	61
Table 3 Specification of Smart Phone Wireless Sensors	61
Table 4 Sample data table for iBeacon device 1	71
Table 5 Algorithm error table for device 1	76
Table 6 Sample data table for iBeacon device 2	77
Table 7 Algorithm error table for device 2	82
Table 8 Sample data table for iBeacon device 3	83
Table 9 Algorithm error table for device 3	88
Table 10 Sample data table for iBeacon device 4	89
Table 11 Algorithm error table for device 4	94
Table 12 Sample data table for iBeacon device 5	95
Table 13 Algorithm error table for device 5	100
Table 14 Sample data table for iBeacon device 6	101
Table 15 Algorithm error table for device 6	106
Table 16 Algorithm error table for field experiment	116
Table 17 Algorithm error table for device 1-6	117
Table 18 UWB Anchor and Tag specification	122
Table 19 Sample data table for anchor 1	129
Table 20 Sample data table for anchor 2	132
Table 21 Sample data table for anchor 3	135
Table 22 Algorithm error table for UWB Anchor 1	138
Table 23 Algorithm error table for UWB Anchor 2	139
Table 24 Algorithm error table for UWB Anchor 3	140
Table 25 Sample data table for UWB field experiment	143
Table 26 Algorithm error table for field experiment	146
Table 27 Algorithm error table for UWB Anchor 1-3 and field experiment	147

Acronyms used in the thesis

ABS	Active Badge System
AoA	Angle of Arrival
AP	Access Point
APS	Ad-Hoc Positioning System
AR	Augmented Reality
BLE	Bluetooth Low Energy
CF	Curve Fitting
CFKF	Curve Fitted Kalman Filter
DV-HOP	Distance Vector Hop
EPG	Electronic Program Guide
FM	Frequency Modulation
GPS	Global Positioning System
HVAC	Heating, Ventilating, and Air Conditioning
IMU	Inertial Measurement Unit
IoT	Internet of Things
KF	Kalman Filter
LBS	Location-Based Service
LSBA	Link State-Based Annulus
MEMS	Micro-Electro-Mechanical-Systems
NFC	Near-Field Communication
NLOS	None Line of Sight
PVR	Personal Video Recorder
QR	Quick Response
RFID	Radio-Frequency Identification
RMSE	Root Mean Squared Error

RP	Reference Point
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RWLS	Residual-Based Weighted Least Square
SSE	Sum of Squares Due to Error
TDOA	Time Difference of Arrival
ToA	Time of Arrival
ToF	Time of Flight
UUID	Universal Unique Identifier
UWB	Ultra-Wide Band
WLAN	Wires Local Area Network
WSN	Wireless Sensor Network

ABSTRACT

Traditional indoor localisation technologies are based on beacon technology, ultrasonics, laser range localisation, or Ultra-Wide Band (UWB) system, and others. Recently, some of these localisation techniques are used in the industry by developers of iBeacon systems for finding the position of an object with Bluetooth sensors. There are various advantages of using the iBeacon-like systems, such as low-cost, a simple signalling process, and the ease of set-up and maintenance. However, using the iBeacon-based system is marked with poor accuracy. With current technology, it is difficult to obtain highly accurate localisation for indoor objects or to perform their tracking. Also, iBeacons are highly susceptible to environmental noise interference and other radio signals. To solve these issues, this research work involves investigation and development of the error modelling algorithms that can calibrate the signal sensors, reduce the errors, mitigate noise levels and interference signals. This thesis presents a new family of error modelling algorithms based on the Curve Fitted Kalman Filter (CFKF) technique. As a part of the research investigation, a range of experiments were executed to validate the accuracy, reliability and viability of the CFKF approach. Experimental results indicate that this novel approach significantly improves the accuracy and precision of beacon-based localisation. Validation tests also show that the CFKF error modelling method can improve the localisation accuracy of UWB-based solutions.