

**MULTI-FLOOR INDOOR LOCATION ESTIMATION SYSTEM BASED ON
WIRELESS LOCAL AREA NETWORK**

CHUA TIEN HAN

UNIVERSITI TEKNOLOGI MALAYSIA

To my beloved parents and brothers.

ACKNOWLEDGEMENT

I am greatly thankful to my supervisor, Professor Dr Tharek Bin Abdul Rahman for his continuous guidance, supports and encouragements. Without his patient, valuable suggestions and comments, I would not be working on this exciting research work.

I also wish to thanks all my fellow friends at Wireless Communication Centre, Universiti Teknologi Malaysia. Thanks for their continuous helps, supports, cheers, friendship and nice working atmosphere they provided.

I gratefully acknowledge the kindness from Mr. Luke Klein-Berndt and Mr. Camillo Gentile from National Institute of Standards and Technology, U.S. for sharing their works with me.

Simply I could not have reached where I am today without my pa, ma and brothers. It has been a long journey for me and they always give me love and encouragement. To them I dedicate this work.

ABSTRACT

The proliferation of high speed wireless technologies and mobile computing infrastructures has fostered a rapid development in location based services. The key to the success of location based services is the estimation of user's location. Indoor location estimation system using various wireless technologies such as infrared and ultrasound are available. However, these systems require specialized infrastructures and incur high costs. This study focuses on design and development of a software-based multi-floor indoor location estimation system using Wireless Local Area Network (WLAN). Location fingerprinting technique is employed to estimate Mobile Terminal's (MT) location. WLAN Received Signal Strength (RSS) measured by MT is used as location fingerprint. Before location estimation, database of location fingerprint is constructed by collecting histograms of RSS at predefined reference locations. During location estimation, current histogram of RSS at unknown location will be compared to the database. The most probable match is selected and returned as estimated location based on Bayesian filtering algorithm. Estimated location is reported as physical location and symbolic location. Before developing the system, study on characteristics of RSS is conducted to help the design, development and implementation of the proposed system. The proposed system is then designed and developed using Java programming language. The performance of the proposed system is evaluated in a two-floor building using off-the-shelf WLAN access points and client device. Finally, various factors which affect the performance of the proposed system are investigated. From the evaluations in the two-floor building, the proposed system achieved best accuracy of 4.56 meters during stationary tests and 4.54 meters during mobile tests with 90% precision. The best percentage of correct floor estimation is 100% for both tests.

ABSTRAK

Perkembangan pesat teknologi wayarles berkelajuan tinggi dan infrastruktur komputer bergerak telah menggalakkan pembangunan cepat dalam perkhidmatan berdasarkan lokasi. Kunci kejayaan perkhidmatan berdasarkan lokasi ialah penganggaran lokasi pengguna. Sistem penganggaran lokasi dalam bangunan yang menggunakan pelbagai jenis teknologi wayarles seperti inframerah dan ultrabunyi boleh didapati. Namun, sistem-sistem ini memerlukan infrastruktur khas dan mendatangkan kos yang tinggi. Kajian ini memfokus pada rekabentuk dan pembangunan perisian sistem penganggaran lokasi dalam bangunan bertingkat dengan menggunakan Rangkaian Kawasan Setempat Wayarles (WLAN). Teknik pencap-jarian lokasi diguna untuk menganggarkan lokasi Terminal Bergerak (MT). Kekuatan Isyarat Diterima (RSS) WLAN yang diukur oleh MT digunakan sebagai cap jari lokasi. Sebelum penganggaran lokasi, pangkalan data untuk cap jari lokasi dibina dengan mengumpulkan histogram RSS di kawasan rujukan yang ditakrifkan awal. Semasa penganggaran lokasi, histogram RSS semasa di lokasi yang tidak diketahui dibanding dengan pangkalan data. Padanan yang paling hampir dipilih dan dikembalikan sebagai lokasi anggaran berasaskan algoritma penapisan Bayesian. Lokasi anggaran dilaporkan sebagai lokasi fizikal dan lokasi simbol. Sebelum membangunkan sistem ini, kajian atas ciri-ciri RSS dijalankan untuk membantu rekabentuk, pembangunan dan pelaksanaan sistem yang dicadangkan. Sistem yang dicadangkan kemudiannya direkabentuk dan dibangunkan dengan menggunakan bahasa pengaturcaraan Java. Pelaksanaan sistem yang dicadangkan dinilai dalam bangunan dua tingkat dengan menggunakan titik capaian dan alat pelanggan WLAN. Akhirnya, pelbagai faktor yang mempengaruhi pelaksanaan sistem yang dicadangkan telah disiasat. Daripada penilaian dalam bangunan dua tingkat, sistem yang dicadangkan mencapai kejituan terbaik 4.56 meter semasa ujian pegun dan 4.54 meter semasa ujian bergerak dengan kepersisan 90%. Peratusan terbaik penganggaran tingkat yang betul adalah 100% untuk kedua-dua ujian.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	v
	ABSTRAK	vi
	TABLE OF CONTENTS	vii
	LIST OF TABLES	xv
	LIST OF FIGURES	xvii
	LIST OF SYMBOLS	xxiv
	LIST OF ABBREVIATIONS	xxvi
	LIST OF APPENDICES	xxviii
1	INTRODUCTION	
	1.1 Background	1
	1.2 WLAN-Based Multi-Floor Indoor Location Estimation System	2
	1.3 Problem Statement	3
	1.4 Objectives	4
	1.5 Research Scope	4
	1.6 Contributions	5
	1.7 Thesis Organization	6

2	WIRELESS INDOOR LOCATION ESTIMATION SYSTEM	
2.1	Basic Architecture of Wireless Indoor Location Estimation System	8
2.2	Location Sensor	9
2.2.1	Classification of Location Sensor	9
2.2.2	Wireless Sensing Technology	10
2.2.2.1	Infrared	10
2.2.2.2	Ultrasound	11
2.2.2.3	Radio Frequency	11
2.3	Location Estimation Technique	12
2.3.1	Proximity Sensing	12
2.3.2	Triangulation	13
2.3.2.1	Lateration	13
2.3.2.2	Angulation	14
2.3.3	Location Fingerprinting	15
2.4	Properties of Wireless Indoor Location Estimation System	16
2.4.1	Network-Based System and Terminal-Based System	16
2.4.2	Specialized Infrastructure and Existing Infrastructure	17
2.4.3	Physical Location and Symbolic Location	17
2.4.4	Accuracy and Precision	18
2.4.5	Scalability	18
2.4.6	Cost	19
2.5	Previous Researches on Wireless Indoor Location Estimation System	19
2.6	Summary	21

3	WLAN-BASED INDOOR LOCATION ESTIMATION SYSTEM	
3.1	Overview of IEEE 802.11 WLAN	22
3.1.1	Basic Components of IEEE802.11 WLAN	23
3.1.2	Topologies of IEEE 802.11 WLAN	23
3.1.3	Basic Operation of IEEE 802.11 WLAN	25
3.2	Overview of WLAN-Based Indoor Location Estimation System	26
3.3	WLAN-Based Indoor Location Estimation Techniques	27
3.3.1	WLAN-Based Proximity Sensing	27
3.3.2	WLAN-Based Triangulation	29
3.3.3	WLAN-Based Location Fingerprinting	29
3.4	Overview of WLAN-Based RSS Location Fingerprinting	30
3.4.1	Basic Operation	30
3.4.2	Reference Location	32
3.4.3	Location Fingerprint	33
	3.4.3.1 Location Information	33
	3.4.3.2 Fingerprint Information	34
3.4.4	Location Estimation Algorithm	36
	3.4.4.1 Nearest Neighbor in Signal Space	36
	3.4.4.2 Probabilistic Algorithm	38
3.5	Bayesian Filtering for Location Estimation	40
3.5.1	Bayesian Filter	40
3.5.2	Implementation of Bayesian Filter	45
3.6	Related Researches	46
3.7	Summary	50

4	METHODOLOGY	
4.1	Overview of the Proposed System	51
4.2	Design and Development Processes	54
4.3	Proposed System Specifications	56
4.4	Experimental Test Bed	57
4.5	Experimental Hardware	58
4.6	Experimental Software	60
4.7	Summary	62
5	CHARACTERISTICS OF WLAN RECEIVED SIGNAL STRENGTH	
5.1	Introduction	63
5.2	Location Dependency of WLAN RSS	65
5.3	WLAN RSS Distribution at a Stationary Indoor Location	67
5.4	Statistical Representation of WLAN RSS Distribution at a Stationary Indoor Location	70
5.5	Variation of Numbers of APs Detected at a Stationary Indoor Location	74
5.6	Effects of User Proximity	77
5.7	Effects of User's Orientation	79
5.8	Effects of Different Environments	82
5.9	Effects of Types of WLAN Client Device	87
5.10	Effects of Multi-Floor Environment	90
5.11	Summary	94
6	SYSTEM DESIGN AND DEVELOPMENT	
6.1	Proposed Multi-Floor Indoor Location Estimation Framework	96
6.1.1	Topological Map Representation	98
6.1.2	Environmental Model	100

6.1.3	Bayesian Filtering	104
6.1.3.1	State Space Representation	106
6.1.3.2	Topological Markov Localization	109
6.1.3.3	Perceptual Model	113
6.1.3.4	Motion Model	114
6.1.3.5	Proposed Location Estimation Algorithm	117
6.1.4	Continuous Space Location Estimation	119
6.1.4.1	Centre of Mass	119
6.1.4.2	Time Averaging	122
6.1.5	Logical Area Estimation	123
6.2	System Development	124
6.2.1	Software Architecture	124
6.2.2	System Interface Component	126
6.2.2.1	Main GUI	126
6.2.2.2	System Configuration	127
6.2.3	Data Collection Component	128
6.2.3.1	RSS Reader	130
6.2.3.2	Access Point Filter	133
6.2.4	Database Component	134
6.2.4.1	Histogram Builder	135
6.2.4.2	Histogram Reliability Checker	138
6.2.4.3	Topological Map Builder	140
6.2.5	Location Estimation Component	142
6.2.5.1	Discrete-Space Location Estimator	142
6.3	System Implementation	152
6.3.1	Off-Line Phase	152
6.3.2	On-Line Phase	152
6.4	Summary	157

7	RESULTS AND DISCUSSION	
7.1	Introduction	158
7.2	Performance Metrics	158
7.2.1	Accuracy and Precision	159
7.2.2	Percentage of Correct Logical Area Estimation	159
7.2.3	Percentage of Correct Floor Estimation	160
7.3	Types of Experiment	160
7.4	Stationary and Mobile Multi-Floor Indoor Location Estimation	161
7.4.1	Experimental Setup	162
7.4.1.1	Test-bed	162
7.4.1.2	Off-line Phase	165
7.4.1.3	On-line Phase for Stationary Multi-floor Indoor Location Estimation	165
7.4.1.4	On-line Phase for Mobile Multi-floor Indoor Location Estimation	168
7.4.2	Experiment 1a: Stationary Multi-floor Indoor Location Estimation	169
7.4.2.1	Accuracy and Precision	169
7.4.2.2	Percentage of Correct Logical Area Estimation and Percentage of Correct Floor Estimation	170
7.4.2.3	Discussion	171
7.4.3	Experiment 1b: Mobile Multi-floor Indoor Location Estimation	173
7.4.3.1	Accuracy and Precision	173

	7.4.3.2	Percentage of Correct Logical Area Estimation and Percentage of Correct Floor Estimation	174
	7.4.3.3	Discussion	175
7.5		Factors Affecting the Performance of the Proposed System	177
	7.5.1	Experimental Setup	177
	7.5.2	Experiment 2a: Effects of number of access points	180
	7.5.2.1	Accuracy	180
	7.5.2.2	Percentage of Correct Logical Area Estimation	182
	7.5.2.3	Percentage of Correct Floor Estimation	183
	7.5.2.4	Discussion	184
	7.5.3	Experiment 2b: Effects of number of topological nodes	185
	7.5.3.1	Accuracy	185
	7.5.3.2	Percentage of Correct Logical Area Estimation	186
	7.5.3.3	Percentage of Correct Floor Estimation	188
	7.5.3.4	Discussion	188
	7.5.4	Experiment 2c: Effects of number of RSS samples per fingerprint	189
	7.5.4.1	Accuracy	189
	7.5.4.2	Percentage of Correct Logical Area Estimation	190
	7.5.4.3	Discussion	191
	7.5.5	Experiment 2d: Effects of off-line phase sampling interval	192
	7.5.5.1	Accuracy	192

	7.5.5.2	Percentage of Correct Logical Area Estimation	193
	7.5.5.3	Discussion	193
7.6		Summary	194
8		CONCLUSION	
	8.1	Conclusion	196
	8.2	Future Works	198
		REFERENCES	200
		Appendix A	205
		Appendix B	209
		Appendix C	210

LIST OF TABLES

TABLE NO.	TITLE	PAGE
3.1	Example of radio map	35
4.1	Specifications of the proposed system	56
4.2	Channel allocation for access points installed in WCC, UTM	60
5.1	Objectives and types of studies on WLAN RSS characteristics	64
5.2	Average RSS tuple from three access points at different measurement locations	67
5.3	Summary of statistics for RSS distribution from access point A7 at location L1 with different numbers of samples	72
5.4	Numbers of RSS samples collected from access points at location L1 over 60 RSS measurements	75
5.5	Average RSS at location L3 and L4 with forward and backward orientations	80
5.6	Average and standard deviation of the RSS distributions for access point A7, A11 and B3 at location L1 during busy office and empty office environments	85
5.7	List of IEEE 802.11b/g WLAN client device	88
5.8	Summary on WLAN RSS characteristics	94
6.1	Paths and tracks represented by the topological map in Figure 6.3	107
6.2	Allowed and restricted state representations	109

7.1	Objectives and types of experiment carried out to study the performance of the proposed system and various factors affecting the performance	161
7.2	Performance of three location modes during stationary multi-floor location estimation	172
7.3	Performance of three location modes during mobile multi-floor location estimation	176
7.4	Access points used to investigate the effects of number of access points on location estimation performance	180

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Basic architecture of wireless indoor location estimation system	9
2.2	Concept of proximity sensing	12
2.3	Concept of triangulation via lateration	14
2.4	Concept of triangulation via angulation	15
2.5	Concept of location fingerprinting	16
3.1	Basic components of IEEE 802.11 WLAN	23
3.2	WLAN topologies. (a) Independent basic service set (b) Basic service set (c) Extended service set	24
3.3	Passive scanning	25
3.4	Active scanning	26
3.5	Basic architecture of a WLAN-based indoor location estimation system	27
3.6	Basic operation of WLAN-based RSS location fingerprinting. (a) Off-line phase (b) On-line phase	31
3.7	Reference locations (a) Regular grid (b) Irregular	32
3.8	Nearest neighbor in signal space (NNSS) and k-NNSS ($k = 3$)	38
3.9	One-dimensional illustration of Bayesian Filtering technique	44
4.1	Basic architecture of the proposed system	51
4.2	Flow chart of off-line phase	52

4.3	Flow chart of on-line phase	3
4.4	Design and development process of the proposed system	55
4.5	Floor 1 of WCC, UTM and the locations of the access points	57
4.6	Floor 2 of WCC, UTM and the locations of the access points	58
4.7	Hardware used in the proposed system (a) DLink DWL-2000AP+ WLAN access point (b) HP Compaq tc1100 Tablet PC	59
4.8	Snapshot of Netstumbler software	61
5.1	Average RSS from three access points at different locations as MT traveled along hallway <i>Path_1a</i>	65
5.2	RSS measured from access point (a) A7 (b) A11 (c) B3 for duration of 12 hours at location L1	68
5.3	Histograms of RSS distribution for access point (a) A7 (b) A11 and (c) B3 measured for duration of 12 hours at location L1	71
5.4	Histograms of RSS distribution for access point A7 at location L1 calculated with (a) 30 (b) 50 (c) 100 (d) 200 (e) 300 RSS samples	73
5.5	Number of access points detected by WLAN client device at location L1 over 60 RSS measurements	75
5.6	RSSs measured from access point A7, A8, A10, A12 and B3 at location L1 over 60 RSS measurements	76
5.7	RSS Measured from access point (a) A6 (b) B3 (c) B4 (d) A5 at location L2 with user absence in the first two hours and presence for the following two hours	78
5.8	Average RSS Measured from access point B3, B4, A5 and A6 at location L2 with user absence in the first two hours and presence for the following two hours	79

5.9	RSS measured from access point A7 at location L1 during (a) Busy office environment (b) Empty office environment	83
5.10	RSS measured from access point A11 at location L1 during (a) Busy office environment and (b) Empty office environment	84
5.11	RSS measured from access point B3 at location L1 during (a) Busy office environment and (b) Empty office environment	85
5.12	Average RSS measured from access point A3, A8 and B3 at location L5 with five different WLAN client devices	89
5.13	RSS measured at different floors from access point (a) A7 and (b) B4 at location L6 and L7 respectively	91
5.14	RSS measured at different floors from access point (a) A4 and (b) B3 at location L8 and L9 respectively	92
5.15	Average and difference of RSS measured from access point A7, B4, A4 and B3 at different floors	93
6.1	Proposed multi-floor indoor location estimation framework	97
6.2	Topological map representation of a two-floor indoor environment	99
6.3	Calibration nodes	101
6.4	An example of normalized RSS histogram collected from one AP at one calibration node	102
6.5	Structure of the proposed environmental model	103
6.6	Structure of proposed state representation	108
6.7	Basic operation of topological Markov localization	111
6.8	Motion Model	115
6.9	State transitional probability	116
6.10	Procedure to recursively update the proposed topological Markov localization algorithm	118

6.11	Concept of centre of mass	120
6.12	Continuous space location estimation using centre of mass technique	121
6.13	Representation of indoor area using logical area	123
6.14	Software architecture of the proposed system	125
6.15	The Main GUI of the proposed system	127
6.16	The Location Options submenu. (a) Discrete or continuous space location estimation. (b) The time averaging interval for time averaging technique	128
6.17	Flow chart of Data Collection Component	129
6.18	Flow chart of RSS reader module	131
6.19	Source code for retrieving RSS tuple using WiFiSpotter API	132
6.20	Example of text file which defines the SSID of the trusted WLANs	133
6.21	Flow chart of access point filter module	134
6.22	Flow chart of Database component	135
6.23	Flow chart of Histogram Builder Module	136
6.24	Flow chart of Histogram Reliability Checker module	139
6.25	(a) Simple graph (b) Directed graph	140
6.26	Source Code for constructing topological map with simple graph and directed graph using JGraphT API	141
6.27(a)	Flow chart of the Discrete-Space Location Estimator Module	143
6.27(b)	Sub-Function: Generate all Possible States	144
6.27(c)	Sub-Function: Generate all Allowed States	145
6.27(d)	Sub-Function: Generate all Possible State Transitions	146

6.27(e)	Sub-Function: Initialize all state probabilities with global probability	147
6.27(f)	Sub-Function: Calculate time-invariant state transition probabilities	148
6.27(g)	Sub-Function: Calculate RSS observation Probabilities	149
6.27(h)	Sub-Function: Predict Current State	150
6.27(i)	Sub-Function: Correct and Normalize the Predicted State Probabilities	151
6.28	Choose and insert floor map	153
6.29	Floor maps for multi-floor environment loaded	153
6.30	Define topological map	154
6.31	Define logical area	154
6.32	Calibration Process. Go to calibration node and face the direction of arrow shown. Press start collect RSS button and wait until progress bar completed	155
6.33	Save the model as radio map	155
6.34	The histograms in radio map can be observed through analyzer. This example shows a part of the histograms collected at calibration node at location (420.0, 476.0).	156
6.35	Load radio map model created in off-line phase	156
6.36	Textual and graphical location report, $\langle x, y, floor, logical\ area \rangle$	157
7.1	Distribution of topological nodes and logical areas on floor 1 of WCC, UTM	163
7.2	Distribution of topological nodes and logical areas on floor 2 of WCC, UTM	164
7.3	Testing locations and testing paths used for performance evaluation on floor 1 of WCC, UTM	166

7.4	Testing locations and testing paths used for performance evaluation on floor 2 of WCC, UTM	167
7.5	CDF of location error for stationary multi-floor location estimation	169
7.6	Comparison of average location error and time duration for 750 location estimates in stationary multi-floor location estimation	170
7.7	Percentage of correct logical area estimation and percentage of correct floor estimation for stationary multi-floor location estimation	171
7.8	CDF of location error for mobile multi-floor location estimation	173
7.9	Comparison of average location error and average MT's walking speed during on-line phase for mobile multi-floor location estimation	174
7.10	Percentage of correct logical area estimation and percentage of correct floor estimation for mobile multi-floor location estimation	175
7.11	Rectangular hallway test-bed with (a) 4 (b) 10 (c) 22 topological nodes	178
7.12	Staircase area test-bed with (a) 4 (b) 7 (c) 9 topological nodes	179
7.13	Effects of number of access points on average location error during stationary location estimation	181
7.14	Effects of number of access points on average location error during mobile location estimation	181
7.15	Effects of number of access points on percentage of correct logical area estimation during stationary location estimation	182
7.16	Effects of number of access points on percentage of correct logical area estimation during mobile location estimation	183
7.17	Effects of number of access points on percentage of correct floor estimation during stationary location estimation	184

7.18	Effects of number of topological nodes on average location error during stationary location estimation	185
7.19	Effects of number of topological nodes on average location error during mobile location estimation	186
7.20	Effects of number of topological nodes on percentage of correct logical area estimation during stationary location estimation	187
7.21	Effects of number of topological nodes on percentage of correct logical area estimation during mobile location estimation	187
7.22	Effects of number topological nodes on percentage of correct floor estimation during stationary location estimation	188
7.23	Effects of number of RSS samples per fingerprint on average location error during stationary location estimation	190
7.24	Effects of number of RSS samples per fingerprint on percentage of correct logical area estimation during stationary location estimation	191
7.25	Effects of off-line phase sampling interval on average location error during stationary location estimation	192
7.26	Effects of off-line phase sampling interval on percentage of correct logical area estimation during stationary location estimation	193

LIST OF SYMBOLS

a	-	Angle
A	-	Set of access points installed in indoor area
$Bel(\bullet)$	-	Current belief / Corrected belief
$Bel^-(\bullet)$	-	Predicted belief
b	-	Number of topological nodes, \mathcal{V}
c	-	Number of edges in topological map, \mathcal{E}
d	-	Direction
D	-	Euclidean distance in signal space
\mathcal{E}	-	Set of edges in topological map
e	-	Edge in topological map
\mathcal{F}	-	Fingerprint information (RSS Values)
f	-	Floor number
\mathcal{G}	-	Graph
i	-	Arbitrary index
j	-	Arbitrary index
l	-	Calibration node
\mathcal{L}	-	Location Information
L	-	Set of calibration nodes
$meanRSS$	-	Mean received signal strength
M	-	Set of single RSS measurement
N_a	-	Number of access points installed in indoor area
N_b	-	Number of access points detected at a given calibration node
N_c	-	Number of calibration nodes
N_m	-	Number of RSS samples in histogram

N_p	-	Number of different RSS values in histogram
N_s	-	Number of state
O	-	Location sensor observation / Observed RSS value
r	-	Radius
RSS	-	Value of received signal strength
\tilde{S}	-	State space
S	-	State
s_t	-	State at time t
t	-	Time
\mathcal{V}	-	Set of topological nodes in topological map
v	-	Topological node
x	-	x-axis coordinate
y	-	y-axis coordinate
z	-	z-axis coordinate
%	-	Percentage
α	-	Normalizing constant
θ	-	Orientation (Forward or backward)

LIST OF ABBREVIATIONS

2D	-	Two-Dimensional
3D	-	Three-Dimensional
a.m.	-	Ante Meridiem
AOA	-	Angle of Arrival
AP	-	Access Point
API	-	Application Programming Interface
BER	-	Bit Error Rate
BSS	-	Basic Service Set
cdf	-	Cumulative Distribution Function
dB	-	Decibel
dBm	-	mili-Decibel
DOA	-	Direction of Arrival
DSSS	-	Direct Sequence Spread Spectrum
ESS	-	Extended Service Set
FHSS	-	Frequency Hopping Spread Spectrum
GHz	-	GigaHertz
GPS	-	Global Positioning System
GUI	-	Graphical User Interface
HP	-	Hewlett-Packard
IBSS	-	Independent Basic Service Set
IEEE	-	Institute of Electrical and Electronics Engineers
ISM	-	Industrial, Scientific and Medical
kHz	-	KiloHertz
<i>k</i> -NNSS	-	<i>k</i> - Nearest Neighbor in Signal Space
LANDMARC	-	Location Identification based on Dynamic Active RFID
LBS	-	Location Based Services
LES	-	Location Estimation System

LOS	-	Line of Sight
MAC	-	Medium Access Control
Mbps	-	Mega bits per second
MILES	-	Multi-floor Indoor Location Estimation System
MiniPCI	-	Mini Peripheral Component Interconnect
MT	-	Mobile Terminal
NNSS	-	Nearest Neighbor in Signal Space
NLOS	-	No Line of Sight
OFDM	-	Orthogonal Frequency Division Multiplexing
OS	-	Operating System
PAL	-	Precision Asset Location
PC	-	Personal Computer
PCMCIA	-	Personal Computer Memory Card International Association
PDA	-	Personal Digital Assistant
PHY	-	Physical
p.m.	-	Post Meridiem
POA	-	Phase of Arrival
RF	-	Radio Frequency
RFID	-	Radio Frequency Identification
RL	-	Reference Location
RSS	-	Received Signal Strength
RSSI	-	Received Signal Strength Indicator
SNR	-	Signal to Noise Ratio
SSID	-	Service Set Identifier
TDOA	-	Time Difference of Arrival
TOA	-	Time of Arrival
UNII	-	Unlicensed National Information Infrastructure
USB	-	Universal Serial Bus
UTM	-	Universiti Teknologi Malaysia
UWB	-	Ultra-wideband
WCC	-	Wireless Communication Centre
WLAN	-	Wireless Local Area Network

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Graphical user interface of the proposed system	205
B	Award	209
C	Bayes' Theorem	210

CHAPTER 1

INTRODUCTION

1.1 Background

The rapid development of mobile computing technology and high speed wireless communication systems has fostered tremendous growth in location based services (LBS). Through LBS, various applications and services are delivered to the user based on their current physical location. Indoor environments present opportunities for a rich set of LBS such as navigational tools for humans and robots, interactive virtual games, resource discovery and asset tracking.

The key to the success of LBS is the estimation of user's location. Location estimation is a process of estimating physical location of a mobile terminal (MT) with respect to a set of reference locations within a predefined space. This research focuses on design and development of multi-floor indoor location estimation system (MILES) using wireless local area network (WLAN). This system is proposed to determine the MT's location in a multi-floor indoor environment.

Currently, there are many location estimation systems (LES) available. Global Positioning System (GPS) is the most common and universally used LES for outdoor area. Unfortunately, GPS is not suitable for indoor applications due to the absence of line of sight (LOS) from the MT to the GPS satellites [1].

Various alternatives are proposed to provide indoor location estimation. Some researches use specialized hardware for indoor location estimation. These hardware are designed specifically and solely for location estimation purpose only. Ultrasonic, infrared, optical and radio frequency (RF) are major technologies used for this type of system. Although these systems able to estimate indoor location accurately, they are usually expensive in terms of investment and maintenance costs.

In order to overcome the disadvantages mentioned above, indoor LES can be developed using existing infrastructures. WLAN, Bluetooth and cellular network are major infrastructures used for this type of systems. These infrastructures are usually developed for other purposes such as data networking and communication. By developing a software layer on top of these infrastructures, a lower cost LES can be achieved. In this study, the proposed MILES is built on top of off-the-shelf WLAN infrastructure.

1.2 WLAN-Based Multi-Floor Indoor Location Estimation System

WLAN is widely deployed in various indoor areas such as homes, offices, schools and museums. Besides using the WLAN infrastructure for wireless data networking, the RF signals transmitted or received by WLAN devices can be used to estimate the MT's location. Because signal strength measurement is part of the standard operating mode of WLAN devices, no other hardware infrastructure is required. WLAN-based LES can be developed using proximity sensing, triangulation or location fingerprinting technique.

Location fingerprinting technique is the most popular solution for WLAN-based indoor location estimation [2]. The basic idea behind location fingerprinting is that RF signal has different characteristics in different indoor locations. Location dependent RF signal elements such as WLAN received signal strength (RSS), signal to noise ratio (SNR) or bit error rate (BER) are used as the "fingerprint" of a particular location.

Location fingerprinting usually works in two phases [3]. First, in off-line phase, the LES is calibrated by collecting location fingerprints at finite pre-determined reference locations (RL) within the targeted multi-floor indoor area and stored in a database called radio map. Second, location is estimated in on-line phase. The current observed location fingerprint is measured and the LES will determine the best match between the on-line observations and the off-line fingerprints in the radio map. The RL with the closest match is then reported as the estimated MT's location. This matching can be done according to deterministic or probabilistic algorithms.

In this study, the proposed system is developed using location fingerprinting technique. WLAN RSS is used as the location fingerprint. Probabilistic algorithm is adopted to estimate the MT's location.

1.3 Problem Statement

Currently, conventional GPS system does not work well in indoor area. Indoor LES based on specialized hardware usually require high investment and maintenance costs. Therefore, an economic LES is needed.

WLAN-based indoor LES is one of the economic alternatives. Many solutions are proposed for this type of system in previous researches and their performances are very encouraging [4, 5, 6, 7]. However, most of the proposed systems are only tested for single-floor indoor location estimation [4, 5, 6, 7]. In reality, an indoor LES is usually used in a multi-floor environment.

In this study, location fingerprinting uses the WLAN RSS to estimate indoor location. The RF propagation channel in indoor environment is complex due to multi-path fading phenomenon. Therefore, a basic understanding of the indoor WLAN RSS characteristics is crucial before the design, development and deployment of the proposed system.

In addition, performance of WLAN-based location fingerprinting system is affected by various factors such as number of WLAN access points (AP) installed. A basic understanding on these factors will help to achieve and improve the targeted LES performance level.

1.4 Objectives

The following objectives are determined in order to solve the problems mentioned above.

- (i) To study the characteristics of WLAN RSS in indoor environment through measurement for WLAN-based indoor location estimation application.
- (ii) To design and develop a WLAN-based indoor location estimation system for multi-floor environment using RSS location fingerprinting technique.
- (iii) To evaluate the performance of the proposed WLAN-based multi-floor indoor location estimation system.
- (iv) To study factors which affect the performance of the proposed WLAN-based multi-floor indoor location estimation system.

1.5 Research Scope

In this study, a software-based MILES is designed and developed. The proposed system is implemented and evaluated over the off-the-shelf IEEE 802.11g WLAN infrastructures deployed in Wireless Communication Centre (WCC), Universiti Teknologi Malaysia (UTM).

The study is divided into four major phases. In the first phase, literatures on current indoor location estimation technologies and previous researches in the field are reviewed. Strengths and weaknesses of available systems are compared.

In the second phase, measurements are conducted to study the characteristics of WLAN RSS in multi-floor indoor environment. The goal of the measurement is to understand the characteristics of WLAN RSS for indoor location estimation application. Results obtained here are used to design and develop the proposed system.

Based on the literature review and results from the RSS characteristics study, the MILES is designed and developed. In this third phase, location fingerprinting technique using WLAN RSS is proposed. Java programming language is used to develop the proposed system.

In the final phase, the performance of the proposed MILES is evaluated via real-time stationary and mobile multi-floor indoor location estimation experiments. This is followed by a series of experiments on effects of four factors on the performance of the proposed system. The factors investigated are number of WLAN APs installed, number of topological nodes, number of RSS samples collected per location fingerprint and off-line phase sampling interval.

1.6 Contributions

Contributions of this study are listed below:

- (i) A test-bed for WLAN-based multi-floor indoor location estimation is built at WCC, UTM. This test-bed can be used as a general platform for future researches related to WLAN-based indoor location estimation and WLAN technology.
- (ii) Characteristics of WLAN RSS as location fingerprints are identified through measurements. The results obtained can be used in future for design, development and deployment of LES based on WLAN RSS.

- (iii) An economical software-based MILES using off-the-shelf WLAN infrastructures is proposed and developed. The prototype can be further developed into commercial product.
- (iv) Practicality and reliability of MILES using off-the-shelf WLAN infrastructures is validated via real-time experiments.
- (v) Various factors affecting the performance of WLAN-based MILES is identified. Results obtained will help to achieve and improve targeted performance of a given MILES in real-time implementation.

1.7 Thesis Organization

The thesis consists of eight chapters. Chapter 1 introduces the background of this study. In addition, the problem statement, research objectives, research scope, research contributions and thesis organization are included.

Chapter 2 contains the literature reviews on general indoor LES technology. Basic architecture of LES, location estimation technique, classification and properties of LES are reviewed. Previous studies on LES using various technologies are also reviewed. Advantages and disadvantages of these systems are identified.

Chapter 3 presents the overview on WLAN-based indoor LES. WLAN technology is reviewed. A detailed description on WLAN-based indoor LES, location fingerprinting technique and previous related studies are given. Strengths and weaknesses of available systems are compared.

Chapter 4 discusses the methodology of the study. Approach taken to achieve the research objectives is presented here. The test-bed, hardware and software components used in the study are also listed.

Chapter 5 presents the study on WLAN RSS characteristics. Measurements are conducted to study the characteristics of WLAN RSS for location fingerprinting application.

Chapter 6 presents the design, development and implementation of the proposed WLAN-based MILES.

Chapter 7 contains the real-time evaluation results of the proposed system. Type of experiments, experimental setups and results are analyzed and discussed. In addition, real-time experimental results on various factors affecting the performance of the proposed system are presented and discussed.

Finally, Chapter 8 concludes the thesis with conclusion and gives directions for future works.