Wellness Protocol: An Integrated Framework for Ambient Assisted Living

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

In

Electronics, Information and Communication Systems

At

School of Engineering and Advanced Technology,
Massey University,
Manawatu Campus,
New Zealand

HEMANT GHAYVAT

2016
Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
Abstract

Smart and intelligent homes of today and tomorrow are committed to enhancing the security, safety and comfort of the occupants. In the present scenario, most of the smart homes Protocols are limited to controlled activities environments for Ambient Assisted Living (AAL) of the elderly and the convalescents. The aim of this research is to develop a Wellness Protocol that forecasts the wellness of any individual living in the AAL environment. This is based on wireless sensors and networks that are applied to data mining and machine learning to monitor the activities of daily living. The heterogeneous sensor and actuator nodes, based on WSNs are deployed into the home environment. These nodes generate the real-time data related to the object usage and other movements inside the home, to forecast the wellness of an individual. The new Protocol has been designed and developed to be suitable especially for the smart home system. The Protocol is reliable, efficient, flexible, and economical for wireless sensor networks based AAL.

According to consumer demand, the Wellness Protocol based smart home systems can be easily installed with existing households without any significant changes and with a user-friendly interface. Additionally, the Wellness Protocol has extended to designing a smart building environment for an apartment. In the endeavour of smart home design and implementation, the Wellness Protocol deals with large data handling and interference mitigation. A Wellness based smart home monitoring system is the application of automation with integral systems of accommodation facilities to boost and progress the everyday life of an occupant.
Dedication

I primarily dedicate this research work to the occupants living alone.

To my parents

Late Shri Bhaskar Rao Ghayvat
Shrimati Sadhana Ghayvat

To my brother

Basant Ghayvat
Acknowledgements

Words can never describe my sense of gratitude to my supervisor Professor Subhas Mukhopadhyay. Prof. Subhas has not only been my Ph.D. supervisor but also a mentor who supported me all the way from my home country India to New Zealand for higher studies. In the course of research, there were some difficult days, in those days, he inspired me to be focused and sincere to the research. This work would not have been possible without his kind support, expert guidance, the trenchant critiques, and most of all his remarkable patience. My sincere thanks to my co-supervisor Dr. Xiang Gui, for his guidance and support throughout the academic program.

I thank School of Engineering and Advanced Technology, Massey University for the resources and infrastructure for research. I acknowledge the efforts of Mr. Ken Mercer, Mr. Colin Plaw, and Mr. Anthony Wade.

I would like to express my sincere thanks to my research colleagues Dr. Nagender Suryadevara, Dr. Asif Iqbal Zia, Mr. Anindya Nag, Mr. Arun Babu, Mr. Md Eshrat E Alahi and Mrs. Afsari Manesh Nasrin.

My special gratitude to my beloved parents, Late Shri Bhaskar Rao Ghayvat and Mrs. Sadhna Ghayvat and sibling Basant Ghayvat for their constant encouragement, support and prayers for my success. I dedicate this thesis to my father who passed away recently, in the course of this research, who greatly longed to see me with a doctorate.
# Table of Contents

Abstract .................................................................................................................. II

Dedication .............................................................................................................. III

Acknowledgements ............................................................................................. IV

Table of Contents ............................................................................................... V

List of Figures ...................................................................................................... IX

List of Tables ....................................................................................................... XV

List of Publications, Contributions and Achievements during the PhD study (2014-2016) ........................................................................................................ XVII

Glossary ................................................................................................................ XXI

Chapter 1. Introduction ....................................................................................... 1

1.1 Introduction ..................................................................................................... 1

1.2 Motivation of Designing Homes for Tomorrow ........................................... 1

1.2.1 Independent Living .................................................................................. 1

1.2.2 Enhance the Comfort and Lifetime ....................................................... 3

1.2.3 Health Services ...................................................................................... 4

1.2.4 Efficient Use of Electricity ...................................................................... 4

1.2.5 Safety and Security ................................................................................ 5

1.3 Problem Formulation .................................................................................... 5

1.4 Problem Solution ......................................................................................... 7

1.5 Reasoning of Wellness Protocol and Approach ........................................... 8

1.6 Scope of Thesis ......................................................................................... 9

1.7 Novel Contribution .................................................................................... 9
Chapter 2. Literature Survey ................................................................. 13
2.1 Introduction .................................................................................. 13

2.2 Smart Home for Wellness .............................................................. 15

2.3 Entities of Smart Home Systems .................................................. 16
    2.3.1 Sensors and Actuators ......................................................... 17
    2.3.2 Controller and Processing Unit .......................................... 19
    2.3.3 Defined Wireless Networking Protocols ............................. 19
    2.3.4 Local Home Gateway and Server .................................... 23

2.4 Smart Home Around the World .................................................... 23

2.5 Activity Recognition Algorithms and Approaches ......................... 36

2.6 Issues of Deployment .................................................................. 41

2.7 Large Data Handling .................................................................. 44

2.8 Introducing Internet of Things and Cloud Computing .................. 45

2.9 Conclusion .................................................................................. 46

Chapter 3. Wellness Protocol Development and Implementation ........... 47
3.1 Introduction .................................................................................. 47

3.2 A Brief About Wellness Protocol System .................................... 47

3.3 Wellness Approach to Protocol Development .............................. 48
    3.3.1 Intelligent Sampling and Transmission Control Algorithm .... 52
    3.3.2 Interference Mitigation ......................................................... 58
    3.3.3 Wellness Dynamic Key Generation for Security ................. 60

3.4 Wellness Sensing Units for Home Monitoring and Control ............ 64

3.5 Wireless Topology, Network Formation for Smart Home System .... 70

3.6 Deployment of Heterogeneous Wireless Sensing Units in a Home .... 71

3.7 Healthcare .................................................................................. 74
Chapter 3. Software and Wellness Data Analysis
3.7.1 Software Description
3.7.2 Angle Calculation Algorithm
3.8 Desired Number of Wireless Sensing Units for AAL
3.9 Software Data Extraction, Storage and User Interface
3.10 Evaluation of Wellness Protocol Data Reliability
3.11 Software Required for Wellness system
3.12 Comparison of Wellness over ZigBee
3.13 Conclusion

Chapter 4. Issues and Mitigation of Wireless Sensor and Networks (WSNs)
Based Smart Building System
4.1 Introduction
4.2 Description of Smart Building System
4.3 Methodology to Measure Interference and Attenuation Loss
  4.3.1 Latency
  4.3.2 Data-Packet Delivery Parameters
  4.3.3 Link Quality Metrics
4.4 Experimental Observations, Analysis, and Mitigation
  4.4.1 Fundamental Tests
  4.4.2 Analytical and parametric tests
  4.4.3 Signal Attenuation inside Smart Building
  4.4.4 Direction of arrival (DOA)
  4.4.5 Mitigation of Interference and Suggestions
4.5 Conclusion

Chapter 5. Activity Detection and Wellness Pattern Generation
5.1 Introduction
5.2 Classification of Events and Activities
List of Figures

Figure 1-1 Single-person households........................................................................................................... 2
Figure 1-2 One person households by Age and Sex, 1970 to 2012 in the US.............................. 3
Figure 1-3 Trend of living alone in the US ................................................................................................. 4
Figure 2-1 General functioning block diagram of smart home system ........................................... 17
Figure 2-2 (a) Iron Press heating system attached to the context aware arrangement, (b) Medicine dosage and time reminder machine “Tabsafe” ................................................................. 26
Figure 2-3 Mum's Wine Cellar .................................................................................................................. 27
Figure 2-4 Camera based monitoring ......................................................................................................... 27
Figure 2-5 Sensor deployment and activity recognition layout ................................................................. 29
Figure 2-6 Block diagram representation smart home for assisted living and care ........... 30
Figure 2-7 Camera installed at Tiger place Missouri ............................................................................... 30
Figure 2-8 (a) Force sensor deployed below the mattress and (b) Appliances are connected to usage monitoring logic .......................................................................................................................... 30
Figure 2-9 Sensing technology applied in home monitoring ................................................................. 31
Figure 2-10 Home Care Lab Bedroom (5th October 2012, Stirling) ......................................................... 32
Figure 2-11 Home Care Lab Kitchen (5th October 2012, Stirling) .......................................................... 32
Figure 2-12 Home Care Lab Lounge (5th October 2012, Stirling) ......................................................... 32
Figure 2-13(a) User is evaluating gestural input via a watch-like device (6th November 2008, Glasgow, © University of Glasgow and (b) Front of the 'MATCH Box' developed by the University of Glasgow team (27th September 2007, Glasgow) ........................................ 33
Figure 2-14 The Ubiquitous Communicator (UC) is used as remote control all over the home ................................................................................................................................. 33
Figure 2-15 Toyota PAPI house at Japan .................................................................................................. 34
Figure 2-16 Green car charger and power supply in the home if needed ........................................ 34
Figure 2-17 Wide open window space for natural light and a big fireplace ........................................ 35
Figure 2-18 Fireplace in the room ............................................................................................................ 35
Figure 2-19 Fire hazard control caused by the fireplace ........................................................................ 36
Figure 3-1 Representation of Wellness Protocol Based Home System .............................................. 48
Figure 3-2 Functional Description of the Developed Smart home Monitoring System ... 49
Figure 3-3 Representation of IEEE 802.15.5.ZigBee Stack Fields and Auxiliary Security Header in Detail ...................................................................................................................................... 49
Figure 3-4 Representation of IEEE 802.15.5.ZigBee Stack Fields and Data Payload in Detail ................................................................. 50
Figure 3-5 Event-priority based packet creation for WSNs for smart home solution .......... 52
Figure 3-6 Snapshot of XCTU to show the periodic sampling rate selection ................. 53
Figure 3-7 Snapshot of XCTU to show the cyclic sleep period ...................................... 53
Figure 3-8 Intelligent sampling and transmission control algorithm ............................... 55
Figure 3-9 Comparative graph on data collection between Zigbee and Wellness protocol for E & E sensing unit ................................................................. 56
Figure 3-10 Comparative graph on data collection of Smart Home system for House 1 ..57
Figure 3-11 Comparative graph on data collection of Smart Home system for House 2 ........................................................................................................................................... 57
Figure 3-12 XCTU snapshot for channel selection ........................................................... 58
Figure 3-13 Other household device functioning over the same channel where zigbee device is operating ............................................................................................................ 59
Figure 3-14 XCTU snapshot to show the ZigBee encryption ........................................... 61
Figure 3-15 Wellness Dynamic Key Generation based Security Algorithm .................... 62
Figure 3-16 Performance benchmark according to CPU cycles ...................................... 63
Figure 3-17 Performance benchmark according to Execution time ................................. 64
Figure 3-18 Prototype of Wireless Sensing Unit design ................................................... 69
Figure 3-19 Image of a real house where smart home monitoring and control system are installed ............................................................................................................ 71
Figure 3-20 Layout structure of the house with sensor deployment and household objects ........................................................................................................................................... 72
Figure 3-21 Outdoor sensing unit for outside temperature measurement ......................... 72
Figure 3-22 E & E sensing unit, which is monitoring and controlling (a) Water kettle, (b) Washing machine, (c) Microwave and (d) Television ................................................. 73
Figure 3-23 Represents the force sensing unit deployment to monitor (a)Sofa, (b) Dining Chair, (c) Bed and (d) Toilet seat ............................................................................................................ 73
Figure 3-24 CRrepresents the PIR sensing unit deployment to monitor (a) Living room and (b) Entry door ............................................................................................................ 74
Figure 3-25 : (a) Contact sensing unit connected to fridge door and (b) Manual push button indicator ............................................................................................................ 74
Figure 3-26 The MPU-60X 0 Motion Processing Units ................................................... 75
Figure 3-27 Block diagram of software system ................................................................ 76
Figure 3-28: The steps of low-level sensor data analysis ................................................. 77
Figure 3-29: Local home gateway for Intel Galileo Coordinator ....................................... 78
Figure 3-30: Wellness protocol system architecture ........................................................ 78
Figure 3-31: Hierarchical representation of WellnessSF (Wellness standard format) tree
diagrams for smart home system, (S-UNIT: SENSING UNIT) ........................................ 79
Figure 3-32: Snapshot of Home Monitoring Website which presents the sub-sections of
monitoring........................................................................................................................... 82
Figure 3-33: Packet error rate of Wellness protocol Vs ZigBee with change in spacing
between Tx and Rx ........................................................................................................... 83
Figure 3-34: Packet delivery ratio of Wellness protocol Vs ZigBee with change in spacing
between Tx and Rx ........................................................................................................... 84
Figure 3-35: Packet loss rate of Wellness protocol Vs ZigBee with change in spacing
between Tx and Rx ........................................................................................................... 85
Figure 3-36: Packet success rate of Wellness protocol Vs ZigBee with change in spacing
between Tx and Rx ........................................................................................................... 85
Figure 3-37: Average Delay of Wellness protocol Vs ZigBee with change in spacing
between Tx and Rx ........................................................................................................... 86
Figure 4-1: Layout of big building heterogeneous sensing system ....................................... 91
Figure 4-2: Arrangement of sensor nodes for experimental investigation ............................. 100
Figure 4-3: Delay as a function of hopping distance .......................................................... 101
Figure 4-4: PDR as a function of hopping distance ............................................................. 101
Figure 4-5: PER as a function of hopping distance ............................................................. 102
Figure 4-6 (a): Layout of attenuation loss test ................................................................. 105
Figure 4-6 (b): RSSI as a function of different building materials, where STx-AS is varied
from .5 m to 6 m ............................................................................................................. 106
Figure 4-7 (a): PDR as a function of different building materials, where STx-AS is varied
from .5 m to 6 m ............................................................................................................. 107
Figure 4-7 (b): Close-up view PDR as a function of different building materials, where
STx-AS is varied from .5 m to 6 m ................................................................................. 107
Figure 4-8 (a): PSR as a function of different building materials, where STx-AS is varied
from 0.5 m to 6 m ......................................................................................................... 108
Figure 4-8 (b): Close-up view PSR as a function of various building materials, where
STx-AS is varied from .5 to 6m .................................................................................... 108
Figure 4-9: Schematic setup for IS location for DOA ....................................................... 110
Figure 4.10: RSSI as a function of the angle between Rx and IS in the line of sight, STx-Rx=3m……………………………………………………………………………………………111

Figure 4.11: PDR as a function of the angle between Rx and IS in the line of sight, STx-Rx=3 m……………………………………………………………………………………………………111

Figure 4.12: PSR as a function of the angle between Rx and IS in the line of sight, STx-Rx=3 m……………………………………………………………………………………………………112

Figure 4.13: RSSI as a function of the angle between Tx and IS in the line of sight, STx-Rx=3m……………………………………………………………………………………………………112

Figure 4.14: PDR as a function of the angle between Tx and IS in the line of sight, STx-Rx=3 m……………………………………………………………………………………………………113

Figure 4.15: PSR as a function of the angle between Tx and IS in the line of sight, STx-Rx=3 m……………………………………………………………………………………………………113

Figure 4.16: RSSI as a function of angle between Rx and IS in multipath fading, STx-Rx=5m……………………………………………………………………………………………………114

Figure 4.17: PDR as a function of angle between Rx and IS in multipath fading, STx-Rx=5 m……………………………………………………………………………………………………115

Figure 4.18: PSR as a function of angle between Rx and IS in multipath fading, STx-Rx=5 m……………………………………………………………………………………………………115

Figure 4.19: RSSI as a function of angle between Tx and IS in multipath fading, STx-Rx=5 m……………………………………………………………………………………………………116

Figure 4.20: PDR as a function of angle between Tx and IS in multipath fading, STx-Rx=5 m……………………………………………………………………………………………………116

Figure 4.21: PSR as a function of angle between Tx and IS in multipath fading, STx-Rx=5 m……………………………………………………………………………………………………117

Figure 4.22: The XBee smart building system is operating at frequency 2.430 MHz………………………………………………………………………………………………………………119

Figure 4.23: Shows the Wi-Fi functioning over the same frequency 2.430 MHz, which degraded the XBee RF link quality………………………………………………………………120
Figure 4.24: Shows the Bluetooth functioning over the same frequency 2.430 MHz, which degraded the XBee RF link quality.

Figure 4.25: Microwave oven distributed all ZigBee channels, and the microwave signal are dissipated across the whole ZigBee spectrum.

Figure 4.26: PSR as a function of the distance between IS and Rx, SIS-Rx = 1m to 16m.

Figure 4.27: PDR as a function of distance between Tx and Rx, SIS-Rx = 1m to 16.

Figure 4.28: Difference in average RSSI between the highest and lowest levels of each factor.

Figure 4.29: Difference in average packet delivery parameter between the maximum and minimum levels for each factor.

Figure 4.30: Offset frequency measurement by RF spectrometer.

Figure 5.1: Activities of daily living.

Figure 5.2: Modeling sub-activity for ADLs.

Figure 5.3: Sample of Sensor activation logged.

Figure 5.4: Representation of sensor activation, object usage, and activity.

Figure 5.5: Smart home room temperature actual and expected for 24 hours.

Figure 5.6: Probability of movement in different locations of home based on PIR sensing unit.

Figure 5.7: Probability of occupancy in different locations of home based on Force sensing unit.

Figure 5.8: Comparison of $\beta_{1,\text{old}}$ and $\beta_{1,\text{new}}$ wellness functions (with two cases with wellness belief and without wellness belief).

Figure 5.9: Comparison of $\beta_{2,\text{old}}$ and $\beta_{2,\text{new}}$ wellness functions (with two cases with wellness belief and without wellness belief).

Figure 5.10: Object usage for one day for house-1.

Figure 5.11: Object usage for one day for house-2.

Figure 5.12: Object usage for one day for house-3.

Figure 5.13: Object usage for one day for house-4.

Figure 5.14: $\beta_{1,\text{old}}$ at four different elderly houses.

Figure 5.15: Wellness Indices for sleeping activity for four different houses up to one week.

Figure 5.16: The ADLs throughout the day.
Figure 5.17: The ADLs of having medicine and meal throughout the day..............151
Figure 6.1: Functional block diagram of Wellness learning algorithm for time series analysis.................................................................154
Figure 6.2: Actual shower usage and its trend..............................................155
Figure 6.3: Actual dining chair usage and its trend.......................................156
Figure 6.4: Actual dining bed usage and its trend........................................156
Figure 6.5: Actual dining toilet usage and its trend.......................................157
Figure 6.6: Shower usage duration and forecasting for upcoming week.............157
Figure 6.7: Dining chair usage duration and forecasting for upcoming week.......158
Figure 6.8: Bed usage duration and forecasting for upcoming week..................158
Figure 6.9: Toilet usage duration and forecasting for upcoming week..............159
List of Tables

Table 1-1: The statistic of householders living alone; it includes all age groups ..........2
Table 2-1: The criteria filter for selecting the research in literature survey ..................14
Table 2-2: The keyword used on google scholar and other research article search engine to find research studies ...........................................................................................................14
Table 2-3: Ambient Sensors to Smart Environment Monitoring .....................................18
Table 2.4: Wireless Network based on IEEE standard ..................................................20
Table 2-5: Wireless Network Standards Not Based on IEEE Standards ......................22
Table 2-6: represents limitations and drawbacks of the recent and current research on the smart home protocol development .................................................................25
Table 2.7: General classification of anomaly detection techniques ................................38
Table 1.8: Traditional Activity Classification (modeling) approaches ..............................38
Table 3.1: Priority of events in descending order .............................................................51
Table 3.2: The layer features and functions are presented .............................................65
Table 3.3: Technical description and functioning of Sensing units ................................66
Table 3.4: The reasons to select Intel board on the top of RPI ..........................................69
Table 3.5: ZigBee device modes and their functions ........................................................70
Table 3.6. More description of user, location unit, mobile unit and annotation of tree diagram of WSL (Wellness Standard format) ..................................................80
Table 4.1: The issues and their range in the experiments ..............................................103
Table 4.2: Obstruction-material details of building environment ..................................104
Table 4.3: Optimum value recorded at STx-AS=6 m ....................................................109
Table 5.1: Selection and deployment location of sensing units .....................................130
Table 5.2: Activity Annotation process at different portion of the day ...........................134
Table 5.3: Number of sensor activation and activity detection for four different houses equipped with hydrogenous sensing units ..................................................146
Table 5.4: Improved Wellness indices for different activities to four different houses .................................................................................................................................149
Table 6.1: Wellness function indices of object usage and forecast of the ADLs...........159
Table 6.2: Annotation used in confusion matrix table

Table 6.3: Confusion matrix to show the accuracy of ADLs detection for different object usage by Naïve Bayes method

Table 6.4: Confusion matrix to show the accuracy of ADLs detection for different object usage by HMM method

Table 6.5: Confusion matrix to show the accuracy of ADLs detection for different object usage by CRF method

Table 6.6: Confusion matrix to show the accuracy of ADLs detection for different object usage by Wellness method

Table 6.7: Accuracy of different machine learning methods
List of Publications, Contributions and Achievements during the PhD study (2013-2016)

Journal papers: 6 (Published only)


Book Chapter


Refereed conference papers: 7 (published only)

9) **H. Ghayvat**, S. Mukhopadhyay, X. Gui, and J. Liu "Enhancement of WSN Based Smart Home to a Smart Building for Assisted Living: Design Issues," in Communication Systems and Network Technologies (CSNT), 2015 Fifth International Conference on, Gwalior India, 4-6 April 2015, pp. 219-224.


November 24, 2015

TO:
Mr. Hemant Ghayvat, Massey University
Mr. Jie Liu, Massey University
Prof. Subhas Chandra Mukhopadhyay, Massey University
Mr. Xiang Gui, Massey University

Dear Mr. Ghayvat, Mr. Liu, Prof. Mukhopadhyay, Mr. Gui,

On behalf of the IEEE Sensors Council I am pleased to congratulate you as a coauthor of the paper Wellness Sensor Networks: A Proposal and Implementation for Smart Home for Assisted Living, IEEE Sensors Journal, Vol. 15, No. 12, December 2015, for your paper being one of the 50 most downloaded Sensors Journal papers in the month of September 2015. It is exciting to note that included in this count are all Sensors Journal papers published since the Journal’s foundation, about 4500 papers in total, and that last year, 439,609 Sensors Journal papers were downloaded from IEEE Xplore. You can view the latest Top 50 papers at:


Thank you for your contribution to the IEEE Sensors Journal!

Best regards,

H. Troy Nagle
President, IEEE Sensors Council
Measurement

Certificate of publication for the article titled:
"Issues and Mitigation of Interference, Attenuation and Direction of Arrival in IEEE 802.15.4/ZigBee to Wireless Sensors and Networks Based Smart Building"

Authored by:
Hemant Ghayvat
S.C. Mukhopadhyay

Published in:
Volume 86C, 2016, Pages 209-226
# Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAL</td>
<td>Ambient Assisted Living</td>
</tr>
<tr>
<td>ADL</td>
<td>(Basic) Activities of Daily Living</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>HMS</td>
<td>Home Monitoring System</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial Scientific and Medical</td>
</tr>
<tr>
<td>DOA</td>
<td>Direction of Arrival</td>
</tr>
<tr>
<td>RSSI</td>
<td>Received Signal Strength Indicator</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>WDKG</td>
<td>Wellness Dynamic Key Generation</td>
</tr>
</tbody>
</table>