DEVELOPMENT OF REAL-TIME WIRELESS SENSOR NETWORK FOR SMART GRID BASED LOW VOLTAGE ADVANCED METERING INFRASTRUCTURE

BY

HIKMA SHABANI

A thesis submitted in fulfilment of the requirement for the degree of Doctor of Philosophy in Electrical and Computer Engineering

Kulliyyah of Engineering
International Islamic University Malaysia

AUGUST 2014

ABSTRACT

Smart distribution grid involves overlaying real-time wireless communication technologies from advanced metering infrastructure (AMI) gateways at the consumer premises to the distribution points with a built up of beacon mode wireless sensor multi-hop mesh network for large coverage data exchanges. Zigbee/IEEE802.15.4 is one of the prominent standards for Wireless Sensor Networks (WSNs) due to its low bandwidth requirements, low cost of deployment, easy network implementation and low-power embedded systems. However, IEEE802.15.4 standard does not specify any mechanism to enable beacon mode for multi-hop mesh networks. Furthermore, with the usage of IEEE802.15.4 guaranteed time slot (GTS), the real-time data is sent at the end of the super_frame after experiencing a slotted Carrier Sensor Multiple Access with Collision Avoidance (CSMA-CA) which may not ensure an immediate access to medium. Despite a reserved GTS, a node contends for channel access during Contention Access Period (CAP) which decreases the network performance. Finally, the scheduling of Contention Free Period (CFP) at the end of the active portion of the super_frame gives the normal data a faster channel access than the real-time data which may wait until the end of the CAP to get a deterministic channel access. Therefore, this thesis modifies IEEE802.15.4 MAC architecture by swapping the CAP with the CFP to improve the channel access time and the Reserved Broadcast Duration Slot (RBDS) is placed at the beginning of the CFP for critical real-time data delivery. All simulations are conducted on Network Simulator version 2 (NS-2) while for network analytical examinations, a 2*D Markov_Chain model is developed from the Modified IEEE802.15.4 MAC protocol. For the sake of energy efficiency no acknowledgement (ACK) is implemented and the routing protocol is not used since this approach is evaluated without the influence of the network layer. With its scalability up to 51 nodes and compared to IEEE802.15.4 MAC standard, the new model improves the network performance such as time_delivery_delay, reliability, goodput, power consumption and throughput as well as SCADA round_trip_time transactions.
.

ملخص البحث

ينطوي شبكة التوزيع الذكية على تراكب تقنيات الاتصالات اللاسلكية في الوقت الحقيقي من البنية التحتية المتطورة لبوابات القياس (AMI) في مقر المستهلك إلى نقاط التوزيع مع أجهزة استشعار لاسلكية لشبكة متعددة الوصلات المتداخلة لتبادل البيانات ذات التغطية واسعة . Zigbee/IEEE802.15.4 هي واحدة من أبرز المعايير لشبكات الاستشعار اللاسلكية (WSNs) نظرا لمتطلباته ذات عرض النطاق الترددي المنخفض ، وانخفاض تكلفة نشر وتنفيذ الشبكة سهلة وهي جزءا لا يتجزأ من أنظمة الطاقة المنخفضة. ومع ذلك ، IEEE802.15.4 القياسية لا يحدد أي آلية لتمكين وضع منارة للشبكات شبكة متعددة الوصلات. علاوة على ذلك، مع استخدام IEEE802.15.4 مضمونة فتحة الوقت (GTS) ، يتم إرسال البيانات في الوقت الحقيقي في نهاية superframe بعد تعرضه لفترة زمنية محددة الاستشعار الناقل متعددة الوصول مع تجنب التصادم (CSMA CA) والتي قد لا تضمن الوصول الفوري إلى التوسط . على الرغم من GTS محجوزة، أي جهاز سيحاول الوصول للقناة خلال الفترة (CAP) مما يقلل من أداء الشبكة. أخيرا ، جدولة خلاف الفترة الحرة (CFP) في نهاية الجزء النشط من superframe يعطي البيانات العادية وصول أسرع للقناة من البيانات في الوقت الحقيقي والتي قد تنتظر حتى نهاية CAP إلى الحصول على وصول القناة القطعية . وبالتالي، التصاميم المبتكرة بهذه الأطروحة لبروتوكول العمارة IEEE802.15.4 MAC عن طريق مبادلة CAP مع CFP لتحسين وقت وصول القناة و يتم وضع RBDS في بداية CFP لتسليم البيانات في الوقت الحقيقي الحرج. لتحليل أداء الشبكة ، تم تطوير نموذج Markov_Chain ببعدين من بروتوكول IEEE802.15.4 MAC المبتكر . من أجل كفاءة الطاقة لا يتم تنفيذ أي إقرار (ACK) و عدم استخدام بروتوكول التوجيه حيث يتم تقييم هذا النهج دون تأثير على طبقة الشبكة . مع قابلية تصل إلى 51 عقد ، والنموذج الجديد يحسن من أداء الشبكة مثل time_delivery_delay ، والموثوقية ،goodput، واستهلاك الطاقة والإنتاجية فضلا عنtransactions SCADA round_trip_time

APPROVAL PAGE

The thesis of Hikma Shabani has been approved by the following:

Musse Mohamud Ahmed
Supervisor

Sheroz Khan
Co-supervisor1

Shihab Ahmed Hameed
Co-supervisor2

Md. Rafiqul Islam
Internal Examiner

Tharek Abdul Rahman
External Examiner

Azah Mohamed
External Examiner

Hassan Ahmed Ibrahim
Chairman

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Hikma Shabani

Signature.. Date. ……………………….

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

DEVELOPMENT OF REAL-TIME WIRELESS SENSOR NETWORK FOR SMART GRID BASED LOW VOLTAGE ADVANCED METERING INFRASTRUCTURE

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below.

1. Any material contained in or derived from this unpublished research may only be used by others in their writing with due acknowledgement.
2. IIUM or its library will have the right to make and transmit copies (print of electronic) for institutional and academic purposes.
3. The IIUM library will have the right to make, store in a retrieval system and supply copies of this unpublished research if requested by other universities and research libraries.

Affirmed by Hikma Shabani

…………………………….. Signature

………………………….. Date

This thesis is dedicated to my parents and my young brother named Sijali Shabani who before he passed away, has been supporting me all the way since the beginning of my studies. Also this thesis is dedicated to my beloved wife and children who have been a great source of motivation and inspiration. Finally, this thesis is dedicated to all who believe in the richness of learning.

ACKNOWLEDGEMENTS

First and foremost Alhamdulillah, praise to Allah S.W.T for the completion of this thesis. It is with his blessings and guidance that I am able to complete this work. Peace be upon his messenger, Muhammad S.A.W, who has graced this world with his blessing. I would like to extend my gratitude to my beloved supervisor Assoc. Prof. Dr. Musse Mohamud Ahmed as well as my co-supervisors named Assoc. Prof. Dr. Sheroz Khan, Assoc. Prof. Dr. Shihab Ahmed Hameed and Assoc. Prof. Dr. Jalel Chebil for all of their huge support, advice, and encouragement over the route of my graduate career. Only Allah can reward their kindness in pointing me to the right direction throughout this thesis over the semesters. Without their close supervision and guidance this work would not be where it is. Through Assoc. Prof. Dr. Musse Mohamud Ahmed and all my co-supervisors, I have learned much about supervisory control and data acquisition through low voltage smart grid distribution system, the importance of keeping in focus the big picture, and I have picked up many tips on how to successfully manage an active research. Working with all of them has instilled within me a desire to devote the next stage of my life to helping to solve some of the many issues about automation systems and communication control limits currently facing the development of our planet. I would like also to thank Prof. Dr. Momoh Jimoh E. Salami, Prof. Dr. Sanu Kutub Mustafa and Prof. Dr. Othman Khalifa for good suggestion, motivation and support. I appreciate very well the recommendations from Assoc. Prof. Dr. Mohamed Hadi Habaebi and Prof. Dr. Aisha Hassan, Kulliyyah of Engineering at International Islamic University Malaysia (IIUM).

I also would like to thanks my friends outside of the research, who have made my time in Malaysia a lot of fun. Shahran Kassim, Sister Aisya and the rest of the Islamic-Outreach-ABIM group members: it's been great and I very much look forward to meeting up with all of you in the future. Not to be forgotten, to all our friends and fellow Muslims, the family of Dr. Kassim Abdullah and Dr. Omar Semasaba who had been giving their full support to me while doing this research.

I would also like to thank my family, both immediate and extended. Without the unconditional love, support, and encouragement from my brothers Mali Hassan, Sijali Shabani who passed away recently, Haji Hassan and my sisters Mwanaidi Shabani, Anzerani Shabani and Zarina Shabani I would not be here today. They are wonderful role models, and I am forever grateful for the stable, loving upbringing that they provided. I am also extremely lucky to have a fantastic set of in-laws, Asiya Hemedi and Ramazani Sudi who also passed away during my study, who have been a constant source of encouragement... and beer... throughout this degree.

I would like to acknowledge the support from the International Islamic University Malaysia-Research Centre by funding this research.

Last and not least, I would like to thank my wife, Rukiya Zubeda and my children, Iqra Ramazan, Aisha Summaiya, Imran Qassem and Asiya Souhaylah. Completing this degree has been a challenge, not as much academically as personally because we lived largely apart during the first time I spent at IIUM. Marrying Zubeda is, in short, the best thing that ever happened in my life, and I can't express how much I appreciate her `holding on'. Without her love and support, none of this would have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACK	Acknowledgement
AMI	Advanced_Metering_Infrastructure
APDU	Application Protocol Data Units
ARP	Address Resolution Protocol
ASDU	Application service data units
AWGN	Additive white Gaussian noise
BE	Backoff_Exponent
BER	Bit_Error_Rate
BI	Beacon_Interval
BO	Beacon_Order
BP	Backoff_Period
BPSK	Binary Phase Shift Keying
CAIDI	Customer Total Interruption Duration Index
CAP	Contention_Access_Period
CC	Central Computer
CCA	Clear Channel Assessment
CCK	Complementary Code Keying
CENELEC	Comité Européen de Normalisation Électrotechnique
CFP	Contention Free Period
CSMA_CA	Carrier_Sensor_Multiple-Access with Collision_Avoidance
CW	Contention_Window
DAS	Distribution Automation System
DC	Duty_Cycle
DER	Distributed Energy Resources
DG	Distributed Generation
D-GTS	Dynamic GTS
DMS	Distribution Management System
DNP3	Distributed Network Protocol Version 3.0
DR	Demand Response
DS	Distribution System
DSCC	Distribution System Control Centre
DSSS	Direct Sequence Spread Spectrum
EMS	Energy Management System
EPA	Enhanced Performance Architecture
EPRI	Electric Power Research Institute
ESI	Energy Services Interface
FFD	Full_Function Device
FHSS	Frequency Hopping Spread Spectrum
FRTUs	Feeder Remote Terminal Units
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTS	Guaranteed Time Slot
HAN	Home Area Network
HMI	Human Machine Interface

HV	High Voltage
I/O	Input/output
ICT	Information and Communication Technology
IEC	International Electro-Technical Commission
IED	Intelligent Electronic Devices
IEEE	Institute of Electrical and Electronics Engineers
IFS	Interframe Spacing
IP	Inactive Period
ISM	Industrial, Scientific and Medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
JISC	Joint Information Systems Committee
KATS	Korean Agency for Technology and Standards
LDC	Local Dispatch Centre
LIFS	Long Interframe Spacing
LNSM	Log-Normal Shadowing Path-Loss Model
LPDU	Link Protocol Data Unit
LQI	Link Quality Indicator
MAC	Medium_Access_Control
MAIFI	Momentary Average Interruption Index
MDT	Mean Down Time
MG	Micro-Grid
MICON	Mining Industry Consultant
MIMO	Multiple-Input-Multiple-Output
MSB	Main Switch Board
MSS	Main Switch Station
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
MV	Medium Voltage
NB	Number of Backoffs
NERC	North American Electrical Reliability Corporation
CIP	Critical Infrastructure Protection
NIPP	National Infrastructure Protection Plan
NIST	National Institute for Standards and Technology
NISTIR	National Institute of Standards and Technology Interagency Report
NS-2	Network Simulator version 2
OFDM	Orthogonal Frequency Division Multiplexing
OQPSK	Offset Quadrature Phase-Shift Keying
PANc	Personal Area Network Coordinator
PE	Pencawang Elektrik
PEV	Plug-in Electric Vehicle
PHY	Physical
PLC	Programmable Logic Control
PMU	Pencawang Masuk Utama
PRTPU	Pending_Real_Time_Packets_Update
QoS	Quality of Service
RBDS	Reserved_Broadcast_Duration_Slot

RCC	Regional Control Center
RED	Receiver Energy Detection
RF	Radio Frequency
RFD	Reduced_Function Device
SAFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
SAS	Substation Automation System
SCADA	Supervisory Control and Data Acquisition
SD	Superframe Duration
SIFS	Short Interframe Spacing
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SO	Superframe Order
SSB	Sub-Switch Board
SSO	Substation Switching Operators
SSU	Stesyen Suis Utama
TCP/IP	Transmission Control Protocol/Internet Protocol
TNB	Tenaga Nasional Berhad
TPDU	Transport Protocol Data Units
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
USA	United States of America
UWB	Ultra-Wideband
VVWC	Voltage, Var, and Watt Control
WAN	Wide Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WPAN	Wireless Personal Area Network
WS	Work Stations
WSN	Wireless Sensor Networks

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND

Electric power systems and the associated equipment items make up a huge infrastructure in the form of lines and grids linked together in inter-connected networks. As the demand for energy goes on rise with the development of life style and societal needs, this infra-structure unfolds larger system at the expansions of almost identical equipment, more or less in modular style (M. S. Thomas, P. Kumar and V. K. Chandna, 2004). With the addition of more and more expansions, the power system suffers from malfunctioning of its unusual kind of scenario, most probably from over and under-shoot of voltages or of current, leading the systems to be with faults never experienced before (S. K. Joo, J. C. Kim and C. C. Liu, 2007). Besides, the complexities are multiplied by the match (or mismatch) of frequency on either side at the point where one can call it like a junction such as transmission and distribution substations. The system is thus with a host of challenges with passage never occurring in observation before. Hence, the operating engineers and skills technicians have been facing the tasks of major blackouts at the expense of revenue loss in the industrial sector beside having the dismay and anger of residential consumers who embracing to suffer from insecure law and order situation in such blackouts (S. Grubic, J. M. Aller, B. Lu and T. G. Habetler, 2008).

Smart-grid offers a solution in the form of system alternative to the traditional style of power systems. The idea of smart grid is to make sources of power generation connected with the load centers and consumers suing innovative style of technology in a structure such the delivery of power to consumers are ensured at a minimum loss and maximum control. The whole structure of smart grid then needs to be equipped with a host of sensing devices networked together in such a mesh providing us us with control, actuation and break at the click of a cursor on a computer (M. E. Kantarci and H. T. Mouftah, 2011).

Wireless sensor network is one such solution deemed these days as an innovative alternative to traditions of kind. The main advatanage of such wireless sensor network is to maximize revenue from timely and accurate almost automatic metering, besides being alert and sensitive to any abnormal conditions arising as result of operability of the network (V.C. Gungor, D. Sahin, T. Kocak, S. Ergut and C. Buccella, 2011). Thus a wireless sensor network provides a kind of highway for data being transported in one direction and control and actuating signals in the reverse direction (P. Kulkarni, S. Gormus, Z. Fan and F. Ramos, 2012). In such WSN, the real_time data delivery and network power consumption issues become concerns from work in this thesis. WSNs is made from nodes playing highly important part in providing the shortest paths from sources to its respective destined location, both in the case of data volume or traffic control signals. Multi-hop mesh of nodes is one alternative in manifesting the idea of smart grid as it configures the paths from sources to destined locations can be easily established with minimal cost of expense of power (V. C. Gungor, B. Lu, and G. P. Hancke, 2010).

Zigbee operating at the non-licensed frequency spectrum of 2.4GHz and making use of the IEEE 802.15.4 is a standard that is robust with low bandwidth, and lower cost of installation which compares to its contemporary counterparts, proves to be a choice in this regard (K. I. Hwang, B. J. Choi, and S.k-hoon Kang, 2010). When coupled with advanced wireless communication, Zigbee has been instrumental in saving life considerably besides ensuring maximum delivery of power in the case of smart grid connectivity (P. P. Parikh, M. G. Kanabar and T. S. Sidhu, 2010). The data acquisition and fault minimization have been considerably lower with using Zigbee, as it is robust under stormy or abnormal weather conditions, and having low bandwidth, that is, it is not affected by the problems coming from interference phenomenon (Q. Pang, H. Gao and M. Xiang, 2010).

The concept of Supervisory Control, and Data Acquisition (SCADA) is effectively implemented using WSN concepts, as such systems have been able to offer better services in terms of more automated metering and better and timely control of malfunctioning. SCADA (WSN-based) is equipped with devices in the form of hardware therefore to harness the potential for the hardware, relevant software is becoming critically important than before (M. M. Musse, 2009). The software plays its roles in the sense of better operability in the shortest possible period of time before the occurring problem unfold into becoming unmanageable (A. Muhammad and M. Asif, 2008). Therefore, this work focuses on a robust WSN protocol most fitted for implementation on smart grid systems based on using Advanced Metering Infrastructure (AMI) needed for networks at the distribution of power to consumer's level.

1.2. RESEARCH MOTIVATION AND ITS SIGNIFICANCE

Since, the advent of Information and Communication Technology (ICT), the electrical distribution networks have been transformed by incorporating various types of technology transitions like the adoption of SCADA systems, sensor devices and wireless communication techniques as part of Smart Grid Technology. Being a fullduplex communication system, Wireless Sensor Networks (WSNs) technology has been extremely gaining popularity with its free license frequency band of 2.4 GHz.

The significance of this research is identified as follow:

i. An overall improvement on energy saving, throughput, data delivery time, transmission probability and reliability performance of a Multi-Hop Mesh Network is obtained.

ii. A Novel 2*D_Markov_Chain_model supported by verifying its performance through mathematical modeling in a Multi-Hop Mesh environment is implemented.

1.3. STATEMENT OF PROBLEM

WSNs are based upon IEEE802.15.4 protocol as IEEE Smart Grid Standard Protocol. However, the above cited protocol encompasses the following drawbacks: Firstly, with the use of its Guaranteed-Time-Slot (GTS), the real_time data is transmitted after the completion of the super_frame whilst the reception is achieved by undergoing a slotted_Carrier_Sensor_Multiple_Access_with_Collision_Avoidance (CSMA-CA) mechanism which may not ensure an instant entry to medium. Secondly, while the node has reserved a GTS, it may compete for medium entree in the Contention_Access_Period (CAP), which shrinkages the performance of the other nodes. Thirdly, the planning of the Contention_Free_Period (CFP), at the completion of the active slice of the supeframe is also a drawback of the IEEE802.15.4 standard protocol as it gives normal data a quicker channel entree than the real_time data, since it may wait until the completion the CAP to get a deterministic medium entree. Fourthly, as it is required to fix a small duty_cycle (DC) to ensure longer sleep time for network energy saving, the real_time data is delayed for minimum time equal to Inactive_Period (IP) time as per equation (1.1) (L. Qingnong, 2008).

$$Inactive\ period = BI - SD \tag{1.1}$$

Where:

$$Beacon\ Interval\ (BI) = aBaseSuperframeDuration \times 2^{BO}$$
$$Superframe\ Duration\ (SD) = aBaseSuperframeDuration \times 2^{SO}$$

$$0 \leq SO \leq BO \leq 14$$

With BO: as beacon order and SO: as super_frame order.

Last but not least, if the Duty_Cycle (DC) as given in equation (1.2) is too small, the delivery_delay upraises as the data will be held until the next active super_frame slice starts the transmission.

$$DC = \frac{SD}{BI} = 2^{(SO-BO)} \tag{1.2}$$

1.4. RESEARCH PHILOSOPHY

Majority of faults and abnormal conditions in power systems stem originating from distribution networks and it is here where more manual or human interference is being exercised. More equipments being operated, and large of number of switches are being turned ON and OFF, associated with more probability of transients happening; accordingly the environment is becoming so hazardous for humans and signals or data moving around in WSNs. Thus the need of robust data transmission arises to be with more challenges, while ensuring better reliability. The accuracy of data and response of equipment to abnormal conditions if delayed by milliseconds could be of magnitude and scale larger than expected particularly in the case of loads becoming heavier and larger with the passage. Therefore, the use of advanced information, control and communication technologies have emerged in recent years, such WSNs play a crucial role leading ultimately to the development of smart grid distribution systems with the key feature of grid-integrating real_time communications between the advanced_metering_infrastructures (AMI) of smart distribution systems. In such scenario, the use of WSN and its protocol should be highly robust with better Quality of Service (QoS) and should offer shortest time delays and minimum power consumption.

1.5. RESEARCH OBJECTIVES

The aim in focus in this thesis is to design a novel IEEE802.15.4 protocol in form of new MAC_architecture, coupled with Advanced_Metering_Infrastructure (AMI) smart-grid applications. The applications are based on beacon_enabled mode for cooperating in two-way communication systems in the form of WSN. The beacon_enabled is further enhanced by the features of embedded AMI utilizing the concepts of multi-hop mesh networks in real_time having high throughput, better reliability and improved data and power delivery. The suggested solutions will be taking into consideration the effect of Beacon_Order (BO), Duty_Cycle (DC) and network in the form of number of nodes.

The objectives of this research are identified as follows

i. To design a smart Zigbee-based beacon-enabled Multi-Hop Mesh Network in Smart Grid intended for auto-metering applications.