ENHANCED LIGHTWEIGHT MEDIUM ACCESS CONTROL PROTOCOL FOR WIRELESS SENSOR NETWORKS

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To my beloved mother and father, family and friends…

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ABSTRACT

A new emerging wireless technology called Wireless Sensor Network (WSN) is a system which composed of a number of sensor nodes that interact with each other intentionally to gather information from the enquired area. These sensor nodes are designed to support unattended operation for long duration, mostly in remote areas, in smart building or even in hostile environment. The limitation features in sensor node architecture which include limited processing capabilities, low memory capacities and low data rate motivates the current research study to focus on designing an energy efficient mechanism that can lengthen the sensor nodes operational duration and relatively prolongs the network lifetime while providing reliable data transmission. This thesis proposes a novel approach, called an Enhanced Lightweight Medium Access Control (eL-MAC) protocol that provides a reliable data transmission and energy efficient MAC. The protocol overcomes problems due to data collision caused by hidden nodes. In addition, the protocol efficiently reduces idle energy consumption by implementing scheduled-based active-sleep algorithm where the node turns to sleep mode in an arranged manner when there is no participation in data communication. Furthermore, it is a structure-less network architecture in which the timeslot is allocated in a distributed manner via an application aware mechanism called Adaptive Multi-timeslot Allocation (AMTA). This allocation mechanism allows the node to occupy more than a slot in a frame based on the traffic condition of the application. The simulation results show that eL-MAC protocol improves power consumption and can prolong the network lifetime compared to Lightweight Medium Access Control (LMAC). Moreover, time slot management introduced in AMTA increases channel utilization by overcoming the effect of prolonging the timeslot length. The feasibility of eL-MAC protocol for low rate data transmission WSN applications is further confirmed by experimental test bed results which show a deviation of less than 10% of throughput performance compared to simulation and an impressive packet received ratio of greater than 90%.

ABSTRAK

Rangkaian pengesan tanpa wayar (WSN) adalah teknologi tanpa wayar yang terkini. Ia merupakan sistem yang terdiri daripada sebilangan nod pengesan yang saling berinteraksi bertujuan untuk mengumpul maklumat dari kawasan yang diingini. Nod pengesan ini direka untuk menyokong operasi tanpa kehadiran manusia untuk jangka masa yang lama, biasanya dalam kawasan kawalan, bangunan pintar atau pun persekitaran berbahaya. Ciri keterbatasan nod pengesan meliputi kebolehan pemprosesan terhad, kapasiti ingatan dan kadar data yang rendah, mendorong penyelidikan menumpu kepada reka bentuk mekanisme penggunaan tenaga yang boleh memanjangkan tempoh operasi nod, melanjutkan hayat rangkaian. seterusnya membolehkan penghantaran data yang boleh dipercayai. Tesis ini mencadangkan kaedah baru, dikenali sebagai protocol kawalan capaian media ringan tertingkat (eL-MAC) yang menyediakan penghantaran data yang boleh dipercayai dan menggunakan tenaga secara berkesan. Protokol ini mengatasi masalah percanggahan data akibat daripada nod yang tersembunyi. Tambahan pula, ia berkesan mengurangkan tenaga terbiar dengan menggunakan algoritma aktif-tidur berjadual di mana nod bertukar ke mod tidur secara tersusun apabila tiada penyertaan dalam komunikasi data. Tambahan pula, ia adalah binaan rangkaian tanpa struktur yang mana slot masa diagihkan secara tersebar menerusi mekanisme berpandukan aplikasi yang dinamai peruntukan slot masa berbilang suai (AMTA). Kaedah pengagihan ini membenarkan nod untuk memiliki lebih dari satu slot dalam sebuah rangka berdasarkan keadaan trafik aplikasi. Keputusan simulasi menunjukkan bahawa protocol eL-MAC memperbaiki penggunaan tenaga dan dapat memanjangkan hayat rangkaian berbanding kawalan capaian media ringan (LMAC). Tambahan pula, pengurusan slot masa yang diperkenalkan AMTA menambahkan kepenggunaan saluran dengan mengatasi kesan pemanjangan slot masa. Kebolehlaksanaan eL-MAC untuk penghantaran kadar data aplikasi WSN yang rendah disahkan dengan hasil eksperimen lapis ujian yang menunjukkan pengurangan pencapaian jumlah lepas kurang dari 10% berbanding simulasi dan kadar penerimaan paket yang mengagumkan melebihi 90%.

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d_0	-	Reference distance
E_{eL-MAC}	-	Energy consumption in eL-MAC protocol
E_f	-	Energy used per frame
E_i	-	Initial energy
P_{pd}	-	Power used in power down mode
$P_r(d_0)$	-	Received signal strength at reference distance
$P_r(d)$	-	Received signal strength at distance d
P_{rx}	-	Power used to receive data
P_{tx}	-	Power used to transmit data
R^2	-	Minimized total error
t_{bcn}	-	Time to transmit beacon message
$t_{lifetime}$	-	Lifetime of sensor node
t_{listen}	-	Time to listen to beacon message
$t_{\max\_active}$	-	Time to transmit a maximum length of data
t_{pd}	-	Time while node in power down mode
t_{sleep}	-	Time to stay in sleep mode
$t_{timeslot}$,t_{ts}	-	Timeslot length
X_σ	-	Gaussian random variable
σ_{dB}	-	Shadowing deviation in dB
$\vee$	-	An OR operation

LIST OF ABBREVIATIONS

ACK	-	Acknowledgement
AEA	-	Adaptive election algorithm
AMTA	-	Adaptive multi-timeslot allocation
API	-	Application programming interface
ASHRAE	-	American society of heating, refrigerating and air-
	-	conditioning engineers
BMAC	-	Berkeley medium access control
CAP	-	Contention access period
CDMA	-	Code division multiple access
CFP	-	Contention free period
CR	-	Communication request
CRC	-	Cyclic redundancy check
CSMA	-	Carrier sense multiple access
CSMA_ACK	-	CSMA with acknowledgement
CSMA-MPS	-	CSMA with minimum preamble sampling
CTS	-	Clear-to-send
DCF	-	Distributed coordinated function
DFI	-	Data forwarding interruption
DLL	-	Dynamic link library
DMAC	-	Data-gathering medium access control
EMAC	-	Eyes medium access control
ELMAC10	-	eL-MAC with 10% duty cycle
ELMAC10_	-	eL-MAC with AMTA and 10% duty cycle
AMTA	-	
ELMAC50	-	eL-MAC with 50% duty cycle

ELMAC50_	-	eL-MAC with AMTA and 50% duty cycle
AMTA	-	
eL-MAC	-	Enhanced lightweight medium access control
FDMA	-	Frequency division multiple access
FFD	-	Full functional device
FRTS	-	Future request-to-send
GUI	-	Graphical user interface
HVAC	-	Heating, ventilation and air-conditioning
IEEE	-	Institute of Electrical and Electronics Engineers
IP	-	Internet protocol
ITU-T	-	International telecommunication union – telecommunication
	-	sector
LED	-	Light-emitting diode
LMAC	-	Lightweight medium access control
LPL	-	Low power listening
MAC	-	Medium access control
MACA	-	Multiple access with collision avoidance
MACAW	-	MACA for WLAN
Mbps	-	Mega bit per second
MFR	-	MAC footer
MHR	-	MAC header
NAMA	-	Node activation multiple access
NAV	-	Network allocation vector
NesC	-	Network embedded system C
NP	-	Neighbor protocol
NS2	-	Network simulator version 2
OS	-	Operating system
OSI	-	Open system interconnection
PAN	-	Personal area network
PC	-	Personal computer
PCS	-	Packet check sequence
PRR	-	Packet received ratio
PS	-	Power save

RFD	-	Reduced functional device
RID	-	Radio interference detection
RSSI	-	Received signal strength indicator
RTS	-	Request-to-send
SABER	-	Sensors and buildings engineering research center
SEP	-	Schedule exchange protocol
SMD	-	Surface mount device
SPI	-	Serial peripheral interface
STEM	-	Sparse topology and energy management
SYNC	-	Synchronize
S-MAC	-	Sensor medium access control
TA	-	Time active
TC	-	Traffic control
TDMA	-	Time division multiple access
TinyOS	-	Tiny operating system
TRAMA	-	Traffic-adaptive medium access
T-MAC	-	Timeout medium access control
UML	-	Unified modeling language
USB	-	Universal serial bus
WLAN	-	Wireless local area network
WMAN	-	Wireless metro area network
WPAN	-	Wireless personal area network
WSN	-	Wireless sensor network
WWAN	-	Wireless wide area network

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CHAPTER 1

INTRODUCTION

1.1 Overview

The ability to communicate with people on the move has evolved remarkably since 1897, where Guglielmo Marconi demonstrated radio's ability to provide continuous contact with ships sailing the English Channel [1]. In the recent years, the mobile radio communications industry has grown exponentially, due to the improvement of digital and RF circuit fabrication, new large-scale circuit integration, and miniaturization technologies which provides smaller, cheaper and more reliable radio communication equipment.

These enhancements in wireless technologies contribute to the development of a new wireless communication field of research called Wireless Sensor Network (WSN). WSN is defined as a large scale deployment of sensor nodes which have the capabilities of communicating through wireless medium, ad hoc networking, and mostly immobile after the randomly deployment in the area of interest [2]. As illustrated in Figure 1.1, sensor nodes that are equipped with these types of sensors can be deployed into wide range of WSN applications such as environmental monitoring [3-7], military applications [8-10], support for logistics [11], and human-centric applications [12],[13]. In most of military applications, sensor nodes are used to collect information, generally for enemy tracking, battlefield surveillance or target classification [8],[9]. At the University of Virginia, the researchers developed intrusion prevention for the army defense system where nodes are scattered in thousands of units that will detect an intrusion of hostile units [10].

As for indoor monitoring application, Sensors and Buildings Engineering Research Center (SABER) installed fifty matchbox-sized "Smartdust Motes" throughout one of the buildings at the Department of Electrical Engineering and Computer Sciences of University of California Berkeley to monitor light and temperature [14]. The collected data can be used to utilize for optimal control of the indoor environment. The use of sensor nodes has also been preoccupied by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) to survey the advantages and drawbacks of wireless technology in the operation of heating, ventilation and air conditioning (HVAC) system [3]. In both applications, sensor nodes are targeted to help in minimizing the energy consumption for healthier environment and greater level of comfort for residents.

Intel Corporation in cooperation with Intel Research Berkeley Labs has studied the case of deploying a sensor network in a vineyard [7]. The same interest has been shown by Accenture Technology Labs [15]. Sensors supply information of humidity, wind, water, as well as soil and air temperature. It is further used for frost detection and warning, pesticide application and disease detection.

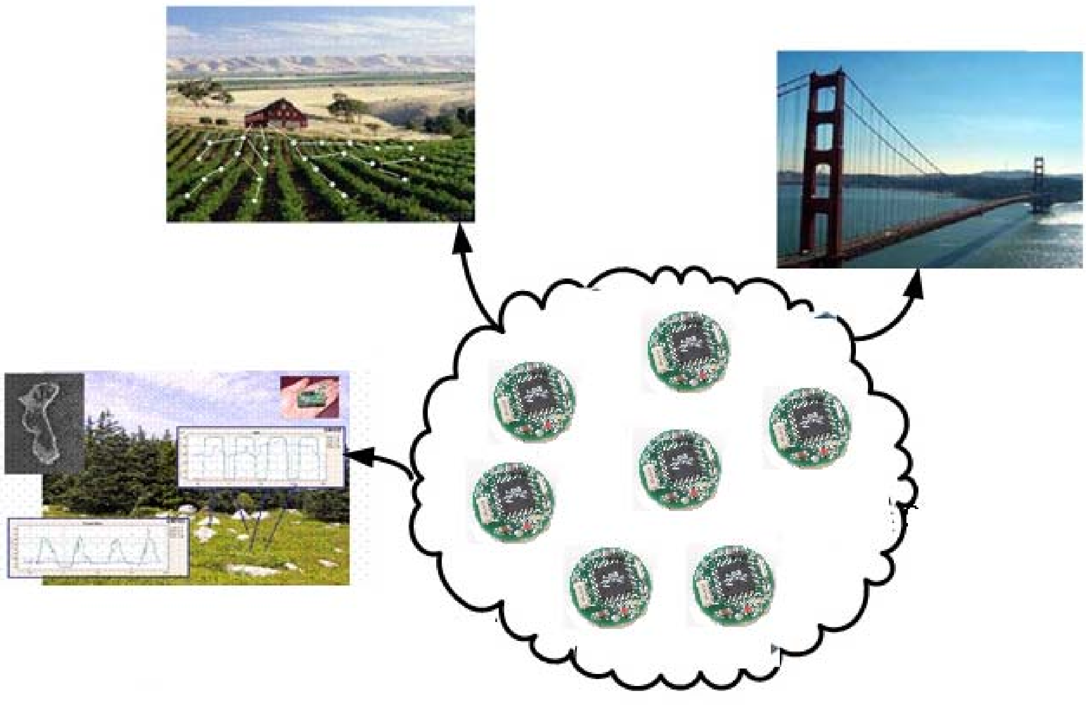

Figure 1.1 Examples of WSN application in real world implementation

Another example of WSN application in environmental monitoring is bird observation on Great Duck Island [4]. The type of researched bird is called Leach's Storm Petrel. These birds are easily disturbed by the presence of humans; hence WSN seems an appropriate observation solution. Sensor nodes are installed inside the burrows and on the surface for measuring humidity, pressure, temperature and ambient light level.

WSN has a wide range of application space as previously described. Common desirable features for most applications include robust and reliable data communications, efficient energy consumption over the WSN's lifetime, dynamic network adaptive to changes in prevailing operating conditions and low unit cost. This results in simple architectures, low processing capabilities and low memory capacities.

1.2 Motivation

In order to meet the requirements of WSN described in the previous section, a thorough understanding of the communication between sensor nodes is necessary. The definition of what constitutes acceptable performance varies in WSN according to particular application domain requirements and the network size.

This thesis addresses WSN communication in large-scale outdoor areas. Such networks typically consist of hundreds or thousands of nodes. Examples are including environmental monitoring, precision agricultural system, industrial machinery control and monitoring and urban traffic monitoring. The applications necessitate the connection of nodes that might be at kilometers away from the base station. Thus, there is a need for multi hop communication. Moreover, these applications require reliable bi-directional communication between node and base station. The sensor nodes are expected to operate in years. Hence, nodes must be equipped with an enhanced power management system that can prolong the network lifetime.

In recent years, a lot of research have been carried out in order to provide an optimize energy usage in WSN. A variety of solution has been proposed at various levels of networking, such as at application layer, routing layer and MAC layer [16]. Since, the MAC layer is located above the physical layer in Open System Interconnection (OSI) reference model [17], it has full ability to control the physical device. Therefore, managing the functionality of this layer has a large impact on the overall energy consumption and hence, the lifetime of a node.

1.3 Problem Statement

Generally, sensor nodes carry limited and irreplaceable power sources. The architecture of sensor nodes comes with a limitation in hardware resource such as low processing capability, low storage capacity and small pack of batteries. These limitation designs are caused by the requirement of WSN application which demands a huge amount of sensor nodes placement and a low cost implementation. Consequently, MAC protocol must be designed with a simple algorithm which uses small size code for low processing and small storage microcontroller. Furthermore, due to the limited capacity of batteries and the difficulty of frequent battery charging or replacement, the MAC protocol design consideration for sensor nodes must be based on efficient energy usage.

Wireless channel is naturally a shared channel. With current existing radio transceiver technology, a wireless node cannot transmit and receive simultaneously. It is a half duplex communication. By default, data transmitted by sensor node is a broadcast transmission to all neighboring nodes. Hence, it is easily exposed to the number of wireless problems such as data collision, overhearing, and idle listening. Furthermore, most low-power wireless networks usually have unreliable links with limited bandwidth, and their link quality can be heavily influenced by environmental factors [18]. These problems lead to inefficient usage of the supplied energy, providing a reliable data transmission can help in prolonging the sensor nodes lifetime.

1.4 Research Objectives

The main objective of this research is to enhance the communication performance of WSN. The term performance enhancement here is described as prolonging the network lifetime and at the same time providing a reliable data communication. As a result, the objectives of the proposed research are:

- To prolong the lifetime of WSN through active and sleep mechanism at the MAC layer implementation.
- To provide a reliable data transmission in WSN by implementing a scheduled based mechanism.

1.5 Scope of Work

In this research, the radio transceiver is based on the IEEE 802.15.4 standard [19]. Therefore, the design of MAC protocol is limited by the capabilities of the given radio transceiver. The design of the MAC protocol is targeted for low rate data communication. The research is divided into three phases; design of MAC protocol, simulation of the MAC protocol and test bed implementation.

The design of the MAC protocol is based on the scheduled based mechanism. Nodes in the network are fairly given the opportunity to transmit data through Time Division Multiple Access (TDMA) mechanism [20]. Diversity of WSN applications requires different design of MAC protocol. In this research, the proposed MAC protocol is targeted to be implemented in agricultural monitoring system. This application requires low rate data communication. Furthermore, the sensor node is a static node, which means its position remains unchanged from the beginning of nodes deployment.

The proposed MAC protocol is deployed based on the existing MAC protocol and implemented in event-driven network simulator. The simulator is developed using Java programming language. The physical layer is based on IEEE 802.15.4

standard. The simulation should reflect real access mechanism. An open source tiny operating system (TinyOS) [21] and Network Embedded System C (NesC) programming language [22] is used to develop the proposed MAC protocol based on TelosB platform [23]. The complied code is programmed into the sensor node. The test bed consists of 9 units of sensor node distributed on the field. The performance metrics such as data throughput, packet received ratio (PRR) and energy consumption of the proposed protocol are studied through simulation and are verified in real test bed implementation.

1.6 Significant Contribution of Research

This thesis describes the development of eL-MAC protocol for WSN applications which provides energy aware mechanism and reliable data transmission. The protocol implements a distributed TDMA technique inherited from LMAC protocol with further enhancements. In addition, an adaptive mechanism call AMTA has been introduced to improve the throughput of data transmission. The contributions of the thesis are listed below:

- A preconfigured duty cycle operation has been proposed for LMAC enhancement. The duty cycle can be preconfigured for different type of WSN applications. It depends on the application requirement which is either for low rate or high rate data communication.

- Leveled timeslot synchronization has been introduced to manage timeslot arrangement among nodes in the network. Node selects the best synchronized node which has the strongest received signal strength and lowest synchronization level. Thus, the algorithm prevents a node from synchronizing with any other nodes.

- The AMTA mechanism has been designed and implemented to increase the throughput performance of eL-MAC protocol. This novel mechanism allows node to occupy several number of timeslot per frame depending on the application's data transmission rate. This results an increased opportunity of packet transmission in a frame and hence improves data throughput performance.

- An event driven network simulator called MoteSim has been developed. The simulator is used to study the performance of eL-MAC protocol. The architecture design of MoteSim is based on a well known network simulator called NS2. But unlike NS2, MoteSim's architecture is not an Internet Protocol (IP) based application.

- eL-MAC protocol for TinyOS system has been developed and implemented into sensor node platform called TelosB. The source code development has been done using NesC programming language. Several new modules in TinyOS system have been introduced includes *ElmacC* module, *ElmacRadioC* module, *DebugC* module and *AppC*. This development is crucial in order to study the performance of the proposed protocol in real test bed implementation.

- The proposed eL-MAC provides energy efficient MAC protocol for WSN applications.

1.7 Organization of the Thesis

The rest of the thesis is organized as follows: Chapter 2 provides the overview of WSN network architecture including application layer, routing layer, MAC layer and physical layer in order give the basic understanding of each layer function. The chapter further describes the existing technique in MAC protocol design which includes the history of MAC protocol in wireless communication, problems in wireless data transmission and the groups of MAC protocols. The last part of the chapter elaborates the current technique in providing the solution for the given problems, and advantage and drawback of each technique.

Chapters 3, 4 and 5 describe the process of designing and implementing the proposed MAC protocol in simulation and real test bed. The design and architecture of the Enhanced Lightweight MAC (eL-MAC) is detailed in Chapter 3. Chapter 4 studies the performance of the proposed protocol within an event driven network simulator against a contention based MAC protocol and the inherited MAC protocol. Chapter 5 details the experimental performance of eL-MAC protocol through implementation of the algorithm on TelosB platform obtained from field measurement. The final chapter concludes the outcomes of the research and proposes a few ideas for future works.