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HIGH-THROUGHPUT AND ENERGY-EFFICIENT CONTIKI MAC LAYER SCHEME IN IEEE 802.15.4 FOR STRUCTURAL HEALTH MONITORING

MOHAMED ABDULKAREM TAHER AL-MEKHLAFI

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By

MOHAMED ABDULKAREM TAHER AL-MEKHLAFI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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April 2021

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The importance of wireless sensor networks (WSNs) in structural health monitoring (SHM) is unceasingly growing because of the increasing demand for both safety and security in the cities. WSN–based SHM system introduces a promising technology with compelling advantages compared to a traditional wired system. Nevertheless, the requirements of WSN-based SHM add extra complications and challenges to network design and the existing limitations of WSN technology. Some of these challenges result from the transmission of huge amounts of data in each data sensing period and the complexity of SHM algorithms. Furthermore, in WSNs, the operating system (OS) with its network protocol stack and media access control (MAC) layer protocol play an essential role in managing the scarce resources, data processing and communication. Nonetheless, in Contiki OS, there are constraints found in the actual version of Contiki that hinder its broader development, both in general and at the specific level of the network stack. Furthermore, there are constraints in implementing the provided Contiki carrier sense multiple access/collision avoidance (CSMA/CA) protocol. These constraints limit the available bandwidth by delaying data delivery and limiting the node's transmission capability along with high-power consumption.

There is a research gap in developing a Contiki MAC layer scheme able to provide high throughput and secure an efficient utilization of the radio, which is inevitably the most critical part regarding power consumption in WSN for SHM. This motivates us to develop and implement a lightweight time division multiple access (L-TDMA) scheme to overcome the existing constraints on the networking stack's implementation of MAC layer on Contiki and satisfy SHM requirements. The proposed concept is integrated with the Contiki architecture and tested experimentally and using the Cooja simulator. Besides, the design concept of the

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frame structure, slot distribution, scheduling and all associated calculations are illustrated. A synchronization model is presented with the aid of the implemented Contiki's implicit network time synchronization scheme. Finally, a case study of a WSN-based SHM system using developed embedded data filtering and transmission algorithms to reduce data communication is performed and taken place on a concrete beam at Civil Engineering Structure Laboratory, UPM.

Simulation and experiments are performed to validate the design concept of L-TDMA scheme and evaluate the sensor node's throughput, power consumption and the efficiency of the proposed embedded algorithms for SHM applications. The maximum number of packets that can be transmitted per second using L-TDMA are 137 packets (throughput of 139 kbps). In contrast, the default Contiki CSMA and TSCH can transmit at a maximum of 8 and 67 packets per second, respectively. The overall average channel throughput that can be provided by Contiki using L-TDMA is approximately 180 kbps at maximum. L-TDMA shows a significant reduction in power consumption compared to the default CSMA/CA, which achieves lower power consumption than CSMA/CA by 73% and 71% using simulation and testbed, respectively. Likewise, L-TDMA has lower power consumption by 9% than TSCH at an offered load of 8 pps. L-TDMA shows a remarkable ability to conserve power in comparison to other protocols in different operating systems. Finally, the implementation of the developed embedded algorithms for strain-based applications resulted in a power consumption reduction of 77% compared to centralized processing.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KELUARAN TINGGI DAN KECEKAPAN TENAGA SKEMA LAPISAN MAC CONTIKI DALAM IEEE 802.15.4 UNTUK PEMANTAUAN KESIHATAN STRUKTUR

Oleh

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Kepentingan rangkaian sensor tanpa wayar (WSN) dalam pemantauan kesihatan struktur (SHM) semakin meningkat, disebabkan peningkatan permintaan keselamatan dan keselamatan di bandar. Sistem SHM berasaskan WSN memperkenalkan teknologi baru dengan kelebihan menarik berbanding sistem kabel tradisional. Walaupun begitu, keperluan SHM berasaskan WSN menambah komplikasi dan cabaran tambahan pada reka bentuk rangkaian dan batasan teknologi WSN yang ada. Beberapa cabaran ini adalah hasil penghantaran sejumlah besar data dalam setiap penginderaan data, dan kerumitan algoritma SHM. Selanjutnya, dalam WSN, sistem operasi (OS) dengan susunan protokol rangkaiannya dan protokol lapisan kawalan akses media (MAC) memainkan peranan penting untuk menguruskan sumber daya dan pemprosesan dan komunikasi data. Walaupun demikian, dalam Contiki OS, terdapat kekangan dalam versi Contiki khusus yang menghalang pembangunan yang lebih luas, baik secara umum dan pada tahap rangkaian. Tambahan pula, terdapat kekangan dalam pelaksanaan protokol *Contiki carrier multi access / collision menghindari* (CSMA / CA) yang disediakan yang membatasi lebar jalur yang tersedia dengan menunda penghantaran data dan membatasi throughput nod bersama dengan penggunaan kuasa tinggi.

Terdapat jurang penyelidikan dalam mengembangkan skema lapisan Contiki MAC yang dapat memberikan keluaran yang tinggi dan menjamin penggunaan radio yang cekap, yang pasti merupakan bahagian paling kritikal dalam hal penggunaan tenaga di WSN untuk SHM. Ini memotivasi kami untuk mengembangkan dan menerapkan skema akses pelbagai pembahagian waktu ringan (L-TDMA) yang dapat mengatasi kekangan yang ada pada implementasi lapisan MAC lapisan lapisan di Contiki dan memenuhi keperluan SHM. Konsep yang dicadangkan digabungkan dengan seni bina Contiki dan diuji secara eksperimen dan menggunakan *simulator* Cooja. Selain

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itu, konsep reka bentuk struktur bingkai, pengedaran slot, penjadualan dan semua pengiraan yang berkaitan digambarkan. Model penyegerakan disajikan dengan bantuan skema penyelarasan masa rangkaian implisit Contiki yang dilaksanakan. Kajian kes sistem SHM berasaskan WSN menggunakan algoritma penyaringan regangan terdistribusi yang dikembangkan untuk pengurangan komunikasi data dilakukan dan dilakukan di makmal UPM pada balok konkrit.

Simulasi dan eksperimen dilakukan untuk mengesahkan konsep reka bentuk skema L-TDMA dan menilai throughput nod sensor, penggunaan kuasa dan kecekapan algoritma tertanam yang dicadangkan untuk aplikasi SHM. Bilangan maksimum paket yang dapat dikirimkan sesaat menggunakan L-TDMA adalah 137 paket (throughput 139 kbps). Rata-rata keseluruhan throughput saluran yang dapat disediakan oleh Contiki menggunakan L-TDMA adalah maksimum 180 kbps maksimum. L-TDMA menunjukkan pengurangan penggunaan tenaga yang ketara berbanding dengan CSMA / CA lalai, yang mencapai penggunaan daya yang lebih rendah daripada CSMA / CA masing-masing sebanyak 73% dan 71% menggunakan simulasi dan ujian. Lebih-lebih lagi, L-TDMA menunjukkan kemampuan luar biasa untuk menjimatkan kuasa dibandingkan dengan protokol lain dalam sistem operasi yang berbeza. Akhirnya, pelaksanaan algoritma tertanam yang dikembangkan untuk aplikasi berasaskan regangan mengakibatkan pengurangan penggunaan tenaga sebanyak 77% berbanding pemprosesan terpusat.

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LIST OF ABBREVIATIONS

ACK	Acknowledgment
ADC	Analog to Digital Converter
ADR	Actual Data Rate
bps	Bit Per Second
CCA	Clear Channel Assessment
CCI	Channel Check Interval
CH	Cluster Head
CPU	Central Processing Unit
CSMA/CA	Contiki Carrier Sense Multiple Access/Collision Avoidance
CTS	clear to send
DAC	Digital-To-Analog Converter
EDR	Effective Data Rate
FFT	Fast Fourier Transform
FIFO	First-In, First-Out
IOT	Internet of Things
IPC	Interprocess Communication
LEACH	Low-Energy Adaptive Clustering Hierarchy Protocol
LPL	Low Power Listening
LPM	Low Power Mode
LPP	Low Power Probing
L-TDMA	Lightweight Time Division Multiple Access
LVDT	Linear Variable Differential Transformer
MAC	Media Access Control
MCU	Microcontroller Unit

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MEMS	Micro-Electro-Mechanical Systems
MHR	MAC Layer Header
MPDU	MAC Protocol Data Unit
OS	Operating System
PHY	Physical Layer
pps	Packet Per Second
QoS	Quality of Service
RDC	Radio Duty Cycling
RFID	Radio Frequency Identification
RTS	request to send
RX	Radio Listening
SHM	Structural Health Monitoring
TCP/IP	Transmission Control Protocol/Internet Protocol
TDMA	Time Division Multiple Access
TSCH	Time Synchronized Channel Hopping
TSE	Time Synchronization Error
TX	Radio Transmission
UTM	Universiti Teknologi Malaysia
WBAN	Wireless Body Area Network
WSN	Wireless Sensor Network

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CHAPTER 1

INTRODUCTION

Wireless Sensor Network (WSN) is a promising technology that becomes a more adopted and fascinating research domain nowadays. WSNs have extensive dimensions in several applications, such as structural health monitoring (SHM), visual surveillance, and habitant monitoring to name but a few. However, WSNs sensor node has scarce resources, for example, bandwidth, energy and computation. In addition to hardware, software such as OS, network or MAC protocols and implemented algorithms can also affect node's power consumption and other performance metrics. Moreover, the characteristics and requirements of the applied application may add extra complications and issues to the available limitation of WSN technology (Noel et al., 2017). Enabling wireless sensor applications through sensor technologies brings a range of issues in WSNs that can be categorized into three groups (Yick et al., 2008): system, communication protocols, and services. As for the system, issues related to the operating system (such as Contiki), platforms, storage schemes need to be considered, in addition to the issues related to implementation adapting of protocols with operating system architecture. As for the communication protocols, there are issues related to enabling protocols (such as CSMA, TDMA, and routing protocols) to control access of nodes to the shared communication medium efficiently. Finally, for services, different challenges may hinder the development of the system services. These services such as synchronization, data aggregation and localization are developed to improve application and network efficiency as well as to optimize system performance. It is noteworthy that the essence of our work in this thesis is centered on Contiki operating system, the implementation of a TDMA-based MAC scheme to overcome the existing constraints associated with Contiki OS, the implementation of the network protocol stack, and the fulfillment of the requirements of the SHM applications. In other words, we focus on system issue, propose a solution using communication protocols and embedded processing, and adapt it to suit system architecture.

This chapter presents a general overview of the essential challenges and trends that encompass such challenges of WSNs for SHM. It explores the challenges associated with Contiki OS and the implementation of a network protocol stack. It also addresses the questions related to designing and implementing the MAC layer scheme through the proposed solutions in this work. Furthermore, the study problem, objectives, and scope are stated, as well as the contributions and publications arising from this thesis are adduced.

1.1 Background

In recent years, WSNs have gained worldwide attention and have demonstrated their usability with the increasing demand for monitoring applications and rapid development in Micro-Electro-Mechanical Systems (MEMS) technology that has facilitated the development of smart sensors. In comparison to conventional sensors,

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wireless sensors are small, with limited computation resources, and inexpensive. A sensor node can sense, gather data from the environment, and according to some local decision process, the measured data is transferred to the destination. WSNs have demonstrated their usability with the increasing demand for monitoring applications, which are now considered suitable for applications such as structural health monitoring (SHM), air pollution sensing, and agricultural monitoring. In this section, before stating the research problem, we provide a brief about WSNs for SHM, key challenges of WSNs for SHM, MAC layer protocols, challenges associated with Contiki OS and implementation of a network protocol stack, and suitability of the IEEE 802.15.4 Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) MAC layer for Real-Time Applications.

1.1.1 WSNs for SHM

The importance of wireless sensor networks (WSNs) in structural health monitoring is unceasingly growing because of the increasing demand for both safety and security in the cities. The speedy growth of wireless technologies has considerably developed the progress of structural monitoring systems with WSN technology. WSN-based SHM system introduces a novel technology with compelling advantages compared to the traditional wired system, which has the benefits of reducing installation and maintenance costs of SHM systems. SHM is a process of estimating the integrity of the civil structures based on suitable analysis of in-situ measured data. This technique is performed in various kinds of structures through detection, localization, and assessment of the damage at earlier stages, which in turn results in increasing safety and decreasing maintenance costs.

A typical WSN-based SHM system contains three main elements: a sensor system, a data processing system, and a health evaluation system (Yi & Li, 2012). Firstly, the aim of sensors used for SHM is to measure the required parameters data of a structure (e.g. acceleration, displacement, and stress) and those effective environmental parameters, such as humidity, temperature, and wind speed. Here, the accuracy and precision of the collected data are fundamental for the correct diagnosis of the structure. Secondly, a data processing system consists of data acquisition, transmission, aggregation, processing, and storage. Wireless sensor networks (WSNs) were studied as data processing systems for SHM and applied to replace traditional wired systems (Ceylan et al., 2016). WSNs contain sensor nodes deployed over a structure, and each node can collaborate with the other nodes to transmit data through the network toward a base station. Because of the availability of the traditional wired system in the market before the existence of the wireless system, it was utilized in SHM applications. The difference between using traditional wired sensor and wireless system in SHM is that the latter has sensor nodes that need a little bit of maintenance and no cables to be installed, and thus they can be installed in remote locations which used to be impractical or inaccessible (Avci et al., 2018; Ji et al., 2017). In WSNs for SHM, data acquisition is achieved by sensor nodes that collect data from SHM sensors. Then, according to communication network type (single-hop and multi-hop), sensor nodes can transmit the measured data, either directly or by forwarding data packets of each other to the base station. Data

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aggregation and processing, which are essential for extracting features of SHM algorithms, can take place in various positions (such as, sensor nodes, cluster heads, and/or base station) and can occur before or after data transmission depending on the data processing strategy and network topology. Thirdly, the health evaluation system is devised to evaluate a structure's overall safety and/or stability when the monitoring criteria are exceeded (Aygün & Gungor, 2011). The architecture of the SHM system using WSN is illustrated in Figure 1.1.

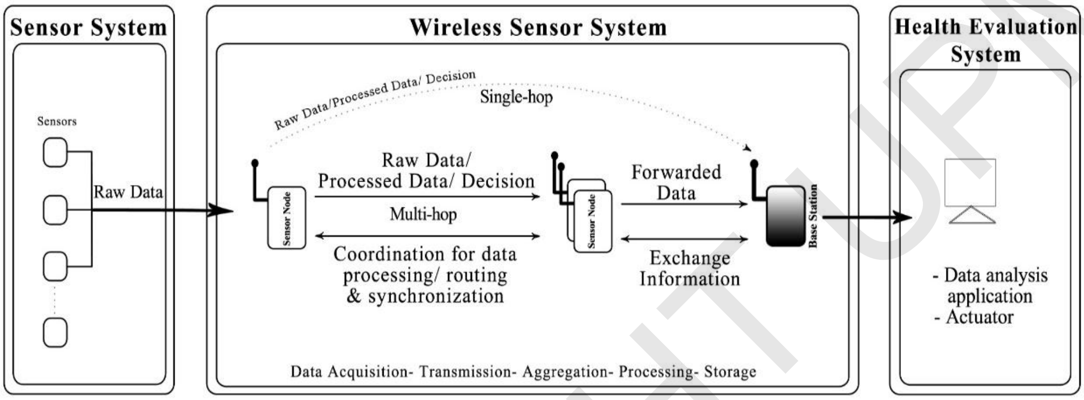

Figure 1.1 : Architecture of SHM system using WSN

1.1.2 Key Challenges of WSNs for SHM

There existed many constraints related to WSN in terms of resource and design, such as low bandwidth, short range of communication, limited processing, limited storage, and a limited amount of energy in each node. What complicates it more is that SHM characteristics and requirements added extra complications and issues to the available limitation of WSN technology. Some of these issues are results of the location, a harsh environment of civil infrastructure, large sensing scope of the wireless monitoring system, a generation and transmission of a huge amount of data in each data sensing period, and complexity of SHM algorithms, which were also developed to be processed at a centralized station. The existing challenges associated with WSNs for SHM in the rest of this section include high data rate and throughput, power efficiency, and SHM algorithms and embedded data processing.

1.1.2.1 High Data Rate and Throughput

The data rate is vital as it provides information about the network throughput requirements for near real-time performance. Additionally, it depends on the sampling frequency, which relies on the structure's essential modes of vibration. In numerous monitoring applications, the traditional uses of WSNs are cases with low data rate, small data size, low duty cycle, and low consumption of power. However, recent SHM for data-intensive applications requires a high data rate, large data size, and a comparatively high duty cycle. In SHM, various types of sensors are used to

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collect information about their surroundings like acceleration, displacement, strain, and stress that differ with the environmental conditions, for example, temperature and moisture. Hence, a high data rate guarantees acquiring a lot of data samples before completing mitigation of the seismic response of a structure and the disclosure of high-frequency accelerations (Pentaris et al., 2014).

On the other hand, having a reliable network for high-throughput data is a serious topic in WSNs for SHM. Applications of WSNs for SHM concerning throughput requirements can be categorized into two types, low and high throughput applications (R. E. Kim et al., 2016). As for the category of low throughput applications, the data may consist of many packets. Nevertheless, in such a data-intensive application, data generation takes place much faster than it can be transmitted. Also, failures, which take place while data is in transmission, usually cause data loss, considerably declining the performance and accuracy of monitoring that can be implemented (Bocca et al., 2011; R. E. Kim et al., 2016; Pentaris et al., 2014).

1.1.2.2 Power Efficiency

Power efficiency is a primary crucial aspect in the development of WSNs. In most cases, a battery is used to power the sensor nodes, and there is an extreme limitation in the available energy amount. Relying on the frequency of making a diagnosis, a wireless SHM system once deployed is anticipated to be effective for months or even years. Therefore, reducing power consumption is a major issue in WSNs for SHM, particularly in resource-constrained sensor networks. Hence, the impacting factors, which make the power efficiency of sensor nodes an essential consideration in WSNs for SHM, are location and environment, working principle and mode, complex SHM algorithms, network protocols, and data processing. Moreover, a variety of techniques have been proposed to solve this problem. Such techniques are as follows: Radio optimization, data reduction, sleep/wake up approaches, power-efficient routing, and battery repletion, as they can be used for extending the WSNs lifespan (Anastasi, Conti, et al., 2009; Rault et al., 2014). Thus, all these factors will be explored and discussed in Chapter 2 and the available mechanisms to address this challenge using hardware or software (OS and MAC protocols).

1.1.2.3 SHM Algorithms and Data Processing

The algorithms used in WSNs for SHM (e.g. modal analysis, damage detection, and system identification.) are more sophisticated computationally than those used in other WSNs application, which may lessen or even neutralize the obtained benefits (Xuefeng Liu et al., 2009). Data processing in WSNs for SHM usually indicates the implementation of SHM algorithms within sensor nodes or base station. In that way, raw data, processed data, or decision will be received by the base station according to the data processing strategy used. A general classification for data processing can be divided into two primary categories: centralized and distributed data processing.

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The primary challenge here is the way of adapting the existing SHM algorithms within the mote's OS for decentralized embedded processing architecture with low power consumption and minimum data communications between sensor nodes for data-intensive SHM (Avci et al., 2018; G.-D. Zhou & Yi, 2013).

1.1.3 MAC Layer Protocols

The IEEE 802.15.4 MAC protocols can provide low duty cycles and provide mechanisms that control access to the shared communication medium in WSN by ensuring that the data transmissions of different sensor nodes do not collide with each other. In the context of WSNs, another responsibility assigned to MAC protocol is to secure an efficient utilization of the radio, which is inevitably the most critical part regarding power consumption. Therefore, MAC layer usually gives the priority for power efficiency, and then reliability and throughput take place. Generally, MAC layer protocols can be classified to fall into one of the two broad categories (Mouzehkesh et al., 2015); contention-based and contention-free (schedule-based). In contention-based protocols, such as CSMA, each sensor node competes for channel access when there is a need for data transmission without any guarantee of success. In contention-free MAC protocols, such as TDMA, a predefined schedule is required, and only one sensor node is assigned to access the channel at any given time. Besides, IEEE802.15.4 MAC layer protocol supports two medium access modes: the slotted mode (beacon-enable mode) and unslotted mode (non-beacon-enable mode) (Tall et al., 2015). The former utilized a slotted CSMA/CA scheme with a superframe structure, whereas the latter utilized unslotted CSMA/CA. In this work, schedule-based protocol (TDMA) is our focus with comparing the performance with CSMA/CA protocol in Contiki.

1.1.4 Challenges Associated with Contiki OS and Implementation of Network Protocol Stack

This section illustrates the constraints associated with the basic design of Contiki network stack, which can be a barrier to implementing a MAC layer protocol and affect its performance.

1.1.4.1 Complexity of Network Stack

The Contiki network stack (Netstack) suffers from excessive layerization, as it adopts a five-layer network stack, which is slightly different from the five layers of TCP/IP model. In-between the Physical (Radio) and the Network layers, where the data link layer is usually located, Contiki has three layers which are Framer, Radio Duty Cycling (RDC), and MAC layers (Pedro, 2014; Roussel & Song, 2015).

While the design of Netstack can theoretically afford more flexibility in the implementation, it truly adds complexity to the development of a MAC protocol (Roussel & Song, 2015). As a part of this excessive layerization and separation, there is a distinction between the RDC layer, which is supposed to manage the way that the radio transceiver is turned on or off, and the MAC layer, which is responsible for ordering and sequencing packet transmissions. Furthermore, to dynamically adapt network efficiency and power consumption to the ongoing traffic, managing both layers in practice is taking place by most modern MAC protocols (e.g.: (Nefzi & Song, 2012)). Therefore, this separation is at best difficult and becomes artificial, which only adds unnecessary complexity to the implementation of MAC protocol. For instance, ContikiMAC, which is the default Contiki RDC protocol, has to be utilized with a MAC protocol such as CSMA/CA or nullMAC protocol that adds more testing scenarios for analyzing the best selection of MAC driver in order to achieve optimal performance. Moreover, the lack of documentation about network stack implementation makes it difficult to understand the design concepts behind various network stack implementations.

1.1.4.2 Unique Packet Buffer

One of the features of the design of Contiki Netstack to save memory is that it is centered on a unique packet buffer that is internally called *packetbuf*; thus, all layers of the stack operate on this *packetbuf* (Halkes & Langendoen, 2007). However, this design has undesirable consequences such as potential packet loss when accessing the buffer while a packet arrives or the disability to properly handle queues. Another disadvantage of this design is the inability to efficiently handle packet queues buffer *queuebuf*, as the centered design of the unique packet buffer means unceasing copies between the packet buffer and the queues, which consequently leads to a waste of processing power, time, and even memory.

1.1.4.3 Delay from Callback Timer

For data transmission, Contiki utilizes a callback timer that gets its arguments as expiry time and a pointer to a defined function that performs as an event handler, which is called eventually after saving the event in the event queue and timer expires. Since events are released in a First-In, First-Out (FIFO) method, there is a possibility not to carry out the events handler immediately in case of the availability of multiple pending events, which restricts the ability of node to transmit data packets (Farooq & Kunz, 2015).

1.1.5 Analytical Studies of MAC Layer

In the WSNs community, MAC layer protocols have taken great attention and explored thoroughly with respect to development or adaption to suit different applications' requirements. However, most of these studies were analytically evaluated and proved or did not implemented experimentally in real WSN platform and did not consider the constraints associated with the OS that have effects on the performance of a sensor node. Thus, several researchers highlighted that analytical studies often fail to foretell the quality of service (QoS) parameters of a sensor node

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from an application's perspective or the inability to apply those protocols to practical. There are several reasons for that allegation: first, the generated overheads due to OS's architecture and network protocol stack have effects on a node's power consumption and performance; second, practical protocols rely on empirical parameter settings (Farooq & Kunz, 2015). While these parameters have a substantial influence on the system performance, they are not comprehensively addressed and analyzed in the analytical studies (Djenouri & Bagaa, 2014); third, it is still very difficult to apply those existing analytical models. One of the reasons for the difficultly of applying those existing analytical models is that most of them don't consist of the network's parameters such as capture effect and actual channel model. The details of actual implementations of the operating system, limit and optimizations are frequently ignored. Otherwise, the model could be too complicated to be analytically resolvable (Despaux et al., 2014). Finally, heavy or centralized computation and global information are required to enhance the system's performance by several available protocols (J. Wang et al., 2016).

On the other hand, there are some simulators that emulate the OS and the network. For instance, Contiki has a simulator named Cooja uses for the rapid development of sensor networks (Tong et al., 2016). One of the important differences from other network emulators like OMNeT++, OPNET, and NS-2/3 is that Cooja carries out simulations according to Contiki OS and entirely emulate hardware platforms. In other words, the codes simulated in Cooja can be uploaded to real mote even without any modification that makes establishing realistic node networks tremendously easier.

Therefore, evaluation of the real implementation, testbed, and OS's emulators (e.g. Cooja for Contiki and TOSSIM for TinyOS) plays an important role to provide an accurate evaluation of MAC Layer protocols' performance as well as to be able to consider the constraints associated with the OS that have effects on the performance of a sensor node.

1.1.6 Suitability of Contiki CSMA for Real Time Applications

Contiki OS provides unslotted IEEE 802.15.4 CSMA/CA MAC protocol, which takes care of the organization of medium access in the WSN, when each sensor node has packets to be transmitted or received. In the MAC layer, when null radio duty cycling (nullRDC) scheme is used and before transmitting every packet, a delay is imposed by the carrier sensing mechanism (Farooq & Kunz, 2015; Tall et al., 2016). Then, carrier sensing is performed, and if the channel is found to be idle, the packet is transmitted immediately. Nevertheless, sensor node backs off for a random amount of time as soon as the clear channel assessment (CCA) detects a busy channel. The random backoff interval relies on the channel check interval (CCI) utilized by the RDC protocols, which is 125 ms for nullRDC and ContikiMAC protocols. It is noteworthy that ContikiMAC is a default implemented RDC mechanism that allows nodes to keep their radio off most of the time. However, nullRDC is a null RDC

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layer, which never turns off the radio; thus, it is usually implemented for testing or comparing it with other mechanisms of RDC.

Furthermore, the Contiki CSMA/CA MAC protocol can work in two modes reliable and unreliable. When a reliable mode is utilized, acknowledgement (ACK) is activated to guarantee the reliability; each received packet will be acknowledged, and MAC layer waits for a period of time to detect an ACK when Tmote sky mote is implemented. After a potential ACK is detected, another delay is imposed to be able to read the packet out from the radio (Farooq & Kunz, 2015). Moreover, when no ACK message is acknowledged and the timer expires, the MAC layer then retransmits the corrupted or lost packet after a random exponential back-off delay if the number of retransmissions does not exceed three attempts of retransmission for the same packet. When the unreliable mode is used, retransmission of data packets is not performed. Thus, enhancements in the node's transmission rate and end-to-end delay may appear as there is no need for the node to wait for ACK reception, yet the packet loss rate may increase.

Generally, the communication process of Contiki CSMA and RDC increases delay, thus it seems that the performance of node's throughput may degrade, which affects the average channel throughput, primarily due to CCA delay and ACK overhead. On the other hand, CSMA/CA suffers from high-power consumption, as the major sources of power wastage, that is caused during communication process, are collision, retransmission, idle-listening, overhearing, and control packet overhead (Khan & Ali, 2016; Kochhar et al., 2018).

In case of SHM applications, the end-to-end throughput along with power consumption are two of the metrics of interest. Therefore, in this work, comprehensive experiments for Contiki 3.0 CSMA/CA protocols take place to examine their suitability for IEEE 802.15.4 WSN-based SHM applications in. In addition, we introduce several factors that affect the node's transmission capability and channel throughput along with power consumption that demonstrate the limitation of Contiki CSMA/CA MAC protocol in WSN for SHM applications.

1.2 Problem Statement

The importance of WSNs in SHM is unceasingly growing because of the increasing demand for both safety and security in the cities. WSN–based SHM system introduces a novel technology with compelling advantages in comparison to the traditional wired system. However, the characteristics and requirements of WSN-based SHM system added extra complications and issues to network design and the existing limitations of WSN technology. Some of these issues are due to the location, generation and transmission of a huge amount of data in each data sensing period, and the complexity of SHM algorithms. The issue here is the limited resource and bandwidth of the node and the power consumption associated with the requirements of SHM algorithms due to their need for computational resources and process procedures (Noel et al., 2017).

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Furthermore, in WSN environment, an application usually executes over the operating system (OS), and data transferred by application program crosses the network protocol stack. Hence, the generated overheads due to OS architecture and network protocol stack possess effects on the node's power consumption and throughput, and thus analytical studies often fail to foretell the QoS parameters of a sensor node from an application's perspective (Despaux et al., 2014; Djenouri & Bagaa, 2014; Farooq & Kunz, 2015; J. Wang et al., 2016), unless considering the constraints associated with the OS that have effects on the performance of a sensor node.

While Contiki OS is one of the most well-known OS of WSN, it is still in the early stage of developing and implementing schedule-based MAC protocols. Consequently, it needs to be evaluated and deeply examined in terms of the constraints associated with it. Furthermore, the existing MAC designs in Contiki are limited, and they may have some restriction in various Contiki versions that hinder its broader development. These constraints exist both in general and at the specific level of Netstack. Lack of documentation, the complexity of Netstack, separation of MAC and RDC layers, centralization of Netstack on a unique packet buffer are all considered constraints in Contiki OS (Roussel & Song, 2015). In addition, the constraints associated with the implementation of the provided Contiki MAC layer protocol, CSMA/CA, limits the available bandwidth in IEEE 802.15.4-based networks by delaying data delivery and limiting the node's throughput (Farooq & Kunz, 2015; Tall et al., 2016). For instance, during the transmission stage, when a packet is available to be sent in the MAC layer, the carrier sensing is delayed by 125 ms, then the packet is transmitted, which limits data transmission. What complicates the above is a high-power consumption associated with CSMA/CA due to collision, retransmission, idle-listening, overhearing and control packet overhead during the communication process.

Generally, some of the aforementioned constraints restrict the implementation of a new MAC protocol, and others directly influence both power consumption and throughput of the sensor node. Therefore, providing flexibility in the selection of MAC protocols to be implemented in an OS becomes critical to best meet the requirements of each certain application as no single MAC protocol is suitable for all situations, and it is highly dependent on the scenario and application's requirements (Mary et al., 2018; Onwuegbuzie et al., 2019). Moreover, embedded data processing becomes substantial for WSN based-SHM systems to enhance network throughput and reducing power consumption (Battista et al., 2016).

These constraints provide a research gap in developing a Contiki MAC layer scheme that is able to provide high throughput and reliability and secure an efficient utilization of the radio, which inevitably is the most critical part regarding power consumption in WSN for SHM. This development must take place by overcoming the existing constraints associated with Contiki OS, MAC protocols, the implementation of the network protocol stack, and the fulfillment of the requirements of the SHM applications. Characteristics of schedule-based protocol motivated us to develop and implement a lightweight TDMA (L-TDMA) scheme to close this

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research gap, which is not available in Contiki 3.0 and would overcome OS's implementation constraints and balance the tradeoff between optimization of node's throughput and power consumption. Lastly, we implement a WSN strain-based SHM system and develop a data filtering and transmission algorithm for embedded data processing using L-TDMA to reduce the amount of data being transmitted, thereby enhancing throughput and minimizing the power consumed for wireless communication.

1.3 Scope of Study

This study proposes high throughput and power-efficient solutions for WSN-based SHM applications. Generally, this work mainly takes place in the embedded system field relating to Contiki OS and its network stack implementation in conjunction with MAC and RDC layer protocols to handle the radio communication. As the implementation of the proposed solutions is carried out to meet SHM applications' requirements, the study's performance metrics are throughput and power consumption. Specifically, at the node level, to optimize throughput and power conservation, protocols and mechanisms need to be developed, which can be extended to involve the operating system's issues to meet the requirement of a specific application. The inclusion of all possible solutions would be a very extensive topic for one study, so this work mainly provides solutions concerning the MAC layer in conjunction with the network stack of Contiki OS. Furthermore, as the role of communication and computation in practice depend basically on the platform and application, the focuses here are based on reducing radio communication, overcoming the imposed constraints on the OS's Netstack and MAC levels, particularly in developing a MAC scheme, and embedded data processing at node level and applying the proposed solutions on a real testbed deployment.

1.4 Aim and Objectives of Study

The main aim of this research is to close the research gap that exists on the implementation of a MAC layer on Contiki OS by providing high-throughput and energy-efficient solutions that fulfill the requirement of WSNs for SHM. The objectives of the research are formulated for the following:

- To investigate the constraints' effect of Contiki OS, network protocol stack's implementation, and MAC protocol on the node's throughput and power consumption.

- To develop and implement a lightweight TDMA-based MAC layer scheme on Contiki that is able to enhance node's throughput along with conserving power.

- To implement a WSN strain-based SHM system using the proposed L-TDMA MAC scheme for optimizing throughput and reducing power consumption.

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1.5 Contributions and Publications Arising from this Thesis

This study contributes to the research domain of Contiki Netstack and its MAC layer protocol implementation and takes part towards the SHM. The contributions of this research are summarized as below:

1. It introduces a comprehensive review for collective experience the researchers have gained from the application of WSNs for SHM, which includes technologies of wired and wireless sensor systems along with wireless sensor node architecture, functionality, communication technologies, and its popular OSs; besides, the state-of-the-art academic and commercial wireless platform technologies used for SHM, and also classification taxonomy of the key challenges associated with WSNs for SHM to assist in understanding the obstacles and the suitability of implementing WSNs for SHM applications.

2. It analyzes the effect of Contiki OS and implementation of the network protocol stack on the node's throughput and power consumption and IEEE 802.15.4 channel utilization by identifying the constraints associated with them. Besides, it studies the suitability of the provided Contiki's IEEE 802.15.4 CSMA/CA MAC layer protocol for real-time SHM applications.

3. It develops and implements the L-TDMA MAC scheme on Contiki OS, which is able to overcome the identified constraints and enhance the node's throughput and power consumption, using simulation and experiments. In addition, it provides a comparative analysis of the proposed scheme with the provided Contiki CSMA/CA MAC protocol and other MAC protocols implemented on TinyOS.

4. It develops and implements embedded data filtering and transmission algorithm that is able to optimize node's throughput, and power consumption and evaluating sensor node performance in comparison with the wired system in a laboratory testbed for concrete monitoring.

5. It presents a comparative analysis of data processing for both centralized and embedded data processing strategies to demonstrate the limits of a standard node Microcontroller Unit (MCU) and MAC protocol when dealing with high-bandwidth sensing.

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1.6 Thesis Organization

The remaining chapters of this work are organized as the following:

Chapter 2 gives an overview of wireless sensor networks for SHM, which consists of different subsections; wired-based and wireless systems comparison with the main components of the WSNs and its well-known operating systems, SHM sensors, hardware design, available mechanisms to address the challenges of WSNs for SHM and SHM algorithms and embedded processing. Furthermore, CSMA and TDMA Protocols comparison and MAC layer power consumption factors are explored and summarized. In addition, the other three sections thoroughly focus on analyzing MAC layer protocols and hence motivates the direction of this research by comprehensively investigating their performance and suitability. The literature review is then concluded with limits of a standard node MCU and MAC protocol when dealing with high-bandwidth acceleration sensing and using different MAC protocols.

Chapter 3 presents a comprehensive overview of the methodology, design, and tools utilized throughout this research study. This chapter is divided into four primary sections; first, flowchart and procedure of the research methodology; second, Contiki L-TDMA MAC scheme design and implementation; third, WSN strain based-SHM system and embedded data filtering and transmission algorithm design and implementation; and fourth, performance metrics and experimental setup. In the first section, the flow chart of research methodology, the tools, and materials are described. In the second section, the design concept and objectives, and L-TDMA's frame structure, synchronization, and scheduling approaches are discussed. A detailed description of the proposed scheme and its architecture and implementation follow. In the third section, the wireless strain sensor, and the proposed embedded data filtering and transmission algorithm with integrating them into L-TDMA and Contiki are described in detail. Finally, performance metrics and experimental setup of both L-TDMA and WSN strain-based SHM system with its proposed embedded data filtering and transmission for strain-based applications and Fast Fourier Transform (FFT) algorithm implementations' scenarios are presented.

Chapter 4 presents the results and discussions. A detailed analysis and performance evaluation and power consumption for the MAC scheme on Contiki are depicted and discussed using simulation and experiment. Comparative evaluation of performance and power consumption for MAC protocols on Contiki and TinyOS are exhibited. Finally, comparative analysis of centralized and embedded algorithms using WSNs in terms of throughput and power consumption are thoroughly discussed.

Chapter 5 summarizes the thesis to exhibit how the objectives of the proposed design and aims of the research are achieved, and suggestions and directions to future work are given.

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