UNIVERSITI PUTRA MALAYSIA

SCHEDULING AND BANDWIDTH ALLOCATION IN COGNITIVE RADIO SENSOR NETWORKS

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By

MOHAMMED AHMED ALI AL-MEDHWAHI

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

November 2018

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DEDICATION

In memory of my mother
To my father
To my wife, for her kindness and devotion, and for her endless support
To my son; ***Hamzah***

. . .

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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November 2018

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The rapid expansion of wireless monitoring and surveillance applications in several domains reinforces the trend of exploiting emerging technologies such as the cognitive radio (CR). A cognitive radio sensor network (CRSN) is a promising technology to meet the rapid demand for implementing wireless sensor network (WSN) applications in new fields beside the conventional ones. CRSN technology enables sensor nodes to utilize licensed radio channels opportunistically for the new applications, which combine various types of data, traffic patterns, and quality of service (QoS) requirements. However, several challenges arise due to the conventional capability-limitation of end-sensor nodes and the strict obligations required for the licensed users. Hence, there is a critical need to manage the network's limited resources efficiently.

In this research, a new paradigm for CRSN is proposed to achieve a significant balancing between network's complexity, cost, lifetime, scalability and QoS satisfaction. In particular, an efficient resource allocation scheme is proposed to deal with multi-level of heterogeneity that becomes a common advantage in the emerging networks. The proposed scheme tackles provisioning multilevel of QoS for two key resource allocation elements, namely, the scheduling and the radio channel allocation.

This research focuses on proposing a new cognitive radio-based medium access control (MAC) scheme that treats the heterogeneous nature of new networks in terms of the traffic pattern and the required QoS. In addition to addressing and modelling delay, throughput, and power consumption, several other performance metrics such as reliability and scalability have been treated efficiently when designing the scheme. The proposed paradigm decreases the consumed power on several fronts and achieves up to 68% as power-saving for the end-sensor nodes.

The effectiveness of the proposed scheme also includes increasing the opportunity to utilize a wider range of the radio spectrum. Furthermore, to reinforce the scheme's

efficiency and mitigate interference, the impact of data packet size on the performance of the adaptive CRSN is also analysed to determine the appropriate size. As a result, the proposed scheme is quite appropriate for real time monitoring and critical communications applications that acquire significant attention in the next 5G of wireless networks.

In addition, the proposed method is analysed and modelled in both homogeneous and heterogeneous radio environments. Simulation results and the comparisons with related works show that the proposed scheme provides satisfactory levels of latency and spectrum utilization thanks to the efficiency of the scheduling and radio allocation mechanism.

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

PERUNTUKAN PENJADUALAN DAN LEBAR JALUR DALAM RANGKAIAN SENSOR RADIO KOGNITIF

Oleh

MOHAMMED AHMED ALI AL-MEDHWAHI

November 2018

Pengerusi: Fazirulhisyam Bin Hashim, PhD
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Perkembangan yang pesat dalam aplikasi pemantauan wayarles dalam beberapa domain telah mendorong trend untuk mengeksploitasi teknolgi baru seperti radio kognitif (CR). Rangkai radio kognitif sensor (CRSN) merupakan sejenis teknologi yang berpotensi tinggi untuk memenuhi keperluan pesat bagi melaksanakan aplikasi rangkai sensor wayarles dalam medan baru selain daripada medan lazim. Teknologi CRSN membolehkan nod sensor untuk mengambil kesempatan semasa mengakses saluran radio berlesen.

Aplikasi baru mempunyai beberapa jenis data, ciri-ciri traffic, dan keperluan kualiti perkhidmatan (QoS). Walau bagaimanapun, beberapa cabaran timbul disebabkan oleh keupayaan konvensional- nod sensor akhir yang terhad dan kewajipan ketat yang diperlukan terhadap pengguna berlesen. Oleh itu, keperluan untuk menguruskan sumber rangkaian yang terhad dengan cekap adalah amat kritikal. Dalam kajian ini, paradigma baru untuk CRSN dicadangkan untuk mencapai keseimbangan yang signifikan antara kerumitan rangkaian, kos, masa hayat, keboleh-skalaan dan kepuasan QoS. Khususnya, skim peruntukan sumber yang cekap dicadangkan untuk menangani keheterogenan pelbagai tingkat dalam CRSN. Skim yang dicadangkan ini menangani peruntukan QoS pelbagai tingkat untuk dua elemen peruntukan sumber utama, iaitu penjadualan dan peruntukan saluran radio. Penyelidikan ini memberi tumpuan untuk mencadangkan skema kawalan capaian media (MAC) berasaskan radio kognitif baru yang melayan keheterogenan rangkaian baru dari segi ciri-ciri traffic and QoS yang diperlukan.

Di samping menangani dan pemodelan kelewatan, daya tampung, dan penggunaan kuasa, beberapa metrik prestasi seperti kebolehpercayaan dan kebolehskalaan telah dirawat dengan cekap semasa merancang protokol. Paradigma yang dicadangkan telah mengurangkan kuasa yang digunakan pada beberapa bidang dan mencapai 68% sebagai penjimatan kuasa untuk nod sensor akhir. Keberkesanan skim yang dicadangkan juga termasuk peningkatan peluang untuk menggunakan spektrum radio

yang lebih luas. Untuk mengukuhkan kecekapan skim, impak saiz paket data terhadap prestasi CRSN mudah suai juga dianalisis untuk menentukan saiz yang bersesuaian. Oleh itu, skim yang dicadangkan agak sesuai untuk pemantauan masa nyata dan aplikasi komunikasi kritikal yang mendapat perhatian penting dalam rangkaian tanpa wayar 5G seterusnya.

Di samping itu, kaedah yang dicadangkan ini telah dianalisis dan dimodelkan dalam persekitaran radio homogen dan heterogen. Hasil simulasi dan perbandingan dengan kerja yang berkaitan menunjukkan bahawa skema yang dicadangkan menunjukkan kependaman rangkaian dan penggunaan spektrum yang memuaskan kerana efisiensi mekanisme penjadualan dan radio.

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I certify that a Thesis Examination Committee has met on 23 Nov. 2018 to conduct the final examination of **Mohammed Ahmed Ali Al-Medhwahi** on his thesis entitled "**Scheduling and Bandwidth Allocation in Cognitive Radio Sensor Networks**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the **Doctor Of Philosophy**.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

5G	5th Generation
ACK	Acknowledgement
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BC	Business Continuity
BE	Backoff Exponent
BE	Best Effort
BPSK	Binary Phase Shift Keying
BS	Base Station
CBR	Constant Bit Rate
CC	Common Control
CCA	Clear Channel Assessment
CH	Cluster Head
CR	Cognitive Radio
CRSN	Cognitive Radio Sensor Network
CS	Carrier Sensing
CSMA	Carrier Sensing Multiple Access
CTS	Clear to Send
CW	Contention Window
DCA	Dynamic Channel Allocation
DDT	Dynamic Distribution Table
DIFS	Distributed Inter Frame Space
DOSS	Dynamic Open Spectrum Sharing
DSA	Dynamic Spectrum Access
DSSS	Direct Sequence Spread Spectrum
ECC	European Communications Committee
ED	Energy Detection
EDF	Earliest Deadline First
FCA	Fixed Channel Allocation
FCC	Federal Communications Commission
FCFS	First Come First Served
HQ	High Queue
IEEE	Institute of Electrical and Electronics Engineers
IFS	Interframe Space
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
IT	Interference Temperature
ITU	International Telecommunication Union
IWSAN	Industrial Wireless Sensor and Actuator Network
LQ	Low Queue
MAC	Medium Access Control
NAV	Network Allocation Vector
NB	Number of Backoff
NRT	Non Real Time
O-QPSK	Offset Quadrature Phase Shift Keying
OSA	Opportunistic Spectrum Access
PAN	Personal Area Network

PCMAC	Pliable Cognitive MAC
PU	Primary User
QoS	Quality of Service
RT	Real Time
RTS	Ready to Send
SIFS	Short Inter Frame Space
SNR	Signal to Noise Ratio
SS	Spectrum Sensing
SU	Secondary User
TDMA	Time Division Multiple Access
TRAMA	Traffic Adaptive Medium Access
WRAN	Wireless Regional Area Network
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 Background

Wireless sensor networks (WSNs) are the most pervasive networks that have rapid increasing applications. Their main work concept is to sample physical values from the application environment and convey them to the management and controlling system where they can be processed and the useful information will be concluded. WSN application fields include e-Health, habitat monitoring, security, home control, industrial control and monitoring, asset tracking, supply chain management and smart cities. Typically, WSN consists of numerous number of small, low power, low transmission range, low data rate and low cost units, called the sensor nodes, deployed in a large scale area. WSN has a sink node that acts as a network gateway and it is responsible for collecting data from the end-sensing nodes.

Internet of things (IoT) is a new concept for enabling the connectivity anywhere, any time for any thing. The interoperability will be available between heterogeneous applications. The IoT concept is mainly driven by the WSN's applications market [1] [2]. WSN operates in the licensed-free radio spectrum bands, i.e., industrial, scientific and medical (ISM) bands, where technologies like cordless phones, Bluetooth, remote controls and WiFi also use the same bands. Sensing-node's resources limitation is the toughest obstacle against achieving high performances in such a hostile radio environment with a sever contention caused by the radio spectrum scarcity. Additionally, the inevitable interference induces high rates of data loss. The resulted excessive energy consumption will ultimately shorten the WSN network's lifetime [3].

Meanwhile, emerging monitoring applications and services employ various forms of data traffic and they are described as heterogeneous networks which means that they are built-up of various sensor types and serve different services. Because of this, there is a rapid need for new solutions that take into consideration the necessity of provisioning multiple QoS levels.

In the same time the new solutions should overcome challenges that can lead to significant performance degradation or even to a network failure, they must cope with WSN common characteristics [4]. In contrast to the congestion situation in the unlicensed bands, most of the licensed bands that are assigned to licensed users tend to become underutilized. Recent studies have shown that most licensed radio bands are underutilized for 15 - 85% of the time depending on the spatial location [5][6]. Utilizing unused radio spectrum becomes a promising solution to alleviate the congestion problem in the unlicensed radio spectrum.

Opportunistic spectrum access (OSA) is a recent concept that describes the dynamic utilizing of the radio spectrum holes in order to increase the efficiency of the spectrum utilization. Owing to that concept, cognitive radio (CR) technology employs the OSA strategy to permit unlicensed users, called secondary users (SUs), to share the

spectrum with licensed users, primary users (PUs). The latter users still have the priority of using the spectrum.

The cognition concept in CR implies obtaining knowledge about the geographical and operational conditions of the working field and exploit this knowledge to achieve deployment objectives through operational changes and then to learn from the resulted status in the next cognition cycle. Similarly, cognitive radio sensor network (CRSN) can be described as a WSN network that has the capability to utilize spectrum holes and it resembles other CR networks in their main principles.

1.2 Problem Statement

Beside the capability constrains that is the key attribute of the sensor nodes, there are strict obligations towards the licensed users in the CRSN. Moreover, the nature of the emerging applications requires providing multilevel of QoS. Currently, the available conceptions of dealing with such challenges are not efficient in terms of managing the available resources.

Existing solutions result in more negative effects regarding the network's complexity, power consumption, interference and cost aspects. In other words, the proposed solutions do not ensure the balancing between the required provisioning of QoS levels for the applications and maintaining the conventional characteristics of the WSN end-sensing nodes.

The majority of those studies employ inefficient architectures for the network and deal with end-sensor nodes as high-capability devices when they design their MAC protocols. Moreover, most of the current studies have not either treat the heterogeneity in the radio spectrum to be utilized in the CRSNs or treat the heterogeneity in the adjacent radio spectrum bands. Furthermore, no real attention to the absolute constraints that the CRSN's system must comply within order to protect primary users. In our study, we present a comprehensive solution that allocates network's resources in such a way that ensures provisioning multi-levels of QoS in the same time of requiring no more significant computational changes in the WSN.

1.3 Motivation

Managing the limited resources of a CRSN is of great significance in the trends of implementing the CR technology in the emerging WSN applications. In this research, we aim at stepping forward to deploy CR technique in WSN applications via proposing an efficient scheduling and radio resources scheme. The scheme copes with the common characteristics of the traditional WSN, ensures provisioning of multilevel of QoS and meets the obligations towards the licensed users.

1.4 Research Objectives

This research aims at proposing an efficient scheduling and resource allocation scheme. Accordingly, the objectives of this study can be summarized as follows:

1. Proposing an appropriate network's architecture with efficient work flow that not only incorporate CR technique, but also maintain sensor common characteristics.

2. Proposing a robust MAC protocol that encompasses an efficient scheduling and resource allocation scheme for a heterogeneous network operating in homogeneous CRSN's radio environment.

3. Enhancing the proposed MAC protocol to be suitable for heterogeneous networks that operate in heterogeneous CRSN's radio environments.

4. Investigating the impact of the packet size on the performance of the CRSN and determining the appropriate size, which is a key element to mitigate interference problem.

1.5 Research Scope

This research is mainly concerned about the affordable techniques and methods by which the traditional WSN can exploit CR technique to enhance its performance and to mitigate effects of the existing problems that associate CRSN implementation. Designing the network architecture and dividing it into two tiers and studying and analyzing the important issues in the each tier shape the general frame of the work. That enables us to focus more on the main issues that related to our main concern in the second tier in which the CR technology is exploited. Evaluating the performance of the proposed MAC protocol out of modelling the main performance metrics of wireless networks, namely delay and throughput.

1.6 Research Contributions

The main contributions of this research include:

1. Reinforcing the trends toward implementing CR technology in WSN domains through overcoming the significant challenges facing WSN technology such as the spectrum scarcity and the hostile radio environment.

2. Presenting a technical feasibility study of how to employ the CR technology in new monitoring fields in an efficient way that adds as less complexity as possible and maintains the conventional advantages of the WSN.

3. Proposing an efficient scheduling and resource allocation scheme for the CRSN that ensures multilevel of QoS provisioning with a robust performance even in various conditions of the radio environment. This scheme treats the real time and critical communications efficiently in terms of the delay and the correlated transmissions.

4. Allowing targeting wider ranges of the radio spectrum by enabling utilization of more channels belonging to different radio environments.

5. Extensive simulations are conducted to study the performance of the proposed scheme under various network settings, and comparisons are made with the related existing works

1.7 Research Challenges

Proposing a scheduling and resource allocation scheme for CRSN networks encounters many more challenges than that for other traditional networks. These challenges include:

- Delay: Delay is one of the key performance metrics and QoS measurements. For many emerging applications, the average packet delay must be in its minimal bounds.

- Power consumption: In designing the operations of the protocol, it is essential to consider the difficulties to renew the ideal sensor's source of energy. Decreasing the average delay time for the data packets does not ensure increasing the network's life time since it might require more computational capabilities and more complex operations.

- Heterogeneous data traffic: Regarding the emerging surveillance and monitoring applications, it is important to treat the diversity of data traffic, traffic pattern, and the required QoS. Special data transmissions such as the correlated transmissions for the event-based measurements is, also, an aspect of this issue.

- Obligation towards the primary network: Lacking of accuracy in the spectrum sensing functions would definitely cause interference between secondary users and primary users signals, which will be harmful for both networks.

1.8 Thesis Organization

This thesis is organized as follows:

- **Chapter 1** generally introduces the research's background, scope, contributions and difficulties.

- **Chapter 2** gives an overview of WSN and CRSN technologies and their mechanisms for scheduling and resource allocation. The key issues were explored with the related problems that have been addressed to date.

- **Chapter 3** explores the framework of the research and presents an idea about the research stages and the methods we take to treat each stage. It also shows the systematically the study is based on.

- **Chapter 4** presents the proposed architecture and working model of the CRSN's network. It also shows the analytical modelling and the evaluation of the network's performance in the first tier of the network architecture.

- **Chapter 5** introduces, in details, the proposed MAC protocol, Pliable Cognitive MAC (PCMAC). It also presents the anlaysing and modelling of the performance of the proposed protocol. Eventually, it evaluates the performance of the proposed protocol with a simulation and a comparison with a wll-known work.

- **Chapter 6** shows the improved version of the proposed protocol, iPCMAC. It presents iPCMAC's outperformance that makes it suitable for the heterogeneous radio environments. It also highlights the significant impact of the packet size on the performance of the protocol and presents performances of packets with various sizes: small, medium and large. It concludes with suggestion about the appropriate size that results in the optimal performance.

- **Chapter 7** concludes the research and recommends the future works.

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LIST OF PUBLICATIONS

Journals Papers

M. Al-Medhwahi, F. Hashim, B. M. Ali, A. Sali. 2016. Pliable Cognitive MAC for Heterogeneous Adaptive Cognitive Radio Sensor Networks. PloS one Journal, 11(6), p.e0156880.

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