ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING BASED COGNITIVE RADIO USING GNU RADIO AND UNIVERSAL SOFTWARE RADIO PERIPHERAL

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To my beloved mother, siblings, friends and colleagues...

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ABSTRACT

The current development of wireless communication infrastructures and technologies have caused frequency spectrum to become scarce. It is also found that underutilization of spectrum occurred on conventional fixed spectrum management policy. Therefore, lots of research has been done to utilize these spectrum in an efficient manner by opportunistically exploiting the underutilize incumbent's spectrum. Cognitive Radio (CR) has been introduced as a promising way to utilize this unused spectrum through frequency, time and space domain. The main functionalities of CR are spectrum sensing, spectrum management, spectrum mobility and self-learning. To support high data transmission rate, Orthogonal Frequency Division Multiplexing (OFDM) with flexible modulation and high spectral efficiency has been considered. In this thesis, an experimental Software Defined Radio (SDR) platform which consists of GNU Radio and Universal Software Radio Peripheral version two (USRP2) are developed for OFDM-based CR system as proof-of-concept. Edge Energy Detection (EED) as a new joint sensing decision mechanism between Energy Detection (ED) and Edge Detection is proposed to improve the sensitivity of spectrum sensing. The experimental work is carried out in an ad-hoc network which resulted in time and frequency synchronization between nodes becoming crucial task. Therefore, Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) protocols are deployed to ensure reliable communication system is achieved. Furthermore, Reinforcement Learning (RL) concept is adopted in this system for self-learning of the surrounding radio environment. The results showed: performance metrics in term of probability of false alarm (P_{fa}) and probability of detection (P_d) for EED are improved by 10% as compared to ED and Edge Detection; CSMA-RL decreases the total number of collision by 50% over CSMA; and the number of data packets loss is decreased during switching transitions. Finally, the proposed system is evaluated with multimedia data transmission applications and results show the throughput and other performance metrics are significantly improved. In conclusion, this proposed CR system is proven beneficial for future communication technology in term of spectrum utilization.

ABSTRAK

Perkembangan infrastruktur komunikasi tanpa wayar dan teknologi telah menyebabkan spektrum menjadi terhad. Spektrum juga didapati tidak digunakan dengan sepenuhnya disebabkan oleh dasar lama polisi pengurusan spektrum yang tetap. Oleh itu, banyak penyelidikan telah dilakukan untuk menggunakan spektrum secara cekap dengan mengeksploitasi spektrum yang tidak digunakan oleh pemilik secara oportunistik. Kognitif Radio (CR) diperkenalkan agar spektrum dapat diguna sepenuhnya melalui domain frekuensi, masa dan ruang. Fungsi-fungsi utama CR adalah pengesanan spektrum, pengurusan spektrum, mobiliti spektrum dan pembelajaran sendiri. Bagi menyokong kadar penghantaran data yang tinggi, Pemultipleksan Bahagian Frekuensi Ortogon (OFDM) dengan pemodulatan yang fleksibel dan kecekapan spektrum yang tinggi telah dipertimbangkan. Dalam tesis ini, eksperimen Radio Takrifan Perisian (SDR) yang terdiri daripada radio GNU dan Periferal Radio Perisian Universal versi kedua (USRP2) dibangunkan untuk pembuktian konsep CR berdasarkan OFDM. Pengesanan Pinggir Tenaga (EED) sebagai satu mekanisme pengesanan spektrum baharu yang menggabungkan keputusan Pengesanan Tenaga (ED) dan pengesanan pinggir telah dicadangkan untuk meningkatkan sensitiviti pengesanan spektrum. Eksperimen ini dijalankan dalam rangkaian *ad-hoc* yang menyebabkan penyelarasan domain masa dan frekuensi antara nod adalah mencabar. Oleh itu, protokol Capaian Berbilang Bahagian Masa (TDMA) dan Capaian Berbilang Deria Pembawa (CSMA) digunakan untuk memastikan sistem komunikasi yang baik dapat dicapai. Tambahan pula, konsep Pengukuhan Pembelajaran (RL) digunakan dalam sistem ini untuk pembelajaran sendiri daripada persekitaran. Hasil kajian menunjukkan: metrik prestasi dari segi kebarangkalian penggera palsu (P_{fa}) and kebarangkalian pengesanan (P_d) dipertingkatkan sebanyak 10% berbanding dengan ED dan pengesanan pinggir; jumlah perlanggaran CSMA-RL berkurangan sebanyak 50% berbanding CSMA; dan bilangan kehilangan paket data dikurangkan semasa beralih peralihan. Akhirnya, sistem yang dicadangkan ini dinilai dengan aplikasi penghantaran data multimedia dan keputusan menunjukkan peningkatkan penghasilan dan lain-lain prestasi metrik yang ketara. Kesimpulannya, sistem CR ini terbukti dapat dimanfaatkan kepada teknologi komunikasi di masa depan terutamanya dalam penggunaan spektrum.

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LIST OF ABBREVIATIONS

ADC	–	Analog-to-Digital Converter
ATIM	–	Ad-hoc Traffic Indication Map
AWGN	–	Additive White Gaussian Noise
CAZAC	–	Constant Amplitude Zero Autocorrelation
CCC	–	Common Control Channel
CFAR	–	Constant False Alarm Rate
CoE	–	Centre of Excellence
CP	–	Cyclic Prefix
CR	–	Cognitive Radio
CRC	–	Cyclic Redundancy Check
CRN	–	Cognitive Radio Network
CS	–	Carrier Sense
CSMA/CA	–	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	–	Carrier Sense Multiple Access with Collision Detection
DAC	–	Digital-to-Analog Converted
DCF	–	Distribution Coordination Function
DFT	–	Discrete Fourier Transform
DIFS	–	DCF Interframe Space
DSA	–	Dynamic Spectrum Access
DVB	–	Digital Video Broadcasting
ED	–	Energy Detection
EED	–	Edge Energy Detection
FCC	–	Federal Communications Commission
FES	–	Frame Exchange Sequence
FFT	–	Fast Fourier Transform
FPGA	–	Field Programmable Gate Array
GSM	–	Global System for Mobile

IP	–	Internet Protocol
IQ	–	Inphase-quadrature
ISI	–	Inter-symbols Interference
ISM	–	Industrial, Scientific and Medical
LTE	–	Long Term Evolution
MA	–	Multiple Access
MAC	–	Medium Access Control
MBWA	–	Mobile Broadband Wireless Access
MCMC	–	Malaysian Communication and Multimedia Commission
OFDM	–	Orthogonal Frequency Division Multiplexing
PC	–	Personal Computer
PHY	–	Physical
PN	–	Pseudorandom Noise
PSD	–	Power Spectral Density
PU	–	Primary User
QoS	–	Quality of Service
RF	–	Radio Frequency
RL	–	Reinforcement Learning
RL-DSA	–	Dynamic Spectrum Assignment based on Reinforcement Learning
SDR	–	Software Defined Radio
SNR	–	Signal-to-Noise Ratio
SU	–	Secondary User
SYNC_REQ	–	Synchronization Request
SYNC_RES	–	Synchronization Response
TDMA	–	Time Division Multiple Access
USB	–	Universal Serial Bus
USRP	–	Universal peripheral Software Radio
UWB	–	Ultra Wide Band
WLAN	–	Wireless Local Area Network
WSN	–	Wireless Sensor Network

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CHAPTER 1

INTRODUCTION

1.1 Background

The radio spectrum of communication technologies are mostly characterized by the fixed spectrum management policy, which it is regulated by government radio regulatory such as Malaysian Communication and Multimedia Commission (MCMC) in Malaysia. Under MCMC regulatory, the radio spectrum is been allocated to various users or services according to the legislation of Malaysia and Federal Communications Commission (FCC) as shown in Figure 1.1 [1].

Before year 1990, the fixed spectrum management policy was being served well [2]. However, there was a dramatic development in communication industries leading to more wireless services emergence nowadays, especially mobile services which tremendously accessing resulted in spectrum congestion. This leads to the scarcity of spectrum and straining researches to start investigating the effectiveness of conventional policy as well as to any possible solutions for the congested spectrum.

As seen in Figure 1.1, the spectrum allocation of Malaysia starts from 3kHz until 420THz. These spectrum bands are assigned to the licensed users and unlicensed users according to their objectives and geographical coverage for long term agreement. Licensed user has the right to operate exclusively in the dedicated radio spectrum in a given geographical area. Meanwhile, unlicensed user has no exclusive right on the radio band and being forced to compete with other users in the unlicensed spectrum.

The spectrum frequencies below 3GHz is noticeably less compact and underutilized compared to the upper of 3GHz frequency as illustrated in Figure 1.1. These underutilized spectrum can be improved through allowing unlicensed user (hereinafter called as a secondary user (SU)) to access and occupy the spectrum opportunistically when it's detected vacant or unusable by the licensed user (hereinafter called as the primary user (PU)).

Another typical spectrum sensing for allocated spectrum scenario is shown in Figure 1.2. The spectrum bands in Figure 1.2 showed those spectrum bands with high distribution of signal strength amplitude are heavily utilized. Meanwhile, other parts of the spectrum bands with low signal strength amplitude are moderately utilized. The rest spectrum bands with experienced almost noise floor signal strength amplitude are sparsely utilized. Those sparsely used spectrum bands or channels are named as spectrum holes, where these spectrum bands are not being utilized temporally and spatially [3] [4] [5].

According to terms and conditions of the FCC's legislation, SU is allowed to coexist with PU under strict restrictions which one of the requirements is no interference to the PU radio spectrum [5]. These coexistence and spectrum sharing between SU and PU spectrum are possible through dynamic spectrum access (DSA) algorithm. By referring to the P1900.1 standard as defined by SCC41 working group [6], DSA is a technique that enables SU having real-time adjustment of spectrum utilization according to the environment changes and system parameters of PU.

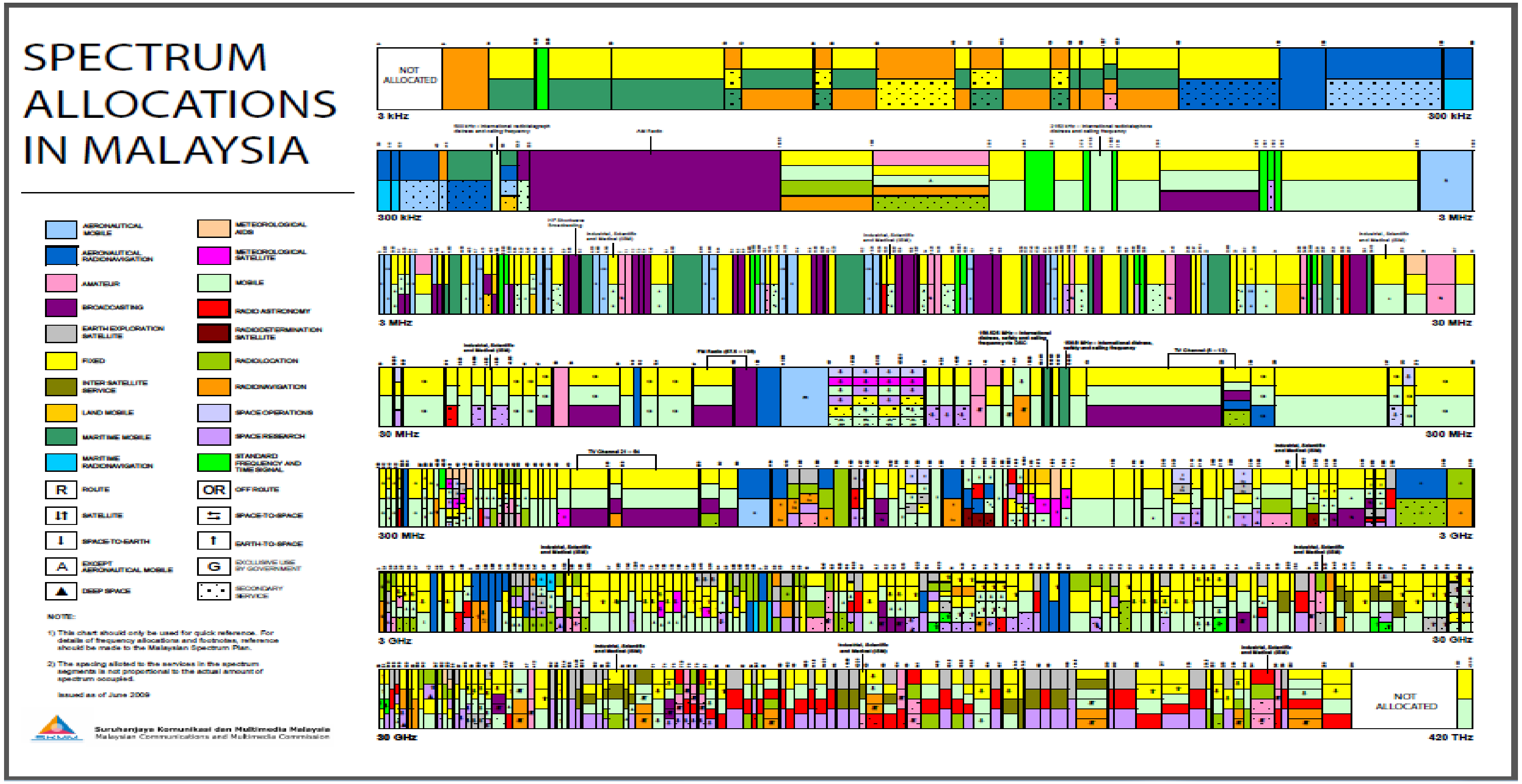

Figure 1.1: Spectrum Allocation in Malaysia Issued June 2009 [1].

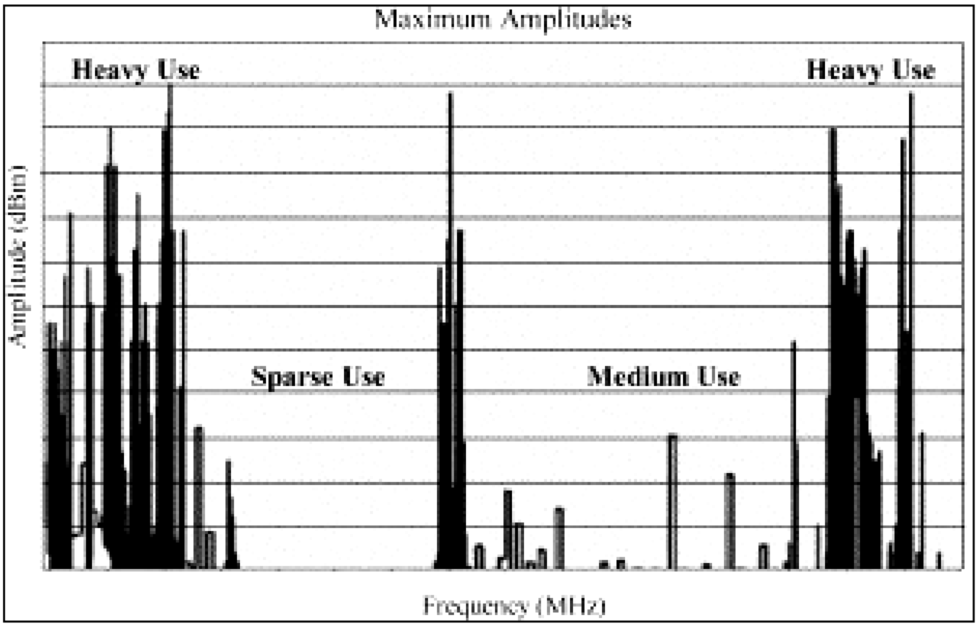

Figure 1.2: Spectrum Sensing.

In order to deploy the DSA technique, an intelligent radio technology called cognitive radio (CR) is introduced. CR is capable of scanning and monitoring the geographical environment; self-learn about the dynamic changes; and make decisions based on the information collected [6]. CR offers as an intelligent solution to the DSA by enabling SU to adapt into the environment of PU in term of frequency and time domain through spectrum scanning, spectrum decision, spectrum management, spectrum sharing and spectrum learning.

1.2 Problem Statement

Most of the current systems for wireless communications, such as IEEE 802.11x (WLAN), IEEE 802.16 (WiMAX), IEEE 802.20 (Mobile Broadband Wireless Access (MBWA)) and Long Term Evolution (LTE), are using Orthogonal Frequency Division Multiplexing (OFDM) signaling [7] since OFDM is flexible in adopting into different transmission environment and available resources due to multi-carriers modulation feature [8]. These provide a suitable physical (PHY) layer platform for CR application. Therefore, a practical implementation of OFDM-based

CR systems on a software defined radio (SDR) platform has to be investigated and evaluated.

In a CR system, spectrum sensing is responsible for scanning and be aware of the unpredictable changes of the PU environment when the SU is accessing into the PU channel opportunistically. The conventional Energy Detection (ED) method is widely used in spectrum sensing due to its simplicity and no prior information is required. However, ED is too dependent on the pre-determined detection threshold level [9], where this drawback causes sensing sensitivity decrement. Hence, a new method should be proposed to improve the ED method.

On the other hand, PU hidden nodes and synchronization are challenging issues to be addressed in CR ad-hoc network. To solve these problems, a cooperative sensing mechanism with suitable multiple access protocol is needed.

In order for the SU to access agilely and adapting into the PU environment without facing lots of failures and collisions, an efficient spectrum management mechanism is required. Self-learning knowledge mechanisms for spectrum management can improve the overall system performance [10]. So far, most of the learning mechanism [11] and other related works [12] have been done in simulation. No development on a SDR platform has ever been addressed yet. Thus, the challenge here is to construct a reconfigurable SDR system that meets and solves the aforementioned problems through a proof-of-concept of OFDM-based CR system.

1.3 Research Objectives

The main goal of this research work is to solve the issue of underutilized spectrum in order to benefit more wireless communication technologies. The specific objectives of this research include:

- To develop a new spectrum sensing algorithm, Edge Energy Detection (EED) through ED and Edge Detection joint sensing decisions.
- To implement a cooperative sensing mechanism using Time Division Multiple Access (TDMA) protocol for CR ad-hoc network.
- To design and implement carrier sense multiple access with collision detection (CSMA/CD) protocol and reinforcement learning (RL) algorithm on spectrum management.
- To develop an OFDM-based CR system on SDR platform and analyzed with multimedia application.

1.4 Research Scope

In this research, the modulation scheme for the PHY layer transmission is OFDM and the environment of PU's spectrum is based on 2.4GHz IEEE802.11 (WLAN) standard. The experimental work is conducted at UTM MIMOS Centre of Excellence (CoE) laboratory on a SDR platform which consists of GNU Radio open source software and the Universal Software Radio Peripheral (USRP2) hardware. Two SU nodes and one PU node are used, where all nodes are in stationary position. Eight channels among WLAN channels are sensed for multi-channel accessing and one channel (center frequency 2.482GHz) is chosen as a common control channel (CCC).

This research is divided into three parts: spectrum sensing and synchronization designs, spectrum management design, and test-bed implementation. The design of spectrum sensing is based on the ED and Edge detection techniques. Both techniques are jointed at decision level by using logic rules for the EED mechanism. The performance metrics of spectrum sensing: probability of false alarm (P_{fa}) and probability of detection (P_d) are carried out and analyzed. To illustrated hidden node problem, two case scenarios: non-hidden node problem and hidden node problem are considered and solved through the implementation of a cooperative EED mechanism and TDMA-based synchronization.

The design of the spectrum management phase includes CSMA and RL management. Finally, multimedia application is tested with the proposed CR system. The performance metrics such as number of collision, throughput, and Audacity[1] software are evaluated through simulation and verified on a test-bed implementation.

1.5 Research Contributions

The development and implementation of OFDM-based CR on the ad-hoc network by using the SDR platform provide a solution for solving the spectrum scarcity problem. The significances and contributions of this research are listed as follows:

- Proposed a novel EED spectrum sensing algorithm with ED and Edge Detection joint spectrum sensing decision.
- Development and implementation of TDMA-based protocol for synchronization and exchanging information in CR spectrum management has improved the CR system performance significantly.
- Proposed a CSMA/CD with RL protocol for medium access control (MAC) layer, which helps the CR to improve on the QoS of application.
- Development of a practical OFDM-based CR system which benefits the future OFDM wireless communication technologies.

1.6 Organization of Thesis

Chapter 1 covers the background of CR, problem statement of research, research objectives, research scope and contributions.

Chapter 2 deliberated on literature review on CR, CR's network architecture, OFDM-based CR system, spectrum sensing, DSA, spectrum management on MAC,

1 Audacity is a free, easy-to-use, multi-track audio editor and recorder for Windows, Mac OS X, GNU/Linux and other operating systems. “http://audacity.sourceforge.net/about/”

SDR platform, related works and identifying the research gap. The reviews on the constraint of spectrum sensing techniques and protocols on MAC are also discussed.

In Chapter 3, the system design and architecture of the proposed OFDM-based CR system in an ad-hoc network are discussed. The CR system design is divided into three phases which are spectrum sensing, synchronization and spectrum management. The experiment of setup includes: SDR platform, parameter setup and the GNU Radio software modules for OFDM, are also described in this chapter.

In Chapter 4, a cooperative EED sensing mechanism is presented. This includes the implementation and performance analysis of the proposed EED mechanism. The performance of the developed cooperative EED with TDMA-based protocol of synchronization on the SDR platform is evaluated for two scenarios cases: non-hidden node scenario and hidden node scenario.

In Chapter 5, the CSMA-RL management is developed and embedded into the proposed system design. The evaluation and analysis of the proposed CR system with multimedia application are presented in this chapter as well.

Chapter 6 concludes the findings of this research and provides recommendations for future works.

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